

The Pennsylvania State University

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**PARAMETRICALLY-INFORMED EARLY-DESIGN GUIDANCE FOR MASS TIMBER
FLOORS FOR EMBODIED CARBON AND STRUCTURAL DESIGN**

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Architectural Engineering

by

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ABSTRACT

Within the last decade, mass timber structures are gaining traction in the U.S. commercial construction market for a variety of reasons, including their prefabrication capabilities, low embodied carbon contribution (EC), ability to expose the timber for aesthetics, and their potential to reduce construction schedules and site work. Of these, the low material EC of timber structural elements can contribute to projects' sustainability goals while industry seeks to reduce energy use in construction and buildings. Because modern mass timber structures are relatively new, there is limited design guidance at the intersection of EC and structural design to guide practitioners' early-stage design decision-making.

Therefore, the goal of this research is to fill in design guidance gaps for mass timber structures by answering questions about trends in EC and structural design, comparisons to baseline concrete floors, the impact of prescriptive fire design options, designing for acoustic insulation beyond code, and key design guidance for mass timber.

To fill in the gap and address these questions, this research focuses on mass timber and hybrid mass timber floor systems. A parametric model was developed for five floor systems, all of which have cross laminated timber (CLT) floors. Two systems have glue-laminated timber (Glulam) framing, one with and one without infill beams. Two systems have steel W-shape non-composite framing, again one with and one without infill beams. The final is a timber-concrete composite floor system with steel shear connectors. The parametric model varied floor geometry, the number of infill beams, the prescriptive fire design approach, and system type to generate a set of approximately 5,500 designs. The designs were automatically sized using the smallest structural elements meeting requirements for flexure, shear, fire design, deflections, and control of walking-induced vibrations. The models assumed code minimum acoustic insulation; however, improved acoustic assembly options were catalogued and studied for their impacts on structural depth, mass, EC, and acoustic insulation metrics including sound transmission class (STC) and impact isolation class (IIC).

The parametric modeling output for each design included minimum element sizes, system depth, material takeoffs, system mass, and EC. The results were used to study the impacts of design variables on performance metrics including depth, mass, and EC. Using the findings of this analysis, design recommendations were developed to inform early-design decision-making.

Some key results and recommendations are summarized here. If reducing EC and mass is a main priority, consider sourcing the most sustainable timber available, avoid designs which are

overly deep, avoid a steel hybrid system with infill beams, and limit designs to a maximum of a single infill beam where applicable and possible. If reducing depth is a main priority, select a steel-hybrid system to take advantage of steel's greater spanning capabilities, select a bay aspect ratio of 1.0 or greater so the steel girders are spanning the short direction, and design for small bay sizes less than 20 feet. When designing for fire, plan to select a minimum 5-ply panel for the combined fire design configuration for a 2-hr FRR with 40 minutes of char and 80 minutes of noncombustible protection. Plan to select a minimum 7-ply panel for the exposed fire design configuration for a 2-hr FRR with 2 hours of char.

Due to the nature of parametric modeling to inform early design, there are limitations to this research to facilitate a clear analysis and understanding of the model results and trends. Connections informed boundary assumptions but were not modeled, the focus was on gravity loads only, systems were modeled at the scale of a single bay, loads assumed residential occupancy or similar loads, a single mid-range wood grade was assumed in structural calculations, fire design is based on prescriptive and conservative design procedures, and design for the control of walking-induced vibrations uses simplified procedures. Despite these limitations, model verification based on real case study projects found that the model produced realistic sizing results, and is considered valid for the scope and goals of this research.

Future work that will come directly out of this dissertation includes the development of an interactive web-based tool and accompanying design guide based on the design guidance and recommendations for mass timber floor system design within this research. The industry would additionally benefit from further research related to this topic, including similar parametric studies of lateral systems, full-scale building analysis, studies into cost and scheduling, parametric studies of the contribution of connections, and research on the optimization of carbon storage versus building height, envelope area, and operational energy.

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DEDICATION

To my soulmate Daniel,
the most lion-hearted person I know.

Love you always, Samantha.

Chapter 1

Introduction and Research Objectives

A variety of building project types over the centuries have incorporated timber structural elements; however, modern buildings follow strict timber design regulations for fire safety, thus largely limiting structural timber's application to only small projects until recently. [1] Increases in building height that led to the modern-day skyscraper were driven by advances in steel and concrete construction, and resulted in a shift away from timber for many commercial projects as structures were built taller. [2] Now, similar advances are in motion for structural timber, where mass timber construction has increased its market share in the US, Canada, and Europe due in large part to recent innovations in engineered timber products such as Cross Laminated Timber (CLT).

Due to these advances and with the provision of the new 2021 International Building Code (IBC) supporting mass timber, U.S. mass timber projects can now be built taller than historical projects, up to 18 stories or more with special approvals [1]. Many of these projects include residential occupancies [5, 6] and have adopted hybrid construction, often utilizing steel and concrete lateral systems. [3] One of many motivators to build such projects is mass timber's potential to reduce a structure's embodied carbon (EC), or the estimated equivalent carbon emissions resulting from fabrication, transportation of materials, and the construction process [5].

The building sector is working to reduce energy usage, and one of the ways to do so is to reduce EC quantities in built projects. Material selection can play an important role in a building's EC, particularly the structure. Structural applications of mass timber may help reduce a project's EC when used in place of, or in strategic combination with, concrete and steel [2, 3]. As a result, more designers are incorporating mass timber into their projects. However, at the time of this writing, there are limited design tools and early design guidance that would assist designers

to better understand what decisions affect their EC reduction goals and in what circumstances all-mass timber or hybrid-mass timber options are best suited for reducing EC.

While a range and variety of structural design software and life cycle analysis (LCA) tools exist to aid designers when looking at LCA of conventional steel, concrete, and masonry structures, many limitations exist for timber in early design. Existing structural software applications often do not easily consider unique serviceability requirements for mass timber, such as control of walking-induced vibrations [8–10]. Other timber-specific software applications typically are not designed for schematic phase or early-design use. While manufacturers often offer technical guides with initial sizing guidance, these are not integrated with guidelines for reducing EC. Although carbon tools are available to estimate EC, these tools tend to focus on estimates for specific projects rather than providing guidance for decision-making. At the time of this research, no resource had compiled both structural design and EC data into a single comprehensive tool or set of detailed recommendations for early-design decision making.

1.1 Research Objectives and Scope

The goal of this dissertation work is to fill the gaps discussed previously that exist in design guidance for mass timber structures by linking EC data and structural design data. Because this research is centered around aiding decision-making during early-stage design, a parametric analysis approach was taken to study and answer the following research questions:

- What are the trends in EC and structural design objectives for a variety of mass timber and hybrid mass timber floor systems?
- How do mass timber and hybrid mass timber floor systems compare to baseline steel-reinforced concrete floor systems in relation to EC and structural design objectives?
- How do prescriptive fire design options affect EC and floor system depth for mass timber and hybrid mass timber floor systems?

- How does designing for improved acoustic insulation beyond code minimum for floor assemblies affect mass timber EC and floor system depth?
- What recommendations and guidance should be provided to inform decision making during early design?

1.2 Organization

Following this introduction, this dissertation is organized into six main chapters that focus on different, but related, aspects of this research. Each of these six main chapters was written as a stand-alone paper, which has either previously appeared in conference proceedings, or is currently in-review for publication as conference papers or journal papers. Each chapter includes an introduction which clarifies the status of the related paper or papers, their context in the overall dissertation, and individual author contributions for multi-authored papers. Below is a summary of the main chapters and how they relate to each other.

Chapter 2: Literature Review of Tall Mass Timber Structures and Parametric Design includes an in-depth literature review of tall mass timber design and research. This paper sets the stage for the importance of mass timber in the construction industry, as well as the knowledge gaps that exist, some of which are partially addressed through the remaining chapters of this dissertation.

Chapter 3: Mass Timber Floor Systems Methodology presents the general modeling and analysis methodologies that were used throughout this research. The modeling for this dissertation focused on mass timber floor systems to test processes and because floor systems contribute a significant portion of total EC to an overall mass timber structural system. This chapter presents a more generalizable framework for how to approach modeling and verification of an early-stage design model, as well as design examples. The following chapters include additional detail and specificity related to the specific content of a given chapter.

Chapter 4: Mass Timber Floor Systems Results and Application is the main chapter of this dissertation discussing the results and analysis for the studied floor systems, focusing on structural aspects and perspectives. Floor systems are compared for structural objectives and features such as element sizing, system depth, mass, controlling limit states, utilization, and span limits. An analysis of embodied carbon in relation to these structural items is also included.

Chapter 5: Impacts of Fire Design on Mass Timber Floors uses the same data set as in Chapter 4, but focuses on how fire design affects mass timber floor design and embodied carbon. This chapter includes two in-press papers, one of which is more academic-focused, the other written with an industry-focused perspective. Both papers consider two passive fire protection options for mass timber: char design using sacrificial timber and protection via a noncombustible material, in this case, drywall. Systems are compared for EC and floor system depth.

Chapter 6: Acoustic Assemblies for Mass Timber Floors looks more closely at how different performance requirements for acoustic insulation of floor assemblies. While the previous chapters assumed code minimum acoustic insulation for the studied floor assembly designs, this chapter analyzes the effects of increasing acoustic insulation metrics on embodied carbon and floor system depth.

Chapter 7: Summary Design Guidance looks more holistically at the work of the previous chapters to summarize the resulting design guidance and recommendations based on the previous results and analyses. This chapter aims to present the work of this dissertation in a format that is more easily accessible and useful to designers looking for data and recommendations for early design decision-making.

Following the main chapters of this dissertation is a brief conclusion chapter noting the key takeaways and findings of this research. Also summarized are the main limitations and suggestions for future work.

Chapter 2

Literature Review of Tall Mass Timber Structures and Parametric Design

This chapter's literature review comes from an in-progress review paper which is intended to review the state of the art on tall mass timber structures, computational design for mass timber structures, and related topics. The paper included in this chapter is an expanded version of the review paper and includes additional information about topics covered in the remainder of the dissertation, including sustainability considerations, embodied carbon data sources and assumptions, early design tools and software, parametric design, and mass timber project trends.

The literature review in this chapter begins with introductory material about the research methodology for the review as well as a history of tall structures to provide context and set the stage for the development of tall mass timber structures. The paper then discusses the unique behaviors and properties of timber structural materials. A section is included to discuss timber's role in sustainability, green building certification, and embodied carbon accounting. Next, structural research, advances, and gaps are discussed, as well as aspects of computational design. The review concludes with a discussions oof multi-disciplinary considerations and current mass timber structure building trends.

2.1 A State-of-the-Art Review of Cross Laminated Timber Applications and Use in the Design and Construction of Mid- to High-Rise Mass Timber Buildings

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2.1.1 Abstract

This paper provides a review of the state-of-art of the application of Cross Laminated Timber (CLT) to mid- and high-rise mass timber projects in the building industry. CLT is a relatively recent innovation in structural engineered timber projects, invented in the 1990's, and entering the United States and Canadian building sectors in the early 2010's. This paper provides some background on the contextual history of tall buildings and wood structures. Then the paper includes a discussion and review of the current knowledge of mass timber within a broad range of disciplines including structural performance, sustainability, architectural design, fire performance, and more. Finally, some timber and hybrid timber project trends and best practices are discussed, followed by a discussion of future work.

2.1.2 Introduction

Historically, timber has been a commonly used structural material in a variety of building project types over the centuries; however, the regulation of wood in building projects is driven by the safety of wood during fires, thus largely limiting its application beyond small projects until

more recent times. [1] Tall modern buildings have been predominately built out of steel, concrete, and masonry. Increases in building heights that led to the modern-day skyscraper were driven by advances in steel and concrete construction, and resulted in a shift away from timber for many commercial projects as structures were built taller.[2] Recently, mass timber construction has increased its market share in the US, Canada, and Europe due in large part to recent innovations in engineered timber products such as Cross Laminated Timber (CLT). Globally, mass timber is being used in increasingly taller structures of 10 stories or more with post-and-beam systems that use CLT floor panels and frames constructed of timber or other structural materials [3].

Where mass timber is being used in taller structures, designers have been mixing structural material types when permitted by building codes. A brief summary of terminology is provided for clarity, and to define the main terms which will be used throughout this paper. An all-timber structure is one in which all of the main structural elements are composed of structural timber products. Although steel connections or concrete acoustical toppings may be included in all timber systems, the structure is considered to be an all-timber structure if the main floor system, beams, columns, and lateral system are all composed of timber elements. [11] A hybrid timber structure is one for which the main structural elements consist of timber and another primary structural material. [12] For example, a hybrid timber building may include a timber-framed gravity system and a concrete core wall lateral system or a timber floor system steel columns. [13]

The objective of this paper is threefold: 1) to provide a current trends context for using CLT in increasingly taller mass timber commercial building structures, 2) to outline current knowledge of design considerations from multiple discipline perspectives in mass timber building design, and 3) to present a summary of notable case studies and a discussion of mass timber project trends. This paper will present a U.S.-focused perspective on the included topics. Based on the observed case studies, this paper includes discussion of both all-timber and hybrid timber

projects. To understand current trends, this paper begins with a discussion of the historical context of tall buildings and timber construction, as well as the primary factors driving increased mass timber use in taller buildings. The paper concludes with a discussion of the challenges and limitations of designing taller structures with CLT and mass timber.

2.1.3 Research Methodology

To properly capture the state-of-the-art of CLT for tall timber projects, a focused approach to the literature was constructed. First, a search for papers was carried out using:

- Google Scholar,
- Wood building organizations' websites, including WoodWorks, ThinkWood, APA – The Engineered Wood Association, and FPInnovations,
- The Council on Tall Buildings and Urban Habitat (CTBUH) tall building database
- And green building rating system organizations' websites, such as LEED, PassivHaus, and The Living Building Challenge.

Google scholar was searched for journal and conference papers using key words and phrases related to mass timber design and research, including but not limited to: Mass Timber, CLT, Tall Wood Structures, Embodied Carbon, Timber Connections, Timber Robustness, Timber Sustainability, Parametric Design, and more. Wood organizations' websites were explored for their available resources and tools, including design guides, educational bulletins, calculation tools, project case studies, and more. Finally, green building websites were explored for rating system rules, embodied carbon tools, and other green building resources.

Journal papers from Google Scholar ultimately came from publications including, but not limited to, Elsevier, Science Direct, ASCE Library, Taylor & Francis, and Springer. Papers were selected mainly from after the year 2010 as a significant amount of timber-specific research has been advanced in the last decade at the time of writing this paper. Some older papers were

selected for historical background or for structural topics which have important references from before 2010. Papers were selected on the basis that they contribute relevant knowledge to the scope of this review paper, contain the most up-to-date information about timber design, and are more widely used and referenced in the timber design field as compared to other papers with similar knowledge and conclusions.

Guideline documents and tools from wood organization websites were selected based on their widespread usage in the timber design field, as well as their scope of timber design calculations. Case study projects from wood organization websites and the CTBUH tall building database were selected based on their relevancy to tall timber, how much they represent potential typical tall timber projects, and how much they pushed forward tall timber design through research or precedent. Sustainability resources were selected based on their usage in industry, and based on evaluating which tools or databases provided the most relevant data for mass timber study.

Papers, guides, tools, and case studies were sorted into main topic areas, which then formed this paper's organizational structure. Once topics were formed and written about based on the selected resources, each topic was studied for the inclusion of background or overview information, details on the current knowledge of that topic, and information about the challenges within that topic. If any of this information was missing for a topic, additional papers and resources were selected until new papers no longer added any significant new information within the scope of the paper. In general, at least five papers were selected for each topic or subtopic to ensure a variety of sources informed the knowledge gathering process.

2.1.4 History of Tall Buildings

Before discussing current literature in mass timber structures, it is important to understand some of the history of mass timber and tall buildings, and how, combined with the properties of wood and available engineered timber products, this history affects tall mass timber structures. Although there is some disagreement in the literature (for example: Korom, Webster, and Weisman[14]–[16], the first modern skyscraper is generally considered to be the 10-story Home Insurance Building constructed in 1885 in Chicago. While the Home Insurance Building is not considered tall by today's standards, tallness according to Foster et al. 2016 is a relative concept for buildings, and is dependent on context, tall building technologies, and building proportions [17]. Despite some early criticisms of the skyscraper, they grew in popularity for a number of reasons. They were seen as an iconic art form, functioned to accommodate more office-type work for growing city populations, offered more daylight and views to occupants over the same square footage as compared to a low-rise building, improved the status of a city or town that built skyscrapers, and inspired populations of people.[2]

2.1.4.1 Technological Developments Driving Heights

Before the mid-19th century, building heights were limited by how many flights of steps occupants could tolerate. However, the invention of the hydraulic elevator, followed by the electric elevator by the end of the 19th century, made buildings of 18 to 20 stories and beyond possible. [2] After the elevator, the next limiting factors for skyscraper height were the structural weight of the system and the area the structural takes up within the floor plate. Early projects used mass masonry walls, which became too heavy for their foundations as well as very thick with increasing building height.[2] This development of cast iron and steel skeletal-framed structures

in the 1870's and 1880's, as well as the introduction of lightweight non-load-bearing curtain wall (CW) in the 1890's allowed structures to be built stronger and taller with a more slender structure and improved views. [17], [18] By 1913, skyscrapers would reach a height of 60 stories with the construction of the Woolworth Building in New York City.[2]

From there, the popularity of the skyscraper and the previous advancements in the technology to make tall buildings possible prompted a race to build the tallest buildings in the world, and eventually the Empire State Building was built in 1931 at a height of 102 stories, the tallest building at that time and for the next 41 years.[19] Alternate systems and further advances were made possible by advancing understanding of structural engineering and the growing adoption and use of computers in the 80's.[20] Modern structural mechanical and finite element analysis (FEA) along with automated analysis processes started developing as early as the 60's and 70's, and computational tools and resources started becoming more widespread around the 80's. [21], [22] Advances continued to be made as high rises became more widespread in parts of the world other than the United States. Early high rises often had small windows and poor airtightness but low energy use before the widespread use of air conditioning. Later, high rises incorporated CW to achieve the aesthetic of an all-glass tower, becoming large energy consumers with comfort issues for occupants.[23]

As environmental awareness increased, the most recent generation of high-rise buildings has sought to improve energy efficiency and occupant comfort. For example, whole building air leakage has been linked to heating demand, and jurisdictions enacting mandatory air leakage testing and performance requirements have observed significant improvements to new building airtightness.[24] Presently, stringent energy standards for operational energy have allowed some of the focus to shift to embodied energy. Timber is therefore a focus of interest because of its light weight and the potential to decrease a structure's embodied energy by as much as 60 to 70 percent.[23] Modern skyscrapers continue to push height limits as innovations in structural

systems are made. Although increasing heights come with a “structural premium” in which, due to the effect of lateral loads, the amount of material required for the structure increases at a greater rate than the height increase, skyscrapers are still generally an efficient approach to providing housing and office space for large populations in urban areas.[7], [20], [25]

In the context of current mass timber technology for mid- to high-rise timber building, Kuzmanovska et al., (2018) suggests defining tall timber as a range of projects from eighteen to twenty-four stories.[3] This range is based on the current generation of tall timber in which timber buildings six to fifteen stories are considered “mid-rise” and fifteen stories or higher are “high-rise”. [3], [26] As Timber continues to push the bounds, the next anticipated generation of high-rise timber buildings will include those from 18 to 30 stories or more depending on code requirements and limitations.

2.1.5 Wood as a Material

Compared to the steel and concrete materials used in modern skyscrapers, wood is a unique construction material because of its organic and hygroscopic nature, orthotropic structural properties, and dimensional responsiveness to changing ambient conditions.[27], [28] Some concerns generally exist regarding wood’s durability as a structural material due to its susceptibility to damage from insects, moisture, and fire.[29], [30] However, mass timber projects designed with engineering principles common to steel and concrete structures are protected from these damage factors and can therefore be designed as long-lasting structures [31].

Light-framed and Mass Timber

The two main modern categories of timber construction include light-framed timber and mass timber. Light-framed timber projects are relatively short buildings which use dimensional lumber in the framing structure, such as nominal 2x4 or 2x6 wall studs and nominal 2x8 through 2x12 floor joists. Thin panel products such as OSB or plywood are often used for floor and roof decking and in shear walls.[32] Light-framed projects of construction Type III are limited by the 2021 IBC to five stories over a 1- to 2-story concrete or masonry podium.[33], [34] Type IV construction, or mass timber, is required for greater allowable heights and more stories.[34] The code defines minimum structural element sizes for mass timber; for example, Glulam beams and girders supporting floor loads must be a minimum of 5” wide by 10.5” deep, and CLT floor panels must be at least 4 inches thick.[1], [34] The minimum code-required dimensions are accomplished through the use of engineered timber products (ETPs).

ETPs are timber products in which small wood material or timber components are built up to form larger structural members, such as panel products or beams, with specific strength properties based on engineering principles and design methods [35]. Engineered timber products can result in panelized wood products, longer spanning capabilities, less structural variability as compared to solid sawn lumber, improved strength and stiffness properties, better quality control and standardization, and more efficient use of raw materials. Some downsides to consider are that engineered timber products use more energy during production and fabrication as compared to solid sawn timber, and the process typically requires the use of adhesives, which may have their own negative effects on the environment [31].

Design Code and Reference Standards

Previous versions of the building code had imposed height limits, which generally restricted timber projects to an absolute maximum of six stories through the heavy timber category.[36] The U.S. 2021 International Building Code (IBC) includes new mass timber categories that allow projects up to 18 stories and 270 feet in height.[34] Figure 2-1 depicts representations of the new mass timber building categories and their respective allowable heights.[1] The Canadian 2020 National Building Code of Canada (NBC) allows mass timber protected by noncombustible materials to be used as a structural element in buildings up to 12 stories [37]. Projects in various countries have also been granted exceptions that allowed taller heights through the use of stricter code approvals processes [38].

Representative Mass Timber Building Sizes, Residential Occupancy (R-1, R-2, NFPA-13 Sprinklered, W=>30', 100% open space)

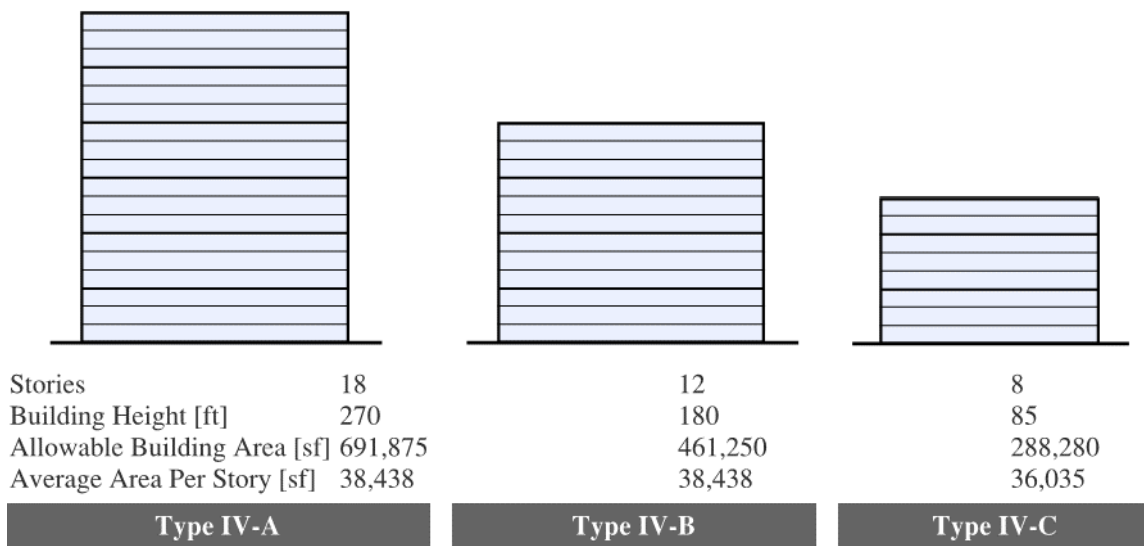


Figure 2-1: New mass timber building categories in the 2021 International Building Code (Figure adapted from Breneman et al. (2019)[1] and based on data from the 2021 International Building Code[34])

CLT structural design guidance is provided in the CLT Handbook, available in a 2019 Canadian Edition and a 2013 US Edition, as well as in the 2021 Mass Timber Design Manual

published by ThinkWood and WoodWorks. Additionally, manufacturers of CLT products provide design values that may be used in structural engineering design equations.[39]–[41] The CLT Handbook provides guidance for a variety of uses of CLT, such as in floor systems, cantilevers, two-way spanning systems, lintels, and deep beams.[42] Analysis methods for CLT in design or research include calculation-based methods, structural design software specifically developed for CLT, and project- or case-specific finite element analysis modeling. However, CLT spans are relatively lightweight compared to steel and concrete systems, and therefore serviceability requirements often control the spans of CLT panels [43]. The 2021 Mass Timber Design Manual offers an overview of the most relevant topics in mass timber design and directs readers to resources and case studies in each topic area.[44]

Gaps in Tall Timber Material Knowledge

There is an established knowledge base of commonly required structural members sizes for light-frame timber construction, and much is known about engineered timber products and their strength and structural properties. However, as mass timber construction is still working to increase its share of the commercial construction market, there are relatively limited sources of consolidated knowledge on the common structural members sizes for various mass timber structural systems, design configurations, and project sizes. Much of the literature on mass timber design focuses on single case study projects or a small set of varied designs, but more comprehensive design knowledge is needed to better understand how the use of ETPs affects structural design and element sizing.

2.1.6 Tall Timber Sustainability

One of the many features driving mass timber interest and research is its potential to improve the sustainability of building construction as well as the sustainability of social and occupant wellness. Owners and developers are more recently interested in the triple bottom line, which includes sustainability of the environment, society, and the economy. [45] As compared to other materials, mass timber has been shown to require less energy during manufacturing and construction, and to store carbon for the life of the building and any reuse beyond. The carbon associated with energy use during material extraction, transportation, manufacturing, and the construction phase of a building is known as embodied carbon (EC). Timber's low EC and high carbon capture positions it as an important material with the potential to significantly improve the sustainability of construction.[6] Owners are also becoming more interested in mass timber for its aesthetics in designs where code permits an exposed timber structure. Timber's finished appearance is a desirable aesthetic for many developers, and it contributes to an interior's biophilic properties, or the natural qualities which promote occupant wellness. [37] Mass timber also represents a growing market which can stimulate local economies in forested regions. [46]

Further, as reported in April of 2021 by the U.S. Department of Energy's U.S. Energy Information Administration – Office of Energy Statistics, the United States residential and commercial building sectors accounted for 40 percent of energy use in the United States.[47], [48] Therefore, improvements to the sustainability and energy efficiency of buildings have the potential for significant impact on climate change mitigation. [45] The push for energy reduction in recent years has positioned sustainability as a primary driver on many new building projects. [49] This is particularly important for mass timber in modern construction and in taller buildings. Taller buildings come with a structural premium, and therefore learning to design structures for lower EC is important for tall buildings, which remain relevant in sustainable design for their

benefits in city planning, efficient land use, and increased housing quantities for large populations.[7]

2.1.6.1 Role of Timber in Emissions and Climate Change Impact

Within the last decade there has been a growing interest in decreasing the embodied carbon of a building, which is recently contributing a larger share of a project's overall energy use as steps are taken to reduce operational carbon (by the user) to reach net zero.[25][50] To meet short term goals of reducing greenhouse gas emissions (GHG) as soon as possible, it is important to understand that EC will make up a significant amount of energy use in newly constructed buildings over the next quarter century.[5] Architecture 2030 projects based on data from the 2017 UN Environment Global Status Report and the 2017 EIA International Energy Outlook that EC will contribute about 33 percent of total cumulative emissions for new construction over the next quarter century, as depicted in Figure 2-2.[5], [51], [52]

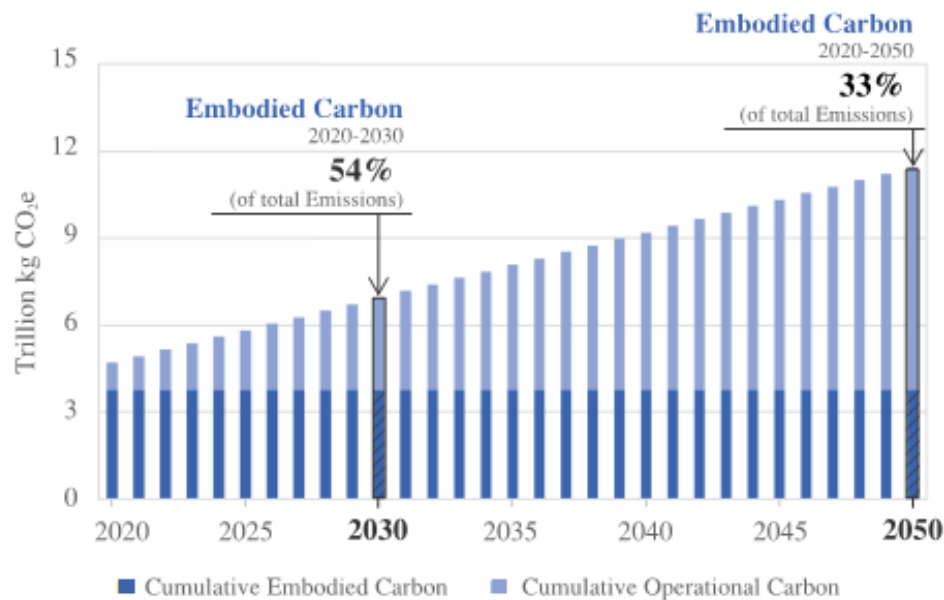


Figure 2-2: Total cumulative carbon emissions from 2020 to 2050 of global 2020 new construction. (Figure adapted from Architecture 2030's plot[5] based on data from the 2017 UN Environment Global Status Report[51] and the 2017 EIA International Energy Outlook[52])

To mitigate climate change, emissions need to be reduced immediately, and carbon storage or reduced EC can help meet this goal. A building's embodied carbon contributes more to overall energy use during a building's lifetime as its operational carbon decreases, such as in buildings designed to approach or reach net zero energy use [50]. However, a life cycle analysis (LCA) uses a variety of assumptions for building lifespan, life cycle boundaries, and end of use scenarios for various building materials, all of which affect the embodied carbon's share of overall energy. A Danish study found lifespans varying from 80 to 120 years depending on building type despite commonly assumed building lifespans of 50 years [53]. Demolition data in the US has shown residential construction lifespans of 130 years, and that the choice of structural material did not affect the lifespan [54]. End of life scenarios for timber could include anything from landfilling to recycling [55]. Additionally, natural disasters, such as the New Zealand earthquakes resulting in large quantities of unexpected construction waste and debris [56], and the potential for changes in technology to allow different end of life scenarios, suggest that it is difficult to rely on assumptions about what will happen to a building 50 to 100 years post construction.

One option to help address climate change challenges is through the use of wood as a building material.[6], [7] The following are benefits and considerations to using wood:

- Utilizing more wood in buildings effectively both reduces emissions immediately and stores carbon. Wood requires less emissions during the manufacturing process and stores 1 to 1.6 tons of carbon per cubic meter for the life of the building structure [57].
- Further, increased wood use in the construction industry can contribute to greater carbon uptake of sustainably managed forests by maintaining younger forests, which absorb more carbon than older forests, and reducing risks of large carbon releases through forest fire, insect attack, and decay [58].
- Finally, timber-based structural product manufacturing processes tend to result in less emissions as compared to concrete production, which uses a significant amount of fossil fuels during cement manufacturing. [57]

- While recycled steel performs better during manufacturing than concrete, many countries use significant amounts of virgin steel because the global demand for recycled steel is higher than the supply, and projections estimate that 50% of steel production globally will still require virgin material to meet the growing demand for steel.[58], [59] New steel requires a large amount of coal and is not the preferred product in sustainable construction[18].
- Replacing concrete and steel with timber can reduce emissions from concrete production, the demands on recycled steel, and the amount of virgin steel manufactured.

Timber is of interest when performing a LCA for a given project to analyze the overall energy use of that project. Although there are many methods for accounting for timber in LCA studies, timber has generally been assumed in LCA research and application to be carbon neutral because of its ability to store carbon. This assumption relies on forestry activities, which maintain the existing “biospheric carbon pool” or, in other words, do not reduce the net total of forest [7]. Whether or not timber can be considered “climate change neutral” depends on the timing of the release and storage of carbon. Therefore, a building structure’s global warming potential could be theoretically calculated by comparing the turnover rate of timber growth in the forestry industry to the expected life span of a building, which can be expected to store carbon in the wood structure for the life of the building [7].

2.1.6.2 Embodied Energy and Carbon Calculations

In addition to emissions and climate change impact, it is common to perform a portion of a building’s LCA by calculating the embodied energy or embodied carbon of the structure.[59] Both embodied energy and embodied carbon are calculated by studying the process involved in including a material in a building, and may include various stages of a building’s lifecycle.[60] Embodied energy and embodied carbon are different as embodied energy is the sum of the energy used directly or indirectly during the processes associated with the cradle to gate phase of LCA,

while embodied carbon is the sum of equivalent emitted carbon as a fuel and during the relevant processes within any stage of LCA.[61]

One EC data source is The Inventory of Carbon and Energy V3 (ICE), authored by Jones and Hammond[61], provides a database, or repository, of the embodied carbon of various common structural materials, and is based on a collection of hundreds of studies and papers investigating embodied carbon of materials. The database notes the kilograms of carbon dioxide equivalent per kilogram of material based on the cradle to (factory) gate LCA boundaries. Embodied energy was removed from the most recent version of the database because the authors no longer consider this metric to be relevant in modern literature and LCA studies.[61] This database has some limitations such as limited accuracy and completeness[62]; however, this database contains credible, peer- reviewed information[63], and values from this database are widely used in LCA research work as it is the most comprehensive material-specific database. Values from ICE for common structural materials are summarized in Table 2-1.

Another source of data includes Environmental Product Declarations (EPDs). Current industry practice in EPDs for mass timber structural products is to neglect the carbon storage portion of EC by declaring biogenic carbon to be zero for the full life cycle, even when the EPD covers only modules A1 to A3. [64], [65] Best practices in LCA dictate that if carbon storage is included for timber products, then End Of Life (EOL) impacts must also be included. [61] Many EPDs focus on the cradle to factory-gate boundaries because these are the boundaries for which assumptions can be reasonably made for specific products. Because much of a building's EC occurs during its early life, it is reasonable to use the A1 to A3 boundaries to help guide early design decisions. Full LCA work is recommended at later stages of design to refine designs and project decisions. When using EPDs to compare materials, special care should be taken to use EPDs that follow the same Product Category Rules (PCRs), which define how an EPD should be produced. [66]

Other energy and embodied carbon databases include: the Database of Embodied Quantity Outputs (deQo), a database of whole building LCA output data [67]; the Embodied Carbon Benchmark Study, a database of LCA results for low carbon construction projects [68]; Tally, an application for Autodesk Revit which calculates LCA based on its own custom LCA database that accounts for materials and construction details [69]; the U.S. Life Cycle Inventory Database, a database by National Renewable Energy Laboratory which includes energy and material accounting data for U.S. products and components [70]; and the Federal LCA Commons, which include LCA data repositories from a collection of US agencies and laboratories. [71] Data source selection should consider the design stage of a project, the boundaries being considered, and project goals and requirements for EC accounting.

Table 2-1: Embodied Carbon of Common Structural and Building Materials in units of kilograms of carbon dioxide equivalent per kilogram of material (Values obtained from (Hammond et al., 2019)[61])

Material	Best Case		Worst Case		Comments
	EC Value (kg/kg)	Assumptions	EC Value (kg/kg)	Assumptions	
Timber	CLT	-1.2	With carbon storage	No carbon storage	Wood is assumed to be sourced from a sustainably managed forest for the best-case scenario
	Glulam	-0.9			
Concrete – Superstructure	0.13	25% cement replaced with fly ash ¹	0.14	15% cement replaced with fly ash ¹	32/40 MPa – For structural use, in situ floors, walls, superstructure
Concrete – Foundations	0.12		0.13		28/25 MPa – For reinforced foundations, ground floors
Steel – Section	1.07	93.3% recycled content ²	2.63	Virgin steel ²	Values are for US-produced steel

¹ Values are interpolated from database values for 15, 30, and 40% fly ash replacement

² Values are obtained using the ICE database-provided recycled content calculator

2.1.6.3 Wood's Impact on Sustainable Certification

As part of building design, many owners now want a green building standard certification for their projects. A variety of sustainability standards are increasingly requiring not only improvements to operational energy use, but also reduced embodied carbon, improved indoor environmental and air quality, occupant well-being, and the overall quality of buildings [72]. In this way, many standards encourage both environmental and societal sustainability, and offer pathways to certification which are supportive of the use of mass timber.

The U.S. Green Building Council's (USGBC) LEED standard v4.1 encourages the use of sustainably-sourced materials, such as Forest Stewardship Council (FSC)-certified wood, and provides credits for reducing the impact of the full project life cycle.[73] The WELL building standard requires access to nature, including the use of natural building materials such as timber, as a prerequisite to the mental health concept within the certification structure [72]. The World Green Building Council has set goals for EC reductions in buildings by 2030 and 2050. [74]

The Living Building Challenge includes certification “petals,” which represent areas that contribute to a project’s overall sustainability. The “Health and Happiness” petal requires access to nature, which can be achieved through the use of natural materials such as wood. The “Beauty” petal can be achieved through natural-inspired concepts like biophilia [75]. Wood’s inherent biophilic properties are recently being demonstrated to improve occupant wellness through a sense of connection to nature [37], and studies have found that occupants respond positively to natural materials in indoor environments, particularly to wood materials [76]. A few studies have also found that the use of mass timber results in buildings which are perceived to have acceptable indoor air quality and which fall within recommended applicable building guidelines [77]–[79].

Finally, although the Passive House Institute US (PHIUS+) Passive Building Standard focuses on limiting operational energy use,[80] research has shown that mass timber, when

arranged strategically within a building design, can effectively contribute thermal mass, therefore potentially improving operational energy use. [81], [82]

2.1.6.4 Relevant Tall Timber Sustainability Research

From 2012 to 2021 a varying number of studies on timber and hybrid structural systems have provided insight into how the choice of building material affects the sustainability of a building. Table 2-2 provides a summary grouping of key studies conducted in this 10-year period. A common trend were studies on hybrid steel and concrete structural system case studies which found that hybrid structures, which use materials where they are most suited, can result in structures with lower embodied carbon as compared to a structure of all one material [83]. This is key in optimizing material usage for multiple variables. Further, there were several studies which involved hypothetical tall building design as a means of learning more about the challenges in tall timber building design.

A study of roof trusses performed an optimization analysis for trusses constructed of either all steel, all timber, or a hybrid of both and found that the truss with the lowest embodied energy was a hybrid of steel and timber. It was found that although timber generally has a lower embodied energy per weight compared to steel, the use of wood in certain parts of the truss required much more massive and inefficient elements as compared to steel. This study establishes the idea that full timber replacement in a structure does not always result in the lowest possible embodied energy for a structure if specific structural element behavior and applications are not properly considered [50].

Table 2-2: Summary of relevant studies on timber and hybrid timber structures in the past 10 years

Study Type	Sub-Type	Study Name	Summary of Findings
Case studies	Parametric study	Embodied energy and GHG emissions of residential multi-story timber buildings by height – A case with structural connectors and mechanical fasteners[84]	Parametric heights study that found that connections contribute significantly to GHG emissions in mass timber buildings
		High-Rise Timber Buildings as a Climate Change Mitigation Measure - A Comparative LCA of Structural System Alternatives [7]	A study of projects of varying building heights of 3-21 stories found significant improvements in climate change impact through wood substitution
	Material comparisons	Comparing the embodied carbon and energy of a mass timber structure system to typical steel and concrete alternatives for parking garages [62]	Comparisons of real parking garage project saw no significant differences in embodied carbon due to large quantities of concrete needed in mass timber garages
	Review	Tall timber buildings: Emerging trends and typologies [3]	Study of projects found trends of increasing mass timber project heights, use of simple form and massing, and increased hybridization of mass timber structural systems.
	Hypothetical design	River Beech Tower: A Tall Timber Experiment [85]	Design of a tall mass timber tower from a practitioner's perspective to identify needed areas of research
Hybrid	Parametric study	Minimizing embodied carbon in multi-material structural optimization of planar trusses [50]	Both studies found that hybrid systems and structural elements experienced improved energy usage in construction by taking advantage of hybrid material-based efficiencies
	Traditional systems	Energy efficiencies of linear-shaped multi-residential apartment buildings built with hybrid structural systems [83]	
Tall building sustainability	Parametric Study	Design space exploration for comparing embodied carbon in tall timber structural systems [86]	A parametric study of tall building forms for mass timber structures identified trends and comparisons at an early-stage design level of detail.
	Review	Tall buildings and sustainability[45]	Extensive review of sustainability efforts for tall buildings, including for environment, social, and economic sustainability.
Policy	Sustainability assessment	Modeling the environmental sustainability of timber structures: A case study [87] Sustainability Assessment of Modern High-Rise Timber Buildings[88]	Development of sustainability assessment models to improve comparisons of timber buildings and application of methods to case study projects
	Barriers to mass timber construction	Mind the Gap: A Policy Gap Analysis of Programmes Promoting Timber Construction in Nordic Countries[89]	Study of policy gaps found that insurance practices and public perception were key factors in the success of mass timber buildings

One cradle to factory gate study comparing parking garages constructed with steel, concrete, or mass timber found no significant differences in embodied energy of the structures when best practices were followed for each structural material. The study cited possible reasons for the timber not meeting better embodied energy expectations as being related to the open-air parking garage building type, which required large quantities of concrete for the timber-concrete composite floor system. The study makes a distinction between timber's sustainability potential as a material and its use in a specific structural system and building typology, noting that the use of timber does not always result in a lower embodied energy structure due to a number of factors for any given specific project [62].

Another study analyzed a variety of building heights between 3 and 21 stories for climate change impact of wood buildings versus concrete equivalents. The study found that using wood reduced the climate change impact by 34-84 percent compared to the equivalent concrete structure, depending primarily on the building height considered [7]. Finally, a parametric study of tall timber building typologies was performed to identify trends and behaviors of mass timber structures for post and beam systems as well as post-beam-panel systems. This study was performed at an early design level of detail for the full building scale.[86]

Many of the studies mentioned incorporate life cycle analysis (LCA) software or EC databases to source material data to use in estimating the impacts of structural material quantities. A variety of data sources exist with different levels of scope, boundary coverage, and applicability. Table 2-3 is a non-exhaustive summary of available software and databases, as well as their application and typical use.

Table 2-3: Life Cycle Analysis and Embodied Carbon Software – Summary of capabilities, with a focus on application to mass timber projects. Note that all tools listed include embodied carbon data, but that results can differ significantly due to differences in the assumptions and methodologies used. [90] (Software capabilities summarized based on WoodWorks’ comparison guide [90] and the ICE V3.0 Documentation [61])

Software/ Plug-ins/ Databases	Primary Use as Database	Design Phase Scope		Scale of Analysis			Timber Applicability	
		Pre-Design/ Conceptual Design	SD*, DD†, CD‡	Material/ Component	Assembly	Whole Building	CLT	Glulam
<i>Athena Impact Estimator for Buildings</i> [55, 56, 57]		✓	✓			✓	✓	✓
<i>Athena Eco Calculator for Commercial Assemblies</i> [56, 57, 58]		✓			✓	✓	✓	✓
<i>Tally (for Revit)</i> [59, 60, 61]		✓	✓			✓	✓	✓
<i>One-Click LCA</i> [62, 63]		✓	✓	✓	✓	✓	✓	✓
<i>Carbon Designer (for One-Click)</i> [100]		✓				✓	✓	✓
<i>EC3</i> [101]	✓			✓				
<i>ICE V3.0</i> [61]	✓			✓			✓§	✓
<i>WoodWorks Carbon Estimator</i> [102]		✓**				✓	✓	✓
<i>WoodWorks Carbon Calculator</i> [103]			✓**			✓	✓	✓

Note: * SD = Schematic Design Phase; † DD = Design Development Phase; ‡ CD = Construction Document Phase

§ CLT data is limited in data quality and number of data points; ** Estimate is for the wood structure only

2.1.6.5 Gaps in Tall Timber Sustainability Knowledge

Having reviewed the research advancements in tall buildings from a sustainability lens, sustainability work remains a complex area to study. In general, while many studies have shown that substituting timber for concrete or steel in the structure can decrease a building’s environmental impact [104], other studies have discovered that there are finer nuances to the substitution of wood, suggesting the need to carefully consider where timber may best be used to

reduce overall climate change impact [50], [62]. While embodied carbon values are provided for the embodied carbon of various structural materials, the raw values cannot be easily compared because of the differences in strength to weight ratios of structural materials, and resulting difference in building mass, material use, and structural efficiency. Additionally, due to the complexities and uncertainties in studying building life cycles and climate change impact of specific components or materials, there is ongoing research to better understand the impact of using mass timber structures in buildings.

Many of the research projects that have been published have formulated results comparing the performance of a case study building against an equivalent baseline building in another structural material. The research tends to analyze either a single case study configuration or a small selection of configurations within a small range of limited variables. One study discussed in the literature review looked at a smaller scale by analyzing a single roof truss, but expanded the scope of configurations by using parametric analysis and optimization techniques. Further research as noted below in the field of Tall Timber design with a sustainability focus could help fill in the observed gaps in the literature and design codes and standards:

- Expand knowledge of embodied carbon for a variety of structural system configurations.
- Study mass timber hybridization to understand where timber, steel, and concrete are best utilized to achieve overall design improvement.
- Incorporate more hybrid options into LCA and EC studies
- Improve the understanding of expected mass timber building life cycles: what types of projects and clients are using mass timber, and what does the life cycle of those related projects typically involve.
- Study embodied carbon data to determine what additional knowledge is needed to gain industry consensus for timber material EC values.
- Incorporate parametric frameworks for the design and analysis of mass timber structures.
- Stronger linkage of structural design data and project design decisions to resulting EC.

2.1.7 Structural Advances in Tall Timber

As mass timber is used in more projects and in greater variety, research is ongoing to prove the structural performance of mass timber. Many engineered wood products exist to form a structural design; however, this paper focuses on CLT panelized products and Glulam beam and column products. Mass timber can be utilized in all parts of the structure, including within both the gravity and lateral systems; however, taller projects tend to take a hybrid approach, often using concrete lateral cores, steel bracing, or steel framing with a timber panel. The following sections summarize key research relating to the gravity system, lateral system, and other structural considerations. Relevant research is summarized within each sub-section, and knowledge gaps are discussed at the end of the structural section.

2.1.7.1 Cross Laminated Timber (CLT) for Structural Systems

In the 1990's, a unique engineered timber product, cross laminated timber (CLT), was developed in Austria and Germany. Early use of CLT began first in Europe in the early 2000's and has since expanded in use around the world in the early 2010's, including in Canada and the United States. The development and use of CLT in recent years has played a significant role in the development of taller timber buildings,[105] with projects being built to 10 stories in the early 2010's and 18 stories by the late 2010's.[3]. CLT has also become more popular in construction because of its potential to increase schedule speeds through panelized and modular construction, lessen the need for skilled laborers on site, decrease noise and disruption to the surrounding community, and the potential to offer a smaller carbon footprint and lower emissions in the fabrication and construction process [106].

CLT is similar in concept to Glulam but increases the width of members to form a panelized product [105]. Advantages of CLT as a product include the following: The configuration of the layers creates a dimensionally stable panel, the panel is fairly strong and can resist in-plane and out-of-plane forces, the configuration provides splitting resistance for many types of connections, and the panel may act as a two-way floor slab similar to concrete [105], [107]. CLT is unique from other previously developed engineered timber products because of its relatively large dimensions and its usage as a prefabricated floor system. CLT panels are manufactured by building up layers of orthogonally-oriented dimensional lumber, laid up on their wide faces and glued together. In some cases, two of the layers may be oriented parallel to enhance structural properties in a certain direction. CLT panels typically consist of three to seven layers but can include more as needed for a given project. Currently, CLT panel size is limited by the manufacturer's available equipment size and transportation to site [104].

2.1.7.2 Gravity Systems

Mass timber floor systems utilizing CLT must meet a variety of architectural and structural requirements and performance objectives. Current project trends most commonly use CLT floor panels in a post-beam-panel configuration. In this configuration, the beams can sit above, below, or flush with the CLT floor panel. Columns are typically designed to bypass the CLT floor to avoid bearing perpendicular to the grain. [108] Other common floor system configurations include point-supported CLT, CLT over bearing walls, post-beam-purlin-panel, and hybrid options such as steel-hybrid systems or timber-concrete composite. [39], [108] Table 2-4 summarizes the common all-mass timber floor configurations as well as some notable but less commonly used options. Table 2-5 summarizes representative hybrid timber floor systems.

Table 2-4: Summary of mass timber floor system options (list is representative, but not all-inclusive.)
Systems summary and figures adapted from the Structurlam Mass Timber Technical Guide [39] and an
article by Elsa Lam for Canadian Architect [109]

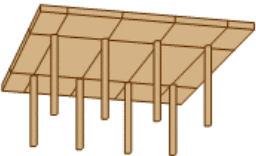
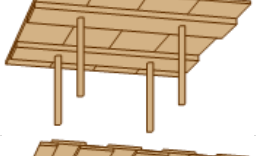
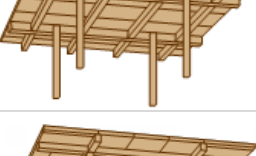
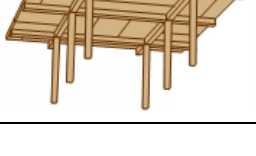
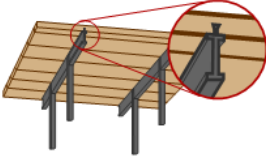
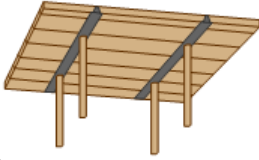
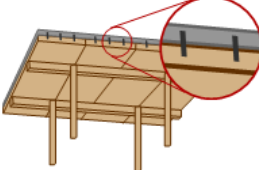
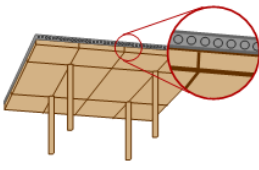
System	Variation	Configuration	Applicability	Typical Bay Span
Post and Panel	Point-supported panels		Hotel, Dormitories, Micro Apartments	8 – 14 ft (2.4 – 4.2 m)
	Stressed skin lattice		Hotel, Dormitories, Micro Apartments (increase span compared to typical point-supported)	15 – 25 ft (4.6 – 7.6 m)
Post-Beam-Panel	Short beam, long deck		Office, Residential (minimize cost)	12 – 20 ft (3.6 – 6 m)
	Long beam, short deck		Office, Residential (minimize system depth)	12 – 20 ft (3.6 – 6 m)
	Wide flat beams on bottom, top, or flush		Office, Residential (long-span bays)	20 – 30 ft (6 – 9.1 m)
	Staggered deck		Office, Residential (long-span bays, minimize material, possible services over beams)	15 – 25 ft (4.6 – 7.6 m)
	Cassette		Office, Residential (long-span bays, minimize material, possible services through cassette)	15 – 25 ft (4.6 – 7.6 m)
	Beams and girders		Office, Residential (minimize floor panel depth)	25 – 35 ft (7.6 – 9.1 m)
	Two-way beams		Office, Residential (square bays, minimize beam sizes)	12 – 20 ft (3.6 – 6 m)

Table 2-5: Summary of hybrid mass timber floor system options (list is representative, but not all-inclusive.) Systems summary and figures adapted from the Structurlam Mass Timber Technical Guide [39], an article by Elsa Lam for Canadian Architect [109], and the DeltaBeam manual [110]

System	Variation	Figure	Applicability	Typical Bay Span
Hybrid light-frame	Light-frame wall-supported panels		Multi-family Residential, Low-rise Small Office	13 – 16 ft (4 – 5 m)
	Non composite steel framing		Office, Public Buildings, Post Disaster Status	15 – 35 ft (4.6 – 9.1 m) (for CLT)
Steel-timber hybrid	Composite steel framing		Office, Public Buildings, Post Disaster Status	8 – 20 ft (2.4 – 6 m) (for CLT)
	Proprietary flush beams		Office, Residential (long span and shallow depth)	20 – 40 ft (6 – 12 m)
Timber-concrete composite	Shear connectors with beams		Office, Residential	20 – 30 ft (6 – 9.1 m)
	Point-supported voided concrete timber composite		Office, Residential (eliminate beams, reduce mass)	20 – 30 ft (6 – 9.1 m)

While common mass timber floor systems have simpler configurations, like the post-beam-panel option, research is ongoing for other systems that show promise for improved efficiency or coordination with services. The staggered floor panel and cassette floor systems are options which may allow for improved integration with services. [109] Loss and Davidson (2016) and Merryday et. al. (2023) performed experimental testing of steel-timber floor systems and components. [111], [112] Dickof et. al. (2023), Muster and Frangi (2020), and Asselstine et. al.

(2020) have tested and modeled various components of point-supported CLT floor systems. [113]–[115] Lukaszewska et al. (2008) and Bajzecerova et. al. (2022) studied shear transfer mechanisms for timber-concrete composite floors. [116], [117] A summary of representative gravity system studies is presented in Table 2-6. This summary is not exhaustive but rather provides a representation of the type of work being done to advance mass timber floor design and performance to achieve more efficient designs and better integration with architectural requirements and services.

Further, while many mass timber panels exist, CLT is commonly used in floor systems because of its dimensional stability and ability to span in two directions. For long-span timber floor systems, other materials have been introduced to create composite or hybrid systems with improved flexural strength and stiffness. For example, steel bars or cables and glass fiber reinforced (GFRP) bars have been used in timber beams. Shape memory alloys have also been tested for their improvements to CLT bending stiffness. [118] Some studies and composite designs have incorporated pre- or post- tensioning elements into timber beams to reduce the amount of tension seen by a timber beam and therefore increase flexural capacity [119]. Floor systems may also incorporate Glulam beams at the perimeter and/or the interior, or other hybrid systems such as CLT over steel beams and the use of topping slabs to meet acoustic and vibration requirements [120].

Finally, while many mass timber floor systems are well-tested and frequently used, additional research and testing is on-going for a variety of efficient and proprietary floor system options. Testing seeks to confirm structural behavior, fire performance, acoustic insulation, and other performance requirements.

Table 2-6: Summary of relevant studies on timber and hybrid timber floor structures

Topic	Sub-Type	Study Name	Summary of Findings
Steel-Timber Floors	Experimental Testing	Innovative composite steel-timber floors with prefabricated modular components (2016) [111]	Presents a proposed steel-timber composite floor design and provides testing results and analysis of performance. A FEM model is discussed which can be used for other steel-timber systems.
		Pushout Tests on Steel-Timber Connections Using Self-Tapping Screws (2023) [112]	Testing was performed for self-tapping wood screws to study composite action performance
	Computational Modeling	Numerical Studies on the Flexural Behavior of Steel-Timber Composite Floor Systems (2023) [121]	A parametric model of steel-timber cross sections is studied for composite action and flexural behavior.
	Design Guidance	Design Guide 37: Hybrid Steel Frames with Wood Floors (2022) [122]	Presents design guidance for steel and mass timber hybrid floor systems.
Point-supported Timber Panels	Experimental Testing	Post + Panel: Next Generation Point Supported CLT Floors Carla (2023) [113]	Testing is performed for point-supported CLT floors, including tests of rolling shear, punching shear, and full-scale floor testing.
		Experimental analysis and structural modelling of the punching behavior of continuous two-way CLT flat slabs (2020) [114]	Testing of point-supported CLT floors was carried out to study punching shear. The results and data from the test is presented.
	Experimental Testing and Numerical Modeling	New edge connection technology for cross laminated timber (CLT) floor slabs promoting two-way action (2021) [115]	Edge connections are proposed to maintain continuity of the minor plies of CLT to allow two-way spanning capabilities for larger bays. Testing and numerical models are performed and compared.
Timber-concrete Composite	Experimental Testing	Performance of connections for prefabricated timber–concrete composite floors (2008) [116]	This paper looks at the shear connections used for timber-concrete composite floors and selects for study a connection used in prefabricated floor systems. The paper discusses the results of various structural experimental testing.
		Prestressed CLT-concrete composite panels with adhesive shear connection (2022) [117]	Testing found that pre-stressing of the CLT panel mitigates the effects of concrete shrinkage in a wet-on-wet approach to the timber-concrete shear connection.
	Review	State of the Art on Timber-Concrete Composite Structures: Literature Review (2011) [123]	This review paper discusses relevant research that has been done on timber concrete composite structures, including fire performance testing, performance of shear connections, prefabrication, fatigue testing, floor vibrations, and assembly acoustic performance.
	Design Guidance	Design guide for timber-concrete composite floors in Canada (2020) [120]	Presents equations and sample calculations for designing TCC floors.
Mass Timber Strengthening	Material Research	A Sustainable Solution for Strengthening Mass Timber Using Shape Memory Alloys (2023) [118]	Testing is performed using shape memory allows to prestress mass timber structural members as a means to improve bending stiffness.
	Post-tensioning	Self-tensioning long-span T-shaped spruce and oak web floors with a CLT upper flange. An experimental approach (2018) [119]	Discusses the results of testing for a proposed pre-tensioned timber floor system.

2.1.7.3 Lateral Systems

Just as there are a variety of timber and hybrid timber options for gravity systems, there too are several material options and configurations for the lateral system of a tall mass timber structure. FP Innovation's "Technical Guide for the Design and Construction of Tall Wood Buildings in Canada" provides a useful summary of common options, their applicability, and code implementation for Canada. [108] Although a similar guide for the US has not been found at the time of this writing, the guidance may be similarly applied to US projects.

FP Innovation's guide notes that concrete core walls are among the most commonly used lateral systems for mass timber because they are well-studied and understood, have good ductility and demonstrated performance, are accepted in building codes, and integrate well with a stair and elevator core. The remaining lateral system options are summarized in Table 2-7 for convenience. Where CLT is used in lateral systems, the in-plane strength and stiffness of CLT shear walls generally depends on a combination of rocking behavior, translational deformation, in-plane bending, and in-plane shear. Rocking and translation generally contribute the most to lateral behavior, both of which are typically controlled by the connections [124]. Additionally, CLT walls used in lateral systems are typically designed for rocking behavior with ductile connections, and in some systems, wood floors may act as a diaphragm that transfers lateral forces to shear walls. Research has generally found that CLT panels behave rigidly under lateral loads and that connection ductility determines lateral system behavior [43].

When considering lateral systems in tall timber buildings, it should be noted that while some studies have proposed seismic response modification factor R values for various specific timber systems [125], [126], (Izzi et al., 2018; Zhang et al., 2017; Pei et al., 2013) values generally agreed upon for a variety of hybrid systems are not yet available, and testing is still in progress or in the planning stage in other research projects [127]. Experimental methods for

lateral systems have included testing performed on specific connections, wall systems, and full-scale structures [125], variations in experimental setups such as boundary conditions, connection ductility, and CLT shear wall behavior [128], and a variety of systems including hybrid systems with CLT floor and steel framing [111], a system called “Finding the Forest Through the Trees (FFTT)” [126], and typical mass timber construction [129]. Additionally, shake table tests have been performed and are currently being planned for several full building mass timber mockups [127], [129]. Table 2-8 provides a non-exhaustive summary of representative studies of lateral systems for tall mass timber structures.

Table 2-7: Summary of common lateral systems for mass timber structures. Adapted from FP Innovation’s “Technical Guide for the Design and Construction of Tall Wood Buildings in Canada” [108]

System	Behavior	Applicability
<i>Mass Timber Shear Walls (Platform Framed)</i>	• High stiffness • Low ductility • Rocking to achieve yielding in connections	Suitable for tall, wind-controlled projects. Use in high seismic zones requires careful detailing to achieve rocking behavior and energy dissipation through yielding of connections.
<i>Mass Timber Braced Frames</i>	• Limited to moderate ductility • High stiffness as a perimeter frame. • Connections highly ductile	Tall wind-controlled structures. Limited guidance for high seismic applications
<i>Mass Timber Moment Frames</i>	• Ductile connections needed; consider wood shrinkage and checking. • Limited stiffness	Not commonly used, further research is needed. Detailing challenges exist for high seismic zones.
<i>Post-Tensioned Mass Timber systems</i>	• High ductility • Self-centering • Rocking with energy dissipative connections	Research is ongoing, but shows promise for high seismic zones.
<i>Concrete Shear Walls</i>	• Ductile • High-performing lateral resistance	Tall timber structures in high seismic zones
<i>Steel Braced Frames</i>	• Ductile • High-performing • Several options for energy dissipation	Tall timber buildings (Concentric, Buckling restrained, or Eccentrically braced)
<i>Steel Moment Frames</i>	• Ductility for seismic zones • Yielding at beam ends	Unobstructed views and open floor plans.
<i>Steel Plate Walls</i>	• Ductility provided by plate yielding	Tall wood structures

Table 2-8: Summary of relevant studies on timber and hybrid timber lateral systems

Topic	Sub-Type	Study Name	Summary of Findings
Wind Design	Experimental Testing	Probabilistic Serviceability-Performance Assessment of Tall Mass-Timber Buildings Subjected to Stochastic Wind Loads: Part I - Structural Design and Wind Tunnel Testing (2018) [130]	Wind tunnel testing is utilized to perform the structural design of a case study tall timber structure. Performance-based wind design methods are used to study performance
		Dynamic Response of Tall Mass-Timber Buildings to Wind Excitation (2020) [131]	Several case study mass timber structure designs underwent wind tunnel testing and an analysis of their dynamic response to recommend improvements.
	Numerical Modeling	Feasibility Study of a Wood-Concrete Hybrid Super Tall Building and Optimization of its Wind-Induced Behavior (2018) [132]	Based on a conceptual design of a tall wood building with concrete cores and timber floors and framing, this research performs optimization for wind performance.
		Probabilistic Serviceability-Performance Assessment of Tall Mass-Timber Buildings Subjected to Stochastic Wind Loads: Part II – Structural Reliability Analysis (2018) [133]	The case study design project from Part I of this paper is analyzed for vulnerabilities to wind load and serviceability performance.
		Structural performance of multi-story mass-timber buildings under tornadolike wind field (2018) [134]	A case study mass timber structure was designed and studied for structural and serviceability performance when subjected to tornadolike wind.
Seismic Design	Experimental Testing	Seismic performance of embedded steel beam connection in cross-laminated timber panels for tall-wood hybrid system (2017) [126]	Presents the results of seismic testing for a steel-timber force-dissipating connection for use in a lateral system design.
		Shake Table Testing of a 10-story Mass Timber Building with Nonstructural Components (2020) [127]	Discussion of the planned methodology for a proposed 10-story shake table test. A goal of the test is to evaluate performance of nonstructural components.
		Experimental Seismic Response of a Resilient 2-Story Mass-Timber Building with Post-Tensioned Rocking Walls (2019) [129]	Summary of the methods and results from a full-scale 2-story CLT structure shake table test. The test achieved performance goals including no unplanned structural damage.
	Numerical Modeling	Ductility Estimation for a Novel Timber–Steel Hybrid System (2016) [135]	Numerical modeling is used to study ductility factors for use with a hybrid wood and steel lateral system for use in seismic design.
	Review	Cross-Laminated Timber for Seismic Regions: Progress and Challenges for Research and Implementation (2016) [128]	Discusses ongoing seismic testing efforts internationally and summarizes the state of CLT seismic research. Critical research topics are identified.
Diaphragms and Components	Diaphragms	Seismic behavior of Cross-Laminated Timber structures: A state-of-the-art review (2018) [125]	Summarizes the results of various seismic testing programs for CLT and proposes a q-behavior factor.
		Experimental Investigation on In-Plane Stiffness and Strength of Innovative Steel-Timber Hybrid Floor Diaphragms (2017) [136]	Discusses the testing performed for a hybrid system which includes CLT flooring with cold-formed steel beams and rolled steel girders. The testing found that the composite shear connections behaved elastically.
	Connections	Perforated steel structural fuses in mass timber lateral load resisting systems (2022) [137]	Structural fuses were tested and analyzed for their performance in dissipating loads during high seismic scenarios. The study found that the fuses yielded sufficiently to prevent damage to timber elements.

2.1.7.4 Fire Safety and Design

Fire performance has been widely studied for wood used in construction. Both passive and active methods of fire prevention exist for mass timber construction [138], and the 2021 International Building Code (IBC) has codified these methods as summarized in Table 2-9. However, this section will focus on the requirements and knowledge surrounding passive methods for the structural elements, which are unique to mass timber. To address concerns of contributions to fuel load and smoke production, several passive fire protection strategies are available, the main ones being the char method and the use of noncombustible protection, specifically gypsum board, which is installed directly onto mass timber elements to protect them from fire.[139] Both the char method and noncombustible protection may be used individually or in combination with timber and gypsum board contributing a portion of the total fire resistance.[34], [140]

The char method is based on unique properties resulting from the large sizes of mass timber as compared to light-framed timber and dimensional lumber. When burned, mass timber experiences a charring effect, by which the large mass of wood allows the formation of a protective char layer at the exterior of the element exposed to fire. Therefore, mass timber products are able to achieve some level of fire resistance ratings using a strategy which increases the size of a structural element to include a sacrificial layer or layers to charring.[105] Further, while mass timber elements sometimes incorporate lower quality lumber grades at the inner laminations to reduce cost and weight, stronger grades may be required where inner laminations are expected to perform as a main outer tension layer during fire design.[141] See Figure 2-3 for an example of how this strategy may be implemented for a CLT panel.

Table 2-9: Summary of representative active and passive fire protection measures codified in the 2021 IBC. Content from the 2021 IBC and “An overview of fire safety within the IBC.” [34], [142]

Fire Safety Category	Subcategory	Description/ Applicability	Relevant IBC Sections
<i>Fire and Smoke Protection Features</i> (Passive)	General	The code-prescribed fire and smoke protection features of Chapter 7 are intended to result in a building which passively resists the spread of fire and smoke.	701
	Fire resistance ratings (FRR)	FRRs are intended to provide structural elements with a minimal level of passive resistance to fire.	703, 704
	Fire walls, barriers, and partitions	Assemblies which must provide a fire and/or smoke separation between occupancies and tenant spaces.	706 - 708
	Smoke barriers and partitions		709, 710
	Prescriptive fire resistance	This section includes tables with demonstrated fire resistance of specific building elements, components, and assemblies.	721
	Calculated fire resistance	This code section discusses how to calculate the fire resistance of various materials and assemblies. This ties into the required FRRs for constructing passively fire-resistant buildings. For a mass timber element, the FRR is the sum of its unprotected rating and that of any noncombustible protection. This item is the focus of this section of the literature review.	722
<i>Interior Finishes</i> (Passive)	Scope and General	To aid the measures of Chapter 7, Chapter 8 prescribes limits for interior finishes and decorations based on flame-spread, flame-propagation, and smoke development.	801, 802
	Wall and ceiling finishes		803
	Interior floor finishes		804
<i>Fire Protection and Life Safety Systems</i> (Active)	General	Chapter 9 prescribes requirements for active fire protection systems based on a building's size and occupancy	901
	Automatic sprinkler systems	These sections focus on means, both automatic and occupant-controlled, of extinguishing an existing fire.	903
	Alternative automatic fire-extinguishing systems		904
	Portable fire extinguishers		906
	Fire alarm, detection, and emergency alarm systems	These sections focus on methods of alerting occupants and emergency service personnel to an emergency.	907, 908
	Smoke control systems	Systems for the control and removal of smoke and heat are intended to allow for occupant egress during the event of a fire.	909
	Smoke and heat removal		910

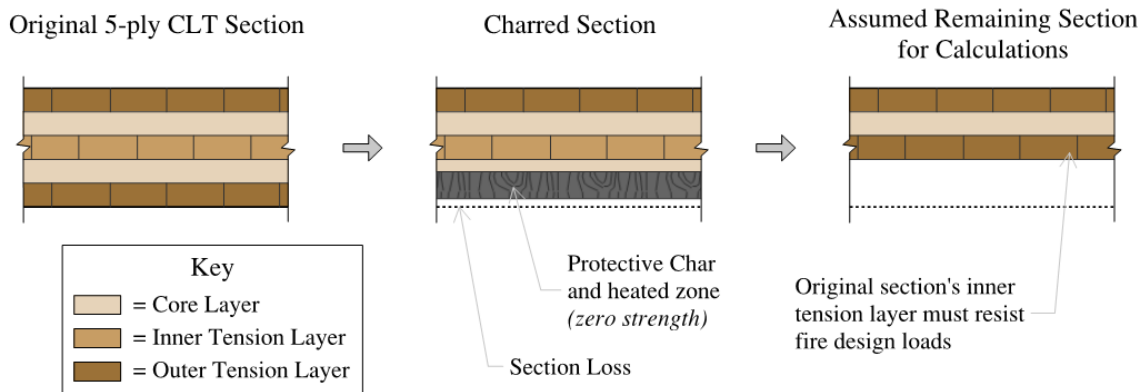


Figure 2-3: Example of charring process and remaining section for use in calculations. (Figure adapted from figures in The CLT Handbook (2019 Canadian Edition) and The 2018 Fire Design Specification for Wood Construction.[105], [141])

The use of noncombustible protection, typically gypsum board, is permitted to provide a fire resistance rating (FRR) based on the number of layers and FRR of the individual layers. In a fully protected strategy, the intent is that the gypsum board provides the full required fire rating, and therefore multiple layers of drywall may be required depending on the required rating. See Figure 2-4 for conceptual examples of how various fire design strategies may be implemented for Glulam and CLT mass timber structural products.

To design for char, the National Design Specification for Wood Construction (NDS) includes a calculation-based method, which estimates the char depth during a given time frame based on the required fire performance rating. The remaining strength and stiffness of a structural member is then determined by assuming the char zone contributes nothing, leaving only a smaller, residual cross section. It is additionally recommended and conservative to include only the section starting from the first fully remaining tension lamination and moving upward in Glulam and CLT design per the NDS to simplify the calculation, as previously depicted in Figure 2-3. The NDS-defined model may currently be used to calculate ratings up to two hours, but requires further validation for longer periods of time.[139], [140]

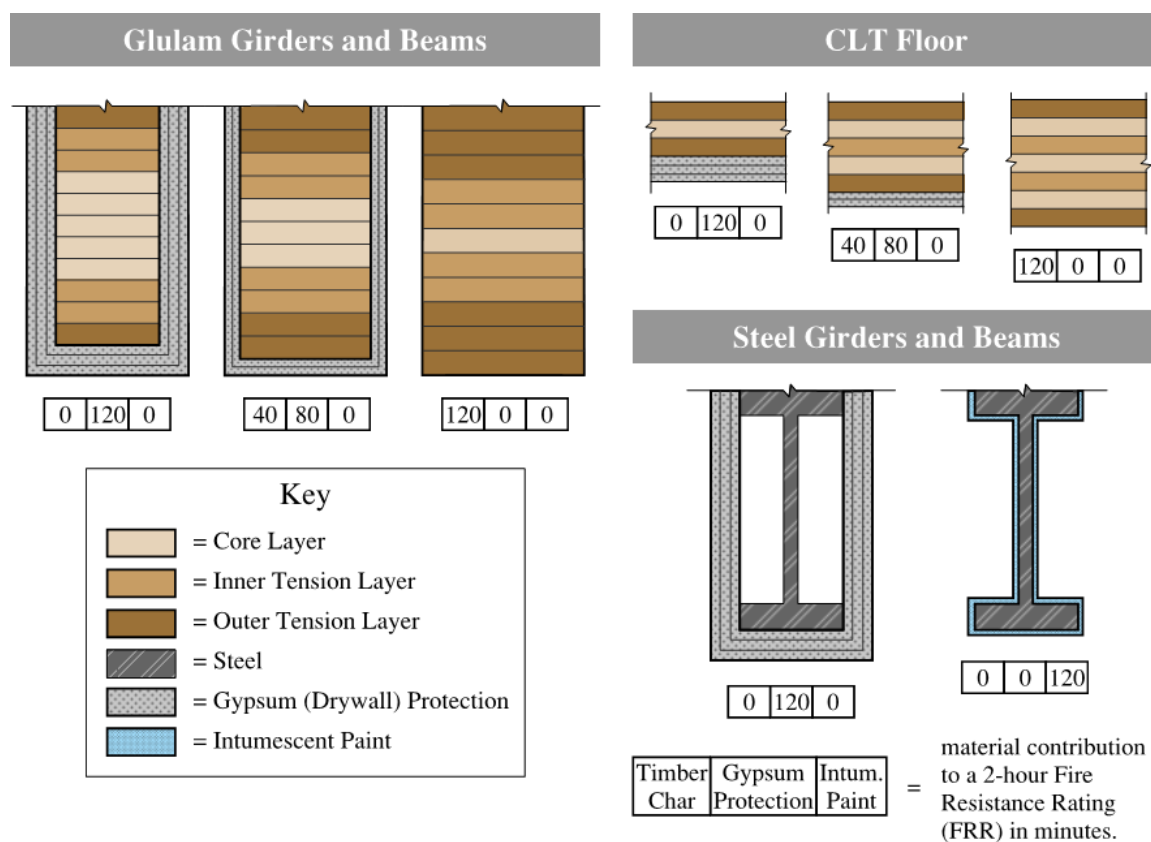


Figure 2-4: Conceptual examples of potential strategies to achieve a 2-hr rating for Glulam, CLT, and W-shape steel sections. (N.T.S.: Number of laminations are purely conceptual and intended to be representative. Figure adapted from figures in The CLT Handbook (2019 Canadian Edition) and The 2018 Fire Design Specification for Wood Construction.[105], [141])

As an alternative to the NDS calculation-based method, structural performance testing is possible. Testing is typically based on the following three criteria: 1) the ability of a test assembly to support to required loads for the entirety of the desired fire resistance rating, 2) the ability to prevent smoke and gasses from crossing to a space adjacent to that in which the fire occurs, and 3) the ability of the assembly to insulate the non-fire-exposed side from excessive temperature increases [139]. Testing has generally found predicable and consistent charring rates in mass timber products [143]. Other fire safety concerns currently under research in the field include the following:

- Contribution to fuel load within a space: Testing has shown that leaving CLT and other mass timber products exposed results in higher rates of fire growth by increasing the fuel load; however, the highest observed temperature was not significantly affected by the presence of exposed timber. If delamination occurred, test fires burned much longer than typical after the fuel provided by the room contents was expended.[143], [144]
- System-level performance: The effect of fire performance on a completed structural system and building is not as well understood. Much of the testing is for single assemblies and components that are not part of a larger framing system.[143]
- Performance of adhesives: If delamination or fall-off of the bottom layer of CLT occurs due to inadequate performance of adhesives, newly exposed timber will contribute to longer fires.[143]
- Spread of fire in concealed spaces: Typically a concern that fire could spread more easily within a concealed space in a timber building [143].
- Self-extinguishment: Testing in more limited settings show CLT can self-extinguish; however, further testing based on natural and long-duration fires is still needed. [144]

2.1.7.5 Other Structural Considerations

In addition to structural design for gravity and lateral loads, many other structural considerations are of interest to mass timber structural design and research. This section explores the current literature on these topics including robustness, connections, advanced materials and long-term loading, and serviceability impacts. Requirements for a given project for each of these topics will vary widely depending on the building usage and location.

Robustness

Robustness is generally viewed as a structure's ability to resist disproportionate collapse and progressive collapse. Disproportionate collapse is defined as when the total structural failure that occurred is much greater than the initial failure caused directly by the initial event.

Progressive collapse describes the manner in which a collapse happens, and is defined as a series of failures that occur in a sequential fashion away from the original damage and event. In the past, structures tended to be overdesigned, and therefore engineers were able to design sufficiently robust structures as a matter of standard default design practices. With advances made in structural analysis and computational software, modern structures are designed to be optimized for efficiency, and do not necessarily result in a robust structure [145].

In general, CLT offers some benefits with respect to robustness: it has the ability to span in two directions, walls can behave as deep beams if needed, and connection capacities between panels can be high. However, CLT is somewhat brittle in tension and CLT panels are heavier as compared to light-framed timber, which can increase impact loads on the floor below if there is a floor panel failure during a collapse event. Timber design can learn some lessons from concrete as well due to some similarities. For example, both CLT and reinforced concrete floor slabs have the ability to span two ways or form shell action following the loss of an element. Additionally, both timber and concrete rely on the ductility at connections and joints. Finally, timber design for robustness can benefit from seismic research and design for timber buildings because of similarities in performance requirements. Details that improve a structure's seismic performance have been shown to potentially improve its robustness as well [145].

Much more research and analysis has been performed in the field of robustness for steel and concrete structures, while not as much information is available regarding timber structures. However, timber design seeks to apply lessons learned from designing steel structures for robustness because both timber and steel have high strength to weight ratios. Because of this similarity, both timber and steel structures commonly include slender columns, which must be checked for buckling under the additional loads following an element loss during a collapse event. Further, timber and steel should both make use of redundant lateral bracing systems in their design for robustness [145]. Table 2-10 summarizes representative research on robustness.

Table 2-10: Summary of representative studies on robustness

Topic	Sub-Type	Study Name	Summary of Findings
Disproportionate Collapse	<i>Experimental Testing</i>	Experimental Study of Disproportionate Collapse Prevention Mechanisms for Mass-Timber Floor Systems (2020) [146]	Controlled removal of an interior bearing wall was tested for collapse prevention, and connection detail to improve performance is proposed.
		Reliability Analysis and Disproportionate Collapse for Multi-Storey Cross-Laminated Timber Buildings (2017) [147]	This paper includes some limited discussion of the use of optimization for the selection of the CLT panel thickness. The paper found that sizing of structural elements is important to the connection behavior.
	<i>Numerical Modeling</i>	Robustness of Multi-Storey Timber Buildings (2017) [148]	This paper includes a case study of a nine-story flat-plate timber building as there are limited case studies available for different types of buildings.
		Disproportionate collapse prevention analysis for post and beam mass timber building (2022) [149]	An alternative load path analysis is applied to a modeled post and beam building to study disproportionate collapse.
		Finite element analysis of alternative load paths to prevent disproportionate collapse in platform-type CLT floor systems (2021) [150]	An alternate load path method is proposed and used to study various mass timber design configurations for removal of a single supporting element.
	<i>Review</i>	Structural Robustness And Timber Buildings – A Review (2019) [151]	Review paper discussing the field of research of robustness for timber buildings.
		Prevention of Disproportionate Collapse for Multistory Mass Timber Buildings: Review of Current Practices and Recent Research (2022) [152]	Review paper discussing both real world case studies and recent research regarding methods of designing for disproportionate collapse.
	<i>Design Guidance</i>	Tie-force procedure for disproportionate collapse prevention of CLT platform-type construction (2019) [153]	Developed analytical procedure best for use on buildings up to 10 stories. More research is needed for novel connections in taller wood buildings
Blast Loading	<i>Experimental Testing</i>	Blast Testing of Loaded Cross-Laminated Timber Structures (2018) [154]	The testing found that the CLT panels could resist the tested gravity loads when subjected to blast loads. Additionally, there was less observable damage to the CLT panel for the loaded case as compared to the unloaded case
		Behaviour of mass timber members subjected to consecutive blast loads (2023) [155]	Glulam and CLT elements are experimentally subjected to blast loads as studied for their structural performance.
		Investigating the Use of Energy Absorbing Connections (EAC) to Enhance the Performance of Mass Timber Structures Subjected to Blast Loading (2021) [156]	Several connection types for mass timber elements underwent static and dynamic experiments to study structural performance and ductility during blast loading.
	<i>Numerical Modeling</i>	Alternate Load-Path Analysis for Mid-Rise Mass-Timber Buildings (2018) [157]	Paper looked at time-based removals for mid-rise CLT/Glulam building. Description of modeling approach in Ansys is provided. For this type of analysis, it may be important to take effects of time into account if modeling progressive collapse scenarios.
	<i>Numerical Modeling</i>	Modeling of Mass Timber Components Subjected to Blast Loads (2021) [158]	An analytical model was developed based on experimental testing to predict structural performance of CLT and Glulam elements when subjected to blast loads.

Connections

The connections used in timber products tend to depend on the system type and loads experienced and may range from conventional structural connections such as self-tapping screws and other dowel-type fasteners to proprietary connections with manufacturer-specific components and engineering design values. Figure 2-5 depicts the main classes of connections. Classes 1 through 3 are defined by the Mass Timber Design Manual. [44] Class 0 was added based on the Index of Mass Timber Connections to include those connections which do not use any steel components; however, this type of connection is not commonly used in mass timber construction at the time of this paper. [159]

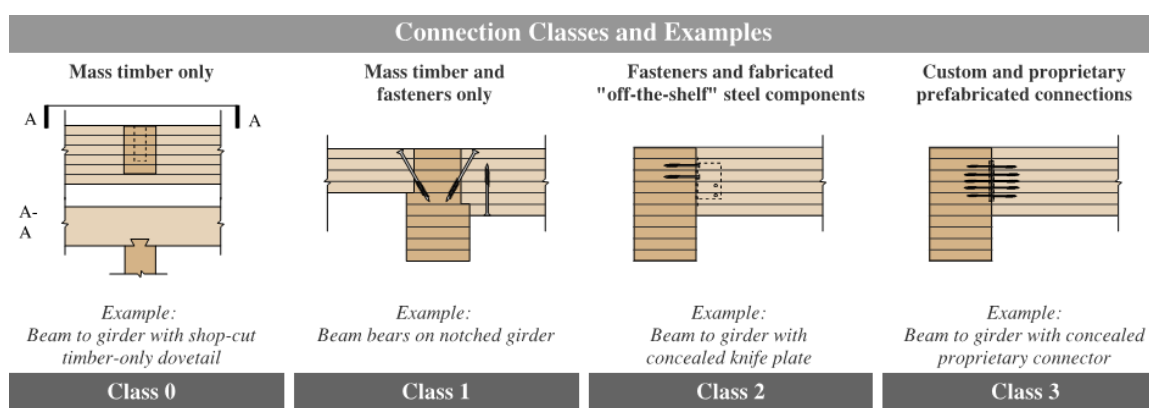


Figure 2-5: Summary of connection classes along with examples (adapted from the Mass Timber Design Manual by ThinkWood and the Index of Mass Timber Connections by WoodWorks.) [44], [159]

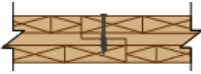
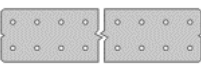
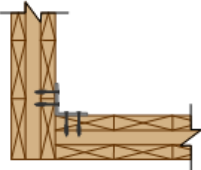
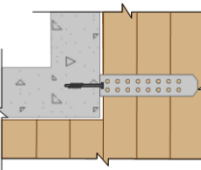
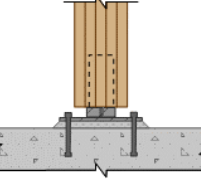
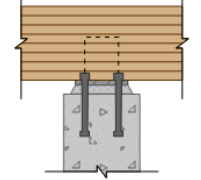
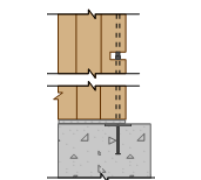
Connections greatly influence global structural behavior and must be carefully designed for strength, stiffness, and ductility needs. [108] As such, connections are often one of the most expensive components of a mass timber structure. To meet structural requirements, connections may be based on extensive testing of proprietary products or based on structural design calculations that follow relevant standards, such as the NDS. [160] Connections are typically required to be elastic unless they must meet special seismic ductility requirements for seismic dissipative connections. Because most CLT manufacturers have CNC capabilities, there is the opportunity for structural designers to incorporate custom and innovative connections. Innovative

connections tend to allow easier on-site erection, and are typically buried within the wood elements for improved fire resistance ratings.[161] Connections between the foundation or podium levels and the wood structure must consider the kinds of loads that are being transferred and also protect the wood from other materials, such as from moisture in curing concrete or from capillary action of water at grade through the foundations. [161]

Connections in a mass timber structure must also meet requirements for aesthetics, fire resistance, constructability, and structural performance. [160] In applications that seek to expose the structure, aesthetics will often drive the design. Designers may want to either hide all steel components or expose steel brackets for a more industrial aesthetic. In both cases, the connection must meet applicable requirements for fire resistance. Concealed steel components may be protected by the surrounding mass timber material, while exposed steel elements may require a fire-resistant coating or similar. [160] Connections must also be designed for the differential shrinkage that occurs between different materials, constructability, construction tolerances, and cost. [160] Table 2-11 provides a summary of common connection categories for mass timber structures, and the WoodWorks Index of Mass Timber Connections provides an in-depth index of the various applications of these connection categories and how they compare for various project criteria. [159]

In addition to the typical considerations noted above for connection design, the steel or aluminum used in connections can have an uncertain impact on the total embodied carbon of a structure. All-timber buildings typically incorporate a significant amount of steel or aluminum in the connections to transfer the loads, especially as the loads get large. [161] Not much literature exists on the contribution of connections to EC; however, Lukic et. al. found that connections contribute significantly and must be included in EC calculations. [84] Further, per the “Technical guide for the design and Construction of Tall Wood Buildings in Canada,” connections often dictate member size, which would have additional impact on EC calculations. [108]

Table 2-11: Summary of mass timber connection categories. Descriptions adapted from Simpson Strong-Tie's product summary. [162] Sample details adapted from the Index of Mass Timber Connections. [159]

Connection Type	Sample Detail	Description and Applicability
<i>Structural screws</i>		Can be used on their own in simple connections or to attach other metal components such as brackets and beam hangers
<i>Strap Ties</i>		Can be used within diaphragms to add robustness and stiffness, or in floor-to-floor details for lateral load applications.
<i>Beam Hangers</i>		Used for beams and purlins attached to columns, beams, or shear walls. Consideration is often given to the connection detail aesthetics depending on the fire design approach.
<i>Angle Brackets</i>		Used to connect mass timber panels to each other in details such as wall to wall, floor to wall, or roof to wall connections. Can be used in hybrid applications.
<i>Holdowns & Tension Ties</i>		Most often used to carry tension loads in lateral systems for elements such as shear walls, braced-wall panels, and diaphragms.
<i>Adhesive Anchors for Timber-Concrete Connections</i>		Used for hybrid systems to gain higher strength for post-installed anchors in both cracked and uncracked concrete elements. Typically used with threaded rods for attachment.
<i>Mechanical Anchors for Timber-Concrete Connections</i>		Used for hybrid systems in both cracked and uncracked concrete elements, as well as with masonry. Specific applications, such as seismic or wind, are dependent on specific anchor design.
<i>Post-tensioning rod systems</i>		Used to resist overturning and uplift forces in lateral force resisting elements. Can provide self-centering behavior in seismic applications.

Advanced Material Behavior and Long-Term Loading

Structurally, wood is an orthotropic material, such that it has different properties when considered parallel versus perpendicular to the grain. [163] When loaded parallel to the grain, wood is strong in tension and works fairly well in compression until buckling occurs. When loaded perpendicular to the grain, the fibers are more susceptible to crushing under compression and splitting under tension. Wood also experiences long-term structural effects such as creep and loss of strength under long term loading. These effects worsen as cycling relative humidity levels are introduced, causing the wood to shrink and expand [31]. The durability concerns include dimensional changes, which are most prominent perpendicular to the grain. Therefore engineered timber products, which either essentially eliminate a predominate grain direction or include components of alternating grain directions, are more dimensionally stable, or less prone to shrinkage and swelling due to changes in relative humidity [164].

Creep effects should be considered in timber projects since wood is a viscoelastic material. [163] Creep refers to additional deflections of the structure under long term loading beyond the initial instantaneous deflections[27], and research has shown similar creep behavior in CLT to other similarly structurally engineered timber products, such as plywood. Creep is accounted for in CLT design through a creep factor, which is included in the applicable design standards and guides such as the NDS[140] and The CLT Handbook.[42], [105] The structural adhesives typically used in CLT products, and which meet product standards, have been shown to experience negligible creep, and therefore do not contribute to creep. Some CLT is mechanically-assembled, rather than glued. Research has shown that mechanically-laminated CLT may experience deflections due to creep and load duration that are four times that of glued CLT.[165]

For taller projects, shortening of glulam under dead loads can be a concern as the effects accumulate over the building height. Axial shortening of Glulam columns is a creep deformation effect that occurs over time and can affect long-term structural performance if not accounted for

during design. [166] The Brock Commons project in British Columbia, Vancouver used steel shims at key levels to accommodate shrinkage and address related issues [38]. The Wood Innovation Design Center included design for differential movement between the structure and enclosure. The project was balloon-framed to limit structural shrinkage, and enclosure details were designed to accommodate movement [29].

Serviceability Impacts

Serviceability-based design requirements such as vibration sensitivity and control along with deflections need to be considered along with structural capacity. [105], [167] The primary focus here is to achieve a level of performance in regard to non-structural considerations such as occupant comfort and durability of floor finishes. [34] Vibrations may be caused either by human activities or by the building's dynamic performance under wind loading. Floor vibrations depend greatly on the flexibility at the supports and require close monitoring for quality control during construction. [168] Floor vibrations should be addressed during design with careful consideration to floor system mass and stiffness because it may not be feasible or practical to correct wood floor vibration issues once a building is occupied. [108] Lightweight tall wood buildings may be more susceptible to vibrations during wind loading than buildings of other materials constructed to the same height. [168]

2.1.7.6 Gaps in Tall Timber Structural Knowledge

Having reviewed the research advancements in tall buildings from a structural performance lens, the following are some key gaps that need further research and attention:

- While many floor system options exist, there is limited test data and design guidance for hybrid systems and specialized systems hoping to gain efficiencies.
- More research and testing is needed to be able to use hybrid lateral systems, mass timber braced frames, and mass timber moment frames in high-seismic applications.
- For fire design, education of stakeholders, including designers, code officials, and owners, to understand how mass timber behaves in a fire, what makes it different from light-framed timber, and how to properly design to meet fire performance requirements. Further research related to topics such as fuel load contribution of mass timber and self-extinguishment is needed as well. [144]
- Mass timber systems could benefit from additional testing and analysis of different types of systems for disproportionate collapse.
- Additional design guidance is needed to aid designers in the implementation of connection design where propriety or off-the-shelf systems cannot be used.
- More project case studies regarding mitigating details for column shortening, tolerance in hybrid systems, and shrinkage and swelling would help designers better understand options they have for these critical details.
- Acoustic insulation design would benefit from more project-specific field testing to verify the real-world acoustic performance of mass timber projects outside of a lab test environment.
- Further analysis and testing is needed to better understand other serviceability criteria such as building drift during wind loading and vibrations due to walking activities of occupants.

2.1.8 Computational Design in Tall Buildings

Computational analysis, optimization and design methods have been widely applied to early design evaluations of multi-disciplinary goals, such as those building features related to operational energy use [169]. Analytical methods vary and may incorporate design cases and computational programs. Often, key decisions regarding structural system design occur in the early design stage of a project. The available computational methods are recently being applied to

tall wood buildings to explore aspects related to architectural design, embodied energy, and structural design [25], [50], [170]. A variety of software programs and plug-ins are available to designers, as summarized in Table 2-12.

While a range and variety of structural design software exists to aid in the design of conventional steel, concrete, and masonry structures, many limitations exist in the software for timber. Existing software applications, such as RISA, SAP, and ETABS, often do not easily consider unique serviceability requirements for mass timber. [8]–[10] Further, out of the main software and plugins, only the Beaver plugin for Grasshopper is designed specifically for parametric design to be able to explore a wide variety of designs in early design. However, Beaver is designed for use with Eurocode 5 and is therefore not applicable for US project work. [171] Other timber-specific software applications typically are not designed for parametric use and have their own limitations.

While manufacturers often offer technical guides with initial sizing guidance, these do not offer sizing advice integrated with guidelines for reducing EC. Although carbon tools are available to estimate embodied carbon, these tools tend to focus on estimates for specific projects and therefore do not provide guidance for decision-making. The Fast+Epp Timber Bay Design Tool appears to be the most helpful early-stage design tool, even providing material volume outputs which could be used separately to estimate EC. However, the tool does not include hybrid structure options, can only look at one design at a time thus limiting the ease of comparisons between options, and requires user inputs for items such as girder width rather than designing to the most efficient size. [172] At the time of this literature review, no resource has compiled both structural design and EC data into a single tool or guide for early-design decision making. Additionally, no resource has compiled EC data in a comprehensive way for a range of variables and floor system structure types such that designers could use this information to guide early design decisions.

Table 2-12: Design software - Summary of capabilities for mass timber design

Design Criteria		Software or Plug-In									
		RISA [8]	SAP [9]	ETABS [10]	Enercalc [173]	Wood Works Sizer [174]	Beaver [171]	BC Calc [175]	GSE Timber [176]	S-Timber [177]	RFEM Timber [178]
Code	IBC					✓		✓			
	ASCE 7			✓		✓					
	NDS	✓			✓*				✓		✓
Loads	Dead	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Live	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Wind	✓	✓	✓	✓	✓		✓	✓	✓	
	Seismic		✓	✓	✓	✓			✓		
	Snow	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Criteria	Flexure	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Shear	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Deflection	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Creep						✓			✓	
	Vibrations								✓†	✓	
	Fire Design					✓			✓		✓
Structural Elements	Floor panel	✓	✓	✓		✓				✓	
	Beam	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Column	✓	✓	✓	✓	✓		✓	✓	✓	✓
	Hybrid			✓						✓	
	Connection					✓	✓			✓	✓
	Multi-span	✓	✓	✓	✓	✓				✓	✓
Parametric Modeling	Parametric design								✓‡	✓‡	✓‡
	Compatible with GH [§]						✓				
	Compatible with others			✓						✓	

Notes: * Based on 2005 NDS ; † Vibration limit states only calculated for sawn lumber joists; ‡ Limited parametric design capacity for analyzing and comparing designs; § GH = Grasshopper.

2.1.8.1 Design Space Exploration

One approach that can be used to evaluate options during early design is Design Space Exploration (DSE). DSE can be coupled with parametric analysis to evaluate possible designs

against performance goals and compare designs to each other. [179] Parametric design is a process occurring in early-stage design that enables designers to compare a variety of design options by changing project parameters. This design process is useful in guiding decisions made during early design and to facilitate earlier coordination across disciplines in early design concepts. [180] Figure 2-6 illustrates the basic DSE approach. Variables are selected which can be changed parametrically to generate designs which populate the Design Space. Designs are evaluated for the performance objectives of interest, thus filling in the Objective Space. By comparing the Design Space and the Objective Space to each other, the modeler may gain insight into how design decisions affect performance goals. [179] This approach has been incorporated similarly into other research related to design or mass timber. [86], [181], [182]

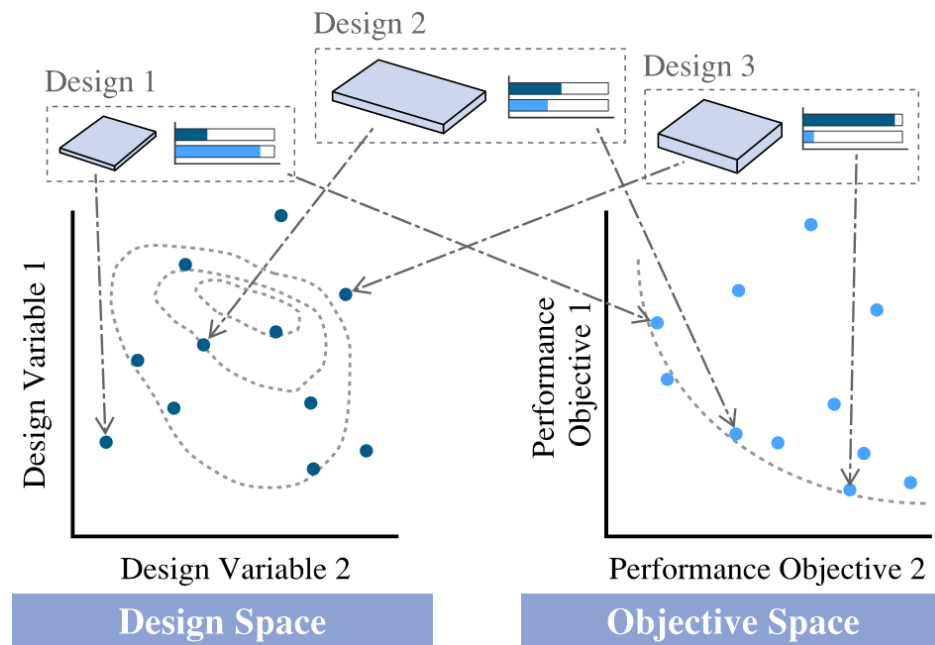


Figure 2-6: Adapted from “Computational Design Optimization” course notes and Brown et al. 2020 [179], [183]

2.1.8.2 Analytical Models

Analytical or numerical models can be a good alternative to experiments as they are significantly less expensive to run compared to an experiment. However, analytical methods are still generally complicated and often require additional research and validation against experimental test data [125]. For example, analytical models for seismic research are still at a stage of development in which they require validation from experimental results, particularly for systems intended for use in higher seismic regions for taller building applications [128].

Analytical methods often use finite element modeling and range in complexity from simplified models, which provide the least realistic results, to complex models, which are the most accurate.

Some methods to model CLT panels include the following, from least to most complex:

- CLT panels are modeled as a truss with either no in-plane deflections considered, or diagonal springs, which represent the in-plane stiffness. [125]
- CLT panels are modeled with shell elements that are either multi-layered or orthotropic to represent the varied orientation of layers within the CLT panel (this is typically the preferred method) [125]
- CLT panels may be modeled more realistically using 3D elements; however, this requires the most computational resources and complexity. [125]

Further, analytical methods typically model connections as springs or link elements.

Connections may be modeled with uniaxial or biaxial behavior, the former being more conservative while the latter is generally more accurate [125]. For lateral systems research for tall buildings many studies have worked to validate FEA models against experimental testing, comparing test data to model behavior and results. [131], [133], [184]–[186]

2.1.8.3 Gaps in Tall Timber Computational Knowledge

Research in computational design and analysis of tall mass timber structures is ongoing as researchers work to fill the gaps in knowledge and improve design guidance and tools. Some areas that have ongoing research and which would benefit from additional study include the following:

- Methods too aid streamline decision making in early design using parametric approaches.
- Processes for the incorporation of all unique timber serviceability needs into design software and tools.
- Additional validation of FEA models for mass timber against experimental data for wind and seismic forces.
- Modeling procedures to expand FEA modeling for taller timber structures based on test data test buildings.

2.1.9 Multi-discipline design considerations

In addition to the most typical structural and serviceability requirements, there are other disciplines that affect and are affected by a mass timber structural design.[44] Similar to projects of conventional construction, mass timber projects require detailed coordination between the structure and other disciplines; however, it is useful to understand mass timber's unique relationships with those disciplines. The sections below discuss some of the main disciplines that should be considered when deciding whether to choose mass timber for a project, as well as during the design and construction phases of a project.

2.1.9.1 Architecture

Mass timber projects include many architectural considerations related to building form and aesthetics, the integration of services, and occupant well-being. [44] The use of mass timber as compared to concrete and steel buildings tends to impose practical limitations on building layouts. In general, mass timber works best for smaller and more regular bay sizes. Special considerations should be made when considering architectural programs that require open floor plans or flexibility for potential future tenant changes and remodeling. [108] Also, taller structures may require unreasonably large wood elements if an all-timber system is used. Case studies in this area are generally limited; however, a parametric design space exploration performed in this field studied trends with regards to feasibility of all timber structures at varying heights, geometries, and layouts. [25]

Further, while mass timber may be popular for the aesthetics of exposed timber, many projects may require that noncombustible fire protection be installed directly to the timber. [34], [105] In these cases, the final visible finish is that of a gypsum ceiling, similar to more traditional structures. [34] Mass timber also affects the integration of building services such as plumbing, electrical, and ductwork systems. Depending on the mass timber system used in a project, creative solutions may be required to determine where to run services and how to address fire safety requirements at service penetrations. [108]

2.1.9.2 Construction Management

Scheduling and cost of construction are drivers in the increasing use of mass timber in taller buildings. In general, mass timber can be constructed using prefabricated elements with very few skilled laborers and smaller cranes as compared to steel and concrete projects.[187]

Projects have shown faster schedules and lower costs during construction.[44] Less research has been done to study if those trends continue for 20+ story projects and/or for hybrid projects.

In general, prefabrication is becoming more commonly used in the construction industry because prefabricated elements can cut down on waste, reduce time and labor required on site, and take advantage of material optimization and precision manufacturing [188]. Because of CNC capabilities in the factory and the customized prefabrication process to manufacturer CLT panels, the process can fit well into BIM processes.[189] The use of CNC machining also allows for precise layout of penetrations for services and windows. CLT panels are inherently dimensionally stable because of their alternating layup between layers, and therefore they can take advantage of the precision of CNC machining by designing and installing panels to tight tolerances [106]. As CLT lends itself well to prefabrication, work can be shifted from the job site to the factory floor, improving worker safety, quality control, scheduling, site storage logistics, and reducing exposure to weather on site. It should be noted that the greater the level of prefabrication for a project, the greater the need to shift design and planning earlier in the design and construction process [190].

Limitations unique to heavy timber include the need for weather protection during construction to limit exposure to moisture and dimensional changes [105], the reduction of construction jobs due to less overall labor required, general lack of knowledge for mass timber construction and implementation, a longer code approvals process, and greater up-front design and planning requirements [188]. Hybrid projects experience additional unique challenges during construction because of the interfaces between different materials with different behaviors and tolerances, and the complexity of scheduling different trades [191]. Additionally, the prefabricated nature of CLT panels may mean that it is more difficult to resolve issues in the field.

Finally, a study performed a cost and schedule analysis for several case study mass timber projects, for which equivalent or nearly equivalent conventional projects were identified.

An average cost savings of 4.2 percent was found for mass timber. In some cases where a mass timber project costs more, these were commonly pilot projects, which were the first mass timber project that some or all of the stakeholders were involved with. The case studies saw an average 20 percent schedule decrease for the mass timber projects. The study concluded that to take advantage of potential cost savings in mass timber, projects should take advantage of previous knowledge and experience [188].

2.1.9.3 Building Envelope Performance

Studies of perceived barriers to CLT structures have revealed that moisture and durability performance are some of the greatest concerns within the industry [29]. These concerns can generally be addressed or mitigated with precautions during construction and through the building enclosure design. A 2016 study found that moisture damage in new construction projects is most often related to factors such as building height, the use of low-slope roofs, and trending architectural designs, which incorporate recesses and projections. Damages due to moisture were generally found to be independent of the choice of structural material [29]. Ultimately, the fundamental design strategies for building enclosures in mass timber structures remain the same as compared to a low-rise wood building or a concrete or steel building; however, there are additional considerations for a tall mass timber building [192].

Mass timber has some unique properties that differentiate it from steel and concrete. Mass timber has a delayed response to changes in relative humidity, which is both beneficial during occupation and a downside during the construction phase. Mass timber typically experiences limited changes with short-term variation in relative humidity, but if it becomes overly saturated within the core, can take months to dry out again and reach its equilibrium in service moisture content.[193] Additionally, wood is a hygroscopic material and is therefore more

susceptible than steel or concrete to fungus, mold, and decay if it is allowed to become and remain wet. [28] Therefore, measures must be taken to protect the wood structure from moisture through best design practices for building enclosures and during the construction process, which are practices commonly used in quality construction regardless of structural material. [192] A common best practice enclosure design approach is the drained and ventilated rainscreen cladding system that makes use of two water control layers for redundancy. [193] This type of assembly is not new and is already considered best practice for commercial construction and quality residential construction regardless of structural material.

2.1.9.4 Acoustic Performance

Building codes require that construction projects meet certain acoustic standards to separate building spaces from other noise-generating spaces. For example, dwelling spaces should be acoustically separated from other dwelling spaces and from machine or equipment rooms. Code requirements can be met by on-site acoustical measurements, by providing pre-approved assemblies known to meet requirements, or by performing design calculations that show an assembly meets the requirements.[194] The two main acoustic rating values include Sound Transmission Class (STC) and Impact Sound Insulation Class (IIC). STC is a measure of the ability of an assembly to insulate against airborne sound transmission between spaces. IIC is a measure of a floor or ceiling assembly's performance in insulating spaces from impact noise generated in the space above. The 2021 IBC requires a minimum STC and IIC of 50 for multi-family buildings, but higher values than that represent better performing acoustic assemblies. [34] For any building, noise is typically controlled by reducing noise sources, reducing vibration of floor and wall assemblies resulting from source noises, and preventing sound transmission through and around floor and wall assemblies. When looking at wood assemblies specifically,

there are acoustical challenges due to wood's lighter weight as compared to concrete and steel.[194]

In general, the biggest complaint in timber buildings is acoustics. A study of impact sound insulation performance of timber floors generally found that acoustic control measures are not as efficient when used in timber buildings as they are for higher-mass systems such as concrete and steel. This is a result of the lighter weight of timber floor systems [195]. Lab measurements specific to CLT have shown that bare CLT alone cannot meet typical code requirements and standards. Typical recommendations for the acoustical design of wood assemblies include using surfaces with dense porosity to reflect sound back to the source, using higher mass elements in an assembly to reduce vibration amplitudes, and separating gypsum board finishes from the wood structure. Floors should also incorporate layers that are capable of dissipating sounds due to impact.[194] Some of the wood building products organizations offer resources which provide acoustic performance data on tested assemblies, including FPInnovation's CLT Handbook and WoodWorks' technical document listing acoustically-tested mass timber assemblies.[105], [196]

2.1.9.5 Gaps in multi-discipline design knowledge

The industry could benefit from additional research to fill in the knowledge gaps related to the disciplines discussed in this section. Doing so will inform newer project design and improve the efficiency and proliferation of mass timber structures. Knowledge gaps include, but are not limited to, the following:

- Expanded guidance and knowledge of the expected structural member sizing and layout options for various loading scenarios in tall timber structures.
- Cost and schedule data collection and analysis to more accurately inform estimates for newer projects.

- Test data and studies on mass timber performance as thermal mass.
- Extensive studies of built projects for acoustic performance, including occupant surveys

2.1.10 Mass Timber Project Trends

This section includes a discussion of some representative projects and trends discussed in the literature to better understand some of the successes and challenges of pioneering projects using CLT or other mass timber elements. Tall timber projects and other notable projects are summarized in Table 2-13. Projects both with all-timber and hybrid timber structural systems are included to represent a variety of systems. Amongst the included representative projects, many consist of hybrid designs, particularly with the inclusion of concrete or steel lateral systems in taller mass timber structures. Further, many of these projects are residential or office buildings.

The current generation of the tallest timber buildings, some of which are hybrid systems composed of timber and either steel or concrete elements, includes projects around 18-20 stories, such as the University of British Columbia Bock Commons project in Canada, Mjøstårnet in Norway [1], [3], and the 24-story Hoho project in Austria. [26] The tallest timber building currently constructed is the 25-story Ascent project in the U.S. [26].

A 2018 survey of mass timber structures categorized buildings by both height and generation, where generations were defined as follows; G1 is from 2009 to 2013, G2 is from 2014 to 2016, G3 is from 2017 to 2018, and G4 are projects scheduled to be completed by 2020. This survey found that the most recent generation of projects to be completed in 2020 included several projects in the 16- to 24-story range. This is taller than previous generations, and the increasing height of mass timber structures is expected to continue.[3] See Figure 2-7 for a summary of project heights surveyed by Kuzmanovska et. al. (2018).

Table 2-13: Notable mass timber buildings [4], [26], [197]–[199]

Project Name	Year	Structure Type	Height (ft / m)	Stories	Location	Building Use	Gravity System	Lateral System
<i>Ascent</i>	2022	Timber-Concrete	284 / 87	25	Milwaukee, WI	Residential	Timber floors and frame	Concrete core
<i>Mjøstårnet</i>	2019	All-Timber	280 / 85	18	Norway	Mixed-Use	CLT floors and Glulam frame	CLT shear walls and Glulam trusses
<i>Hoho</i>	2020	Timber-Concrete	279 / 85	24	Austria	Mixed-Use	Concrete-timber composite floors	Wood shear walls/concrete core
<i>Haut</i>	2022	Timber-Concrete	240 / 73	22	Netherlands	Residential	Concrete-timber composite floors	Concrete core and CLT shear walls
<i>Sara Kulturhus Centre</i>	2021	Timber-Steel	238 / 73	20	Sweden	Hotel/Exhibition	Steel-timber hybrid	Laminated timber core
<i>De Karel Doorman</i>	2012	Timber-concrete-steel	231 / 71	22	Netherlands	Residential/Retail	Timber floors and steel frame	Concrete core
<i>55 Southbank Boulevard</i>	2020	Timber-steel	229 / 70	19	Australia	Hotel/Office	Timber and concrete floor/walls, steel columns	Concrete core
<i>Brock Commons</i>	2017	Hybrid	190 / 58	18	Canada	Residential	Post and panel (CLT and Glulam)	Concrete cores
<i>Treet</i>	2015	Hybrid	161 / 49	14	Norway	Residential	Glulam truss, CLT floors and walls	Glulam trusses
<i>503 on Tenth</i>	2023	All-Timber	164 / 50	10	Portland, OR	Office	Timber floors/frame	Timber
<i>INTRO Tower</i>	2022	Timber-Concrete	130 / 40	9	Cleveland, OH	Mixed-Use	Timber floors/frame	Concrete core
<i>Forte Tower</i>	2012	Timber-Concrete	106 / 32	10	Melbourne, Australia	Residential	Timber/concrete floors/frame	Concrete and timber core
<i>Stadthaus</i>	2009	All-Timber	95 / 29	9	United Kingdom	Residential	CLT floors and walls	CLT shear walls
<i>Carbon 12</i>	2018	Timber-Steel	95 / 29	8	Portland, OR	Residential	Timber floors/frame	Steel frame
<i>Bullitt Center</i>	2013	Hybrid	91 / 28	6	Seattle, WA	Office	Timber floors/frame	Steel frame
<i>Emmons on 3rd</i>	2014	Timber-Concrete	86 / 26	8	Seattle, WA	Residential	Timber/concrete floors/frame	Concrete and timber core
<i>Platte Fifteen</i>	2019	All-Timber	70 / 21	5	Denver, CO	Office	CLT floors and Glulam frame	Concrete core, Glulam frame, steel rod bracing

As with other structural materials in their historical development, there are many gaps in the knowledge regarding tall mass timber structures which, if answered, may continue to drive innovations and height increases. Building trends have shown that each generation of tall timber building, as previously defined per the 2018 survey conducted by Kuzmanovska et. al., is increasing in height, and architects choose more often to expose the CLT and engineered wood structure where they are able, or will alternatively use finishes that mimic the look of the wood structure for aesthetic design goals [3]. Further, the use of wood, if exposed architecturally, has been shown to improve overall occupant well-being [37], and is therefore encouraged for use in sustainability standards, which promote occupant wellness standards [72], [75].

The drive for innovation is also a factor as projects seek to distinguish themselves by using timber for taller buildings in ways the material has never been used before. This could arguably be seen as a return to construction's roots for taller buildings, as wood is considered to be the oldest building material used in man-made shelters, and has been utilized with varying forms and advancements throughout the history of construction [200].

		Number of Stories																								Average Number of Stories/ Total Number of Projects	
		Up to 7			8	9	10 to 15						16 and Up														
Generation	Year	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24							
G1	2009			1	1																9.4 stories 8 projects						
	2010			1																							
	2011			1																							
	2012			1		1																					
	2013				1						1																
G2	2014		2	1																	7.8 stories 11 projects						
	2015		1	1		1																					
	2016	1	1	1	2																						
G3	2017		2	4	2	1			1	1				1							9.9 stories 12 projects						
G4	+				4	3		2						2	2			1		1							
																						14.0 stories 15 projects					

Figure 2-7: Heights of tall mass timber projects within generation-based categories (Figure adapted from Kuzmanovska et al. (2018)[3])

2.1.11 Discussion and Conclusions

A review of the literature has revealed the importance of hybrid timber systems in taller wood buildings, as all timber systems lose practicality with increasing height. However, there are gaps in knowledge regarding fire performance, seismic performance and the related seismic response modification coefficients, embodied carbon, construction costs, and more within the field of hybrid timber construction.

As previously discussed, technological advances such as the development of curtain walls, the use of computational design aids in structural design, and the competitive nature of the building industry have historically driven the heights of the tallest buildings in the world for steel and concrete structures. Based on current trends in mass timber construction, it can be argued that tall timber buildings are undergoing a revolution that is similar to what was seen for skyscrapers in the late 19th century and early 20th century. Just as steel and concrete buildings faced criticism and technological limits that required solutions, so is timber construction seeking to make advancements in technology to address current limitations and concerns that restrict their height. Another similarity to historical skyscraper developments, mass timber is in competition within industry to build the tallest mass timber structures, further driving research and advancements.

Chapter 3

Mass Timber Floor Systems Methodology

The majority of the research work in this dissertation focuses on a parametric analysis of a variety of mass timber and hybrid mass timber floor system types and configurations, the results of which are discussed in Chapter 4 of this dissertation. While each floor system-related study's specific methodology is discussed in more detail with each study presented in Chapter 4, this Chapter presents a generalized overview of the methodology used throughout the research.

Included here is an expanded version of a paper which appeared in the proceedings for the 2023 Structures Congress, a conference hosted by the Structural Engineering Institute (SEI) of the American Society of Civil Engineers (ASCE). [201] The intent of the paper included in this chapter is to discuss not only the general methodology of the research in this dissertation, but also how others may use and apply similar methods to their own research or project design work. The work of this paper was also presented by this dissertation's author in a session at the 2023 Structures Congress. The original conference paper has been expanded here to include additional clarifications to the studied floor systems, additional tables showing assumptions and embodied carbon material values, more in-depth fire design discussion and figures, an additional design example, and minor revisions to the text and figures.

As there are multiple authors on the original paper, a discussion of author contributions is included. The dissertation author and first author on the original paper, Samantha Leonard, performed the modeling, data extraction, and analysis work, and drafted the paper, including producing the tables and figures, and the writing and revisions of the final paper. The dissertation advisor and second author on the original paper, Ryan Solnosky, provided regular feedback on the research work, analysis, and writing for this paper.

3.1 Guiding mass timber design and research: A parametric modeling approach to understanding impacts

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3.1.1 Abstract

Mass timber structures have been gaining ground in recent years due to several factors including aesthetics, scheduling, and sustainability. However, there is limited guidance on how key design decisions, such as mass timber structural types and bay sizes, affect a project's ability to meet sustainability targets, particularly at the early design stage when many decisions are made. To create a dataset that would help inform early decisions, a parametric modeling approach was developed to study five mass timber and hybrid mass timber structural floor systems. This paper discusses the methods used in the model, as well as a model verification process using code and solution verification. The model consists of both a Grasshopper model interfaced with Rhino and a spreadsheet-based model, which are used to evaluate the multi-disciplinary nature of the design space. This modeling process is part of a larger research effort to develop early-stage design guidance for practitioners.

3.1.2 Introduction to recent timber structures

The building sector is working to reduce energy usage, and one of the ways to do so is to reduce embodied carbon (EC), or the estimated equivalent carbon emissions resulting from, fabrication,

transportation of materials, and the construction process [5]. Material selection can play an important role in a building's EC, particularly within the structure. Mass timber is a structural material which may help reduce a project's EC when used in place of or in strategic combination with concrete and steel [2, 3]. However, at the time of this writing, there are limited design tools and early design guidance that would help designers understand what decisions affect EC and in what circumstances all-mass timber or hybrid-mass timber options are best suited for reducing EC. This paper includes a brief literature review of mass timber and the available design tools and guidance, then discusses how a parametric model was developed and tested to generate data that can be used to inform early design guidance for mass timber floor systems. Also included is a discussion of some representative results, followed by an example of how model data can be applied to make decisions for a hypothetical case study project.

Just recently, US mass timber projects can now be built taller than earlier projects, partly due to advancement in mass timber knowledge, and with the help of the new 2021 International Building Code (IBC). Here, new mass timber construction types allow the construction of taller mass timber projects to be as tall as 18 stories [1]. Table 3-1 summarizes the tallest mass timber buildings in the US at the time of this writing, many of which include residential occupancies and hybrid-mass timber construction [4]. Further, there are nine mass timber projects under construction with 26 more proposed that are 8 stories or greater [4]. Due to the prevalence of residential occupancies in mass timber projects [5, 6], the modeling discussed in this paper focused on residential occupancies, but could be expanded to include other occupancies and loading requirements.

Table 3-1: Recent US tall mass timber buildings [5, 7]

Project Name	Year Completed	Structure Type	Height (ft / m)	Stories	Location	Building Use
<i>Ascent</i>	2022	<i>Timber-Concrete</i>	284 / 87	25	<i>Milwaukee, WI</i>	<i>Residential</i>
<i>503 on Tenth</i>	2023	<i>All-Timber</i>	164 / 50	10	<i>Portland, OR</i>	<i>Office</i>
<i>INTRO Tower</i>	2022	<i>Timber-Concrete</i>	130 / 40	9	<i>Cleveland, OH</i>	<i>Mixed-Use</i>
<i>Carbon 12</i>	2018	<i>Timber-Steel</i>	95 / 29	8	<i>Portland, OR</i>	<i>Residential</i>
<i>Emmons on 3rd</i>	2014	<i>Timber-Concrete</i>	86 / 26	8	<i>Seattle, WA</i>	<i>Residential</i>

3.1.3 Existing design aids for mass timber

While a range and variety of structural design software and life cycle analysis (LCA) tools exist to aid in the design and LCA of conventional steel, concrete, and masonry structures, many limitations exist for timber and early design. Existing structural software applications, such as RISA, SAP, and ETABS, often do not easily consider unique serviceability requirements for mass timber, such as control of walking-induced vibrations [8–10]. Further, out of the most-used software and plugins, only the Beaver plugin for Grasshopper is designed specifically for parametric design to be able to explore a wide variety of design options in early design. However, Beaver is designed for use with Eurocode 5 and is therefore not applicable for US project work [171]. Other timber-specific software applications typically are not designed for parametric use and have their own limitations.

While manufacturers often offer technical guides with initial sizing guidance, these do not offer sizing advice integrated with guidelines for reducing EC. Although carbon tools are available to estimate embodied carbon, these tools tend to focus on estimates for specific projects and therefore do not provide guidance for decision-making. The Fast+Epp Timber Bay Design Tool appears to be the most helpful early-stage design tool, even providing material volume

outputs which could be used separately to estimate EC. However, the tool does not include hybrid structure options, can only look at one design at a time thus limiting the ease of comparisons between options, and requires user inputs for items such as girder width, rather than designing to the most efficient size [172]. At the time of this literature review, no resource has compiled both structural design and EC data into a single tool or guide for early-design decision making. Additionally, no resource has compiled EC data in a comprehensive way for a range of variables and floor system structure types such that designers could use this information to guide early design decisions. See Chapter 2 Tables 2-3 and 2-12 in sections 2.1.6 and 2.1.8 for summaries of available structural design software, LCA tools, and their capabilities.

3.1.4 Methods

In this research, a parametric evaluation model is used to explore a range of structural floor system types and configurations for structural design and embodied carbon goals, based on the design space exploration (DSE) approach. This section discusses the specific systems and assumptions which are currently used in the model for this research; however, the same methods can be applied to any structural floor system. Therefore, discussion is included regarding the thought-processes behind decisions and assumptions made, the limitations of various structural assumptions, and the effect of model components on design resolution and specificity.

3.1.4.1 Floor systems

Both all-mass timber and hybrid-mass timber floor systems were included in the current model. Figure 3-1 depicts the floor systems included in the model for this research, as well as the abbreviated names to be used herein. Figure 3-2 further describes the systems depicted in Figure

3-1. Hybrid floor systems are included to add applicability to the many hybrid mass timber projects being built, and because hybrid systems present an opportunity to include mass timber in projects with constraints that would otherwise prevent the use of all-mass timber structures. Systems were selected based on relevance to early design, applicability to a wide range of applications, and to represent both all-mass timber and hybrid-mass timber options. Systems were limited to those with rectangular, regularly-spaced bays, and which take advantage of multi-bay spanning capabilities.

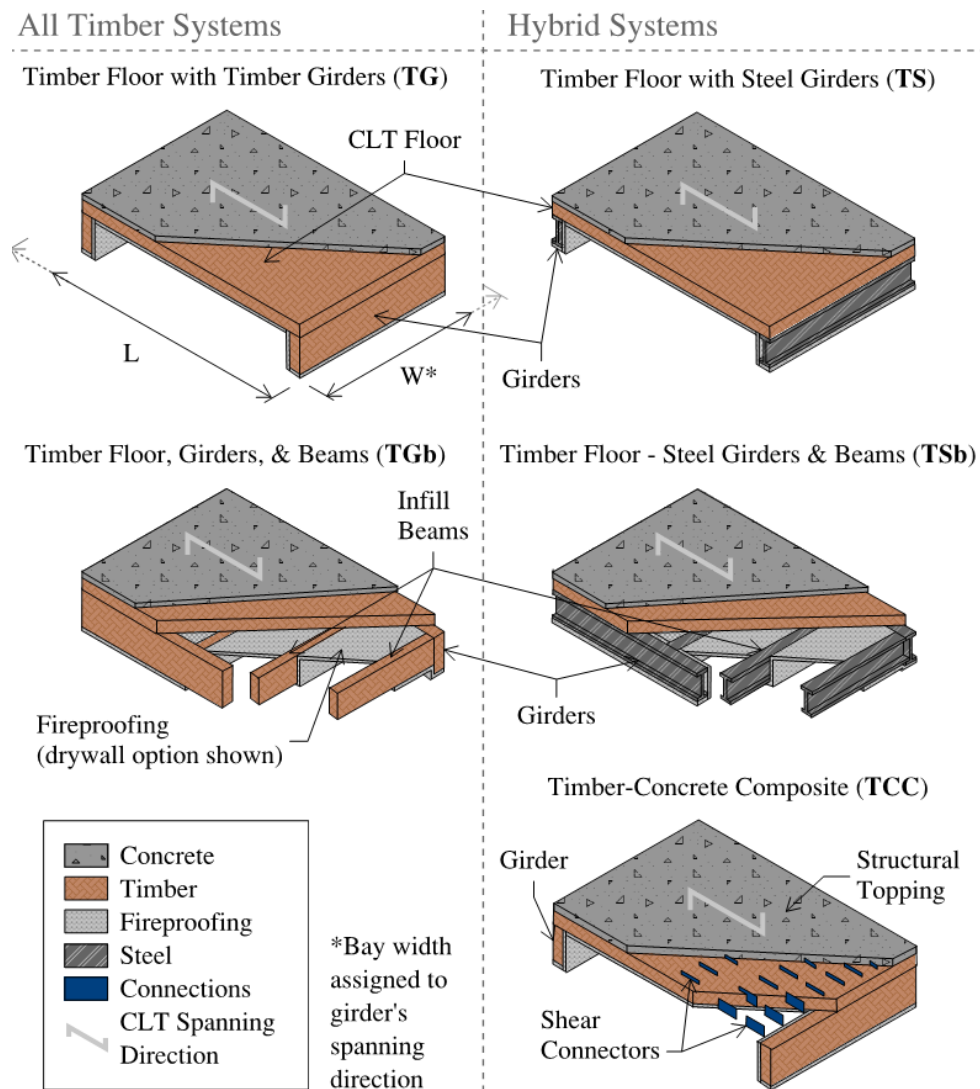


Figure 3-1: Studied floor systems. Note that only isolated bays are shown for clarity.

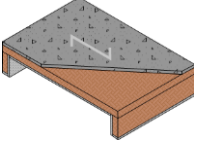
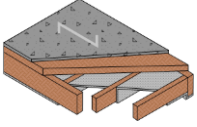
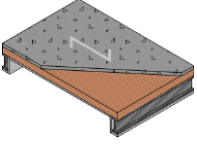
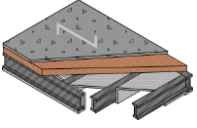
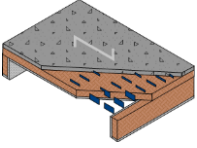
System Abbr.	System Name	System Components
TG 	<i>Timber Floor with Timber Girders</i>	• CLT floor panels span between girders located at each end of the bay • Glulam girders span the bay width • Non-structural concrete topping is provided for acoustic performance and to control walking-induced vibrations • If non-combustible protection is used, drywall is installed directly against the underside of the CLT panels and wraps the girders
TGb 	<i>Timber Floor with Timber Girders and Beams</i>	• CLT floor panels span between infill beams located at each end of the bay with an additional beam located in the center of the bay • Glulam infill beams span between girders located at each end of the bay • Glulam girders span the bay width • Non-structural concrete topping is provided for acoustic performance and to control walking-induced vibrations • If non-combustible protection is used, drywall is installed directly against the underside of the CLT panels and wraps the girders and beams
TS 	<i>Timber Floor with Steel Girders</i>	• CLT floor panels span between girders located at each end of the bay • Steel W-shape girders span the bay width • Connection of CLT to steel girders is non-composite • Non-structural concrete topping is provided for acoustic performance and to control walking-induced vibrations • If non-combustible protection is used, drywall is installed directly against the underside of the CLT panels and as a box-out around the girders
TSb 	<i>Timber Floor with Steel Girders and Beams</i>	• CLT floor panels span between infill beams located at each end of the bay with an additional beam located in the center of the bay • Steel W-shape infill beams span between girders located at each end of the bay • Steel W-shape girders span the bay width • Connection of CLT to steel girders and beams is non-composite • Non-structural concrete topping is provided for acoustic performance and to control walking-induced vibrations • If non-combustible protection is used, drywall is installed directly against the underside of the CLT panels and as a box-out around the girders and beams
TCC 	<i>Timber-Concrete Composite Floor with Timber Girders</i>	• CLT floor panels span between girders located at each end of the bay • Glulam girders span the bay width • A concrete topping is provided for acoustic performance and to control walking-induced vibrations • The concrete topping is connected to the CLT floor panels to act compositely through the use of steel shear connectors • If non-combustible protection is used, drywall is installed directly against the underside of the CLT panels and wraps the girders

Figure 3-2: Summary description of studied floor systems

3.1.4.2 Parametric model

The model for this research couples DSE with parametric analysis to evaluate possible designs against performance goals and compare designs to each other. Figure 3-3 illustrates the basic DSE approach. Variables are selected which can be changed parametrically to generate designs which populate the Design Space. Designs are evaluated for the performance objectives of interest, thus filling in the Objective Space. By comparing the Design Space and the Objective Space to each other, the modeler may gain insight into how design decisions affect performance goals [179]. This approach has been incorporated similarly into other research related to design of mass timber [14–16].

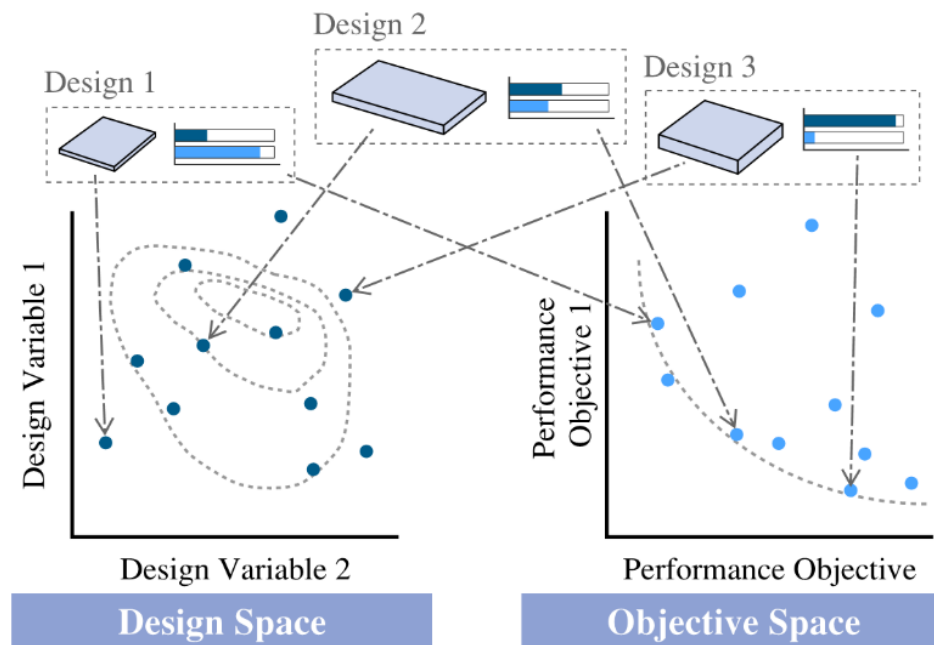


Figure 3-3: Conceptual depiction of design space exploration (figure adapted from N. Brown, 2020)

A variety of variables were considered in developing the parametric model for this research, including, but not limited to, bay length, framing material, number of infill beams, fire-proofing strategy, and wood species. However, the inclusion of too many variables in a DSE data

set can obscure a clear understanding of the results. Therefore, one goal of this research has been to select the variables which are most likely to help achieve the goal of understanding the effect of design decisions on EC for the studied floor systems. For example, although wood species can affect EC, the variability in strength of many wood species obscured trends related to other variables such as bay length, and designers may have little control over the wood species used. Therefore, a single representative wood species was selected for the model.

Coding Processes

As previously discussed, limited tools exist for mass timber design within a parametric framework. Although software applications and plugins are being developed, with increased availability expected in the future, non-proprietary methods of creating parametric models are needed to improve accessibility to parametric and DSE methods for design. The modeled floor systems and their design processes drove the model construction. This section discusses the specific processes used in the model construction for this research.

The floor systems with non-structural toppings follow relatively straightforward design checks, and could therefore be coded within Grasshopper. Note that Grasshopper is a parametric modeling tool that can be used within Rhino, an architectural modeling software [202].

Grasshopper acts like a visual scripting platform; “components” act as mini script bundles which perform specific actions, such as generating a line from two coordinate inputs. Users also have the option to create their own custom Python components, which can be opened to allow scripting. For this work, structural element design for most of the floor systems was carried out through the use of these custom Python components. Figure 3-4 and Figure 3-5 show a screenshot from a portion of the Grasshopper model used in this research and accompanying partial flow chart, respectively.

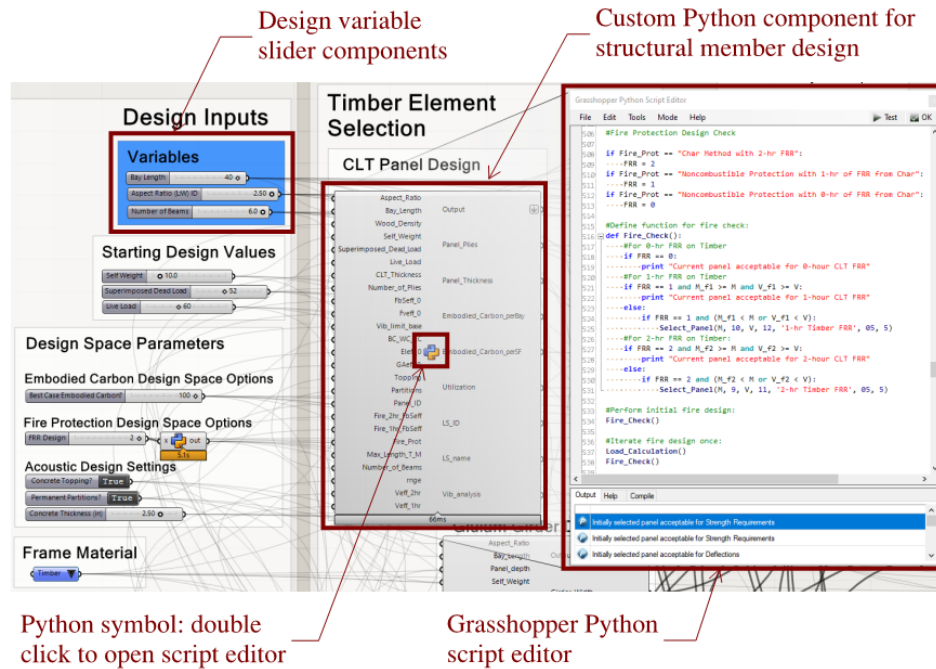


Figure 3-4: Example screenshot of a portion of the Grasshopper model with an open Python script editor

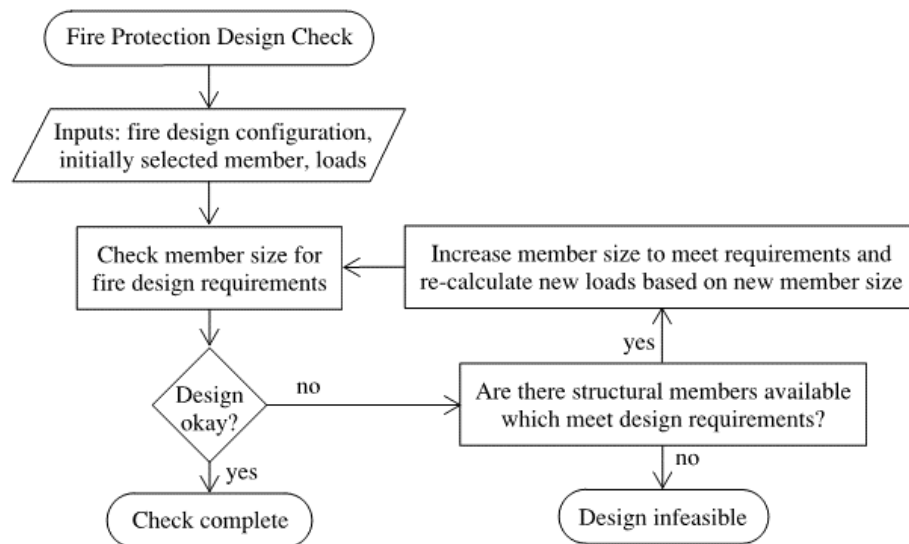


Figure 3-5: Partial flow chart of the example process scripted in Figure 3-4

For the TCC system, the more complex design process required everything to be known about the final design so design checks can be performed. For this reason, this system alone used a pre-generated database of possible final designs, using a spreadsheet-based model to check each

and remove all invalid and inefficient designs instead of a grasshopper model. Figure 3-6 and Figure 3-7 show a representative screenshot from the spreadsheet-based model and accompanying flow chart, respectively.

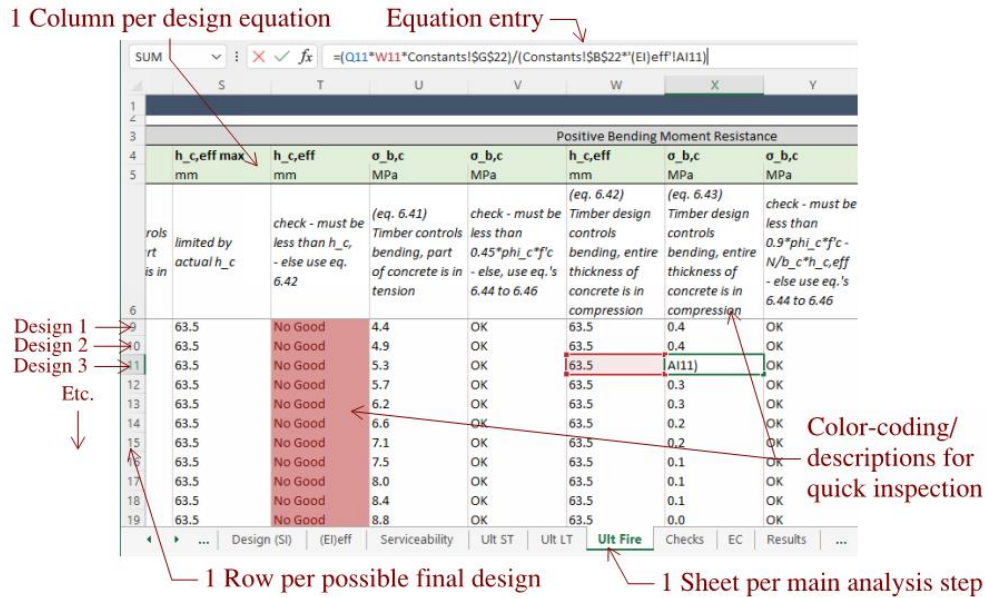


Figure 3-6: Screenshot of a portion of the spreadsheet-based model for the TCC system design

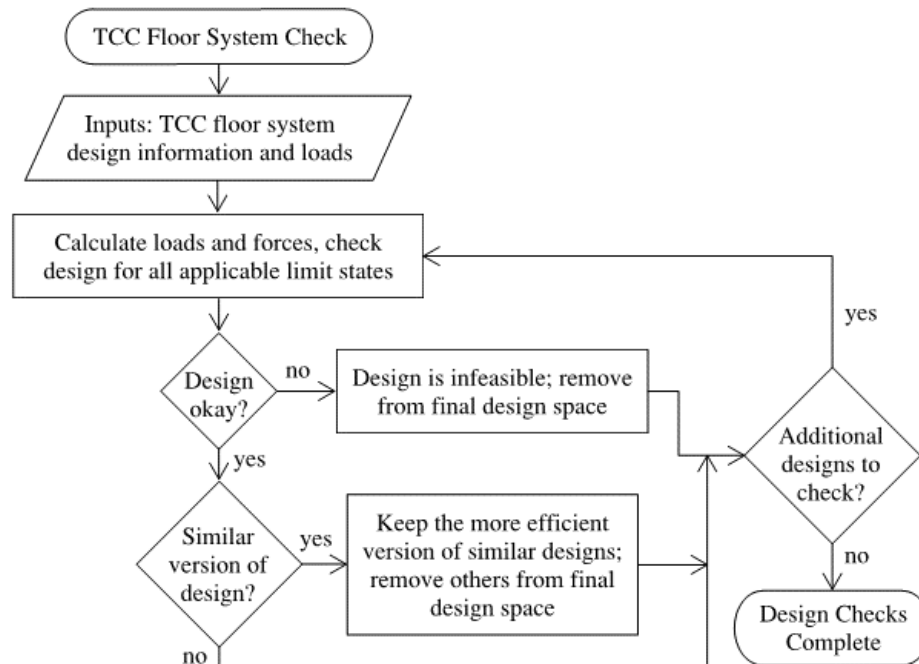


Figure 3-7: Simplified flow chart of the TCC system design process used in the model shown in Figure 3-6

For research purposes, the current model attempted to use the best approach for each floor system included with a goal of testing different parametric modelling approaches for mass timber floor system design. Within industry applications, any floor system could be modeled in grasshopper using custom script, and as more timber-focused plugins are developed, this approach could become more accessible. Alternatively, any system could be modeled and checked parametrically using a spreadsheet-based method by assigning a design check equation to a column and using a line-by-line approach for each design iteration. For firms and designers who don't have access to higher-end parametric tools like Rhino and Grasshopper, this can be an alternative option that still allows the use of parametric analysis methods. Figure 3-8 provides the overall flow map showing how each model fits into the overall floor systems analysis process. Additional clarifications and details regarding the modeling process and steps is provided in Appendix A of this dissertation.

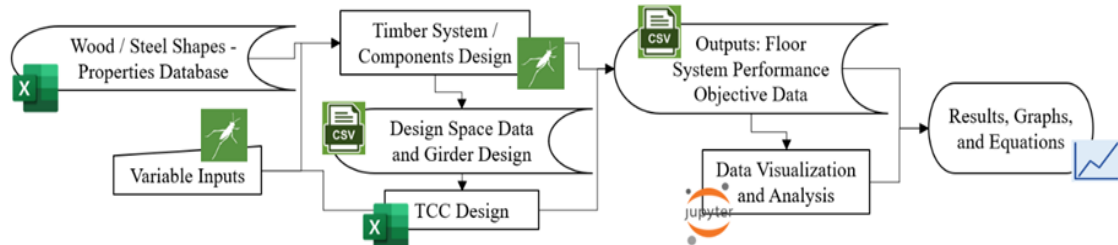


Figure 3-8: Parametric modeling flow chart

3.1.4.3 Structural modeling

Expanding further, custom Python code components were created to size each structural element in each floor system design. The design equations used in the code follow the Allowable Stress Design (ASD) methodology for all but the TCC system; however, the same modeling process could be used following Load Resistance Factor Design (LRFD) with consistent use of the equations and factors. Each element is designed based on the applicable codes and reference

guidelines for the relevant limit states, including flexure, shear, deflections, creep, walking-induced vibration control, and fire design, consistent with previous work by Leonard et. al. [203].

These custom code components work by selecting an initial element size from a database given initial loading assumptions, then resizing as needed with revised loading calculations. The structural element is checked against the required loads and forces for each limit state, then resized and rechecked as needed until it meets the design limit state requirements. The model for this research currently prioritizes the lowest-weight elements, creating a slight preference for the lowest EC options, rather than the lowest depth elements. Reordering the database can be performed simply to meet the modeler's preferences.

The assumptions used in the model and summarized in Table 3-2 included pinned connections, maximizing the number of spans, residential occupancy loads, and a nonstructural concrete topping. Some assumptions affect serviceability requirements more than others; for example, the inclusion of a concrete topping was an important assumption used to maximize the floor span limits for controlling walking-induced vibrations. Assumptions like these can be customized by the modeler.

Table 3-2: Structural design assumptions

Item	Assumed Condition	Additional Comments
<i>Boundary Conditions</i>	Pinned connections	Chosen to be able to initially assume simple connections.
<i>Number of Spans</i>	Maximum permitted based on manufacturing and transportation limits	This allows model to take advantage of additional allowable span like for vibrations in multi-span conditions
<i>Span Length</i>	Equal to bay length	Conservative for timber as NDS defines span length as distance between faces of supports
<i>Bay Location</i>	Center bay	For EC accounting, perimeter girders and beams are considered to be shared with the adjacent bay
<i>Live Load</i>	40 psf residential + 20 psf allowance for partitions = 60 psf (2.87 kN/m ²)	Based on ASCE 7-10 for a residential occupancy, private rooms and corridors serving them. Live load reduction is neglected due to small tributary area in designs.
<i>Superimposed Dead Load</i>	20 psf + 19 psf for a 1.5" nonstructural concrete topping = 39 psf (1.87 kN/m ²)	20 psf (0.96 kN/m ²) is for mechanical, utilities, finishes, and other items
<i>Steel Shapes</i>	W-Shapes only	Shapes obtained from the AISC steel shapes database [204]

3.1.4.4 Fire Design

Because fire design provisions are particularly unique for timber element design, the approaches used are discussed further here. Although the 2021 IBC permits both prescriptive codified requirements and performance-based design (PBD) methodologies [34], the authors found that prescriptive methods are more appropriate for early-stage design resolution [205]. Further, the model assumed typical sprinklers for active fire protection and focused on variations in passive methods, which in some cases permit a designer to expose the timber for aesthetic purposes. The research generally uses three options permitted by the IBC to meet Fire Resistance Ratings (FRR): 1) the use of noncombustible protection, 2) the char method, or 3) a combination of both.

The model uses interior gypsum board installed directly to the timber as the primary material providing noncombustible protection. Where steel framing is used with exposed timber, an intumescent coating is assumed. Char method design is performed following the 2021 Fire Design Specification (FDS) [141]. The 2021 FDS include a calculation-based method, which estimates the effective char depth for an FRR up to 2 hours. The effective char zone is then assumed to contribute nothing to strength, and the remaining section is used to calculate the new properties to use in design checks. The FDS also allows a designer to use the properties of a CLT panel whose number of laminations do not exceed the uncharred laminated in the remaining section, as shown in Figure 3-9.[26, 27] These options and their corresponding configurations for various floor system elements are clarified in Figure 3-10.

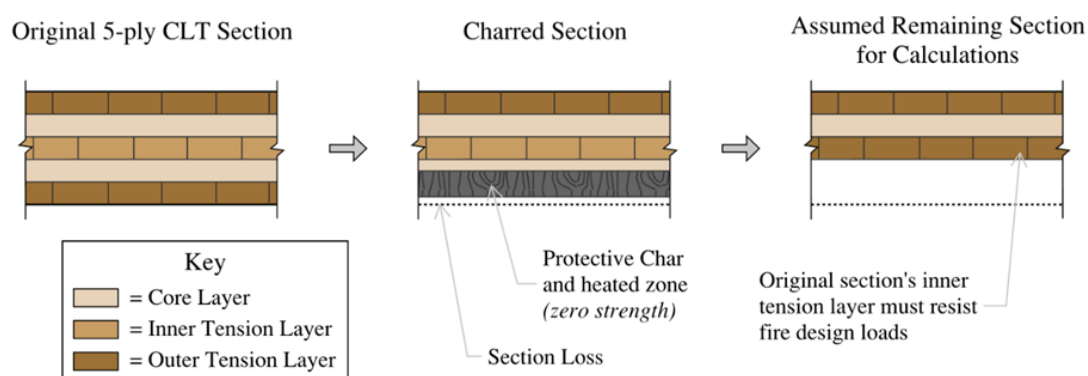


Figure 3-9: Example of charring process and remaining section for use in calculations. (Figure adapted from figures in The CLT Handbook (2019 Canadian Edition) and The 2018 Fire Design Specification for Wood Construction.[105], [141])

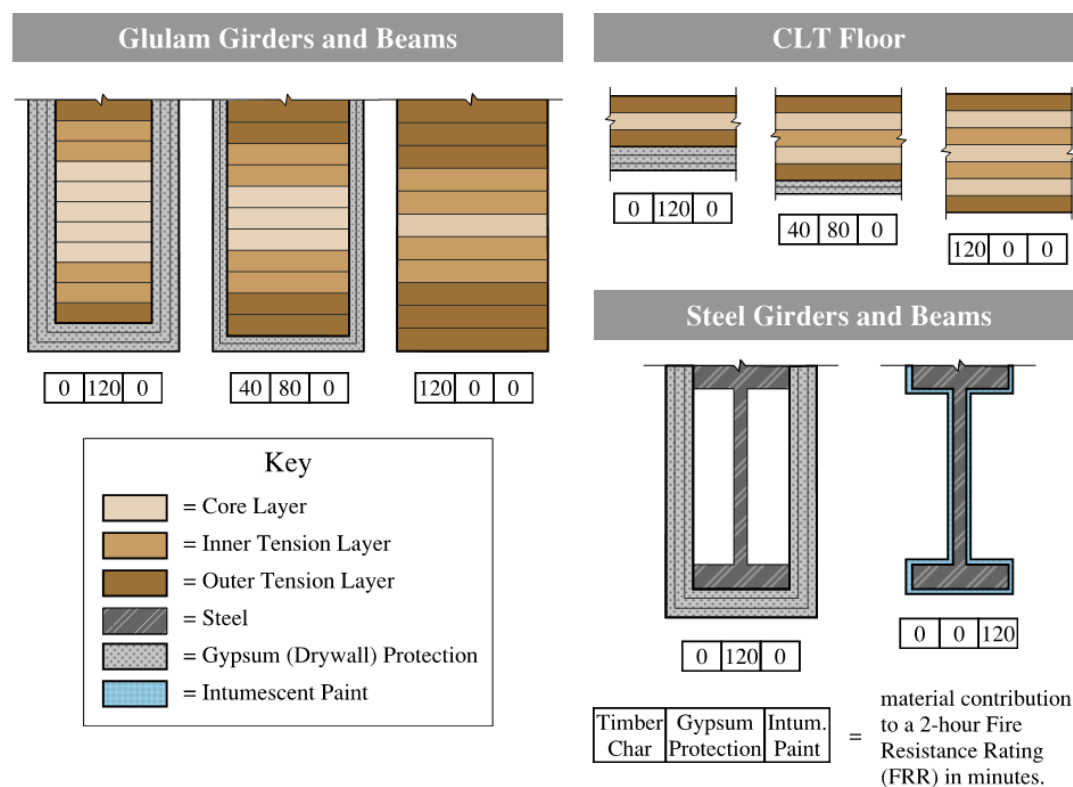


Figure 3-10: Conceptual examples of potential strategies to achieve a 2-hr rating for Glulam, CLT, and steel sections. (N.T.S.: Number of laminations are purely conceptual and intended to be representative. Figure adapted from figures in The CLT Handbook (2019 Canadian Edition) and The 2018 Fire Design Specification for Wood Construction.[105], [141])

3.1.4.5 Embodied carbon modeling

Because proprietary LCA tools are not yet interoperable with parametric design tools and software, this research gathered EC data for each material. Depending on the paper or chapter and its intended audience, EC values were obtained following two paths; one aimed at an academic audience, and one aimed at a practitioner-based audience. This paper uses the academic-focused EC data; however, the practitioner-focused data is included as well for reference.

For the general audience, EC values for structural materials, including steel, concrete, and mass timber, are obtained from ICE V3.0, a meta-database focusing on Modules A1 to A3 from standards EN 15978 and EN 15804, which was developed by Craig Jones and Geoffrey Hammond at the University of Bath [61]. The ICE database includes timber values for scenarios which both include or do not include carbon storage. Non-structural materials including drywall, joint compound, and intumescent paint do not appear in ICE. Therefore, EC data was pulled from a combination of industry resources and publicly-available Environmental Product Declarations (EPDs) for the non-structural materials. The same values were used for non-structural materials for an audience using more specific values, such as practitioners designing for a specific project.

Most structural material EC values for the practitioner audience are obtained from industry-wide EPDs, and the CLT values come from the average of five North American EPDs. The carbon-storing values for CLT and Glulam are based on the methods used by the American Wood Council (AWC) in their Glulam EPD. In the AWC EPD, 100% landfilling is assumed for the end-of-life scenario, and the EPA Waste Reduction Model (WARM) [43] is followed to estimate net permanent carbon storage. [65] Table 3-3 summarizes the material EC values used both in this paper and in the other chapters of this dissertation, as well as their data sources.

The models for this research use the final structural element sizing for each given design to perform material take-offs of the structural materials and other significant assembly elements,

including fireproofing and the concrete topping. A rough take-off for columns is included based on a bottom column in a 10-story project. Further, where gypsum board is used as fireproofing, a 10% combined waste factor is applied to the material take-off for gypsum board and joint compound.[206] Other material waste factors are considered negligible at this stage of modeling. Material take-off values are multiplied by their corresponding EC material values and then summed for a total EC estimate for the floor system. Dividing by the bay area normalizes the total EC per area.

As currently used in this research, the model focuses on EC in the A1 to A3 modules, also known as the cradle to factory gate boundaries. This is because at an early design stage resolution of modeling, not enough is known to make reasonable estimates and assumptions about the occupancy and end of life stages of the building's life. The model focuses on mass timber EC data in which the ICE carbon storage values are omitted, because carbon storage can only be used for "sustainably-sourced timber." This is consistent with industry-standard EPDs and practice, in which biogenic carbon is taken as a net zero value to conservatively estimate EC (for example, see Structurlam's EPD for CLT. [64]) However, the model can be adjusted for different EC assumptions and data sets as needed, and this is done through a sliding scale representing the percent of sustainably sourced timber (SST). In this research, 0 percent SST omits carbon storage, and 100 percent SST includes carbon storage. Differences in assumptions can significantly affect whether the mass timber is a carbon-storing component or not, thus affecting final floor system results, overall carbon-storing capabilities, performance, and design recommendations. Therefore some discussion of different timber EC assumptions is included in the Results and Discussion section of this paper.

Table 3-3: Embodied carbon of common structural and building materials [lb CO₂ eq/lb]
(1 lb CO₂ eq/lb = 1 kg CO₂ eq/kg)

Material Information		Industry-Focused EC Material Coefficients		General-Focused EC Material Coefficients	
Material	Material Assumptions	EC Value	Data Source	EC Value	Data Source
Cross Laminated Timber (CLT)	Carbon storage is neglected	0.27	Average of five North American CLT EPD's following ISO 21930:2017 A and B [64], [207]–[210]	0.437	ICE V3.0 [61] – Timber, CLT
	Carbon storage is included ¹	-1.19		-1.20	
Glued Laminated Timber (Glulam)	Carbon storage is neglected	0.25	American Wood Council EPD for North American Glued Laminated Timber [93]	0.512	ICE V3.0 – Timber, Glulam
	Carbon storage is included ¹	-1.04		-0.90	
Reinforced Normal Weight Concrete (Slab)	3001-4000 psi	0.17	Combination of plain concrete and reinforcing steel values (~5% of total mass is reinforcing steel)	0.13	ICE V3.0 – RC 32/40 (32/40 MPa) with 25% cement replacement with fly ash
	4001-5000 psi	0.20			
	5001-6000 psi	0.21			
	6001-8000 psi	0.23			
Normal Weight Concrete with WWR (Topping)	3001-4000 psi	0.15	Combination of plain concrete and reinforcing steel values (~3% of total mass is reinforcing steel)	See value for reinforced concrete (only 3001-4000 psi concrete considered in research performed using ICE data)	
Plain Normal Weight Concrete	3001-4000 psi	0.13	NRMCA EPD for concrete with 25% cement replacement with fly ash [211]		
	4001-5000 psi	0.16			
	5001-6000 psi	0.17			
	6001-8000 psi	0.19			
Reinforcing steel	98% Recycled steel content	0.85	Concrete Reinforcing Steel Institute (CRSI) EPD [212]	1.07	ICE V3.0 – Steel, Section
Steel (section)	93% Recycled steel content	1.22	AISC Industry-wide EPD for Hot-rolled structural sections [213]		
Gypsum Board (drywall) ²	Type X:	0.28	Industry-wide gypsum board EPD [214]	Same as industry value	
Joint Compound ²	Conventional ready-mixed	1.19	Industry-wide joint compound EPD [215]	Same as industry value	
Intumescent Paint (for steel)	Solvent-based	2.31	Technical guides and product data sheets [59],[216],[217]	Same as industry value	

¹ Linear interpolation used for values between 0 and 100% carbon storage, carbon storage value based on assuming 100% landfilling at EOL based on the EPA Waste Reduction Model (WARM) [218]

² A 10% waste factor is applied to the total combined material takeoff for drywall and joint compound

3.1.4.6 Model verification

Verification and validation are two methods used in engineering computational modeling to confirm that a model is working as expected [219]. While verification is the process of checking that the equations and assumptions in a computational model are being properly implemented, validation is the process of checking that the computational model produces satisfactorily accurate results consistent with those determined by experimental methods and observations of the real world [220]. Researchers, labs, and manufacturers have performed design equation validation for mass timber structural products through physical testing [221]. Therefore, this research focuses on verification to confirm proper model behavior for mass timber structural design. Both code verification and solution verification exist and are implemented through the use of hand calculations and case study analysis, respectively. The process and results of the model verification are discussed in the following sections.

Hand calculation checks

Code verification involves checking the implementation of programmed processes and equations within the code and can be performed by performing tests of each piece of the code or script [220]. This process has been applied to custom components created for this research. Sample hand calculations were used to spot check various element designs to confirm whether design equations are implemented correctly in the custom Python script within Grasshopper. Below is an example hand calculation showing a spot check of the vibration serviceability design check. Here, a one-way spanning CLT floor panel is being designed for a 20-foot (6.1-meter) square bay. A 7-ply panel is initially selected for flexure, shear, and deflections. The panel is then checked for control of walking-induced vibrations using the simplified method from the 2019 Canadian CLT handbook, [105] which is a method recommended for early design [167]. The

following equations and processes are used (note that extensive calculations are omitted for brevity; see Definitions section for variable definitions):

$$L \leq 0.11 \frac{\left(\frac{(EI)_{\text{eff}}}{10^6}\right)^{0.29}}{m^{0.12}} \quad (3-1)$$

Equation 1 using values from the above-described example gives the following:

$$L \leq 0.11 \frac{(2.6 * 10^6 \text{ N} * \text{mm}^2)^{0.29}}{(103 \text{ kg/m})^{0.12}} = 4.6 \text{ meters} = 15 \text{ feet}$$

Because the panel meets key requirements related to partitions and topping area density, the CLT Handbook permits an increase of 20%:

$$L \leq 1.2 * 4.6 \text{ meters} = 5.5 \text{ meters} = 18 \text{ feet}$$

The 20-foot (6.1 m) bay has a clear span of approximately 19 feet (5.8 m), which is greater than that permitted; therefore the design must size up to a 9-ply panel for vibration control. The floor system model also selected a 9-ply panel for this sample design to meet vibration control requirements.

Case study comparisons

In contrast to code verification, solution verification involves checking that the solution given by the model converges, or has low error as compared to the expectations for the design problem [220]. For this research, this equates to checking that the model results are consistent with solutions given by other professional engineering design methods. Solution verification here focuses on comparing the floor systems models results to a selection of representative project case studies to check if the model produces similar designs to actual buildings. Note that these case studies do not all include the same design assumptions as the floor systems model, and therefore the intent of the comparisons are not to reproduce identical design solutions, but to check that the model generally performs as expected for early design resolution.

Case studies were selected based on several factors, including availability of project design information, applicability to the floor systems being modeled, regularity of layout, and the use of all-mass timber or hybrid-mass timber elements. Table 3-4 summarizes the main case studies used in verifying the model. Key takeaways from each are included, but a number of aspects were studied in comparing model results to the case studies, including element size comparisons, the controlling limit state of each element, and element sizes following different design checks.

Table 3-4: Summary of case studies used to verify model performance and main takeaways

Case Study Name	Floor System Type	Key Takeaways from Model Run	Design Information Source
<i>Brock Commons</i>	Two-way post and panel all-timber	The model selected the same CLT panel as the case study.	Publicly-available case study. [222]
<i>Platte Fifteen (5-story office building in Denver, CO)</i>	Post-beam-purlin-panel all-timber	The model selected the same CLT panel as the case study and similar Glulam beams. The model selected larger purlins based on vibration design criteria.	Publicly available project-specific WoodWorks case study publication.[198]
<i>West 2 (Penn State University)</i>	Steel-timber hybrid	The model selected deeper, but lighter steel girders and beams as compared to the case study, but the same CLT panel.	Project structural drawings and specifications.[223], [224]
<i>Seattle Mass Timber Tower (Hypothetical Design Project)</i>	Post-beam-panel floor system	The model selected the same CLT panel as the case study, but selected larger beams to meet vibration design criteria.	“Tall with Timber: A Seattle Mass Timber Tower Case Study” [225]
<i>U of M Olver Design Building</i>	Timber-concrete composite with beams	The spreadsheet-based model confirmed the TCC floor is acceptable.	“Inspiration through Innovation.” [226]

A more thorough discussion of the Platte Fifteen case study is provided here as an example of the process used to compare case study information to the model results. The project consists of a mass timber frame built out of CLT and Glulam with a uniform layout, and is exposed at the interior [198]. A nonstructural concrete topping is used to help achieve acoustic requirements of STC 53 and IIC 45. The CLT is by Nordic Structures, and an office corridor live

load of 80 psf (3.83 kN/m²) is assumed [227]. Figure 3-11 includes a project photo and a summary typical bay layout. Table 3-5 summarizes the case study structural design elements sizes and the results of the floor systems model.

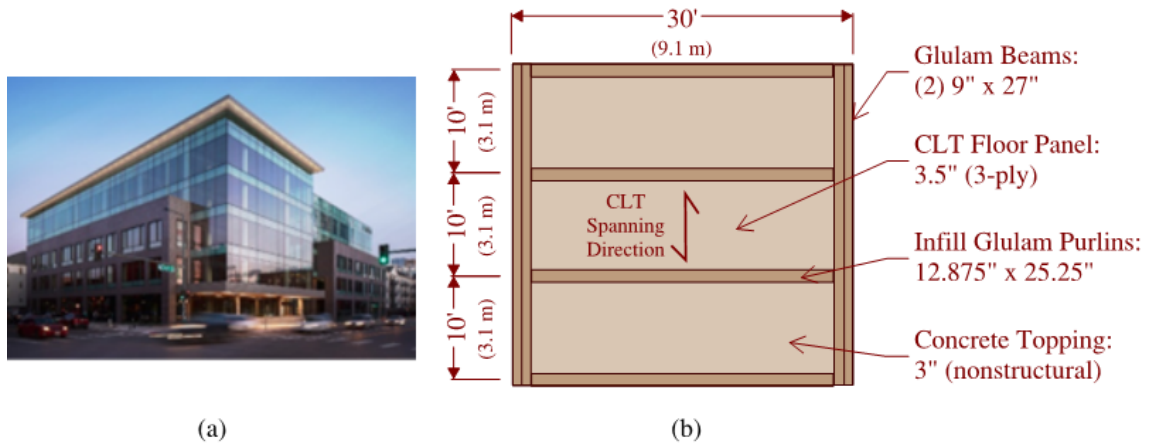


Figure 3-11: Platte Fifteen (WoodWorks Case Study). Photo by JC Buck reprinted with permission from WoodWorks. Architect: OZ Architecture. Structural Engineer: KL&A Engineers and Builders; (a) Rendering of Project, (b) Typical floor layout

Table 3-5: Comparison between model results and case study design

Element	Case Study Design	Model Design	Model Controlling Limit State
CLT Floor Panel	3-ply (3.5" / 89 mm)	3-ply (3.5")	Shear
Glulam Girder	9" x 27" (or doubled: 18" x 27" / 457 x 686 mm)	15.5" x 29.5" (394 x 749 mm)	Bending
Glulam Beam	12.875" x 25.25" (327 x 641 mm)	15.5" x 27.5" (394 x 699 mm)	Vibration Control

The model selected the same CLT panel as the case study project, but selected a different girder and beam. The case study used two side by side girders which are wider but shorter than the model's selected single girder, and the case study beam is smaller than the model's selected beam. Prior to the vibration check, the initial beam size was 12.875" by 21.5" (327 x 546 mm), which is closer to the case study's beam size. Therefore, it is likely that the model followed more conservative vibration requirements. However, the beam and girder sizes selected are similar enough to the case study to demonstrate good model performance for early design. All case study comparisons indicate that the research model code tends to size mass timber and steel elements

somewhat conservatively, particularly for longer-spanning bays, and especially when considering serviceability criteria such as vibration serviceability. However, element sizes are still fairly similar between the case study and model, demonstrating that the floor system models perform well for an early-stage design level of detail prior to the design refinement that occurs later in the design process.

3.1.5 Results and discussion

While the focus of this paper is on the model creation and verification process, this section includes representative model results to demonstrate the types of data and insights that can be extracted from these models. Only representative results are presented for brevity reasons. The results below focus on high-level plots comparing the larger data set. More refined data analyses for individual systems or fire design options will be performed in future work, but is out of the scope of this paper. Additionally, model results are used to discuss the application to a hypothetical early-stage design example.

3.1.5.1 Representative model results

Figure 3-12 shows an initial overview of EC versus bay span for the five studied floor system types. Data presented is for 0 percent sustainably-sourced timber (SST), in which carbon-storage is omitted from the timber EC values. The shaded area for each data line represents a range of the bay aspect ratios (bay AR) and, for the TGb and TSb systems, the number of infill beams. The relevance of bay AR and infills varies by system and bay span. Particularly for the TGb and TSb systems, differences which are negligible at shorter spans become more significant with increasing span length. Another clear trend that appears at this level of data visualization is that

the systems without infills (TCC, TG, and TS) exhibit a stepped-behavior as the design increases panels depth. Because CLT panel options include only limited sizes, and the CLT panel makes up a large portion of total EC, the EC trendline steps up when the panel sizes up. The infills (in the TGb and TSb systems) smooth out the EC trend line because the same panel size can often be used for more designs within the same fire design configuration.

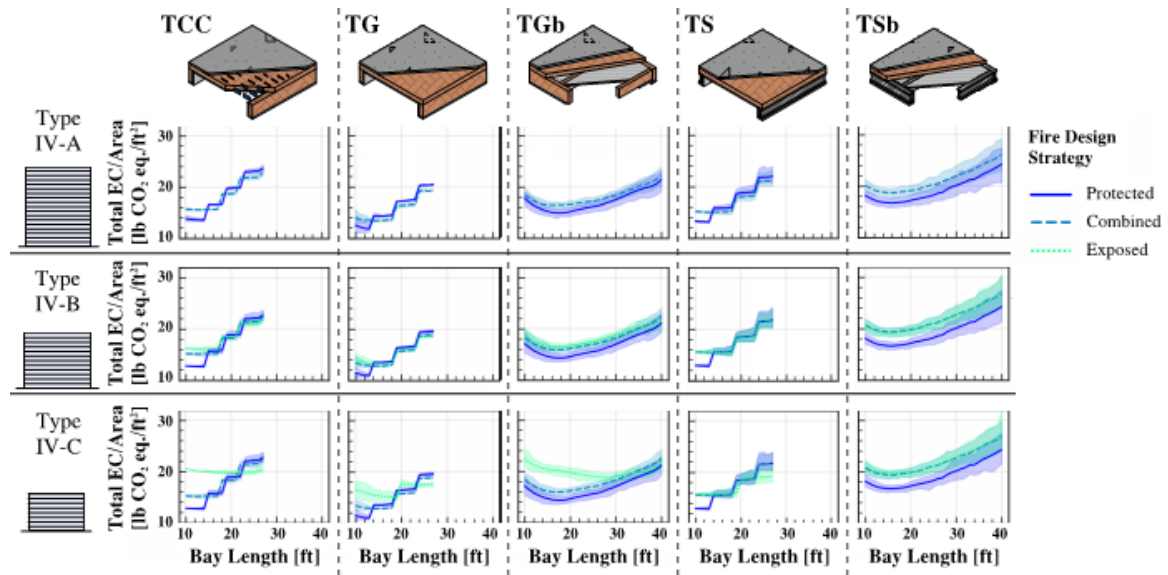


Figure 3-12: EC versus bay span for the studied floor systems and IBC construction types

(1 lb CO₂ eq./ft² = 4.88 kg CO₂ eq./m² ; 1 ft = 0.3048 m – Typical all data figures)

Figure 3-13 presents a multi-objective view of the floor systems data focusing on a single plot for Type IV-A construction using the fully protected fire design configuration. Data is included for both 0 and 100 percent SST options. Comparing EC versus floor system depth, this plot shows the differences in systems as well as the relationship between bay length, EC, and depth for those systems. Figure 3-13 also demonstrates that the timber EC assumptions regarding the inclusion of carbon storage drastically change the resulting recommendations for decreasing floor system EC. Further, if carbon storage is included in the EC value, most of the designs across the design space become carbon-storing.

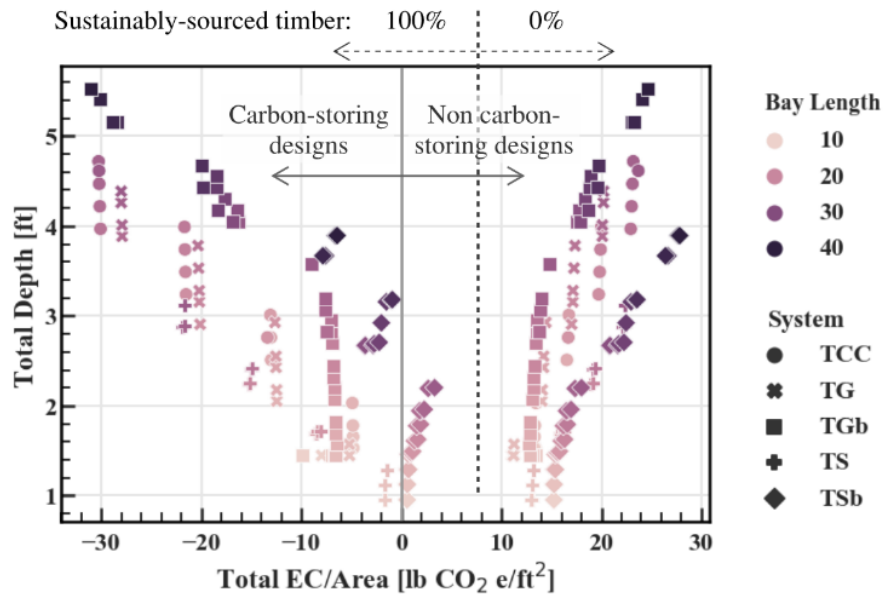


Figure 3-13: System depth versus EC for fully protected Type IV-A with 1 infill beam and bay AR of 1

3.1.5.2 Design Example A

A hypothetical 8-story condominium example was used to demonstrate how the model results could be used to inform early design decisions. The project is 100 x 250 feet (30.5 x 76.2 meters), and the architect wants a bay size that is 10 to 15 feet (3.1 to 4.6 meters) wide (in the 100' building direction) and spanning 15 to 20 feet (4.6 to 6.1 meters) long (in the 250' building direction). The project is Type IV-C mass timber construction, and the architect is exploring options for exposing the underside of the timber floor slab while considering sustainability goals and depth restrictions. The total system depth must be 3 feet (0.91 meter) or less at any point on the floor. A core goal is to minimize EC within the architectural restraints and project budget; however, the budget does not allow for a premium on sustainably-sourced timber for the structural elements. A summary graphic of this example is provided in Figure 3-14.

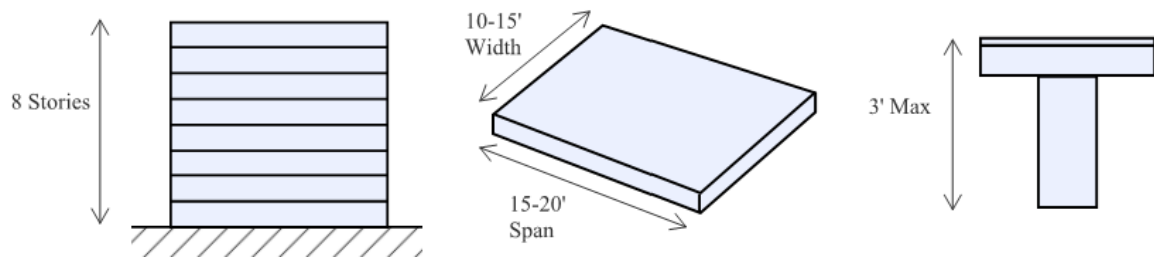


Figure 3-14: Design example project A geometry summary

Based on desired floor plan and bay dimensions, the possible ARs are closest to the modeled ARs of 1.0, 1.5 and 2.0. Initial analysis of the data for these ARs at the bay spans of interest found a negligible difference in EC. A bay AR of 2.0 typically resulted in the lowest system depth; however, while going from a 2.0 to 1.0 Bay AR resulted in a 9-inch (229 mm) depth increase on average, the difference between a 2.0 and 1.5 bay AR was less significant, increasing only 3 inches on average (76 mm). Because more possible ARs for the example problem are closest to a bay AR of 1.5, which did not have significant differences in depth as compared to the 2.0 bay AR, a bay AR of 1.5 was used moving forward in the example problem.

Further initial analysis of varying the number of infill beams for the TGb and TSb systems found that, at the bay spans of interest with an AR of 1.5, providing 1 infill beam resulted in the lowest EC and floor system depth. Figure 3-15, based on these initial starting points, can be used initially to compare fire configuration options, embodied carbon, depth, bay length, and system type. If the only goal is to minimize EC, then either the fully protected TGb system or the combined-approach TG system with a 15' (4.6 m) bay span should be selected. Another goal is to aesthetically expose the underside of the mass timber floor, for which the TS system offers the best combination of both EC and floor system depth for the fully exposed configuration. Because a system depth up to 3 feet (0.91 m) is permitted, the TG system will be considered initially in addition to the TS system as it offers more exposed timber aesthetically with a similar EC value to the TS options.

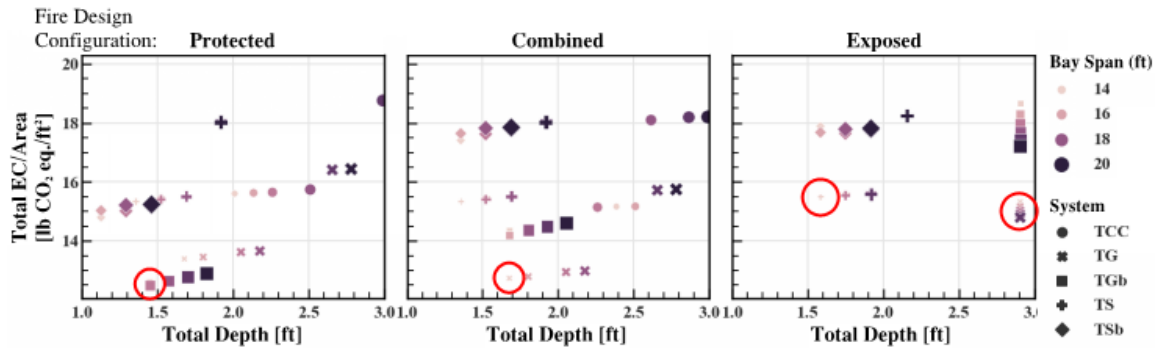


Figure 3-15: EC versus depth for a bay AR of 1.5 and 1 infill beam. Designs of interest are circled in red.

Based on the discussion of Figure 3-15, the plot in Figure 3-16 can be used to confirm EC comparisons between systems for each fire design configuration to refine a bay span selection. For the exposed configuration, there appears to be negligible differences in EC between the TS and TG systems and for bay spans from 15 to 19 feet (4.6 to 5.8 meters), offering some aesthetic design flexibility for this project. For any areas that don't need to be aesthetically exposed, the combined approach with the TG system or the protected approach with either the TGb or TG system at spans of 15 to 18 feet (4.6 to 5.5 meters) offer the lowest EC. Further, the protected approach for the TGb system offers the lowest floor system depth among the lowest-EC designs per Figure 3-15. Based on the above discussion, the initial options shown in Figure 3-17 should be considered moving forward in the early design decision-making process.

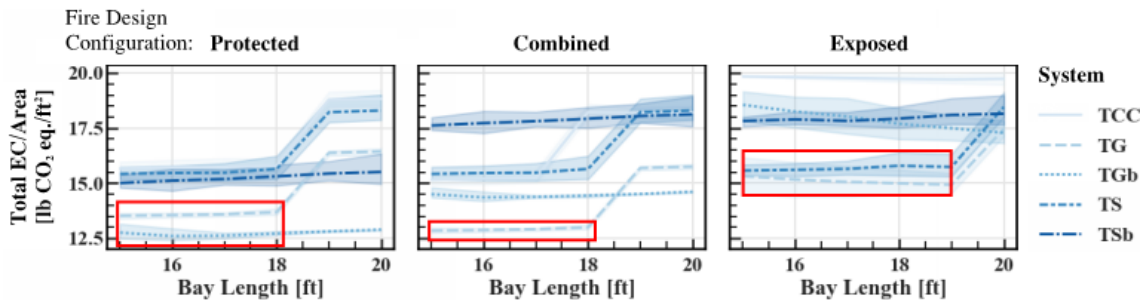


Figure 3-16: EC versus bay span for 1 infill beam. Shaded area shows ranges of results for bay ARs of 1, 1.5, and 2. Design ranges of interest are boxed in red.

Project Spaces	Design Option 1			Design Option 2			Initial Bay Size
	System	Max depth (ft m)	Min. EC/Area (lb CO ₂ eq/ft ² kg CO ₂ eq/m ²)	System	Max depth (ft m)	Min. EC/Area (lb CO ₂ eq/ft ² kg CO ₂ eq/m ²)	
Aesthetically exposed timber	TG	2.9 0.88	14.9 72.7	TS	1.9 0.58	15.5 75.6	15' to 18' span; Bay AR ~ 1.5
Concealed timber	TGb (1 infill beam)	1.6 0.49 (1.9" 49 mm drywall)	12.4 60.5	TG	2.2 0.67 (1.9" 49 mm drywall)	13.4 65.4	

Figure 3-17: Initial design options summary

Finally, Figure 3-18 shows material breakdowns for these initial options to show where design refinements could be targeted to further reduce EC in later stages of design. Further, other options for sustainable timber assumptions are included, which indicate that a premium should be considered to source more sustainable timber to achieve a carbon-storing floor assembly.

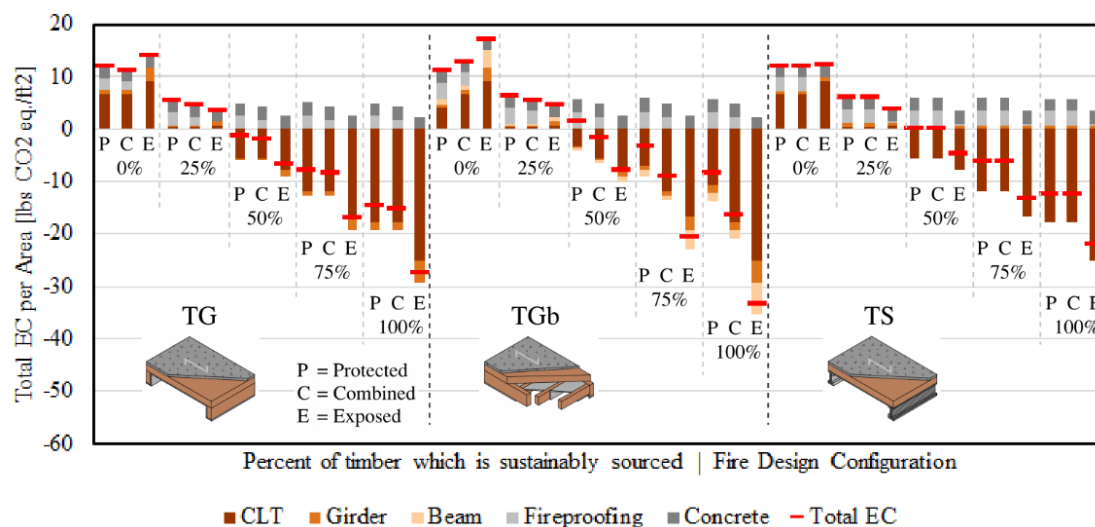


Figure 3-18: Material EC for varying fire design configurations and timber sourcing (bay size = 15' x 10')

Design is an iterative process, so while a linear process was demonstrated for examining various data plots for the example to arrive at initial recommendations, a designer will iterate through the decision-making process to understand the more complex relationships of the variables while looking for tradeoffs. Therefore, additional data analysis beyond what is demonstrated here can be used to study options during early design for a project. Below is one more application example to demonstrate how a different design scenario and goals can lead to a different initial design selection using this data set for guidance.

3.1.5.3 Design Example B

A hypothetical 5-story office building example was used to demonstrate how the model results could be used to inform early design decisions. The architect wants a bay size that is 15 to 25 feet (4.6 to 7.6 meters) wide and spanning 25 to 35 feet (7.6 to 10.7 meters) long. The project is Type IV-C mass timber construction, and the architect wants to expose the structural timber in common and office areas at a minimum. There is some flexibility in total system depth, which may be refined later during design. The owner is willing to pay a premium for sustainably-sourced timber and wants a carbon-storing floor system. Large bays and an open floor plan are desired. A summary graphic of this example is provided in Figure 3-19.

While the model was previously run for residential live loads of 60 psf (2.87 kN/m²), including partitions, similar loads are assumed here for office spaces (50 psf, 2.4 kN/m²), neglecting corridors but including partitions (15 psf, 0.72 kN/m²), for 65 psf (3.1 kN/m²) total. Although the model can be rerun for the new live load, it is assumed at this stage that the additional 5 psf (0.24 kN/m²) results in negligible differences to structural element sizing. Therefore, the existing model data will be used for this design example .

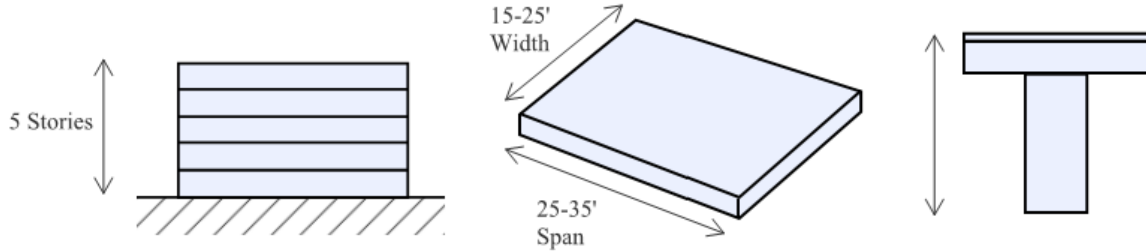


Figure 3-19: Design example project B geometry summary

As with the previous design example A, initial analysis found that of the possible bay ARs for the desired bay dimensions, a 1.5 bay AR provided a satisfactory combination of EC, depth, and bay size options. Therefore, a bay AR of 1.5 is used moving forward. Similarly, for the TGb and TSb systems, providing 1 infill beam resulted in the lowest EC and system depth, and will be used moving forward.

Based on the initial starting point as noted above, Figure 3-20 can be used initially to compare fire configuration options, embodied carbon, depth, bay length, and system type. Because one of the goals is to have a carbon-storing floor system, only designs below the horizontal red line in Figure 3-20 will be considered. Further, the systems without infill beams are not ideal for the longer bay spans required, and therefore will not be considered in the initial design. For the remaining systems (TSb and TGb), selecting the exposed approach to fire design offers the greatest carbon storage, at about -23 and -29 lb CO₂ eq/ft² (-114 and -145 kg CO₂ eq/m²) for the TSb and TGb systems, respectively. Between these two systems, there is a trade-off between carbon storage and depth. While the TGb system offers the most carbon storage, it is also much deeper than the TSb system. The TGb system is about 3.6 ft (1.1 m) deep in this design scenario, while the TSb system is about 2.7 ft (0.82 m) deep. One possible initial design approach is to consider that the TGb system may be used where more exposed timber is desired and depth is not a concern, and that the TSb system should be used anywhere with more severe depth

constraints. Based on the above discussion, the initial options shown in Figure 3-21 should be considered moving forward in the early design decision-making process.

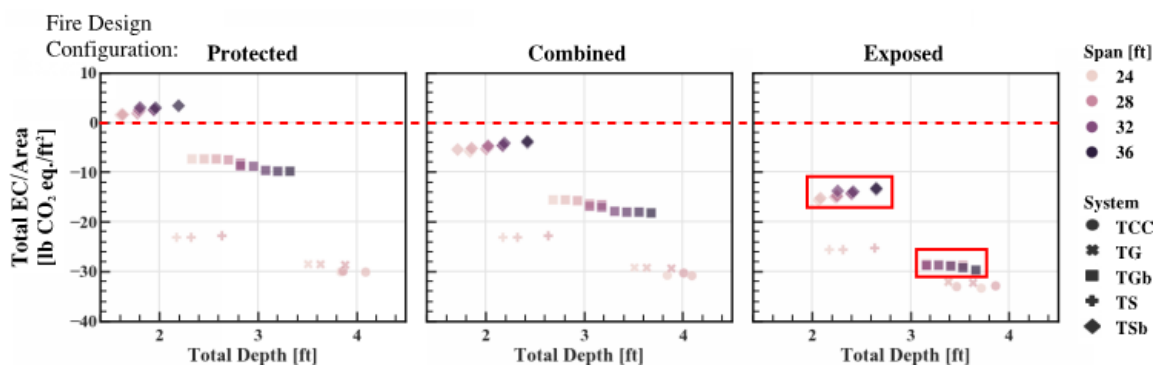


Figure 3-20: EC versus depth for a bay AR of 1.5 and 1 infill beam. Designs of initial interest are circled in red. EC = 0 shown with a horizontal red dashed line.

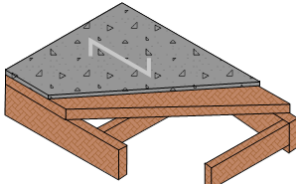
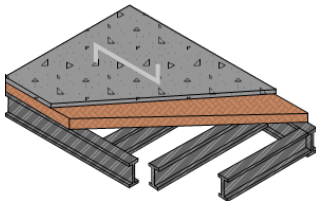
Project Spaces	Design Option 1			Starting Bay Size
	System	Max depth (ft m)	Min. EC/Area (lb CO ₂ eq/ft ² kg CO ₂ eq/m ²)	
	TGb (1 infill beam)			
“Taller” Spaces		3.6 1.1	-29.7 -145	15’ to 18’ span; Bay AR ~ 1.5
	TSb (1 infill beam)			
“Shorter” Spaces		2.7 0.82 (1.9” 49 mm drywall)	-23.3 -114	

Figure 3-21: Initial design options summary

3.1.6 Conclusions

A parametric model was built at an early-design stage resolution to help better understand the impacts of design decisions on embodied carbon and floor system depth for mass timber systems. Several modeling techniques and tools were used in building the model for this research, including custom code components in Grasshopper and the use of spreadsheet-based modeling. Both types can be used in model creation depending on a design team's capabilities, access to software, and the type of design process and equations involved for a given design problem. While the early-stage model produced conservative designs as compared to a set of case study project comparisons to meet goals for the control of walking-induced vibrations, the final design element sizes were similar enough to the case studies to demonstrate the applicability of the early-stage design model. The provided representative model results used in this research found the following key points:

- While system type significantly affects EC and system depth, timber EC accounting assumptions have the most significant impact on EC, even making the difference between whether a design is carbon-storing or non-carbon storing.
- Hybrid systems can offer multi-objective solutions to design, offering lower depths as compared to the all timber systems, while achieving carbon-storing designs through the use of sustainably-sourced timber floors.
- The impact on EC and system depth of variables such as bay aspect ratio and the number of infill beams depends on floor system type and bay span.
- An early-stage design model such as the one implemented for this research is most helpful early in design when decisions are still being made about bay layouts, structural system types, and fire design configurations.
- The model will not be helpful in cases where most or all of the early-stage decisions have been made, or are controlled by other aspects of the design, such as cost, architectural floor plans, or IBC code requirements for more stringent design scenarios.

3.1.7 Data availability statement

The full data set generated by all floor systems models for and discussed in this paper is available by request from the corresponding author.

3.1.8 Acknowledgements

The authors would like to thank M. Kevin Parfitt, Dr. Nathan Brown, Dr. Ali Memari, and Corey Gracie-Griffin for their advisement on this work. This research is supported in part by the Graduate Assistance in Areas of National Need (GAANN) Fellowship and the J. Roger Glunt Graduate Fellowship in Housing, hosted by the Pennsylvania Housing Research Center (PHRC). Neither fellowship had any role or input in the planning and implementation of this research, and the included results do not reflect the views of these organizations.

The Platte Fifteen case study project photo is reprinted in this paper with permission from WoodWorks. The complete case study [198] and life cycle assessment [228] of the project are available online at woodworks.org.

3.1.9 Definitions

L = Vibration-controlled clear span limit (m)

m = Mass of CLT per length of 1-m wide panel (kg/m)

EI_{eff} = The effective bending stiffness of the panel in the major strength direction (N-mm²)

Chapter 4

Mass Timber Floor Systems Results and Application

Using the modelling methodologies discussed in the previous chapter, the mass timber floor systems are studied for structural design metrics like depth and mass, and for embodied carbon (EC). While Chapter 3 included some representative results, this chapter discusses the model results in more detail and includes additional discussions of material take-offs, design limit states, and design capacities. Chapter 3 also included design examples with different timber carbon storage assumptions to represent both a conservative assumption of no carbon storage, as well as an assumption based on the availability of responsibly-sourced wood in the U.S. However, all plots and charts in Chapter 4 present findings based on the later of those assumptions unless otherwise noted.

This chapter makes up the main structural results for the studied mass timber floor systems in this dissertation, and is written to be a self-contained journal paper, and will be refined and submitted to a publication for review following the completion of this dissertation.

4.1 Comparisons of Structural Performance and Design Among Cross Laminated Timber Floor Systems

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4.1.1 Abstract

Interest in mass timber structural solutions for larger and taller buildings continues to grow in the United States for a number of reasons. As compared to traditional concrete and steel structures, mass timber structures tend to be lighter, have smaller foundations, are easier to install onsite, have shorter construction schedules, and are better suited to prefabrication off-site. Further, the use of mass timber can reduce a structure's embodied carbon and, with proper design for fire safety, can be aesthetically exposed. Currently, there is limited design guidance for comparing mass timber structural design options during the early design stage of a project. This research seeks to better understand how the use of mass timber affects various structural design objectives, including depth, element size, and mass, which all relate to embodied carbon. This work provides structurally designed mass timber and hybrid mass timber floor systems that have been parametrically generated to create a data set which can be analyzed for trends. In total 2,832 different mass timber and 3,307 hybrid timber designs will also be compared to a set of baseline concrete floor systems (flat plate and voided slab) designs. In total 6,139 configurations in timber

and 616 in concrete form the data set. This paper provides discussions revolving around controlling limit states, demand capacity ratios of elements, and component contributions to depth and embodied carbon. Some key resulting design considerations are summarized here. Designers seeking to reduce depth should select hybrid options, and those seeking to reduce EC should consider eliminating the concrete topping if it is feasible to do so. To reduce mass and EC, a designer should seek to design for a maximum 5-ply panel or use a more refined calculation approach to minimize the panel depth for designs requiring a 2-hr FRR.

Keywords

Mass timber, hybrid mass timber, structural design, early-stage design, parametric modeling, embodied carbon

4.1.2 Introduction and Literature Review

Modern structures within the commercial building construction industry have been predominately built out of steel, concrete, and masonry. Advances in these materials led to taller construction that resulted in a historical shift away from wood construction [2]. However, there has been increased interest in mass timber for a variety of reasons, including innovations in mass timber products and the development of Cross Laminated Timber (CLT) [3], the need to reduce embodied carbon (EC) of buildings [6], [7], the desire and ability to expose the wood structure aesthetically [3], [105], and the potential benefits to occupants through biophilia [229].

Structurally, mass timber is lighter weight than traditional construction types, thus it can reduce the size and cost of foundations [44]. CLT, the focus of this research, is considered the first large format two-dimensional mass timber structural element [187]. CLT is especially well-suited to pre-fabrication and demonstrates both two-way spanning behavior and dimensional

stability due to the cross-wise layup of the panel layers. [104], [187] Further, mass timber and CLT connections with other materials are relatively easy to construct and can be incorporated into hybrid structures, allowing materials to be used where they are best suited. [50], [187] Finally, mass timber has been shown to reduce EC as compared to traditional structures. One study found a 26 lb CO₂ eq/ft² reduction as compared to concrete systems that had a range of 63-127 lb CO₂ eq/ft². [230]

4.1.2.1 Mass Timber Floors

CLT is used in gravity floor systems to meet a variety of architectural and structural performance requirements. CLT is often used in projects with a post-beam-panel configuration with beams sitting below or flush with the CLT floor panel. [108] Other systems using CLT include point-supported two-way spanning floors, CLT over bearing walls, post-beam-purlin-panel, and hybrid options like steel-timber hybrid or timber-concrete composite. [39], [108] Figure 4-1 provides a non-exhaustive summary of mass timber and hybrid mass timber floor system.

For variations 3 and 5 in Figure 4-1, WoodWorks offers early design recommendations for panel and bay sizing based on different fire ratings. These recommendations are summarized in Table 4-1. Some manufacturers offer initial design span tables, but many span tables do not include fire design options or offer limited options specific to certain spans.

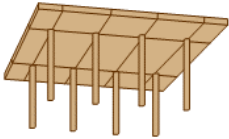
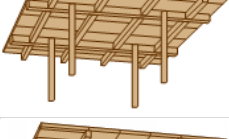
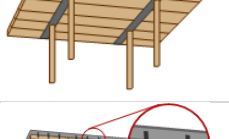
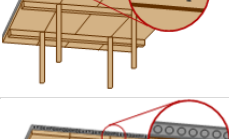
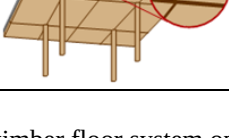
System	Variation	Figure	Applicability	Spans
Post and Panel	1. Point supported panels		Hotel, Dormitories, Micro Apartments	8 – 14 ft (2.4 – 4.2 m)
	2. Stressed skin lattice		Hotel, Dormitories, Micro Apartments (increase span compared to typical point-supported)	15 – 25 ft (4.6 – 7.6 m)
Post-Beam-Panel	3. Short beam, long deck		Office, Residential (minimize cost)	12 – 20 ft (3.6 – 6 m)
	4. Staggered deck		Office, Residential (long-span bays, minimize material, possible services over beams)	15 – 25 ft (4.6 – 7.6 m)
Post, Beam, Purlin, Panel	5. Beams and girders		Office, Residential (minimize floor panel depth)	25 – 35 ft (7.6 – 9.1 m)
	6. Two-way beams		Office, Residential (square bays, minimize beam sizes)	12 – 20 ft (3.6 – 6 m)
Steel-timber hybrid	7. Non composite or composite steel framing (w & w/out beams)		Office, Public Buildings, Post Disaster Status	15 – 35 ft (4.6 – 9.1 m) (for CLT)
	8. Proprietary flush beams		Office, Residential (long span and shallow depth)	20 – 40 ft (6 – 12 m)
Timber-concrete composite	9. Shear connectors with beams		Office, Residential	20 – 30 ft (6 – 9.1 m)
	10. Point-supported voided concrete timber composite		Office, Residential (eliminate beams, reduce mass)	20 – 30 ft (6 – 9.1 m)

Figure 4-1: Summary of mass timber floor system options (list is representative, but not all-inclusive.) Systems summary and figures adapted from the Structurlam Mass Timber Technical Guide [39] and an article by Elsa Lam for Canadian Architect [109]

Table 4-1: Summary of bay size recommendations provided by WoodWorks [231]

Fire Resistance Rating	CLT Panel Size	Efficient Span Length ft (m)	Number of Purlins	Grid Size
0 hour	3-ply panel	10-12 (3-3.7)	1	20 x 20 (6.1 x 6.1)
			2	30 x 30 (9.1 x 9.1)
1 or 2 hour	5-ply panel	14-17 (4.3-5.2)	0	15 x 30 (4.6 x 9.1)
			1	30 x 30 (9.1 x 9.1)

4.1.2.2 Structural Design Tools for Mass Timber

Despite the increasing use of mass timber, existing structural design software is still best suited to the design of conventional structures, and has limitations for mass timber design, such as challenges modeling and checking designs for the unique serviceability criteria of mass timber. [8]–[10] Further, parametric design plugins for mass timber are generally limited in US applications and codes. [171] Timber-specific software programs also have limitations on elements included and do not offer parametric capabilities to easily compare options during early design. Table 4-2 summarizes design software and their capabilities.

Further, manufacturers provide technical guides for their products, however, they do not offer sizing advice and are not integrated with other goals like reducing EC and meeting specific FRR requirements. The Fast+Epp online parametric design tool offers initial sizing requirement, but does not include hybrid options and has limited ability to compare designs across a wide range of options, as it looks at one design at a time. [172] While the focus of this paper is on structural aspects of mass timber design, it considers embodied carbon, and at the time of this writing, there are limited resources compiling both structural design and EC data into a single tool or guide for early-design decision making. A discussion of resources is discussed further by Leonard and Solnosky [201].

Table 4-2: Design software - Summary of capabilities for mass timber design

Design Criteria		Software or Plug-In									
		<i>RISA</i> [8]	<i>SAP</i> [9]	<i>ETABS</i> [10]	<i>Enercalc</i> [173]	<i>Wood Works Sizer</i> [174]	<i>Beaver</i> [171]	<i>BC Calc</i> [175]	<i>GSE Timber</i> [176]	<i>S-Timber</i> [177]	<i>RFEM Timber</i> [178]
Code	<i>IBC</i>					✓		✓			
	<i>ASCE 7</i>			✓		✓					
	<i>NDS</i>	✓			✓*				✓		✓
Loads	<i>Dead</i>	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	<i>Live</i>	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	<i>Wind</i>	✓	✓	✓	✓	✓		✓	✓	✓	
	<i>Seismic</i>		✓	✓	✓	✓			✓		
	<i>Snow</i>	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Criteria	<i>Flexure</i>	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	<i>Shear</i>	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	<i>Deflection</i>	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	<i>Creep</i>						✓			✓	
	<i>Vibrations</i>								✓†	✓	
Structural Elements	<i>Fire Design</i>					✓			✓		✓
	<i>Floor panel</i>	✓	✓	✓		✓				✓	
	<i>Beam</i>	✓	✓	✓	✓	✓		✓	✓	✓	✓
	<i>Column</i>	✓	✓	✓	✓	✓		✓	✓	✓	✓
	<i>Hybrid</i>			✓						✓	
	<i>Connection</i>					✓				✓	✓
	<i>Multi-span</i>	✓	✓	✓	✓	✓				✓	✓
Parametric Modeling	<i>Parametric design</i>								✓‡	✓‡	✓‡
	<i>Compatible with GH[§]</i>										
	<i>Compatible with others</i>			✓						✓	

Notes: * Based on 2005 NDS ; † Vibration limit states only calculated for sawn lumber joists; ‡ Limited parametric design capacity for analyzing and comparing designs; § GH = Grasshopper.

4.1.2.3 Life Cycle Assessment and Embodied Carbon

Because one of the motivators of mass timber use in structures is embodied carbon (EC), Life Cycle Assessment (LCA) research of mass timber has been ongoing since the 1990's. As buildings are designed to reduce energy consumption during the use stage, the impact of EC in LCA calculations becomes more significant. [13] Hens et. al. used a design space exploration approach to studying tall mass timber structures for EC, finding that floor assemblies accounted for approximately 28 and 39% of total embodied carbon for post-and-platform and post-beam-panel systems respectively. [86] In a study of tall wood building construction types, Chaggarris et. al. found IBC defined Type IV construction provides significant EC reductions for taller projects while IBC defined Type III construction is beneficial for shorter construction. [232] Further, many researchers have compared mass timber and concrete structures for EC, using general project data, conceptual designs, or specific case studies. Researchers have found varying levels of EC reductions by using mass timber instead of conventional reinforced concrete. Robati et. al. found a 10% reduction for mass timber buildings in Australia, [230] Puettman et. al. found reductions ranging from 22 to 50% for hypothetical project designs in the U.S., [233] and Chen et. al. calculated reductions of 21 and 70% when looking at the “product stage through end of life stage” and the “product stage through beyond end of life” modules respectively for a 12-story mass timber building as compared to an equivalent concrete building. [234]

This research sought to integrate structural and EC considerations using parametric modeling to evaluate mass timber, steel-hybrid mass timber, timber-concrete composite mass timber, and conventional concrete floor systems for a range of design options. This paper first discusses the methods used in the parametric model and data sources used. Next is a presentation of the results and discussion of observed trends in structural and EC design objectives. Finally, the paper concludes with a summary of key takeaways for early design guidance.

4.1.3 Methods

In this research, mass timber, hybrid mass timber, and concrete baseline floor systems were modeled parametrically across a range of key design variables. Each system model followed an automated sizing algorithm which selected the lowest-EC size elements for each considered design option. Each design was sized for and checked against several limit states including flexure, shear, deflections, fire design, and control of walking-induced vibrations. Models generated data for structural design objectives, element sizing, and material take-offs. The material take-offs were further used to estimate EC. Once data was collected for the range of systems and design variables considered, design space exploration (DSE) was utilized to evaluate designs and compare them to each other.

Five main variables (system, fire design configuration, bay span, bay aspect ratio, and number of infill beams) generated a set of 2,832 mass timber designs, 3,307 hybrid mass timber designs, and 616 baseline concrete designs. The next three sections explain the methodology in more detail.

4.1.3.1 Parametric Modeling

Five floor systems were modeled parametrically with variables for bay length, system type, fire design method, and sustainable timber sourcing assumptions. Floor systems included mass timber, hybrid mass timber, and baseline concrete systems, and are depicted in Figure 4-2 and discussed in more depth by Leonard et. al. [203] Total system depth is measured as shown in Figure 4-3. The mass timber floor systems were modeled using a combination of Grasshopper (GH), custom author-created python components within GH, and spreadsheet-based models and databases.

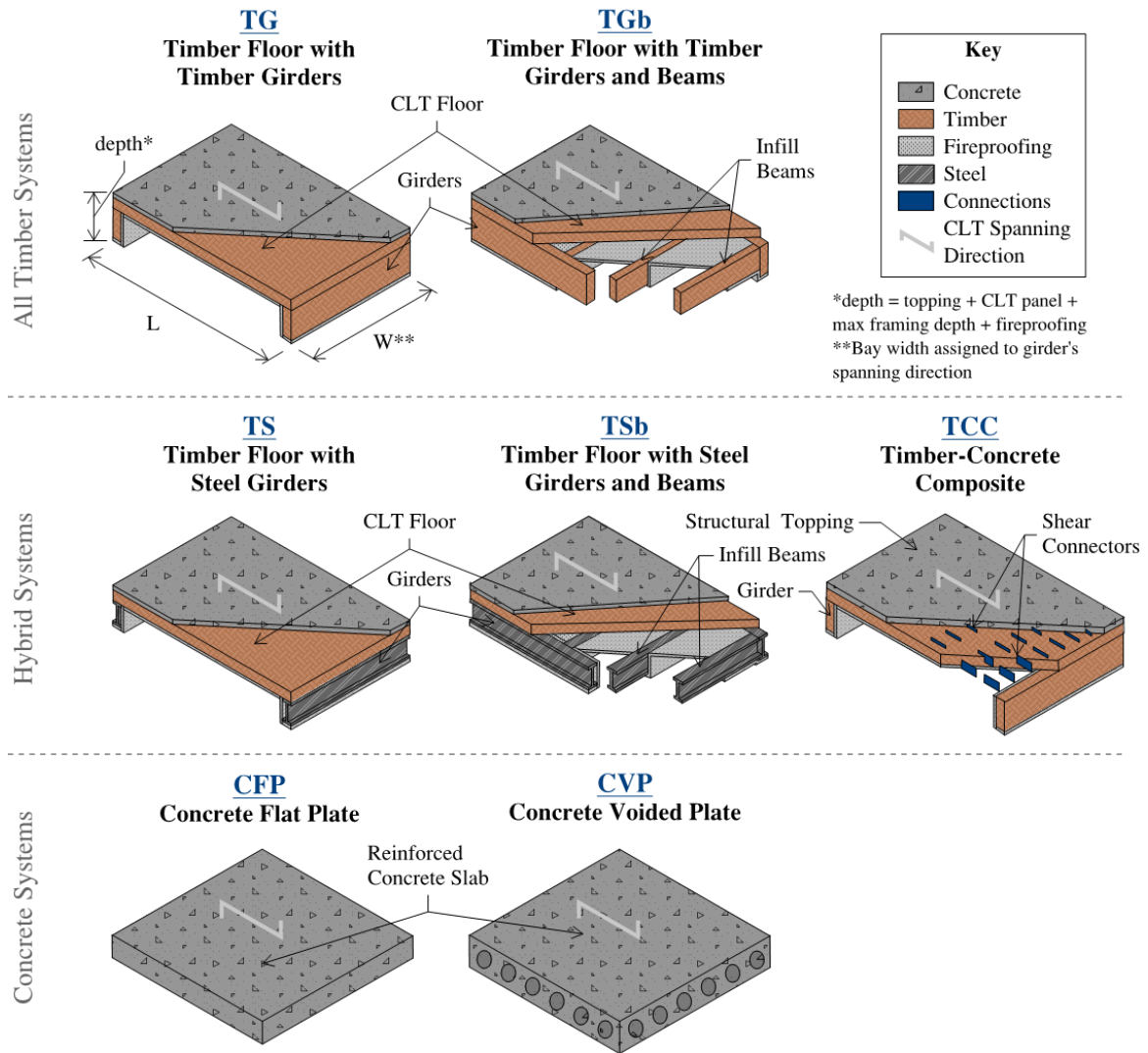


Figure 4-2: Studied floor systems (only example configurations of each are shown)

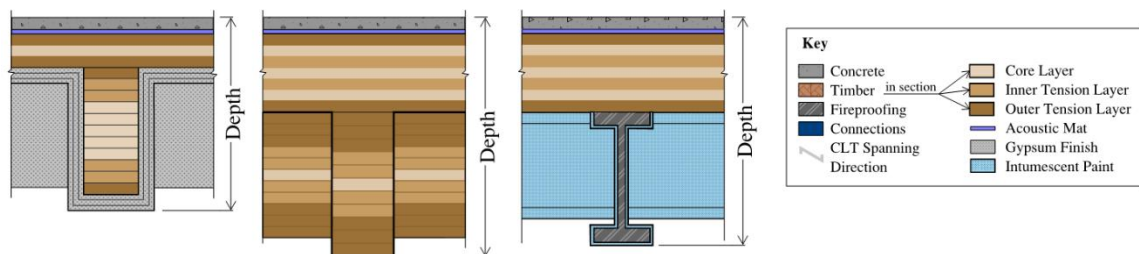


Figure 4-3: Total system depth calculation examples. Total depth includes the concrete topping, CLT panel, the maximum of either the girder or infill beams, and the fireproofing. An assumed acoustic mat between the concrete topping and CLT floor is assumed to have negligible depth. Sections shown here include infill beams which are shallower than the girders.

The parametric modeling methodology is further described by Leonard and Solnosky. [201] The concrete baseline systems utilized a GH model developed by Broyles. [235] Table 4-3 summarizes the variables and their ranges with define the set of possible design options within the design space. Parametric design and related analysis strategies such as DSE are increasingly used in early design to help explore a greater variety of options, giving designers more flexibility during early design as compared to more traditional approaches. [179] This research uses similar concepts of parametric design to evaluate the performance of the studied floor systems, similar to the methods used in research by Jelusic and Kravanja (2017), Mayencourt and Mueller (2019), and Hens et al. (2020).[86], [181], [182]

Table 4-3: Summary of variables and their ranges or options in the parametric model

Variable	Range or Options to Change in Model	Additional Notes
<i>Bay Length</i>	10 to 40 feet, in 1-foot increments (3 to 12 meters, in 0.3-meter increments)	Range covers most bay lengths currently used in mass timber Residential occupancy projects
<i>Bay Aspect Ratio</i>	0.5, 0.75, 1.0, 1.5, 2.0, 2.5	Concrete systems were designed only for square bays (1.0 bay aspect ratio)
<i>Fire Design Configurations to Achieve FRR</i>	• 2 hours from char method • 2 hours from noncombustible protection • Combined: 1 hour from each method	Options cover a range of strategies for a 2-hr FRR, a common FRR required by Type IV construction.
<i>Percent of Sustainably-Sourced Timber (SST)</i>	0%, 25%, 50%, 75%, and 100%	Options based on assumed timber-sourcing capabilities for a typical project
<i>System Type</i>	• Timber Floor with Timber Girders (TG) • Timber Floor with Timber Girders and Beams (TGb) • Timber Floor with Steel Girders (TS) • Timber Floor with Steel Girders and Beams (TSb) • Timber-Concrete Composite Floor with Timber Girders (TCC) • Concrete Flat Plate (CFP) • Concrete Voided Plate (CVP)	Systems were selected to cover a variety of all-timber and hybrid timber options, and were selected in part due to the feasibility of modeling the system parametrically at an early design stage.

4.1.3.2 Embodied Carbon Evaluation

While the focus of this paper is on the structural design objectives of the studied floor systems, some discussion of material take-offs as it relates to EC is included. EC is estimated for each design by multiplying material take-offs with their respective material EC factor. Total EC is normalized by dividing out the bay area. Material EC values, summarized in Table 4-4, are collected for the A1-A3 LCA modules from industry-wide or manufacturer-specific environmental product declarations (EPDs). Timber EC values and assumptions regarding carbon storage vary within industry and are therefore modeled for varying levels of carbon storage based on a proxy percent of sustainably-sourced timber (SST).

Table 4-4: Embodied carbon of common structural and building materials [lb CO₂ eq/lb]
(1 lb CO₂ eq/lb = 1 kg CO₂ eq/kg)

Material Information		Industry-Focused EC Material Coefficients	
Material	Material Assumptions	EC Value	Data Source
Cross Laminated Timber (CLT)	Carbon storage is neglected	0.27	Average of five North American CLT EPD's following ISO 21930:2017 A and B [64], [207]–[210]
	Carbon storage is included ¹	-1.19	
Glued Laminated Timber (Glulam)	Carbon storage is neglected	0.25	American Wood Council EPD for North American Glued Laminated Timber [93]
	Carbon storage is included ¹	-1.04	
Reinforced Normal Weight Concrete (Slab)	3001-4000 psi	0.17	Based on a combination of plain concrete and reinforcing steel values (~5% of total mass is reinforcing steel) [211], [212]
Normal Weight Concrete with WWR (Topping)	3001-4000 psi	0.15	Combination of plain concrete and reinforcing steel values (~3% of total mass is reinforcing steel)
Plain Normal Weight Concrete	3001-4000 psi	0.13	NRMCA EPD for concrete with 25% cement replacement with fly ash [211]
Reinforcing steel	98% Recycled steel content	0.85	Concrete Reinforcing Steel Institute (CRSI) EPD [212]
Steel (section)	93% Recycled steel content	1.22	AISC Industry-wide EPD for Hot-rolled structural sections [213]
Gypsum Board (drywall) ²	Type X:	0.28	Industry-wide gypsum board EPD [214]
Joint Compound ²	Conventional ready-mixed	1.19	Industry-wide joint compound EPD [215]
Intumescent Paint (for steel)	Solvent-based	2.31	Technical guides and product data sheets [59],[216],[217]

¹ Linear interpolation used for values between 0 and 100% carbon storage, carbon storage value based on assuming 100% landfilling at EOL based on the EPA Waste Reduction Model (WARM) [218]

² A 10% waste factor is applied to the total combined material takeoff for drywall and joint compound

4.1.3.3 Structural Design

Each structural element for each design is automatically sized with custom python code components within GH following Allowable Stress Design (ASD) methodology. ASD is a commonly used method for wood design, has less wood design variables to program, and is also an acceptable method for steel design which is why it was selected. [236] All elements were designed to meet the criteria for flexure, shear, deflections and creep, control of walking-induced vibrations, and fire design per the following codes as applicable and as summarized in Table 4-5.

Table 4-5: Limit states included in the structural sizing code

Element	Shear	Flexure	Deflections	Vibrations	Fire	Code and Standards
<i>CLT Floor Panel</i>	✓	✓	✓ (including creep)	✓	✓	2018 National Design Spec for Wood Construction[140]; 2021 Fire Design Spec for Wood Construction[141]; The 2013 and 2019 CLT Handbooks[42], [105]
<i>Glulam Framing</i>	✓	✓	✓	✓ (as a supporting element for CLT)	✓	
<i>Steel Framing</i>	✓	✓	✓	✓ (as a supporting element for CLT)	N/A	AISC Steel Construction Manual[237] and AISC Specification for Structural Steel Buildings[236]

Limit States

Designs are sized by selecting the lowest-weight element which meets a given limit state criteria. Limit states are checked one at a time and then resized and rechecked based on new loads as needed until the requirements for all limit states are met, as depicted in Figure 4-4. For each design, the final element demand capacity ratio (DCR) is calculated for each limit state, where the limit state with the greatest DCR is considered the controlling limit state. Table 4-6 summarizes important equations within each limit state, and Table 4-7 summarizes the key modeling assumptions.

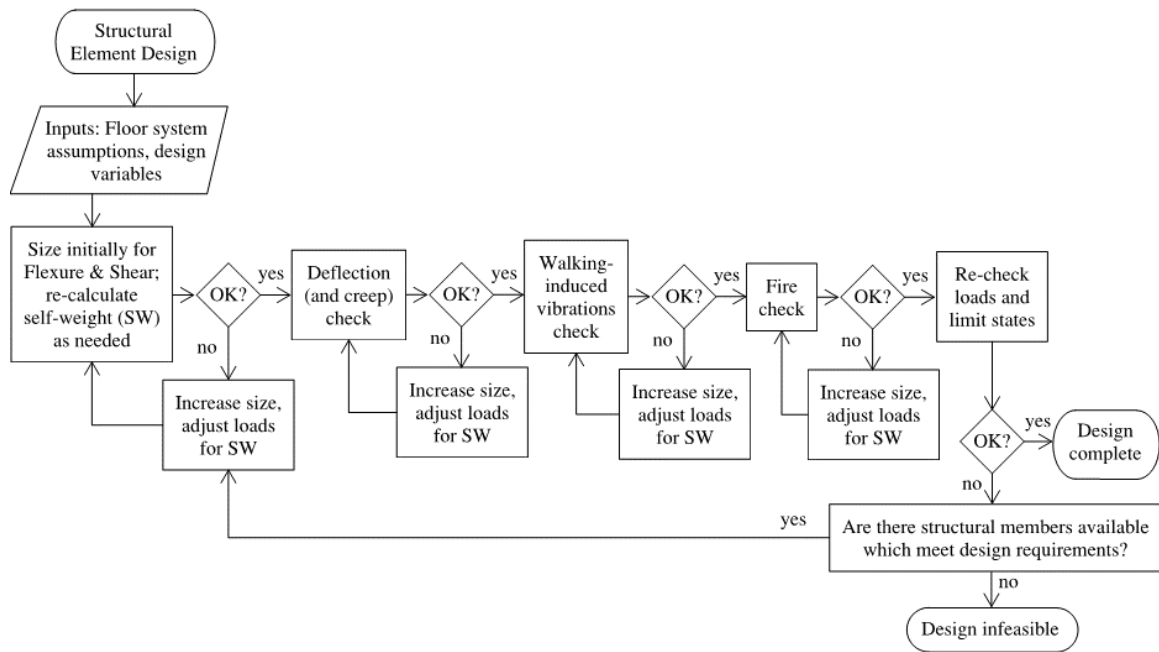


Figure 4-4: Limit states flow chart

The structural model was verified using sample design hand calculation and five case study projects representing the range of floor systems modeled, and for which structural design information was publicly available. Two of the limit states are somewhat specific to mass timber floors due to the lightweight nature of the system. One is the control of walking-induced vibrations. Because of the early stage nature of the modeling, a simplified approach is used based on both the CLT Handbook [105] and the WoodWorks U.S. Mass Timber Floor Vibration Design Guide [167]. More refined analyses for vibration control may be required in later stages of design, but is out of the scope of this paper.

Table 4-6: Key equations used during each limit state design check

Limit State	Key Equations	Variable Definitions	Code or Standard
Flexure	$M_{max} = 0.125 * w * L^2$ $F_b S_{eff} \geq M_{max}$	M_{max} = maximum moment	2018 NDS
		$F_b S_{eff}$ = panel flexural capacity, from the manufacturer's technical data	[140]; AISC Steel Construction Manual[237]
		w = bay width (girder-spanning direction)	
		L = bay length (beam-spanning direction)	
Shear	$V_{max} = 0.625 * w * L$ $V_s \geq V_{max}$	V_{max} = maximum shear force	2018 NDS
		V_s = panel shear capacity, from the manufacturer's technical data	[140]; AISC Steel Construction Manual[237]
Deflections	$EI_{app} = \frac{EI_{eff}}{1 + \frac{K_s EI_{eff}}{GA_{eff} L^2}}$ $\Delta = \frac{wL^4}{185EI_{app}}$ $\Delta_{TOT} \leq L/240$ $\Delta_{LL} \leq L/360$	EI_{eff} = panel bending stiffness, from the manufacturer's technical data	2018 NDS [140]
		EI_{app} = reduced bending stiffness to account for shear deformation (CLT only)	
		K_s = shear adjustment factor	
		GA_{eff} = Effective shear stiffness of CLT section	
		Δ = Deflections	
Control of walking-induced vibrations	CLT Option 1:	CLT Option 1 per the 2019 Canadian CLT Handbook, values based on SI units	2019 Canadian CLT Handbook [105]; U.S. Mass Timber Floor Vibration Design Guide [167]
	$L \leq 0.11 \frac{\left(\frac{(EI)_{eff}}{10^6}\right)^{0.29}}{m^{0.12}}$	m = Mass of CLT	
	CLT Option 2:	CLT Option 2 per simplified procedure in the U.S. Mass Timber Floor Vibration Design Guide	
	$f_n = \frac{3.54}{\sqrt{\Delta}} \geq 3 \text{ Hz}$	f_n = estimated fundamental natural frequency	
	More analysis required if: $3 - 4 \text{ Hz} < f_n < 15 \text{ Hz}$	$F_{span} = 1.0$ for a simple beam and 0.7 for a multi-span beam	
Fire design	Framing:		
	$(EI)_{girder} \geq F_{span} * 132.18 * L_{girder}^{6.55}$		
	$M'_f = K * F_b S_{eff} * C_L \geq M_{max}$	K = conversion factor between allowable design stresses and average ultimate strength; = 2.85 for bending, =2.75 for shear	2018 NDS [140]; AWC Technical Report No. 1 [238]
	$V'_f = K * V_s * C_L \geq V_{max}$	C_L = beam stability factor	

Table 4-7: Structural design assumptions

Item	Assumed Condition	Additional Comments
<i>Boundary Conditions</i>	Pinned connections	Chosen to be able to initially assume simple connections.
<i>Number of Spans</i>	Maximum permitted based on manufacturing and transportation limits	This allows model to take advantage of additional allowable span like for vibrations in multi-span conditions
<i>Span Length</i>	Equal to bay length	Conservative for timber as NDS defines span length as distance between faces of supports
<i>Bay Location</i>	Center bay with identical bays on each side around it	For EC accounting, perimeter girders and beams are considered to be shared with the adjacent bay
<i>Live Load</i>	40 psf residential + 20 psf allowance for partitions = 60 psf (2.87 kN/m ²)	Based on ASCE 7-10 for a residential occupancy, private rooms and corridors serving them. Live load reduction is neglected due to small tributary area in designs.
<i>Superimposed Dead Load</i>	20 psf + 19 psf for a 1.5" (38 mm) nonstructural concrete topping = 39 psf (1.87 kN/m ²)	20 psf is for mechanical, utilities, finishes, and other items
<i>Steel Shapes</i>	W-Shapes only	Shapes obtained from the AISC steel shapes database [20]

Additionally, mass timber has unique fire performance properties which allows it to be exposed. However, the structure must be designed specifically for fire safety to do so. Mass timber is permitted to be designed to meet require fire resistance ratings (FRR) through the use of noncombustible protection, sacrificial timber char layers, or a combination of both, as depicted in Figure 4-5. Fire design is performed based on the procedures included in the 2018 National Design Specification for Wood Construction (NDS) and the 2021 Fire Design Specification for Wood Construction (FDS). [140], [141] Further, the American Wood Council (AWC), publishers of the FDS and NDS, have published “Technical Report No. 10: Calculating the Fire Resistance of Exposed Wood Members,” which provides further guidance for the applicability of design

procedures. [238] Where all or a portion of the FRR is provided by noncombustible protection, 2 layers of ½” (12.7 mm) Type X drywall provide 60 minutes of protection and 3 layers of 5/8” (15.9 mm) Type X drywall provide 120 minutes of protection. [139] For the steel framing, fire protection is provided by intumescent paint at conditions where the adjacent timber is exposed, and by one or more layers of drywall boxed around the steel where the adjacent timber has at least 1 hour of drywall protection.

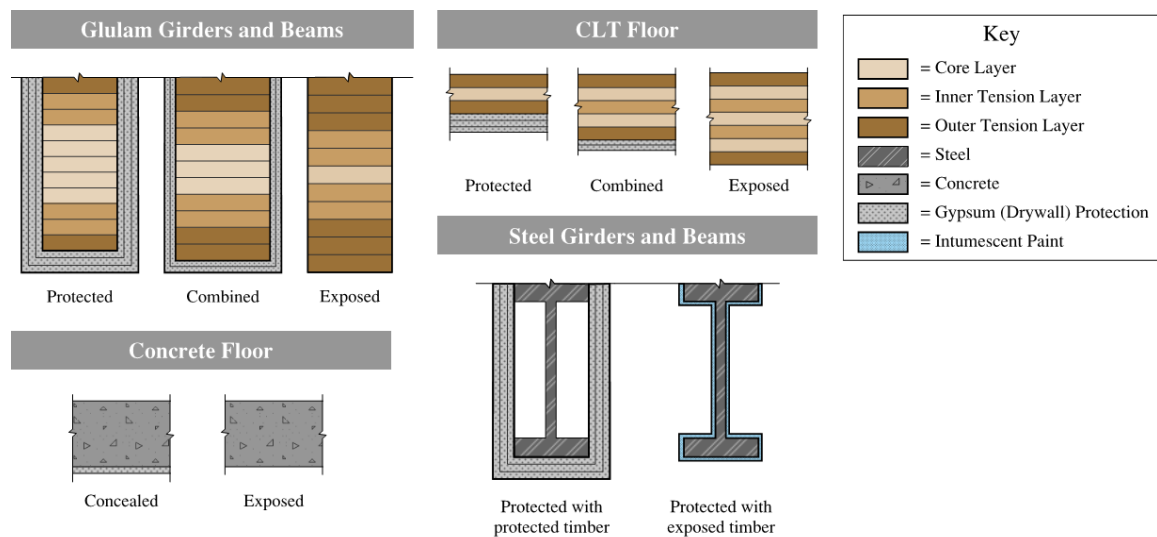


Figure 4-5: Conceptual examples of potential fire design and aesthetic configurations. (N.T.S.: Number of laminations are purely conceptual and intended to be representative.) Figure adapted from figures in The CLT Handbook (2019 Canadian Edition) and The 2021 Fire Design Specification for Wood Construction.[105], [141]

Wood Materials

To limit model complexity and focus on studying the design objectives, only a single mid-range timber grade was considered for each main wood element in this research. Table 4-8 summarizes the wood properties utilized in this study. Designers should understand however that grade, wood species, and EC assumptions will significantly affect the EC of mass timber elements.

Table 4-8: Structural design assumptions for timber components. Values are base properties before NDS adjustment factors.

Item	Assumed Condition	Additional Comments
CLT Panels	Spruce-Pine-Fir and Douglas Fir Density = 26 pcf (1.24 kN/m^3) $E = 1.4 \times 10^6 \text{ psi}$ ($9.65 \times 10^6 \text{ kN/m}^3$) $F_B = 875 \text{ psi}$ (6033 kN/m^3) $F_V = 135 \text{ psi}$ (931 kN/m^3)	Uses Structurlam Grade V2M1.1 as a baseline reference. Panel layup options include 3, 5, 7, and 9 plies, with 1-3/8" (35 mm) plies. <i>Note: Panels with thinner, 5/8" (16 mm), tangential plies were found in initial analysis to be inefficient for the char design methods used in the model, and are therefore not considered in this research.</i>
Glulam Framing	Douglas Fir Density = 35 pcf (1.68 kN/m^3) $E = 1.7 \times 10^6 \text{ psi}$ ($11.7 \times 10^6 \text{ kN/m}^3$) $F_B = 1800 \text{ psi}$ ($12,411 \text{ kN/m}^3$) $F_V = 240 \text{ psi}$ (1655 kN/m^3)	Uses Structurlam Grade Series 24F-V8 as a baseline reference. Size options include those ranging from 5.125" (130 mm) wide x 11.75" (298 mm) deep to 20" (508 mm) wide x 56.75" (1441 mm) deep.

Figure 4-6 uses CLT product data and EPDs from a range of manufacturers and demonstrates the wide variation in EC per unit of bending strength per square foot of panel. Data is shown for a range of SST assumptions. The relationships between relative grade strength and EC changes when different levels of SST are considered. Figure 4-7 includes a conceptual visualization of the unit considered on the vertical axis of the Figure 4-6 plots.

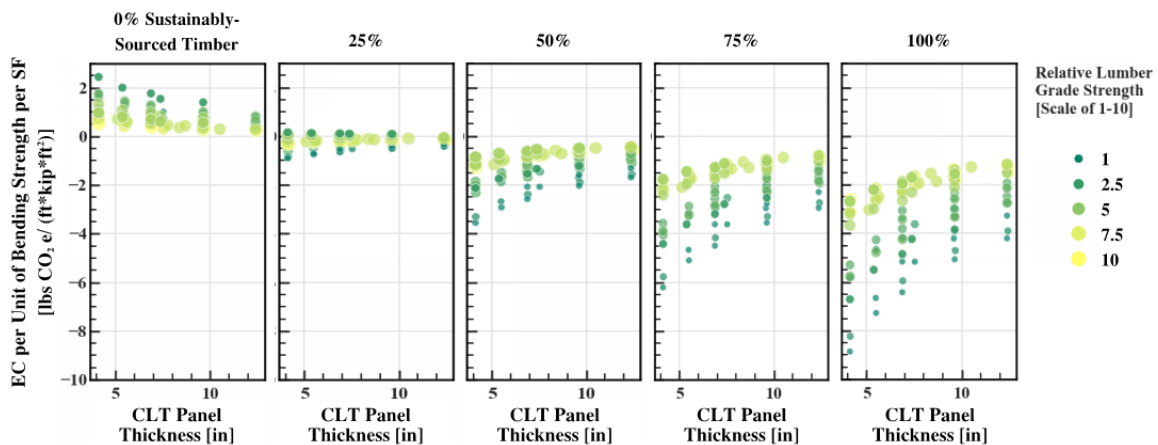


Figure 4-6: EC per Unit of Bending Strength per 1 SF panel versus CLT Panel Thickness; a relative lumber grade strength rating of 1 represents the weakest grade, and a rating of 10 represents the strongest grade (Strength and grade data obtained from manufacturer technical guides [39]–[41], [239]; EC data based on manufacturer EPDs, or ICE V3.0 values where EPDs are not available [61])

(1 lb CO₂ eq/(ft²*kip*ft²) = 3.6 kg CO₂ eq/(kN-m²*m²); 1 inch = 25.4 mm)

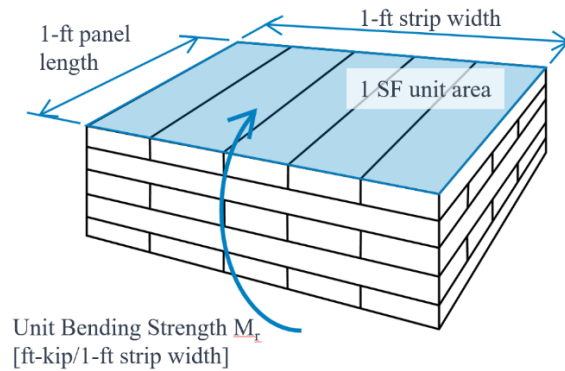


Figure 4-7: Representative example of 1 unit of bending strength for a 1 SF panel. This is the normalized unit for the data shown in Figure 4-6. (1 ft = 0.305 m.; 1 ft² = 0.093 m²; 1 ft-kip = 1.36 kN-m)

While a range of SST assumptions are discussed in the results section, most plots will focus on 75% SST. The primary assumption for the results and discussion are based on the AWC web-based Wood Sourcing Tool, which presents data on sustainable timber sourcing by region. [240]. The data for each region from this tool is summarized in Figure 4-8. Most U.S.-sourced wood is considered responsible, and the authors anticipate that responsible sources will continue to gain better certification moving forward. Therefore, the focus is on a 75% SST based on most regions having mostly responsible timber and at least some certified timber.

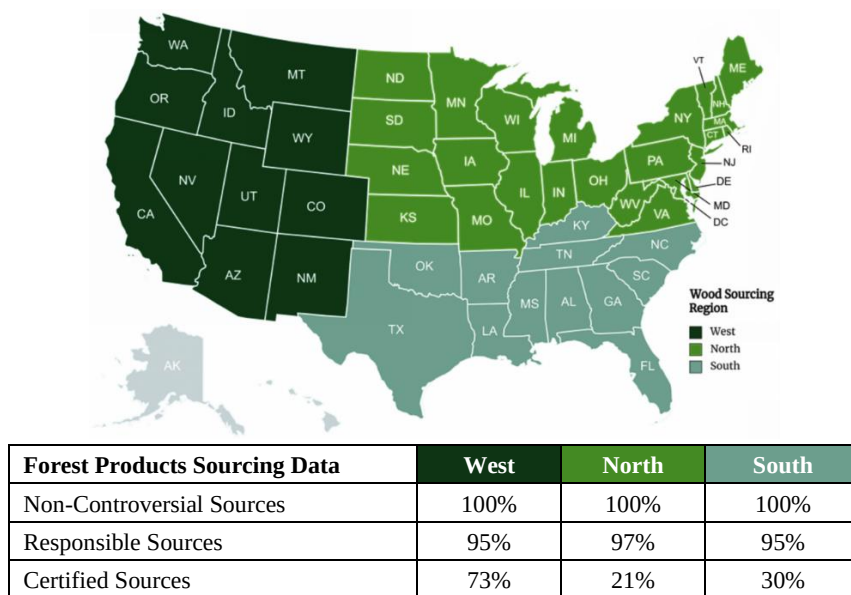


Figure 4-8: Forest product sourcing map for the United States and corresponding data by sourcing category and region. Data from the AWC's "Wood Sourcing Tool" [240] at <https://awc.org/wood-sourcing/>

4.1.4 Results and Discussion

The following section presents the results of the modeling and analysis. Some comparisons to baseline concrete systems are provided toward the beginning; however, much of the remaining results focus on the mass timber and hybrid mass timber floor systems. While many plots focus on 75% SST, consistent with the discussion in the EC section of this paper's methodology, a short discussion of other SST assumptions is provided. Described here are three main perspectives including structural performance, material take-offs and EC, and controlling limit states and design capacity ratios.

4.1.4.1 Structural Performance

First is a presentation of overall results for all studied systems, including concrete baseline comparisons. Figure 4-9 includes summary results across the entire design space, showing average values and ranges for each system. Generally, mass timber systems are much deeper as compared to the baseline concrete systems, (per Figure 4-9a) but are significantly lighter (per Figure 4-9c) and have lower EC (per Figure 4-9e). The all-timber systems have a depth range of approximately 1.5 to 6 feet, the steel-hybrid systems have a depth range of 1 to 5 feet, and the timber-concrete composite system has a depth range of 1.7 to 6 feet. The all-timber systems are between 2-3 feet (0.6-0.9 m) deeper, and the hybrid steel-timber systems are 1-2 feet (0.3-0.6 m) deeper as compared to the concrete systems. The CFP and CVP systems' mass varies within a range of about 80 to 280 psf (390-1370 kg/m²). The mass timber systems' mass is within a range of about 40 to 75 psf (200-370 kg/m²). Assuming 75% SST the concrete baselines are not competitive at any span. The baseline concrete systems EC has a range of 16-55 lbs CO₂ eq. / ft² (78-268 kg/m²), and varies significantly with bay size, while mass timber systems are carbon-

storing, except for the TSb system. Further discussion on varying SST options is included later in the material take-offs section of the results. The main advantage of the concrete baseline is lower depth, which will be easier to coordinate with services, will result in lower floor-to-floor heights, and may have lower operational energy usage due to less total enclosure volume of conditioned space for the same number of stories. The higher mass of the concrete baseline systems has some advantages including improved vibration control and acoustic insulation, but some disadvantages, including larger foundations and construction equipment needs and higher seismic forces. Note per Figure 4-9b that both concrete systems exhibit a lower rate of depth increase when increasing bay spans as compared to the mass timber systems. The concrete system depth increase at a rate of approximately 1 inch per every 11 psf, and the mass timber systems depth increases at a rate of approximately 15 inches per 1 psf. Note there is more variability in depth due to bay size as compared to concrete. Conversely, concrete experiences a much higher rate of mass increase with increasing bay span.

The Figure 4-9 depth versus bay length data is expanded in Figure 4-10 for additional comparison of the mass timber systems to the concrete baselines. Figure 4-10 presents trendlines for each system and fire design configuration which represent mean values. The shaded bands surrounding each trend line represent a 95% confidence interval. In all mass timber systems, the exposed design options are anywhere from approximately 6 inches to 1.5 feet deeper because additional depth is typically required to meet fire design requirements for the mass timber elements. For the all-timber systems, the combined and protected fire design configurations have more comparable depths, with the combined options being only approximately 3-6 inches deeper. For the steel-hybrid systems, only the CLT floor panel is affected by char design requirements, and therefore differences in total system depth are fairly small (3-6 inches or less) between all three fire design configurations. The concrete systems are inherently fire-resistive and the options to expose or conceal the concrete with gypsum board are an aesthetic matter rather than a

structural issue. Differences in system depth with and without finish gypsum board are negligible for the concrete systems.

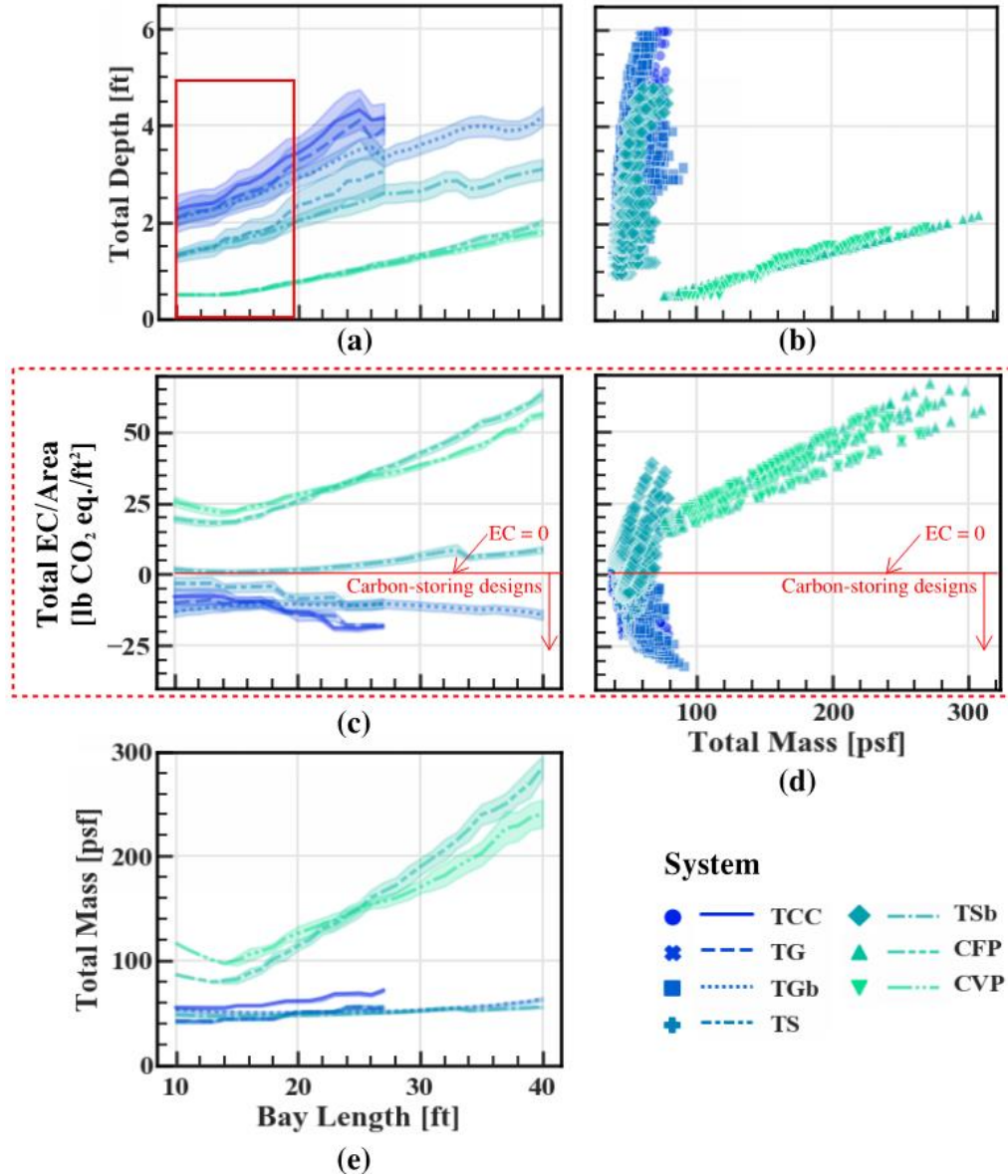


Figure 4-9: Overall results and average values and ranges for sizing and EC of each studied system across the full design space for 75% SST. Solid red outline at top left represents range of data explored more closely in Figure 4-10. Dashed red outline represents EC plots studied more closely for varying SST assumptions in Figure 4-10. The horizontal solid red line on the EC plots represents EC = 0.

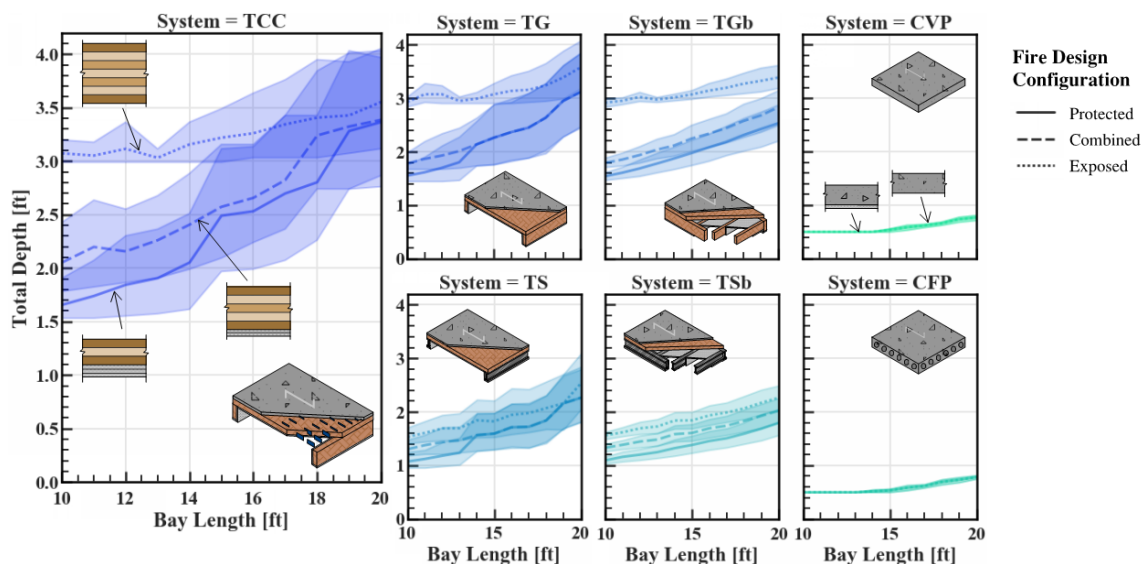


Figure 4-10: Depth versus bay length for different systems with varying fire design configurations for 10 to 20 ft (3 to 6.1 m) bay spans and 75% SST.

An analysis of design objectives versus bay span is presented for the systems with infill beams in Figure 4-11. Data plotted for these systems is colored based on the number of infill beams, with a range of values representing differences due to varying bay aspect ratio. The number of infill beams generally does not appear to cause significant differences in depth, EC, or mass; however, there is some marginal improvement to EC and mass for the TSb and TGb systems, respectively.

Within mass for the TGb system, the lowest mass for all infill options occurs at approximately 16-18-foot bay spans, ranging from 48 psf with 1 infill to 58 psf with 5 infills. Below and above this span range, most infills result in an increase in mass. This is because infills are inefficient for smaller bays, and must meet exponentially-increasing design requirements for increasing bay spans. At the largest spans, the system mass ranges from approximately 61 to 78 psf for 1 to 5 infills, respectively.

Further, for the TSb system EC, the number of infills has a greater impact beyond 20-25 ft spans. Providing 1 infill offers EC of approximately 5-10 psf, while adding more infills

continues to increase EC up to approximately 20 psf. All infill options for the TGb system are similarly close to net-zero carbon within a range of -8 to 2 psf.

Based on this data and the recommendations by WoodWorks to select only 1 or 2 infill beams for an economical design, plots moving forward will be based on data with only 1 infill beam moving forward. Further, the use of 1 infill beam is likely the best option to help reduce the CLT panel span while limiting the impact on coordination of services and construction.

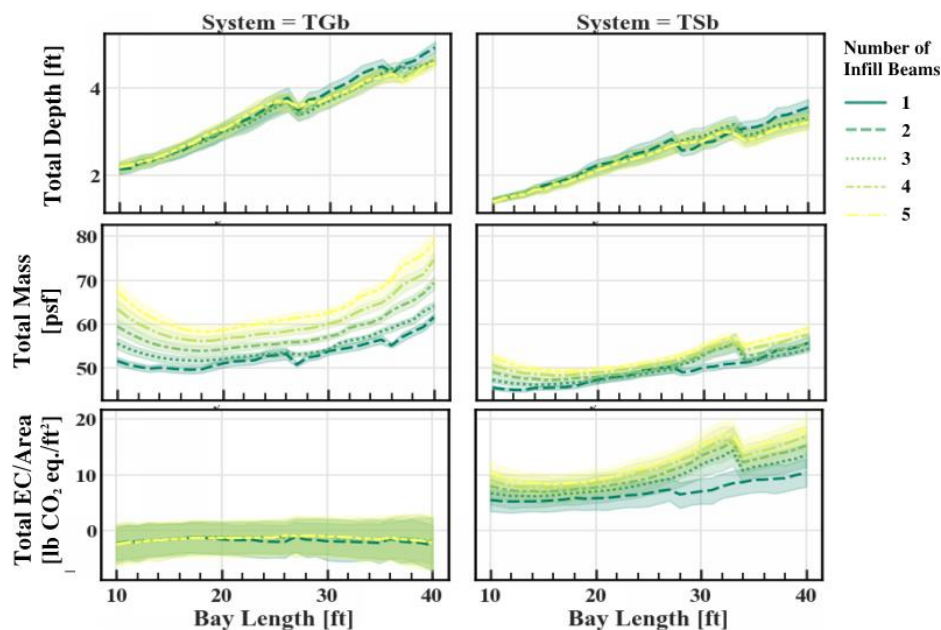


Figure 4-11: Design objectives versus bay length for floor systems with infill beams and 75% SST.

Figure 4-12 looks more closely at the effect of bay aspect ratio on depth versus bay length, focusing on the data for 75% SST, the combined fire design configuration, and designs with only 1 infill beam where applicable. In this case, bay aspect ratio does not change based on the presence of infills. Because width varies significantly with bay aspect ratio, narrower bays are of course shallower for designs with the same length, as the girder span along the width is shorter. However, the data in Figure 4-12 interestingly shows that the depth of narrow bays increases in some cases at a greater rate than the wider bays, especially for the systems with infill beams (TGb and TSb). This is because for a given bay span, those designs with a smaller bay aspect ratio (0.5)

have a larger bay area with girders spanning in the longer direction as compared to those designs with a greater bay aspect ratio (2.0). Flat regions in the trend lines occurring below 20-ft spans represent regions where minimum element sizes control, including minimum dimensions for mass timber elements and minimum available steel W-shapes.

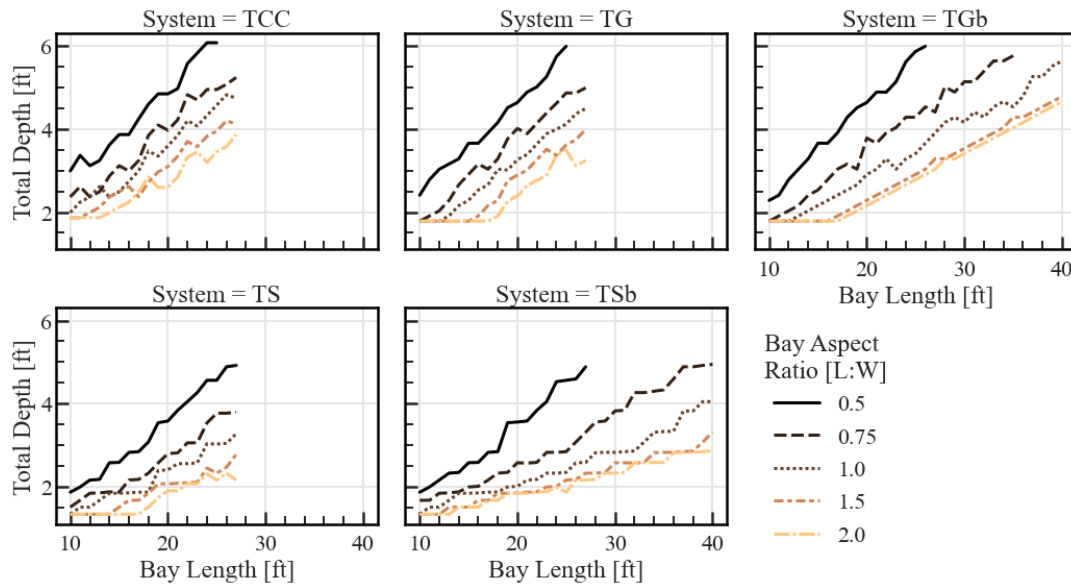


Figure 4-12: Depth versus bay length for designs with the combined fire design approach and 1 infill beam where applicable. Data divided by system.

The same data from Figure 4-12 is shown similarly in Figure 4-13, but organized by bay aspect ratio instead of system type. In this plot, the all-timber systems increase in depth with increasing bay span at a greater rate as compared to the all-steel systems. This is because the total depth is controlled by the framing depth, and the steel framing is able to span further using shallower sections as compared to timber framing.

Based on this data, a common bay aspect ratio of 1.5 will be used moving forward to focus the discussion on other variables and performance metrics. This ratio is selected because it represents mid-range depth performance as compared to other bay aspect ratios.

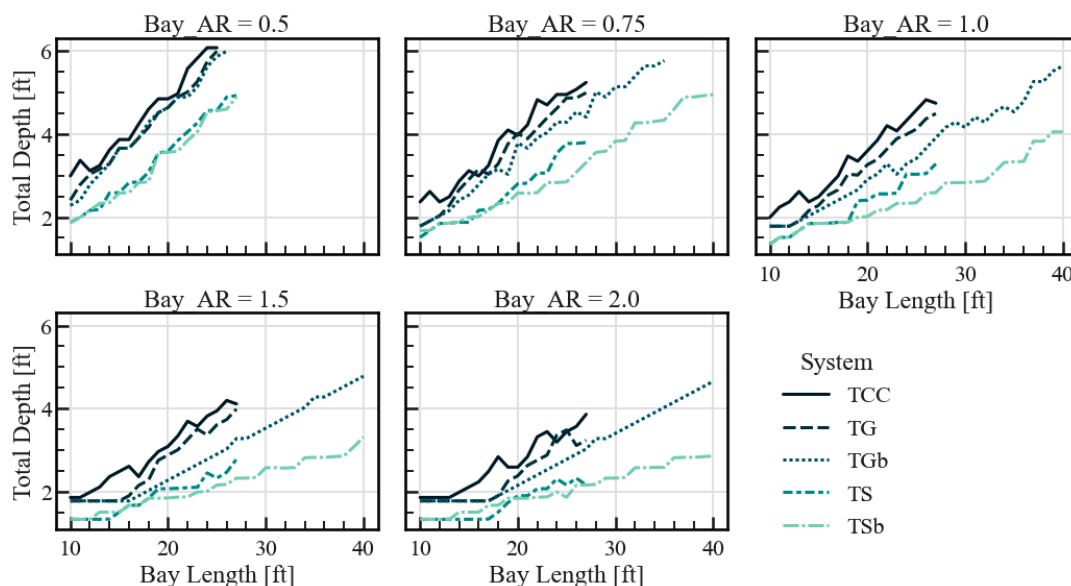


Figure 4-13: Depth versus bay length for designs with the combined fire design approach and 1 infill beam where applicable. Data divided by bay aspect ratio.

Some additional discussion of the affect of fire design configuration is included here based on the data presented in Figure 4-14 which focuses on designs with 75% SST, a bay aspect ratio of 1.5, and 1 infill beam where applicable. This reinforces the takeaway from Figure 4-10 that most systems and fire design configurations are comparable at many bay spans. The exception is for the non-steel-hybrid systems with bays around 20 ft (6.1 m) or less. These systems can be up to 50% deeper depending on the span when comparing the exposed configuration with the protected designs. There are more significant differences in EC between different fire design configurations, particularly in the systems with infill beams, which can expect the greatest amount of carbon storage with the exposed designs as opposed to the protected designs, which either do not store much carbon or are non-carbon-storing in the case of the TSb system. The systems without infills see more comparable EC between the protected and combined options, with differences of 1 lb CO₂ eq./ft² or less, except at around 10 ft (3 m) spans or less, which have differences of up to 4-6 lb CO₂ eq./ft². Finally, mass of the system tends to be comparable at all spans for the designs without an infill beam. Further, per Figure 4-14, for the

systems with 1 infill beam (TGb and TSb), the all-timber system (TGb) sees the greatest mass for the exposed option and the steel-hybrid system (TSb) sees the greatest mass for the combined and protected options, which are comparable.

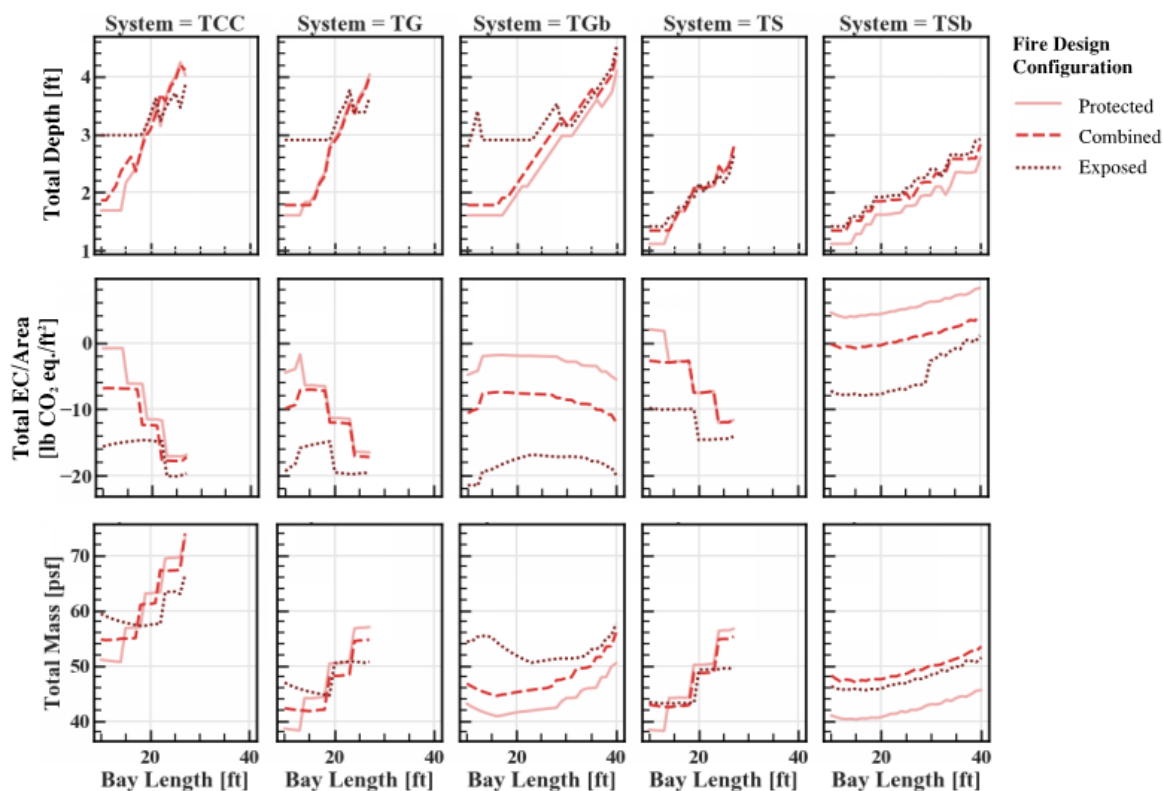


Figure 4-14: Design objectives vs bay length for systems with 75% SST, a bay aspect ratio of 1.5, and 1 infill beam where applicable, colored by fire design configuration.

4.1.4.2 Material Take-offs and Embodied Carbon

Each design's sizing not only affects those objectives, but also the material take-offs and EC estimates. Although the results plots so far have focused on 75% SST, there are a variety of assumptions existing within both academia and industry regarding carbon storage. [61], [64], [65] One of the most important implications of these different carbon storage assumptions is the impact on whether a design can be considered carbon-storing or not. Therefore, a brief discussion is included here comparing the different carbon storage assumptions. Figure 4-15 includes results

for varying levels of SST, ranging from 0 to 100%. An SST that equals 0% represents a design which does not consider any carbon storage, a common assumption amongst product EPDs and LCA work. [64] Different mass timber floor systems become carbon storing at different SST levels and at different bay spans. Per Figure 4-15, at 50% SST, the all-timber systems (TG, TGb, and TCC) are carbon-storing ($EC < 0$) for most bay spans and designs. At 50% SST, the steel-hybrid systems are not yet carbon-storing. By 100% SST, most systems are carbon-storing, except for the TSb designs above approximately 30-foot bay spans.

Designers should take care however to consider a full LCA for a building rather than focusing only on floor system results. As demonstrated in Figure 4-16, carbon-storing designs store more direct carbon in the wood elements as depth, span, and mass increase because greater quantities of wood have the ability to store more carbon. However, these three items have negative impacts on energy use and embodied carbon elsewhere which are out of the scope of this study, as deeper systems can result in more enclosure area, and greater mass can impact foundations and construction planning.

As demonstrated in Figure 4-16, when carbon storage is neglected, the concrete systems are competitive with the mass timber systems at spans from about 14 to 18 ft when factoring potential error across different material EC assumptions. However, as more carbon storage is considered, there is a greater difference between the concrete and mass timber systems' estimated EC. At a span of 15 feet where the concrete systems' EC is the lowest (18 and 22 lbs CO₂ eq./ft² for the CFP and CVP systems, respectively), the mass timber systems with 0% SST have a range of 13 lbs CO₂ eq./ft² (for the TG system) to 19 lbs CO₂ eq./ft² (for the TSb system). However, with 50% SST, the mass timber system shave a range of -2 lbs CO₂ eq./ft² (for the TG system) to 8 lbs CO₂ eq./ft² (for the TSb system).

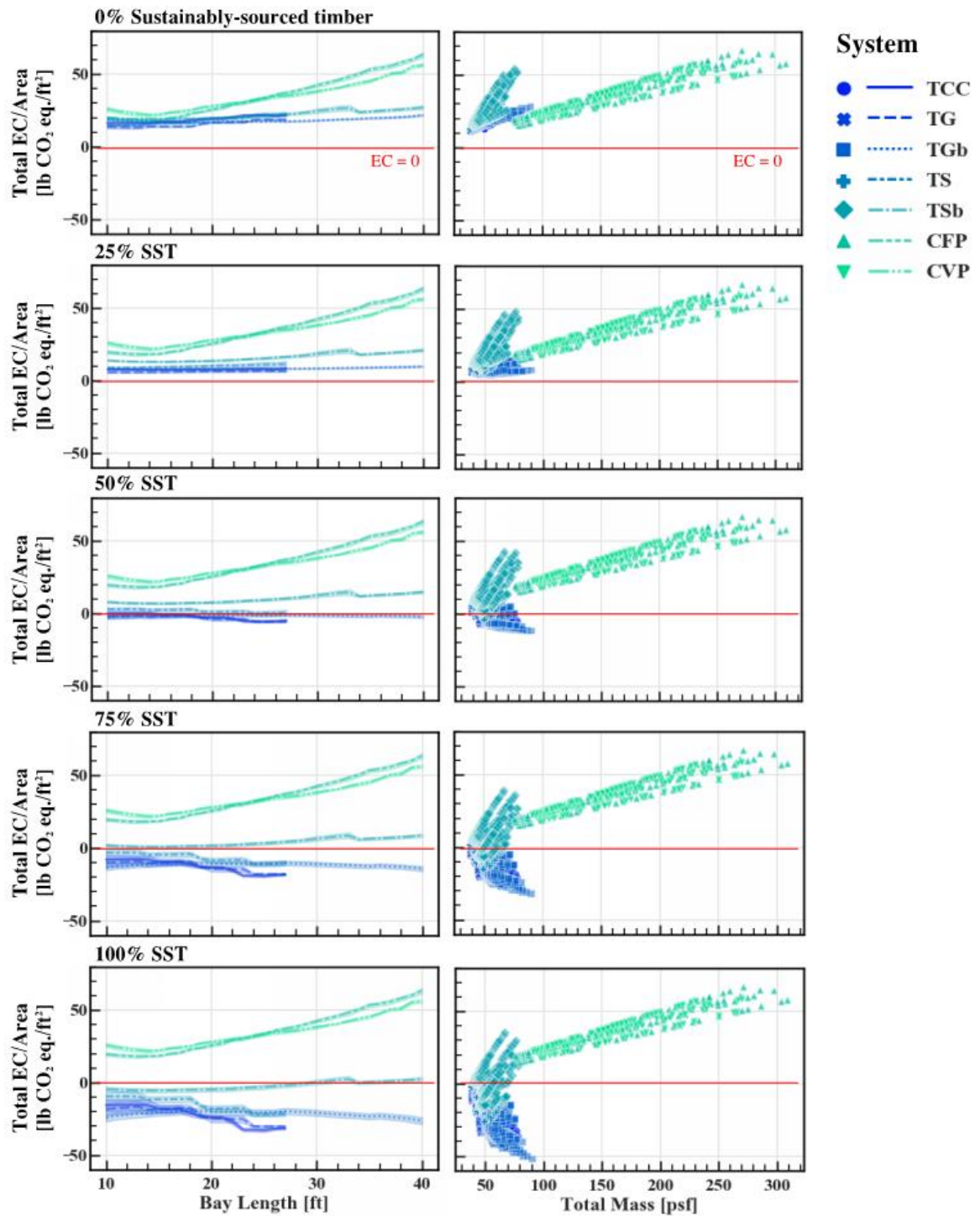


Figure 4-15: EC versus bay length and mass for a range of SST assumptions. Averages are shown for the full dataset.

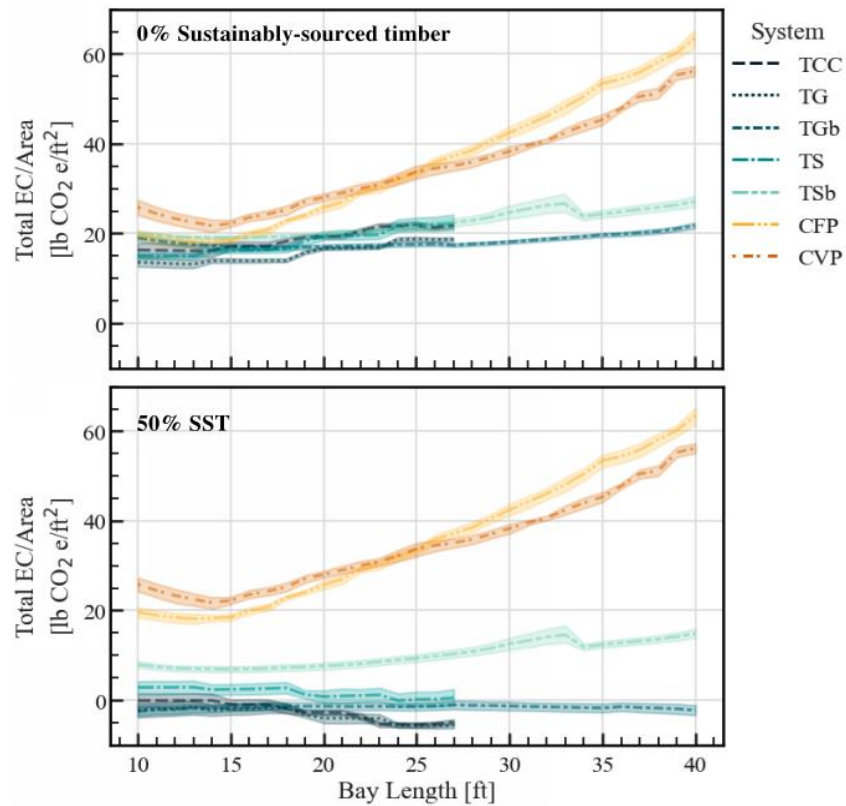


Figure 4-16: EC versus bay length for 0% and 50% SST

Figure 4-17 provides one more comparison focusing on bay aspect ratio, similar to Figure 4-12, but comparing EC (75% SST) to bay length instead of depth to bay length. In this plot, there are many conditions where EC is comparable for various bay aspect ratios and spans. Some key takeaways, however, are that the wider bays with an aspect ratio of 2.5 tend to have lower EC for the TG, TS, and TSb systems. The TG and TS systems store more carbon with wider bays because the CLT panel spans further and requires deeper sections. Further, the narrow bays with an aspect ratio of 0.5 tends to store more carbon for the TGb system because the infill reduce the CLT spanning requirements such that the CLT panel depth has less control over total EC.

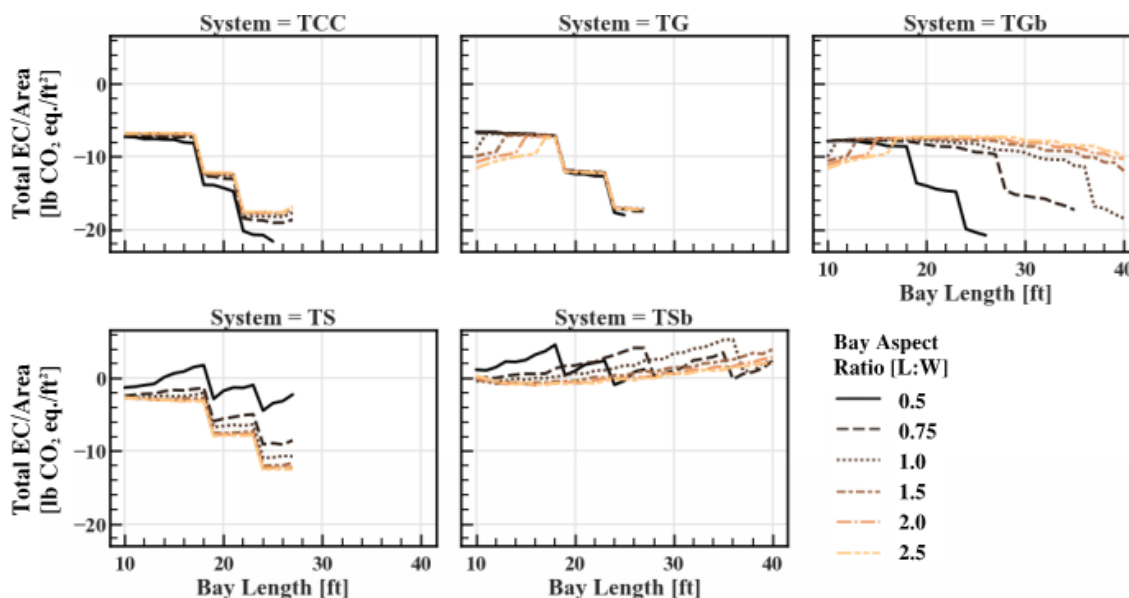


Figure 4-17: Depth versus bay length for designs with 75% SST. The combined fire design approach, and 1 infill beam where applicable.

Finally, an example is presented to show the component contributions to depth, mass and EC for each system at the range of applicable bay spans. Figure 4-18 shows the main component contributions for designs with 1 infill beam where applicable, a bay aspect ratio of 1.5, the exposed fire design configuration, and 75% SST. While the CLT panels contribute very little to total depth (30% or less), they make up a large portion of the system mass (50% or more) and carbon storage (75% or more). Further, while the concrete topping makes up only a negligible contribution to total depth (1.5 inches for most systems), it contributes significantly to mass (~30-50%) and somewhat to EC (25% or more). A designer seeking to reduce mass would ideally look for solutions that minimize or eliminate the need for a concrete topping while balancing serviceability requirements for vibrations and deflections, as well as to select lighter weight CLT options. Note that removal of a concrete topping and design for the lightest systems are not entirely ideal as they tend to have issues with acoustic insulation and walking-induced vibrations. Further, designers seeking to increase carbon storage who are working on an assumption similar to 75% SST should prioritize CLT panel products with high carbon storage.

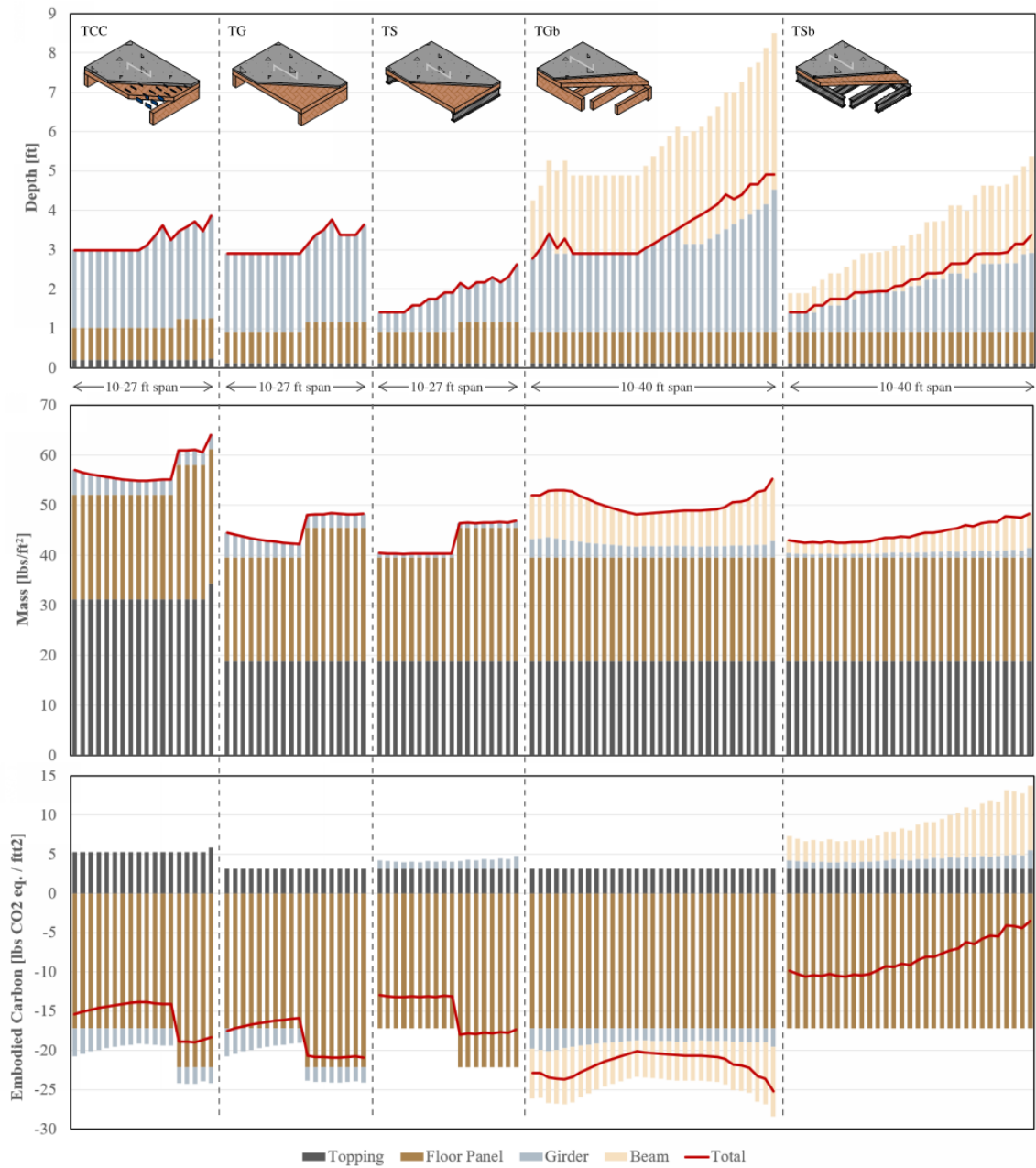


Figure 4-18: Depth and EC versus bay span for each mass timber and hybrid mass timber system. Component contributions to each are represented as stacked bars. Note that beams and girders are flush at the top, so the deeper of the two will control total maximum system depth.

4.1.4.3 Design Limit States and Design Capacity Ratios

In addition to studying EC, it was critical to study what design limit states are controlling the various elements to examine performance. Figure 4-19 through Figure 4-21 presents depth, mass, and EC data for designs with 1 infill beam and a bay aspect ratio of 1.5, with points colored by the CLT controlling limit state and styled based on the fire design configuration. Limit states for girders and beams are discussed later in this section. The plots in Figure 4-19 through Figure 4-21 are further separated into designs which are the most likely to meet vibration criteria and designs which likely need to be refined further in later design stages.

These figures show that although flexure, shear, and fire design control many of the designs, a significant portion of the designs would need to be further analyzed and potentially refined later in the design process to control walking-induced vibrations, including for all designs spanning more than about 20 ft (6.1 m) in the systems with infills, and for almost all of the designs in the systems without infills.

Further per Figure 4-19, in most of the designs using the exposed fire design configuration, the CLT is controlled by fire design. Many of the protected designs with the infill beam are controlled by shear at spans below about 25 ft (7.6 m) and by flexure for longer spans. Finally, many protected designs are controlled by flexure in the systems without infills, with some designs using the combined approach being controlled by vibrations for the TCC system. Deflections do not appear to control the CLT sizing for any of these designs. Many of the designs without infills are controlled by flexure for protected and combined fire design configurations and by fire for the exposed configurations at all bay spans. Figure 4-20 and Figure 4-21 present the same data and point styling for limit states and fire design, but the points are plotted for mass versus span and EC versus span to offer alternative visualizations.

Figure 4-19: Depth versus bay length showing CLT controlling limit states and fire design configuration. (a) includes designs where vibration criteria are fully met, (b) designs may need to be refined for vibration control in later stages of design.

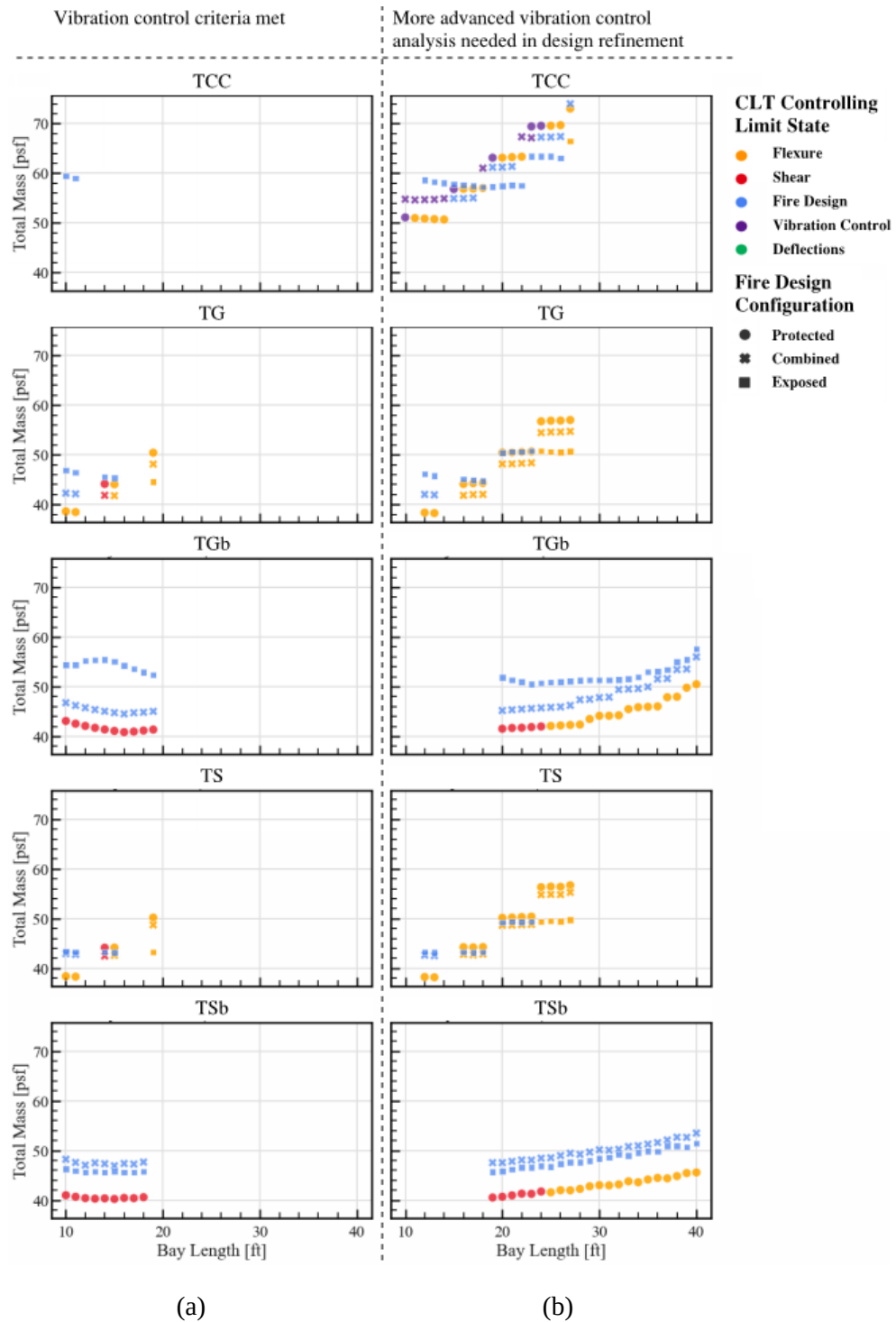


Figure 4-20: Mass versus bay length showing CLT controlling limit states and fire design configuration. (a) includes designs where vibration criteria are fully met, (b) designs may need to be refined for vibration control in later stages of design.

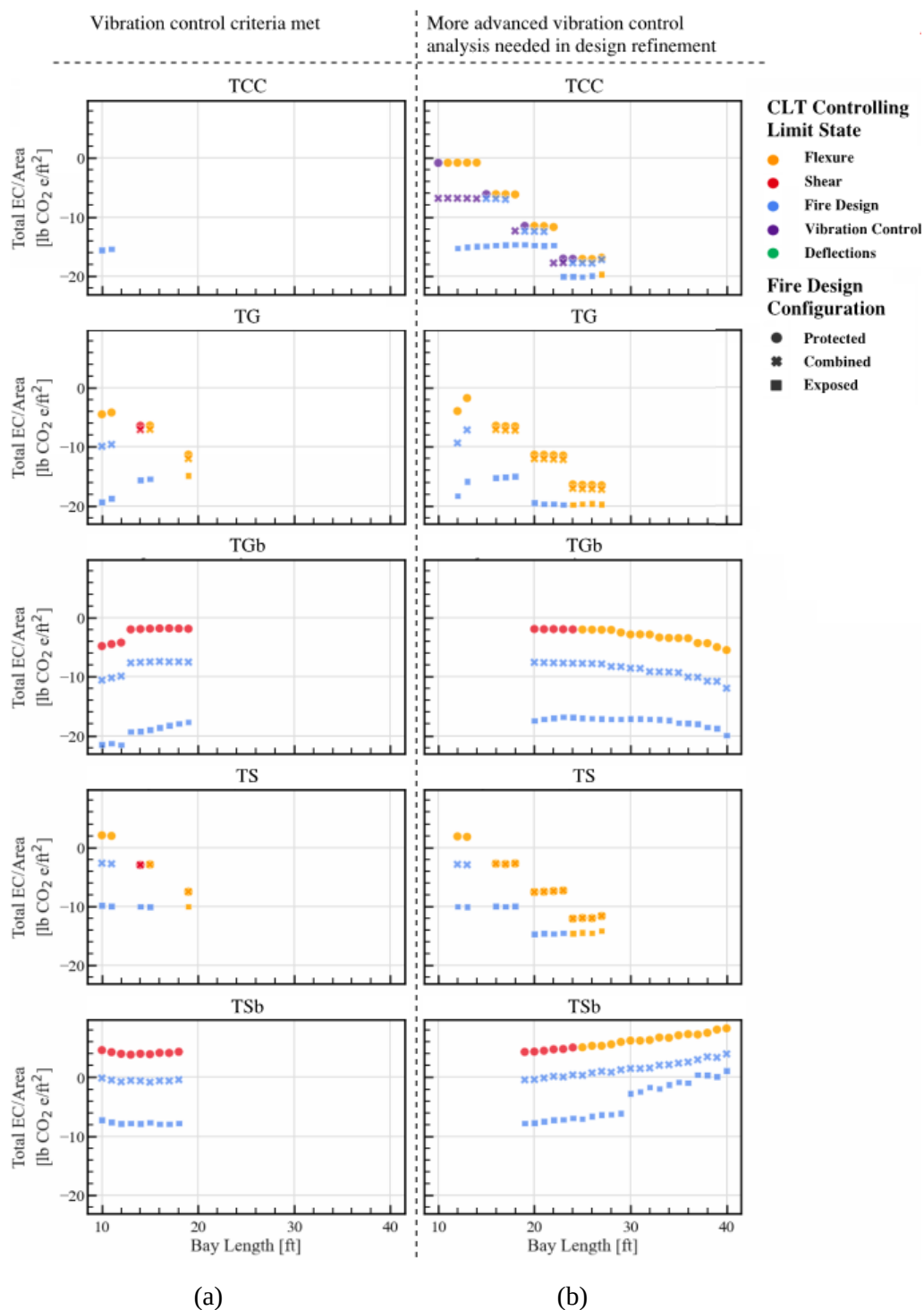


Figure 4-21: EC versus bay length showing CLT controlling limit states and fire design configuration. (a) includes designs where vibration criteria are fully met, (b) designs may need to be refined for vibration control in later stages of design.

Designs were additionally studied for demand capacity ratios (DCR) based on the controlling limit states for the floor panels, girders, and infill beams. DCR is calculated by dividing the required member capacity by the available member capacity for the controlling limit state for each element in a design. Figure 4-22 includes DCR versus bay length for the main floor system elements, with points color and styled based on the controlling limit state. The TCC system is not included in this and the following plot because it was designed based on a difference set of guidance out of Canada. Note that the results for the CLT DCR for the TGB and TSb systems are the same, as well as for the TG and TS systems. This is because the CLT panels are designed for the same spans in each set of systems.

The CLT panels see higher DCRs at higher bay spans where flexure controls, and lower DCRs at any span where fire design controls, and lower DCRs at lower spans where shear controls. This is likely due to the conservative assumptions made for fire design in the parametric model, as well as minimum panels sizes that control designs at lower bay spans. The girders are often controlled by flexure and see high DCRs commonly above 75% for most spans. This is likely because more options are available for girders sizes, and thus the design can be refined more to optimized member size as compared to the CLT panel design. The beams have the highest DCR around 15 to 20 ft (4.6 to 6.1 m), but the DCR drops off for shorter and longer bay spans outside that range. This is likely because the designs with 1 infill beam shown in Figure 4-22 are most efficient at the 15-20 span range. A single infill becomes inefficient at lower spans and requires larger sizes for vibration control at larger spans. Many of the beams are controlled by vibration control as the span increases, likely because although the loads are less for infill beams than for girders, the elements must be designed for additional stiffness to accommodate CLT panel design for the control of walking-induced vibrations.

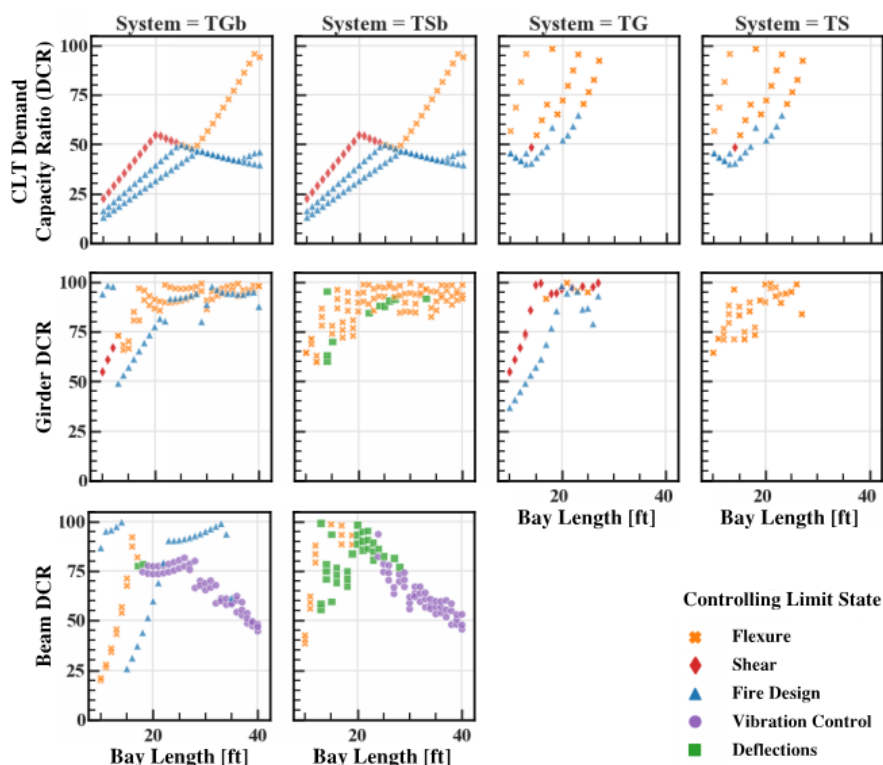


Figure 4-22: Demand capacity ratio vs bay length for CLT, Girders, and Beams. Points are colored and styled based on the controlling limit state for each element type.

Finally, Figure 4-23 presents the same data as Figure 4-22, but colored based on the element size. Note that there are clear trend lines for each CLT panel size which also corresponds to the controlling limit states shown in the previous figure. This plot reinforces earlier findings in this section regarding system depth, as both the girders and beams are deeper by approximately 1-2 feet for the all-timber systems as compared to the hybrid-steel systems. Girder depths for the all-timber systems can be as deep as 4 feet (1.2 m), and beams, which in this case span longer than the girders due to the 1.5 bay aspect ratio, can be as deep as 5 feet (1.5 m), which can present significant coordination challenges and architectural design impacts. Girder and beam width for the TGb system falls within a range of 5 to 20 and 5 to 16 inches, respectively. Girder and beam width for the TSb system falls within a range of 4 to 18 and 4 to 12 inches, respectively. For the

TG, TS, and TCC systems, the girder width falls within a range of 5 to 18, 4 to 16, and 5 to 20 inches, respectively.

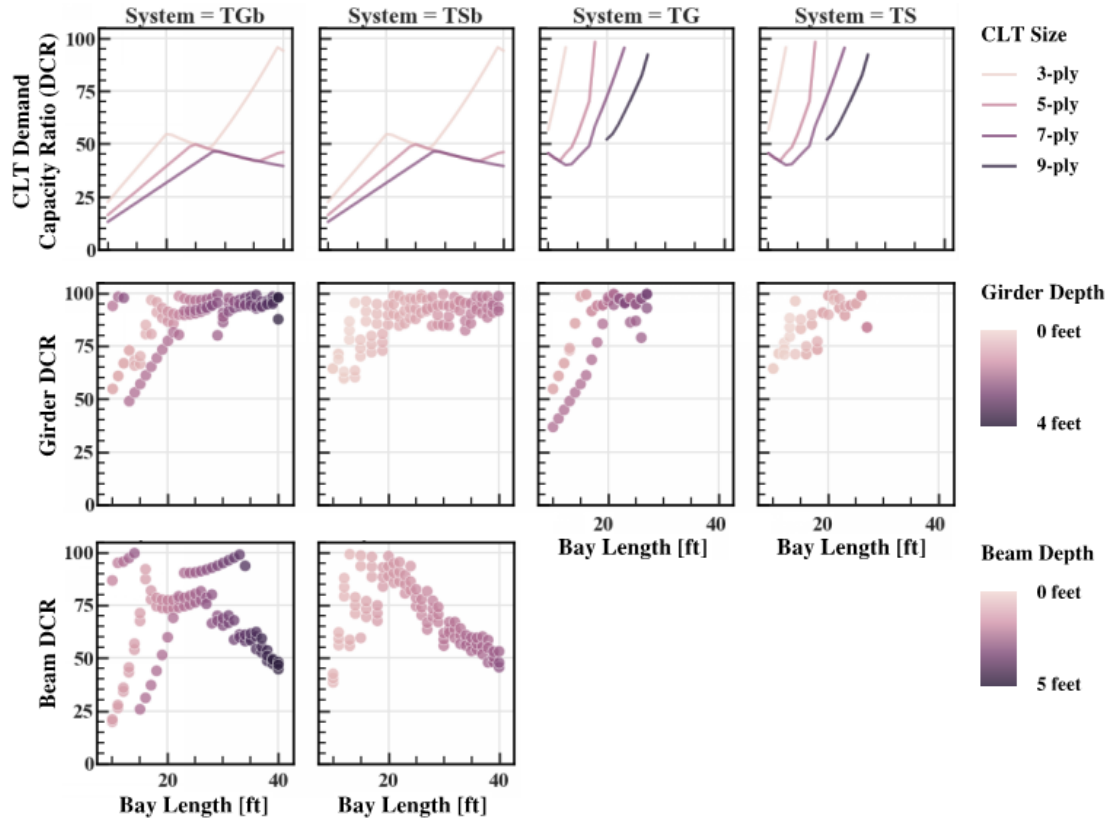


Figure 4-23: Demand capacity ratio vs bay length for CLT, Girders, and Beams. Points are colored based on the depth of each element type.

4.1.5 Conclusions

Below is a summary of the key takeaways from the research performed in this paper on mass timber floor systems, structural design, and EC. When comparing the mass timber systems to baseline concrete designs, the most significant advantage of the concrete system is reduced depth. The hybrid-steel mass timber systems are the next shallowest systems, while the timber-

framed systems are the deepest. In this research, depth acts a proxy for other considerations that are out of the scope of this work, including:

- floor-to-floor heights and total envelope area, which affect cost and operational energy
- ease of integration with services and HVAC systems
- project cost
- total building height and wind loading

Further, the concrete baselines are more massive than all other systems. While there are some serviceability challenges for mass timber systems which are too light, the mass of the concrete baseline systems has a significant impact on foundation sizes and construction equipment needed.

Amongst the mass timber systems, fire design is a key decision related to whether or not the timber will be exposed. Differences in total system depth between the fire design options is the greatest for the all-timber systems in which the framing sizing controls the depth more so than the CLT sizing. Conversely, the CLT floors control EC and mass more than depth. Further, while concrete toppings contribute very little to depth, they add significant mass and some EC. Designers seeking to reduce depth should select hybrid options, and those seeking to reduce EC should consider eliminating the concrete topping if it is feasible to do so. Note that concrete toppings are often incorporated to improve serviceability criteria, but those criteria may be less of a challenge for smaller bay sizes. Further, to reduce mass and EC, a designer should seek to design for a maximum 5-ply panel or use a more refined calculation approach to minimize the panel depth for designs requiring a 2-hr FRR. The next chapter will look in greater detail at the impact of fire design on performance objectives for mass timber.

Finally, a key consideration is the carbon storage assumption for timber, which can vary widely in industry and academia depending on end-of-life assumptions and LCA boundaries

considered. One of the most important implications of this assumption is whether or not many of the designs are carbon-storing. However, even when carbon storage is assumed, designers should ultimately consider a full LCA as they refine their design. Designers should seek to optimize carbon storage and system depth while considering the full building LCA holistically to include other factors that are out of the scope of this study. While carbon-storing designs will store more carbon in the timber as element sizes and depths are increased, a larger structure will impact energy use and embodied carbon elsewhere in a manner which is out of the scope of this research, including impacts on foundations, enclosure area, cost, and more.

4.1.6 Future Work and Limitations

A limitation of this work is that it focuses on gravity floor systems with rough estimates included for gravity-only columns. This field would benefit from similar research for lateral systems and full-scale building analyses and comparisons. As previously noted, depth is considered in this research as a proxy for many other factors; however, further research into those factors such as effects on building height, operational energy, cost, and integration with services will be beneficial to understand EC from a more holistic approach. Other limitations are that connections and foundations are not considered in this research.

Chapter 5

Impacts of Fire Design on Mass Timber Floors

While the previous chapter focused on structural aspects of parametric mass timber design, this chapter includes two journal papers (currently under review) which look more closely at prescriptive fire design and embodied carbon (EC) for mass timber floors. The first, “Prescriptive Fire Design Provisions’ Impacts on Embodied Carbon for Mass Timber and Hybrid Mass Timber Floors,” is written for an academic audience and includes detailed discussion of the research methodology. This paper is under review with the Journal of Architectural Engineering. It includes results that look at a variety of general trends related to EC, vibration control, material contributions, and more. The timber material EC assumptions for carbon storage take the most conservative approach currently considered for timber, and assume that biogenic carbon is net zero, such that the EC value does not include any carbon storage for A1-A3 boundaries.

While this first paper lays the foundation for more floor systems research, it is the goal of this PhD research to present findings applicable to industry. The second paper, “The Impact of Prescriptive Fire Design Provisions on Embodied Carbon for IBC Type IV Construction,” was written for a practitioner audience. This paper is under review with the Practice Periodical on Structural Design and Construction. Key differences include more time spent summarizing mass timber buildings in the 2021 IBC for easy reference, more concise methodology discussion, and results which are presented in self-contained sections for each mass timber construction types, to be accessible as needed. Further, timber EC values assume some carbon storage based on the AWC’s approach to EPDs using the EPA WARM model with 100% landfilling at end of life, and based on the availability of responsible timber in the U.S. Finally, a design example is added to this paper to demonstrate the applicability of the design guidance resulting from this research.

5.1 Prescriptive Fire Design Provisions' Impacts on Embodied Carbon for Mass Timber and Hybrid Mass Timber Floors

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5.1.1 Abstract

Structural mass timber is being used more often in buildings over the last five years given its potential to be a sustainable alternative. However, concerns still exist around the fire safety of mass timber structures, and current mass timber building designers must consider a variety of fire protection strategies, including but not limited to noncombustible protection and design for sacrificial char thickness. This research focuses on better understanding how prescriptive code fire protection strategies affect the sustainability goals which have partially driven mass timber use. This paper studies how decisions during early design can reduce Embodied Carbon (EC), the initial energy use of a structure's construction. Five structural floor system types were modeled parametrically for various levels of fire protection. System types included timber-concrete composite, steel-hybrid, and all-timber. The resulting EC data analysis shows that all-timber systems perform the best for EC when the fully protected option is used at shorter spans, when the combined approach option is used at mid-range spans, and when the fully exposed timber option is used at longer spans. Across all studied systems, the shallowest possible depth occurred for the 10-ft. (3.05 m) spanning steel-hybrid systems at 11.5 inches (292 mm) deep for the fully protected

system, and the lowest possible EC was 10.5 lbs. CO₂ eq/SF (51.3 kg CO₂ eq/m²) for the fully protected 10-ft. (3.05 m) all-timber system.

Keywords

Mass timber, hybrid mass timber, embodied carbon, prescriptive fire design, parametric model, CLT, Glulam

5.1.2 Introduction

The U.S. Energy Information Administration, an agency of the U.S. Department of Energy, reports that as of April 2021, the building sector makes up 40 percent of energy use in the United States.[47], [48] Further, the embodied carbon (EC) of buildings, or the energy used to extract and manufacturer building components, is expected to account for 33 percent of global emissions from 2020 to 2050 for new buildings constructed in 2020.[5] as depicted in Figure 5-1. Therefore, improvements made to the EC of newly constructed buildings has the potential to reduce overall energy emissions.

In the U.S., mass timber is one structural building material that has been shown to use less EC as compared to concrete and steel [6], with Cross Laminated Timber (CLT), Concrete, and Steel having an estimated EC of 11.4, 19.5, and 524.5 pounds of equivalent carbon dioxide emissions per cubic foot (lbs CO₂ eq./ft³) of material, respectively [61] (182.6, 312.4, and 8401.7 kgs CO₂ eq./m³). Although it can be challenging to directly compare materials based on these numbers due to differences in material properties, research has shown that substituting concrete and steel either partially or fully with mass timber can reduce the EC of a building's structure.[7] For this and other reasons, mass timber is becoming a more widely-used structural material choice.[3] Mass timber has the potential to positively affect what's known as the triple bottom line; environment, society,

and the economy.[45] The sustainability benefits were mentioned before, however, mass timber contributes to biophilia, which improves occupant wellness[229], and has the potential to revitalized local economies that once relied on forestry.[46]

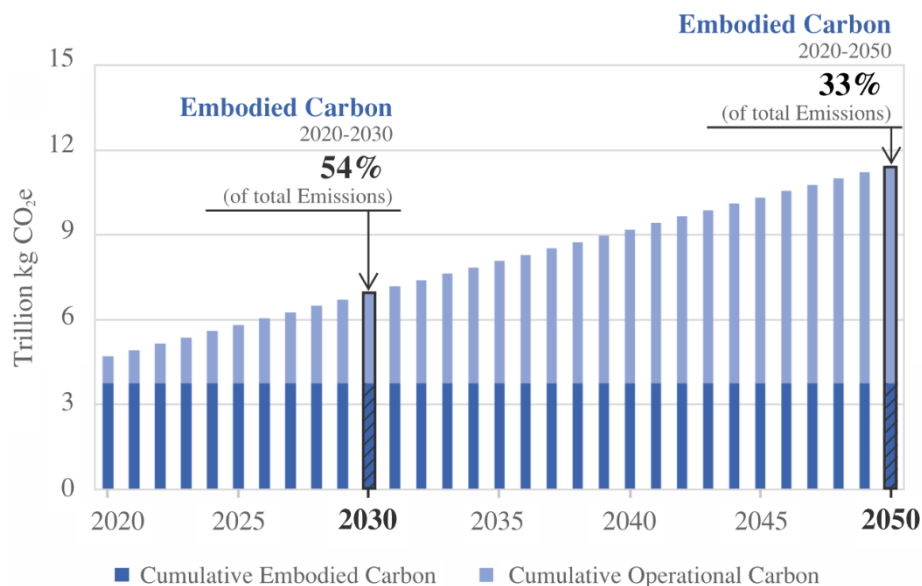


Figure 5-1: Total cumulative carbon emissions from 2020 to 2050 of global 2020 new construction. Figure adapted from Architecture 2030's plot [5] based on data from the 2017 UN Environment Global Status Report [51] and the 2017 EIA International Energy Outlook [52]; 1 Trillion kg CO₂e = 1.1 billion tons CO₂e

A key interest in the use of mass timber is for the ability to expose some of the structure to the interior aesthetically[3], where permitted by code[34]. When accounted for properly in design, this can be implemented safely due to the ability of mass timber to maintain some strength through the formation of a protective char layer on the exposed timber member during a fire event.[105] However some concerns, both perceived and technical, remain for the applications of exposed timber.[30], [143] Additionally, while mass timber may be selected for both its sustainability and aesthetic benefits, no literature at the time of this review has been found to include an analysis of how fire performance design options affect a design's embodied carbon in a way that will help designers determine if mass timber is worth pursuing or not at the start of design, or whether sustainability goals can be met. This paper will first review the existing literature and building

codes most relevant to this topic. Following this is a discussion of the modelling methodology and results for all studied floor systems. Finally, the key findings are summarized in a conclusion.

5.1.3 Literature and Code Review

This section includes a discussion of the topics that are most relevant to this research, including an overview of fire safety in mass timber structures, a discussion of current design knowledge and tools for mass timber projects, and a summary of the building code sections that are applicable to this research.

5.1.3.1 Fire Safety

Fire safety design has been widely studied for wood used in construction.[139], [143], [241]–[243] Fire design can be carried out using prescriptive- or performance-based design (PBD) methodologies, where prescriptive codes dictate specific design requirements, while PBD sets design performance requirements for which possible designs are evaluated.[205], [244], [245] Prescriptive and PBD methodologies are both discussed in this section; however, the focus of this research is on prescriptive code provisions. Further, both passive and active methods of fire prevention exist for mass timber construction[138]; however, this section will focus on the requirements and knowledge surrounding passive methods for the structural elements, which are unique to mass timber. To address concerns of contributions to fuel load and smoke production, several passive fire protection strategies are available, the main ones being the char method and the use of noncombustible protection, specifically gypsum board, which is installed directly onto mass timber elements to protect them from fire.[139] Both the char method and noncombustible

protection may be used individually or in combination, with timber and gypsum board contributing a portion of the total fire resistance.[34], [140]

The char method is based on unique properties resulting from the large sizes of mass timber as compared to light-framed timber and dimensional lumber. When burned, mass timber experiences a charring effect, by which the large mass of wood allows the formation of a protective char layer at the exterior of the element exposed to fire. Therefore, mass timber products are able to achieve some level of fire resistance ratings using a strategy which increases the size of a structural element to include a sacrificial layer or layers to charring.[105] Further, while mass timber elements sometimes incorporate lower quality lumber grades at the inner laminations to reduce cost and weight, stronger grades may be required where inner laminations are expected to perform as a main outer tension layer during fire design.[141] See Figure 5-2 for an example of how this strategy may be implemented for a CLT panel.

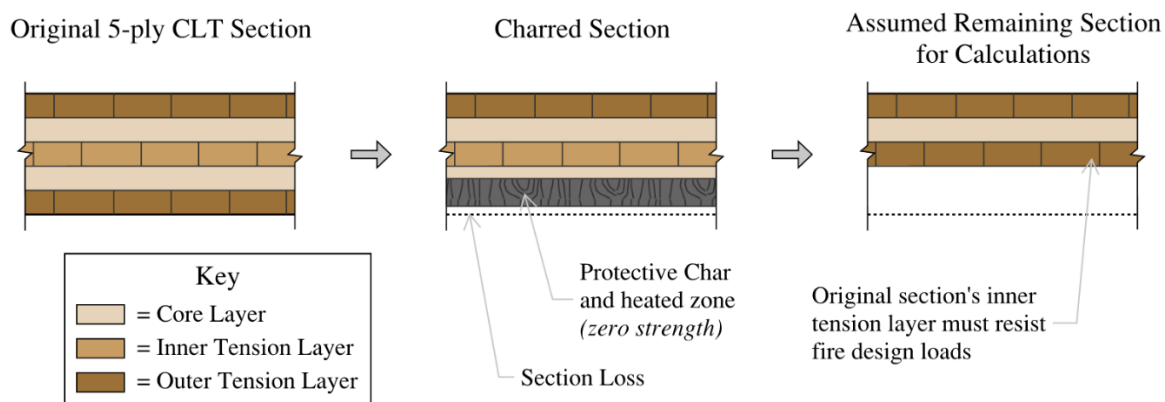


Figure 5-2: Example of charring process and remaining section for use in calculations for a sample 5-ply panel. (Figure based on The CLT Handbook (2019 Canadian Edition) and The 2018 Fire Design Specification for Wood Construction.[105], [141])

The use of noncombustible protection, typically gypsum board, is permitted to provide a fire resistance rating (FRR) based on the number of layers and FRR of the individual layers. In a

fully protected strategy, the intent is that the gypsum board provides the full required fire rating, and therefore multiple layers of drywall may be required depending on the required FRR.

The National Design Specification for Wood Construction (NDS) includes a prescriptive calculation-based method, which estimates the char depth during a given duration based on the required fire performance rating. The remaining strength and stiffness of a structural member is then determined by assuming the char zone contributes nothing, leaving only a smaller, residual cross section. The NDS additionally recommends a conservative approach in CLT design to simplify calculations, in which the cross section after char includes only the section starting from the first fully remaining tension lamination and moving upward, as previously depicted in Figure 5-2. The NDS-defined model may currently be used to calculate ratings up to two hours, but requires further testing and validation for longer periods of time.[139], [140]

Alternatives to the NDS calculation-based method or even in conjunction, structural performance testing and advanced design procedures such as performance-based design (PBD) are possible. Testing is typically based on the following three criteria: 1) the ability of a test assembly to support the required loads for the entirety of the desired fire resistance rating, 2) the ability to prevent smoke and gasses from crossing to a space adjacent to that in which the fire occurs, and 3) the ability of the assembly to insulate the non-fire-exposed side from excessive temperature increases [139]. Testing has generally found predictable and consistent charring rates in mass timber products [143]. Other fire safety concerns currently under research in the field include the following:

- Contribution to fuel load within a space: Testing has shown that leaving CLT and other mass timber products exposed results in higher rates of fire growth by increasing the fuel load; however, the highest observed temperature was not significantly affected by the presence of exposed timber. If delamination occurred, test fires burned much longer than typical after the fuel provided by the room contents was expended.[143], [144]

- System-level performance: The effect of fire performance on a completed structural system and building is not as well understood. Much of the testing is for single assemblies and components that are not part of a larger framing system.[143]
- Performance of adhesives: If delamination or fall-off of the bottom layer of CLT occurs due to inadequate performance of adhesives, newly exposed timber will begin the charring process again and contribute to longer fires.[143]
- Self-extinguishment: Testing in more limited settings show CLT can self-extinguish; however, further testing based on natural and long-duration fires is still needed.[144]

One approach to address fire safety concerns in design is PBD, which is a design methodology that involves the evaluation of design options by a Fire Protection Engineer (FPE) for fire and life safety, specifically to ensure that sufficient occupant egress times are provided.[245] PBD generally involves the following three steps: 1) the defining of fire performance criteria and potential designs to meet those criteria, 2) the evaluation of potential designs by the FPE for scenarios such as fire spread and occupant evacuation, and 3) the selection of a final design out of the qualified design options.[205] While PBD is a method that allows greater design flexibility by acknowledging that multiple approaches may exist to design a building for fire safety,[244] many challenges remain as summarized below, and PBD-based building codes are therefore not widely used in the US[205]:

- Guidelines for PBD remain generic in current codes, and therefore much of the engineering judgement is conducted by the FPE on a given project. As a result, consistent safety standards are difficult to apply even to similar project types across different locations.[205], [244], [245]
- The use of computational fluid dynamics (CFD) software is still relatively recent within the last 15 years,[245] and limitations of the software remain which can make it challenging for engineers to learn and properly incorporate into the design process.[205]
- There can be greater technical challenges that make PBD much more difficult than following prescriptive code requirements, and therefore more education is required for designers and FPEs.[244]

- Authorities having jurisdiction (AHJ's) are often less accepting of projects using PBD because of the greater liability and risk associated with those projects. The more a project deviates from prescriptive requirements, the more critical an AHJ may be of the design.[205]

A key takeaway from this discussion of fire performance is that while technical challenges exist, mass timber buildings can be safely designed to feature exposed structural elements. Depending on the chosen fire design strategy, design for fire performance can potentially control the final structural element sizing. This research looks towards the more prescriptive code provisions as a first step given that more designers are comfortable and knowledgeable of these provisions over advanced PBD methodologies.

5.1.3.2 Knowledge Gaps in Design

Although there are gaps in technical knowledge as discussed in the introduction of this paper, the work in this paper focuses on filling in gaps related to the knowledge available to designers to help them make decisions during early design. Mass timber design guidance, although developing rapidly, is still limited. Although a variety of structural design software programs and plugins are available, the existing software does not easily take into consideration the unique serviceability requirements that often control the design of mass timber structures. Table 2-3 in Chapter 2, section 2.1.6 provides a summary of the main structural software programs for mass timber design and their capabilities and limitations based on their available website descriptions.

Further, manufacturers' published sizing charts typically default to a single fire performance strategy; that of fully protected with noncombustible protection. Guides that do provide information about different fire performance options can be unclear, and do not provide clear comparisons between the different options, nor do they clearly explain how choices can affect

embodied carbon. Carbon tools are available that either calculate or estimate embodied carbon for whole buildings, building assemblies, or products and components, as summarized in Table 2-12 in Chapter 2, section 2.1.8; however, these tools tend to be designed for studying individual products, and do not provide general design guidance to assist with decision-making. At the time of this literature review, no resource has compiled EC data in a comprehensive way for different fire performance options for a range of floor system designs, such that designers could use this information to guide early design decisions.

5.1.3.3 Mass Timber in the Building Code

The 2021 International Building Code (IBC) defines mass timber structural elements as those belonging to Type IV construction which meet the minimum dimensions as shown in Figure 5-3 and notes that mass timber typically consists of solid, built-up, panelized, or engineered wood products.[34] Type IV construction may also include noncombustible elements in addition to the mass timber. Interior and exterior load-bearing and non-load-bearing walls in Type IV construction are required to be constructed of mass timber or noncombustible materials.[34] For residential R-2 occupancy, the focus of this research, Figure 5-4 summarizes the code-allowed building heights and areas for Type IV construction. The residential R-2 occupancy includes buildings with more than two dwelling units that tend to have permanent occupants, as opposed to the R-1 occupancy for transient occupants, and no special care or living arrangements as described in the R-3 and R-4 occupancies.[34] This occupancy was selected as the focus of this research because many larger mass timber projects built in recent years are apartments, student housing, or mixed used buildings that include residential occupancies.[3] The IBC requires specific Fire Resistance Ratings (FRR) depending on the construction type and structural or non-structural element type, as summarized in

Figure 5-5. For mass timber, or Type IV, construction, the FRR rating is permitted to come from the mass timber, its noncombustible protection, or a combination of both.[34]

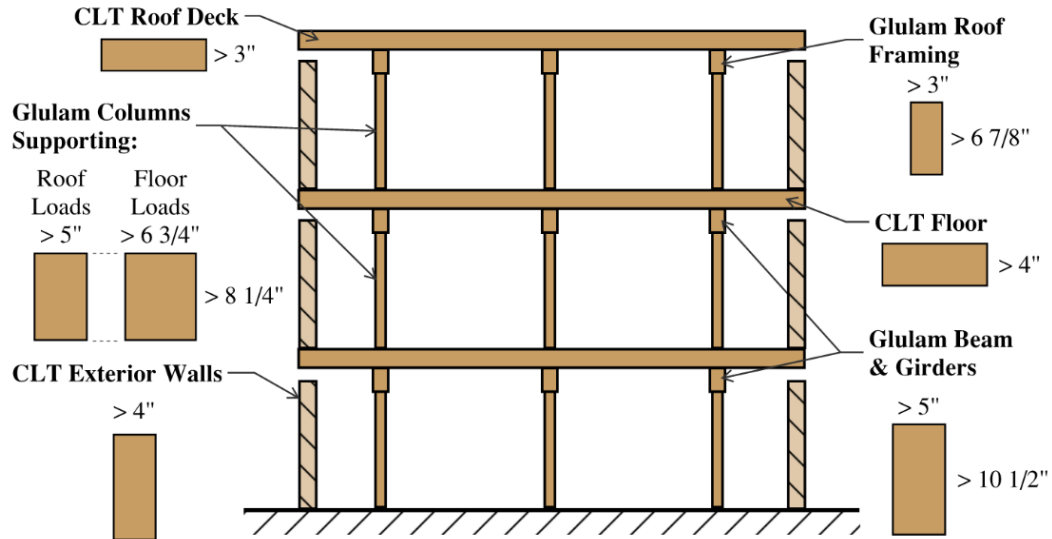


Figure 5-3: Minimum element sizes for CLT and Glulam mass timber (Dimensions are from the 2021 IBC.[34]; 1 inch = 25.4 mm)

Representative Mass Timber Building Sizes, Residential Occupancy
(R-1, R-2, NFPA-13 Sprinklered, W=>30', 100% open space)

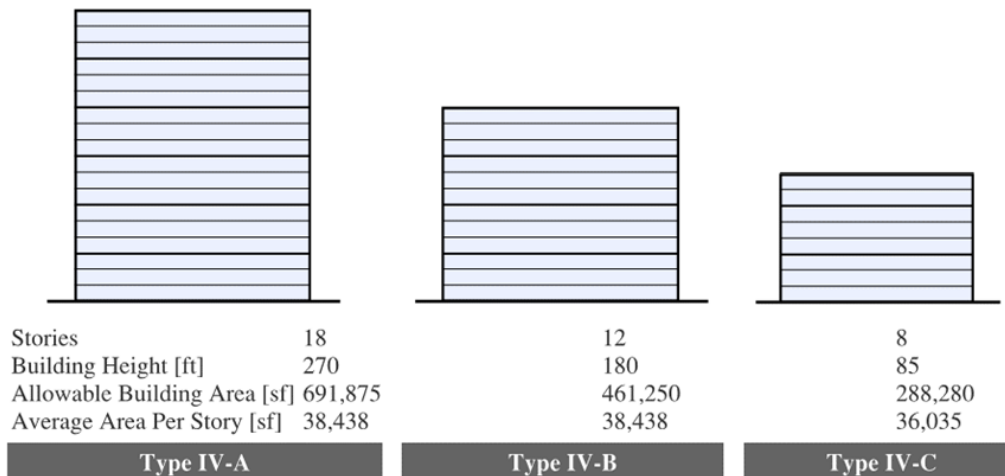


Figure 5-4: New mass timber building categories appearing in the 2021 IBC (Figure adapted from Breneman et al. (2019)[1] and based on data from the 2021 IBC[34]; 1 ft = 0.305 m; 1 ft² = 0.093 m²)

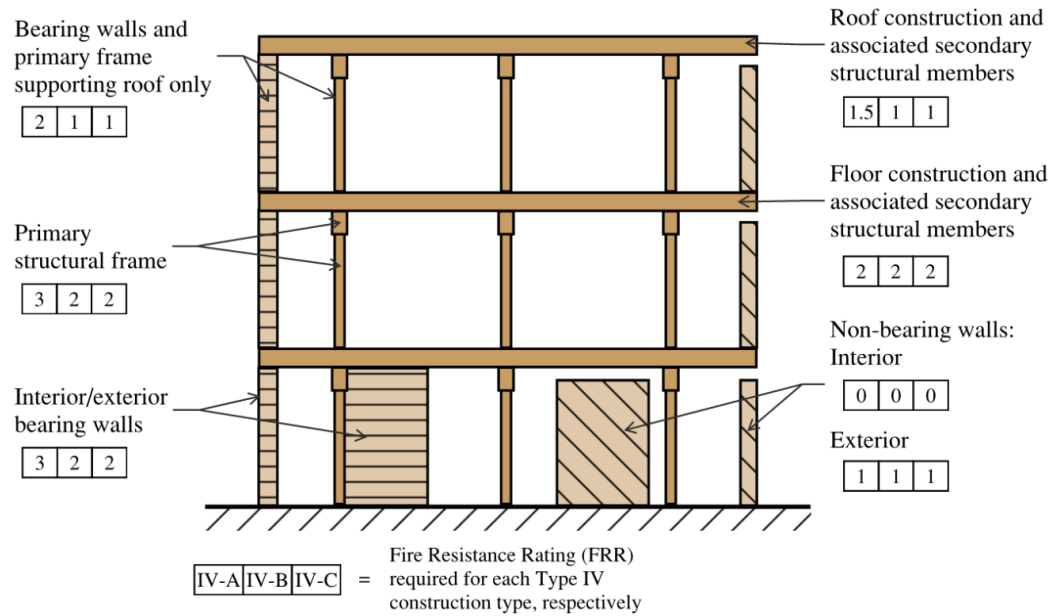


Figure 5-5: Fire resistance ratings for Type IV construction (Based on Table 601 from the 2021 IBC [34])

This section presented a summary of key aspects of mass timber in the building code, particularly for residential construction, the focus of this research, to provide context for this paper. There are resources within the literature that more thoroughly discuss mass timber in the building code, such as “Tall Wood Buildings in the 2021 IBC: Up to 18 Stories of Mass Timber,” published by WoodWorks.[1]

5.1.4 Research Methodology

For this research, mass timber floor systems were studied using a parametric evaluation approach based on design space exploration (DSE). DSE is a framework that involves mapping the designs in a design space to performance metrics in an objective space. The design space is the collection of designs resulting from changing variables in a parametric model, and the objective space is the corresponding set of performance objective metrics assigned to each design through simulation or calculation.[86], [179], [183] Parametric design and analysis is increasingly being used in architecture as a way for designers to explore a range of designs and possibilities. When

parametric design is coupled with DSE, this combination gives designers greater flexibility during early design as compared to traditional design methods by being able to look at many sets of solutions.[179]

This research uses DSE concepts coupled with parametric analysis software to evaluate the performance of mass timber floor systems over a range of designs possibilities. This approach is similar to the methods used by Jelusic and Kravanja (2017), Mayencourt and Mueller (2019), and Hens et al. (2020).[86], [181], [182] Multiple floor system types were modeled for a range of bay lengths, different bay aspect ratios, different numbers of infill beams, varying sustainable timber sourcing assumptions, and different fire design configurations. The inclusion of more variables in parametric modeling can quickly result in an overwhelming amount of data which is difficult to clearly analyze; therefore to limit the number of variables included in the analysis, this paper focuses only on designs with bay aspect ratios equal to 1, and for only 1 infill beam where infill beams are included. The modeled floor systems are shown in Figure 5-6. Table 5-1 further describes the systems depicted in Figure 5-6. Hybrid options are included in this research because they present an opportunity to introduce mass timber in projects with constraints that would prevent the selection of a fully-mass timber system. The following sections further describe the various aspects of the methodology in more detail.

Because of the narrow focus of this research to understand prescriptive fire design, there are limitations inherent in the research scope. The two major items omitted were the connection of members and the foundations of the project. Connections are neglected in the model, and further work will include the analysis of how significantly connections contribute to the embodied carbon of a floor system and building. Connections have not been included at this stage because the focus of this work is on an early-stage design level of detail. As noted in Table 5-3, pinned connections are assumed in the model to allow for theoretically simpler connections which are less likely to have a large contribution to floor system EC as compared to fixed connections. Foundations are

also neglected within this paper's scope as the focus is on how varying floor system designs can affect the embodied carbon of the floor system. Concrete elements such as foundations and parking garages will be studied further in future work to understand their impact on a full building design. This research also focuses on gravity loads, and does not consider whether a floor system needs to carry any diaphragm loads or action. This is a topic for future study to determine how significantly diaphragm design affects timber element sizing within a floor system. Further, floor system designs represent just one option that can meet minimum acoustic code requirements in the IBC with the use of an acoustical mat product between the CLT and topping. Note that the acoustical mat product is neglected in the EC calculations in this research. Other acoustic assembly options exist, and some projects may require improved acoustic performance over code minimum. The study of acoustic assemblies and varying acoustic performance options is planned for future work, but is out of the scope of this research.

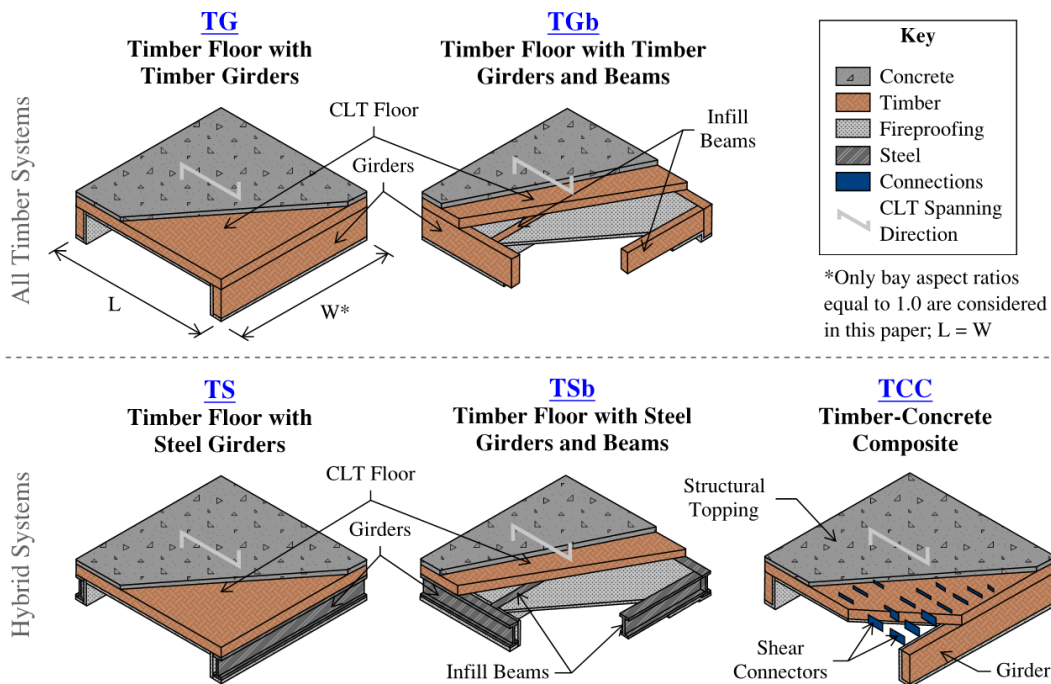


Figure 5-6: Studied floor systems; Not drawn to scale (N.T.S.); Note that only isolated bays are shown for clarity; however, each system is modeled as a central bay surrounded by adjacent equal bays.

Table 5-1: Summary description of studied floor systems

System Abbr.	System Name	System Components
<i>TG</i>	Timber Floor with Timber Girders	• CLT floor panels span between girders located at each end of the bay • Glulam girders span the bay width • Non-structural concrete topping is provided for acoustic performance and to control walking-induced vibrations • If non-combustible protection is used, drywall is installed directly against the underside of the CLT panels and wraps the girders
<i>TGb</i>	Timber Floor with Timber Girders and Beams	• CLT floor panels span between infill beams located at each end of the bay with an additional beam located in the center of the bay • Glulam infill beams span between girders located at each end of the bay • Glulam girders span the bay width • Non-structural concrete topping is provided for acoustic performance and to control walking-induced vibrations • If non-combustible protection is used, drywall is installed directly against the underside of the CLT panels and wraps the girders and beams
<i>TS</i>	Timber Floor with Steel Girders	• CLT floor panels span between girders located at each end of the bay • Steel W-shape girders span the bay width • Connection of CLT to steel girders is non-composite • Non-structural concrete topping is provided for acoustic performance and to control walking-induced vibrations • If non-combustible protection is used, drywall is installed directly against the underside of the CLT panels and as a box-out around the girders
<i>TSb</i>	Timber Floor with Steel Girders and Beams	• CLT floor panels span between infill beams located at each end of the bay with an additional beam located in the center of the bay • Steel W-shape infill beams span between girders located at each end of the bay • Steel W-shape girders span the bay width • Connection of CLT to steel girders and beams is non-composite • Non-structural concrete topping is provided for acoustic performance and to control walking-induced vibrations • If non-combustible protection is used, drywall is installed directly against the underside of the CLT panels and as a box-out around the girders and beams
<i>TCC</i>	Timber-Concrete Composite Floor with Timber Girders	• CLT floor panels span between girders located at each end of the bay • Glulam girders span the bay width • A concrete topping is provided for acoustic performance and to control walking-induced vibrations • The concrete topping is connected to the CLT floor panels to act compositely through the use of steel shear connectors • If non-combustible protection is used, drywall is installed directly against the underside of the CLT panels and wraps the girders

5.1.4.1 Parametric Modeling

The parametric model generates a variety of floor system designs by changing variables in a systematic way to capture changes. For this project, these included: bay length, fire design strategy, percent of sustainably-sourced timber, and system type. The range of the variables are summarized in Table 5-2. Note that the fire design strategies make use of current accepted equations and design practices set out in the 2021 IBC, 2018 NDS, and 2021 FDS.[34], [140], [141] Additionally, a constant 2-hour FRR was used in all designs to limit the number of variables and because this is a common FRR used in the studied building type. Further, while Type IV-A construction requires a 3-hour rating for primary framing, this type does not allow any exposed timber, and the primary goal of this study is to compare the effects of aesthetic choices on EC (i.e. comparing exposed and protected timber design options). The parametric model is based on an early-stage design level of scope, and more in-depth performance-based design and fire engineering methods are out of the scope of this research. This approach and programmed “code” can be adjusted in the future for further routines.

Table 5-2: Summary of variables and their ranges or options in the parametric model

Variable	Range or Options to Change in Model	Justification
<i>Bay Length</i>	10 to 40 feet, in 1-foot increments (3.05 to 12.2 meters)	Range covers most bay lengths currently used in mass timber residential occupancy projects
<i>Fire Design Configurations to Achieve a 2-hr FRR</i>	• 2 hours from char method • 2 hours from noncombustible protection • Combined: 1 hour from each method	Options cover a range of strategies for a 2-hr FRR, which is the maximum FRR required by Type IV construction where some exposed timber is still permitted.
<i>Percent of Timber that is Sustainably Sourced</i>	0 to 100%, in 25% increments	Options allow for a range of sustainably-sourced timber from best to worst scenarios
<i>System Type</i>	• Timber Floor with Timber Girders (TG) • Timber Floor with Timber Girders and Beams (TGb) • Timber Floor with Steel Girders (TS) • Timber Floor with Steel Girders and Beams (TSb) • Timber-Concrete Composite Floor with Timber Girders (TCC)	Systems were selected to cover a variety of all-timber and hybrid timber options, and were selected in part due to the feasibility of modeling the system parametrically at an early design stage.

The parametric model was constructed using a combination of Grasshopper for Rhino, custom Python components, spreadsheet-based databases, and custom Python post-processing code. The overall modeling and analysis flow chart is depicted in Figure 5-7. While the variable inputs include those summarized in Table 5-2, the models are designed to export data for the performance objectives, which includes floor system geometries, performance, and embodied carbon quantities. Once the results are obtained for these objectives, data analysis is used to study the trends, which is discussed further in the section on DSE Methods.

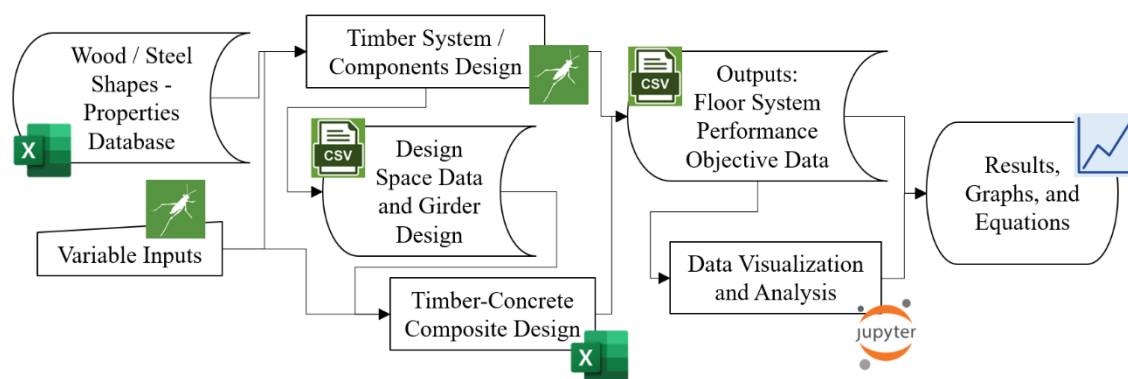


Figure 5-7: Parametric modeling flow chart

5.1.4.2 Structural Design

The structural sizing of each element in the floor system for each design is performed by custom python code that was created by the lead author specifically for this research. The code uses the Allowable Stress Design (ASD) methodology, as this is a commonly used method for the design of wood structures. ASD is also used in the design of the steel framing for consistency and because it is an accepted approach for steel design[236] (AISC 360) even though LRFD is more typical. Both ASD and LRFD are presented in academia as equally acceptable approaches.[246] Additionally, a review of the literature found that while in some cases ASD and LRFD may provide the optimum design for timber and steel, respectively, in general both result in similar designs.[247], [248] Each element is designed for shear, flexure, deflections and creep, walking-

induced vibrations, and fire design per the following codes and standards as applicable: 2018 National Design Spec for Wood Construction[140], 2021 Fire Design Spec for Wood Construction[141], 2013 and 2019 CLT Handbooks[42], [105], AISC Steel Construction Manual[237], and AISC Specification for Structural Steel Buildings[236].

The custom code works by determining the required capacities for an element for a given limit state, and then selecting the shallowest timber element, or the lowest weight steel element. Shallower timber elements are prioritized because very deep sections can become a problem in mass timber structures for architectural coordination, and lower weight steel sections are prioritized to mitigate the higher material EC value of steel. Then the design is rechecked and resized as needed until the requirements of all considered limit states are met. Elements are sized and checked for each limit state in the order listed in the previous paragraph, and are rechecked with new self-weight loads for all design states whenever the element is sized up to meet a specific limit state's criteria. The assumptions used in the model are summarized in Table 5-3. The structural model was verified using sample design hand calculation and five case study projects representing the range of floor systems modeled, and for which structural design information was publicly available.

Table 5-3: Structural design assumptions

Item	Assumed Condition	Additional Comments
<i>Boundary Conditions</i>	Pinned connections	Chosen to be able to initially assume simple connections.
<i>Number of Spans</i>	Maximum permitted based on manufacturing and transportation limits	This allows model to take advantage of additional allowable span like for vibrations in multi-span conditions
<i>Span Length</i>	Equal to bay length	Conservative for timber as NDS defines span length as distance between faces of supports
<i>Bay Location</i>	Center bay	For EC accounting, perimeter girders and beams are considered to be shared with the adjacent bay
<i>Live Load</i>	40 psf residential + 20 psf allowance for partitions = 60 psf (2.87 kN/m ²)	Based on ASCE 7-10 for a residential occupancy, private rooms and corridors serving them. Live load reduction is neglected due to small tributary area in designs.
<i>Superimposed Dead Load</i>	20 psf + 19 psf for a 1.5" nonstructural concrete topping = 39 psf (1.87 kN/m ²)	20 psf (0.96 kN/m ²) is for mechanical, utilities, finishes, and other items
<i>Steel Shapes</i>	W-Shapes only	Shapes obtained from the AISC steel shapes database [204]

Wood Materials

Further, to limit the complexity of the model and the number of variables considered, only a single wood species and grade was included for each timber element. This was done because the species and grade was found to have a significant effect on embodied carbon of the timber elements, complicating the analysis goals for understanding impacts specifically of the prescriptive fire design provisions. Figure 5-8(a) looks at CLT panel product data from a variety of manufacturers, and demonstrates the wide variation in EC per unit area per unit of bending strength, which is affected primarily by the lumber strength, and partially by the panel depth. Figure 5-8(b) provides a visual depiction of the Figure 5-8(a) vertical axis units for reference. Values range from about 0.4 to 3.4 lbs. CO₂ eq / ft-kip*SF (1.4 to 12 kg CO₂ eq / kN-m*m²), and so designers should be aware that wood grade and species selection is important to limiting EC. Designers should also note that the data in Figure 5-8(a) neglects carbon storage, but that the selection of more sustainably-sourced timber will change the relationships currently shown. If the timber exhibits net carbon storage, then the data in Figure 5-8(a) is flipped to favor the thinner, lower strength CLT panels. Further discussion of wood species and the effects of sustainable timber sourcing is out of the scope of this research. Based on the above discussion, a median grade was selected to allow for clearer comparisons of the fire design aspects, which is the focus of this paper. Table 5-4 summarizes the selected wood properties and range of sizes used in the database from which the parametric model selects elements.

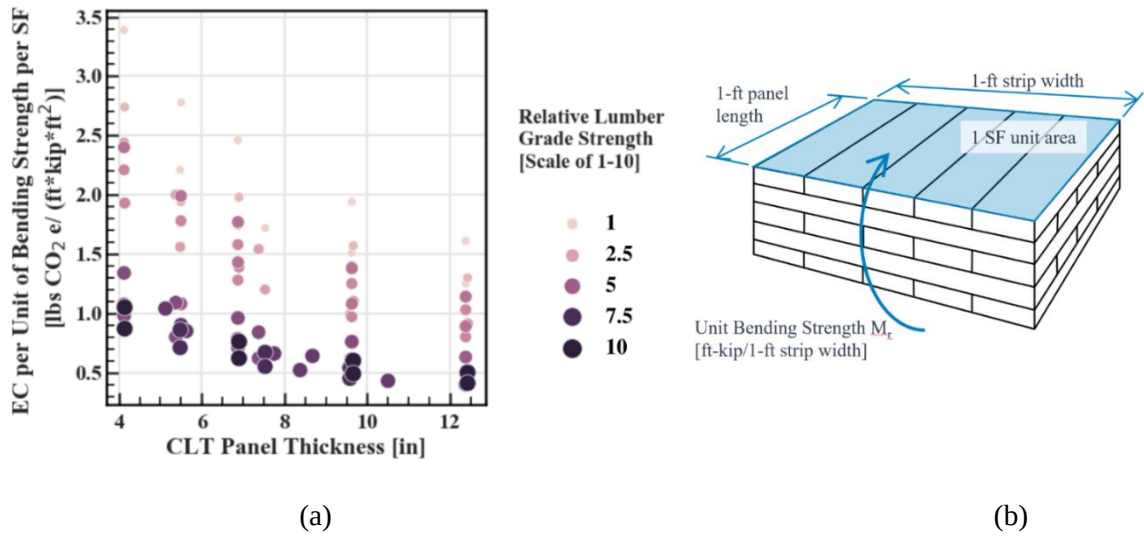


Figure 5-8: **(a)** EC per Unit of Bending Strength per 1 SF panel versus CLT Panel Thickness, colored by ranked relative lumber grade strength, where a rating of 1 represents the weakest grade, and a rating of 10 represents the strongest grade (Data obtained from various manufacturer technical guides[39]–[41], [239]; 1 lb CO₂ eq/(ft-kip·ft²) = 3.6 kg CO₂ eq/(kN·m·m²)) **(b)** Representative example of 1 unit of bending strength for a 1 SF panel. This is the normalized unit for the data shown in Figure 5-8. (1 ft = 0.305 m.; 1 ft² = 0.093 m²; 1 ft-kip = 1.36 kN·m)

Table 5-4: Structural design assumptions for timber components

Item	Assumed Condition	Additional Comments
CLT Panels	Spruce-Pine-Fir and Douglas Fir	Uses Structurlam Grade V2M1.1 as a baseline reference. Panel layup options include 3, 5, 7, and 9 plies, with 1-3/8" (35 mm) plies.
	Density = 26 pcf (1.24 kN/m ²)	<i>Note: Panels with thinner, 5/8" (16 mm), tangential plies were found in initial analysis to be inefficient for the char design methods used in the model, and are therefore not considered in this research.</i>
Glulam Framing	Douglas Fir Density = 35 pcf (1.68 kN/m ²)	Uses Structurlam Grade Series 24F-V8 as a baseline reference. Size options include those ranging from 5.125" (130 mm) wide x 11.75" (298 mm) deep to 20" (508 mm) wide x 56.75" (1441 mm) deep.

5.1.4.3 Fire Design

As previously discussed in the introduction, mass timber can be designed to meet a required FRR through prescriptive techniques such as the use of the char method, noncombustible protection, or a combination of both. All three of these techniques are included in the parametric model as three different fire design configurations. Where noncombustible protection is fully or partially providing the FRR, it is assumed that 2 layers of ½” (12.7 mm) Type X drywall can provide 60 minutes of protection and 3 layers of 5/8” (15.9 mm) Type X drywall can provide 120 minutes of protection.[139] The required drywall quantity for a design was determined based on the hours of provided protection and the surface area of the floor system underside, accounting for any girders and beams. Based on typical densities for drywall and the above-noted protection times, it was determined that 1- and 2-hours of drywall protection equate to 3.33 and 6.25 pounds respectively of drywall material per square foot (16.3 and 30.5 kg/m²) of structural system surface area to be protected, including that of girders and beams.

For the steel framing, fire protection is provided by intumescent paint at conditions where the adjacent timber is exposed, and by one or more layers of drywall boxed around the steel where the adjacent timber has at least 1 hour of drywall protection. Based on publicly available product data, it was determined that intumescent paint applied at 0.55 lbs. per square foot (2.7 kg/m²) of steel surface area provides 2 hours of protection. For both cases where noncombustible protection is provided, whether drywall or intumescent paint, the material quantities are incorporated into the calculation of total estimated system EC. Where mass timber contributes to FRR through incorporation of char method, the equations from the 2021 Fire Design Specification for Wood Construction (FDS)[141] are used to determine char depth and strength under fire conditions. The FDS is intended to be a supplemental standard to the 2018 National Design Specification for Wood

Construction (NDS)[140] and therefore uses the same equations, but elaborates on discussion and application of the equations.

The calculated contribution of wood to FRR using the 2018 NDS and 2021 FDS calculation methods is not permitted to exceed 2 hours[140] due to the limitations of available test data for mass timber assemblies at the time of those publications.[42] Some of the key equations are summarized below; however, the full 2021 FDS should be referred to during any design that uses this method. Further, the American Wood Council (AWC), publishers of the FDS and NDS, have published “Technical Report No. 10: Calculating the Fire Resistance of Exposed Wood Members,” which provides further guidance for the applicability of design procedures.[238] Equation 1 calculates the char rate to be used based on exposure time:

$$\beta_t t^{0.813} = \beta_n t \quad (\text{at } t = 1 \text{ hr}) \quad (5-1) \text{ [FDS Eq. 3.2-1]}$$

Where:

β_t = the non-linear char rate, based on the required exposure time, t , in hours

β_n = the nominal char rate, based on a 1-hour exposure time

For glued laminated timber, Equation 2 calculates the char depth to be used at each exposed face:

$$a_{char} = \beta_t t^{0.813} \quad (5-2) \text{ [FDS Eq. 3.2-2]}$$

For cross laminated timber with equal lamination thickness throughout the section, Equation 3 calculates the char depth using the values from Equations 4 and 5:

$$a_{char} = n_{lam} * h_{lam} + \beta_t (t - (n_{lam} * t_{gl}))^{0.813} \quad (5-3) \text{ [FDS Eq. 3.2-5b]}$$

Where:

$$t_{gl} = \left(\frac{h_{lam}}{\beta_t} \right)^{1.23} \quad (5-4) \text{ [FDS Eq. 3.2-6]}$$

$$n_{lam} = \frac{t}{t_{gl}} \quad (5-5) \text{ [FDS Eq. 3.2-7]}$$

The fire design is then performed by applying the appropriate adjustment factors to the reduced cross-sectional dimensions after the effective char depth is accounted for. Reduced cross-sectional dimensions are based on the effective char for each exposed surface, per Equation 6. The 20% increase to the char depth is intended to capture both the effects of rounding of a timber element that occurs as the member chars, [19] and the loss of strength in the heated pyrolysis zone immediately interior of the char layer.[140]

$$a_{eff} = 1.2 a_{char} \quad (5-6) \text{ [FDS Eq. 3.2-8]}$$

Checks are performed for both flexure and shear using a Design Stress to Member Strength Factor, K , of 2.85 for flexure and 2.75 for shear. Further, in the design of CLT, the FDS allows a designer to use the properties of a CLT panel with a number of laminations not exceeding those fully remaining after the effective char depth is accounted for. The FDS requires that Glulam elements manufactured with different lamination grades throughout be designed such that the expected outer tension layer after char depth is accounted for is of a sufficient grade to meet fire design strength requirements. [26] Figure 5-9 depicts the various options used in the parametric model based on the methods discussed in this section. As shown for the steel framing, where drywall protection is used, it is installed as a box encasing the steel beam. Although spray-on fireproofing and an acoustical drop ceiling may be another option commonly used for steel framing, the box encasement method was selected to maintain a similar aesthetic and drywall EC accounting framework as in the systems with Glulam framing. The steel sections in Figure 5-9 are depicted as the same size across fire design options; however, minor changes in size may occur where CLT panels are sized up for fire design, resulting in higher loads carried by the steel section.

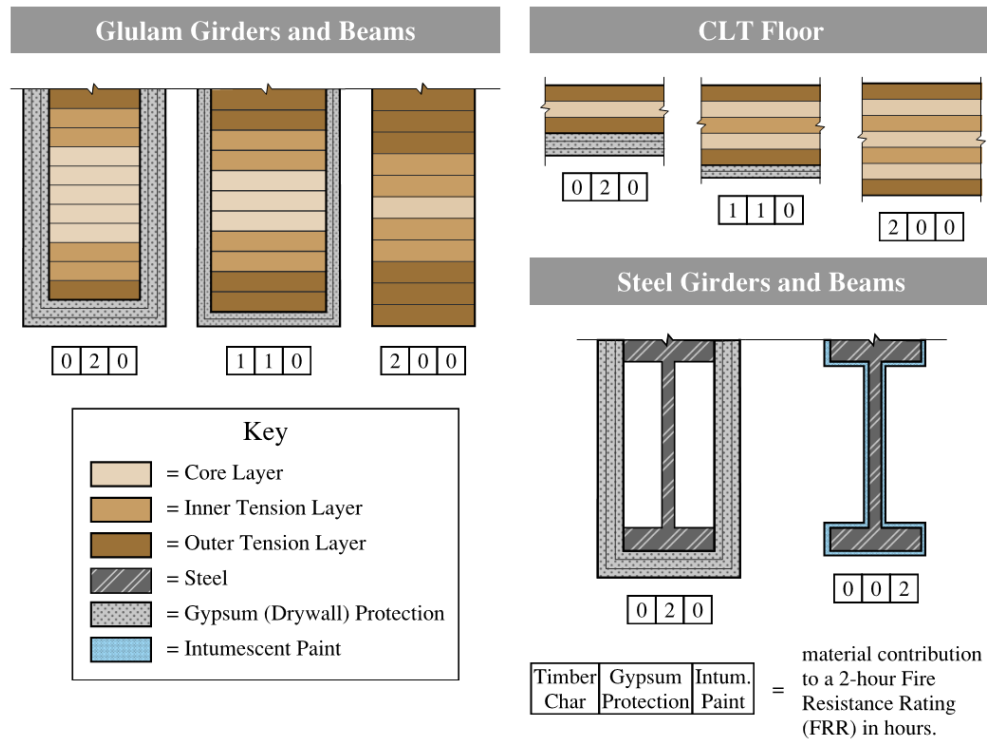


Figure 5-9: Conceptual examples of potential fire design configurations to achieve a 2-hr FRR for Glulam, CLT, and Steel sections. (N.T.S.: Number of laminations are purely conceptual and intended to be representative.) Figure adapted from figures in The CLT Handbook (2019 Canadian Edition) and The 2021 Fire Design Specification for Wood Construction.[105], [141]

5.1.4.4 Embodied Carbon Evaluation

Embodied carbon estimates in this study focus on the structure and any elements which would be significantly affected by the variables in the design space, such as fire design. This includes the floor panel, girders, beams if present, fireproofing, and the non-structural concrete topping. Currently, a rough approximate estimate is provided for columns as bay size and building height will affect column contributions to total embodied carbon. Embodied carbon values for each material in the model are obtained from the publicly available Inventory of Carbon and Energy (ICE) Database, Version V3.0, developed by Craig Jones and Geoffrey Hammond at the University of Bath.[61] This is a meta-database which compiles peer reviewed literature values into a database of embodied carbon for common building materials. Embodied carbon values are provided within

the boundaries of Modules A1 to A3 in the European sustainability standards EN 15978 and EN 15804 in units of kilograms of carbon dioxide equivalent per kilogram of material.[61] This database has some limitations such as limited accuracy and completeness[62]; however, as this database is considered to contain credible, peer-reviewed information[63], values from this database are considered acceptable for use in this research.

Materials which do not appear in the ICE database include the drywall, joint compound, and intumescent paint. For these materials, a combination of industry resources and publicly-available Environmental Product Declarations (EPDs) were used to determine material EC values, as summarized in Table 5-5. For drywall and joint compound, a 12% waste factor is assumed for drywall,[206] but the waste factor for joint compound is likely to be lower, and as such, a 10% waste factor is applied in the model to the total EC takeoff for both drywall and joint compound combined. Table 5-5 provides a summary of the embodied carbon values used from the database; however, the floor systems model is designed such that adjustments can be made for different assumptions, such as timber values including carbon storage for cases where more sustainably sourced timber can be sourced. In this paper, the focus is on timber for which carbon storage is neglected, as carbon storage can only be claimed for sustainably sourced timber[61], which is not always available. Further, current industry practice in EPDs for mass timber structural products is to neglect the carbon storage portion of EC by declaring biogenic carbon to be zero for the full life cycle, even when the EPD covers only modules A1 to A3. Finally, best practices in LCA dictate that if carbon storage is included, then End Of Life (EOL) impacts must also be included[61]. The focus of this research is on the cradle to factory-gate boundaries because these are the boundaries for which assumptions can be reasonably made during early design, and therefore EOL is automatically excluded. Because much of a building's EC occurs during its early life, it is reasonable to use the A1 to A3 boundaries to help guide early design decisions. Full LCA work is

recommended at later stages of design to refine designs and project decisions; however, this is out of the scope of this paper.

Table 5-5: Embodied carbon of common structural and building materials
(Values obtained from ICE V3.0[61] unless otherwise noted; 1 lb CO₂ eq/lb = 1 kg CO₂ eq/kg)

Embodied Carbon of Structural Materials (lb CO₂ e/lb)			
Material	EC value	Material Assumptions	Data Source
<i>Timber</i>	<i>CLT</i> 0.437	Carbon storage is neglected	ICE V3.0[61] – Timber, CLT – No Carbon Storage
	<i>Glulam</i> 0.512		ICE V3.0 – Timber, Glulam – No Carbon Storage
	<i>CLT</i> -1.20	Carbon storage is included	ICE V3.0 – Timber, CLT – Including Carbon Storage
	<i>Glulam</i> -0.90		ICE V3.0 – Timber, Glulam – Including Carbon Storage
<i>Reinforced Concrete</i>	0.13	25% Cement replacement with fly ash	ICE V3.0 – RC 32/40 (32/40 MPa)
<i>Steel (section)</i>	1.07	93% Recycled steel content	ICE V3.0 – Steel, Section
<i>Gypsum Board (drywall)</i>	0.28	Type X: a 10% waste factor is applied to the total combined EC takeoff for drywall and joint compound	Industry-wide gypsum board EPD[214]
<i>Joint Compound</i>	1.19	Conventional ready-mixed	Industry-wide joint compound EPD[215]
<i>Intumescent Paint (for steel)</i>	2.31	Solvent-based with 40.7 SF/gallon (1 m ² / liter) coverage to achieve 1 hour of fire protection	“A brief guide to calculating embodied carbon” by the Institution of Structural Engineers[59] Hilti All Weather High Build CFP-SP AWHB intumescent steel fire proofing – product data sheet[216] FlameOFF Fire Barrier Paint – product data sheet [53]

After the floor systems model performs the structural design for each given parametric design, the weights for each material in that design are calculated and multiplied by their embodied carbon factor. Both individual materials and system composition EC are recorded. These estimates are then normalized into a per square foot value by dividing the total EC by designed bay size.

5.1.4.5 Design Space Exploration Methods

As previously discussed in the Parametric Modelling section, this research uses Design Space Exploration (DSE) to study the floor systems data for trends and insights. DSE is an approach that can be used to better understand how design choices affect the performance of a variety of design

configurations.[179] Figure 5-10 shows how designs in the Design Space can be mapped and studied against their corresponding performance metrics in the Objective Space.[183] This method will not result in any predictive modeling capacities, but rather is intended to help understand the performance trends of designs in the design space to be able to better inform decisions making, or even feed information into other analysis tasks such as machine learning.[86], [179]

For this research, due to the relatively small size of the design space and the fast computational time for each design, the entire design space was sampled for all the variables and ranges listed in Table 5-2. The design space includes 2,325 designs, of which this was narrowed down to 1,740 designs that met all the relevant strength and serviceability requirements. Therefore, about 75% of the designs in the design space met the requirements for the early-stage design model. While conservative assumptions were made in the design to control walking-induced vibrations, 1,220 (70%) of the qualified designs were found to require additional vibrations analysis and design refinement in the later stages of design, which is out of the scope of this research.

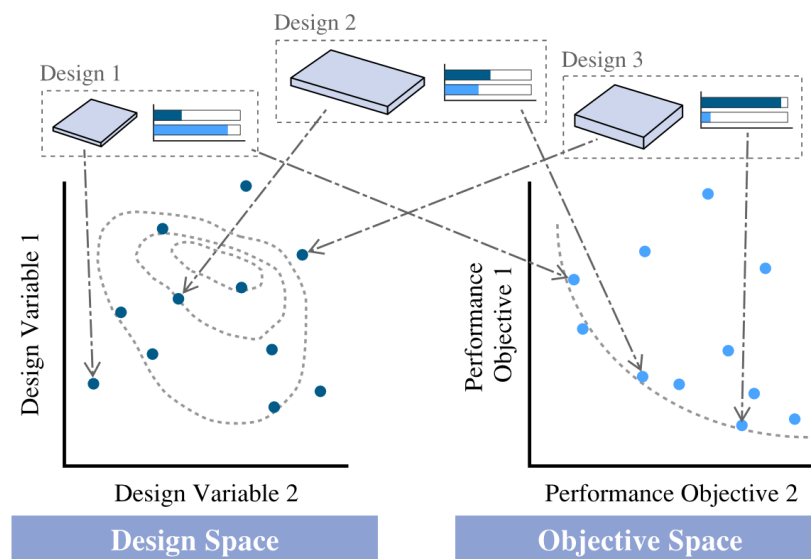


Figure 5-10: Conceptual depiction of design space exploration; designs in the Design Space are mapped to performance metric outcomes in the Objective Space (figure adapted from Brown, 2020[183])

5.1.5 Results and Discussion

Given the methodology and model setup previously described, the simulations were conducted, and data was generated. From here a detailed analysis of the results was undertaken. The analysis of the results found trends and insights that help better understand how these prescriptive fire design provisions affect the design objectives of interest to the structural engineer. Below, each section discusses the observed trends for a particular objective or design aspect. Data results are grouped such that they focus on system depth, total system EC, material and component contributions to EC, and material trade-offs between fire design options. Key terminology is used to reference the three fire design configurations noted in Table 5-2 throughout the results and discussion section. Table 5-6 summarizes the terminology and labeling associated with each configuration. Further, the term “system” refers to one of the five floor structure types from Figure 5-6. The terms “non-carbon-storing” and “carbon-storing” timber in this section refer to timber with positive and negative material EC values, respectively. Based on the material EC data from Table 5-5, CLT and Glulam are carbon-storing when the percentage of sustainably-sourced timber is greater than 26% and 36%, respectively.

Table 5-6: Summary of terminology used to describe fire design configurations

Fire Design Configurations to Achieve a 2-hr FRR	Figures and Tables (labeled based on the timber’s contribution to FRR in hours)	Short-hand label in legends	Simple description in text
<i>2 hours from noncombustible protection</i>	Timber FRR = 0	0	Fully protected option
<i>Combined: 1 hour from each method</i>	Timber FRR = 1	1	Combined approach option
<i>2 hours from char method</i>	Timber FRR = 2	2	Fully exposed option

5.1.5.1 Structural Floor System Depth Trends

First is a discussion of floor system depth and the related results. Figure 5-11 shows the resulting total structural system depths for each fire design configuration, colored based on the floor system type. System depths are based on the structural depth only, and do not include the additional thickness of fireproofing and concrete topping material. The total system depth including all non-structural components would require further coordination in later stages of design. In Figure 5-11(a) for the fully protected option (Timber FRR = 0), at spans 15 ft. (4.57 m) or shorter, all systems are less than 26.2 inches (665 mm) deep. Across all studied systems, the shallowest possible depths occur for the 10-ft. (3.05 m) spanning TS and TSb systems at 11.5 inches (292 mm) deep. Within the 20- to 30-ft. span range (6.09 to 9.14 m), floor system depths vary significantly between systems, from a range of 19.6 to 32.0 inches (498 to 813 mm) at the shallowest for the TSb system to a range of 37.3 to 50.9 inches (947 to 1290 mm) at the deepest for the TCC system. Further, the deepest 50.9-inch TCC system within the 20- to 30-ft. range occurs at its max system span of 27 ft. (8.23 m). The systems with beams (TGb and TSb) were the only systems able to achieve spans longer than 27 ft., reaching the maximum 40-ft. (12.2 m) span length included in this research. In systems without beams (TCC, TG, and TS), the CLT span length limits the maximum span length due to requirements for controlling walking-induced vibrations. At the longest span considered, 40 ft., the TGb system must become very deep to meet all the design requirements, reaching a depth of 61.9 inches (1.57 m). At 40 ft., the TSb system's steel frame mitigates the additional depth required for a long-spanning all-timber system, reaching a depth of 46.7 inches (1.19 m).

Figure 5-11(b) and (c) show results for the combined approach (Timber FRR = 1) and fully exposed (Timber FRR = 2) options, respectively. While general increases to system depth can be seen in the combined approach option plot, the most significant increases to depth occur for the fully exposed option in Figure 5-11(c). The increase in depth in any system with at least 1 hour of

timber char design is a result of the additional sacrificial timber element thickness to meet the char method design requirements. The systems with Glulam framing (TCC, TG, and TGb) experience the greatest increases to depth (up to 43, 42, 52% for each system respectively) because both the floor panel and framing depths must often be increased in char design. In the steel hybrid systems (TS and TSb), the steel sections merely receive a different fire-protective option such that only the floor panel depth is increased (resulting in a maximum total EC increase of 23 and 20%, respectively). The deepest possible design of 66.12 inches (1.68 m) occurs for the TGb system at a 40-foot (12.2 m) span using the fully exposed system.

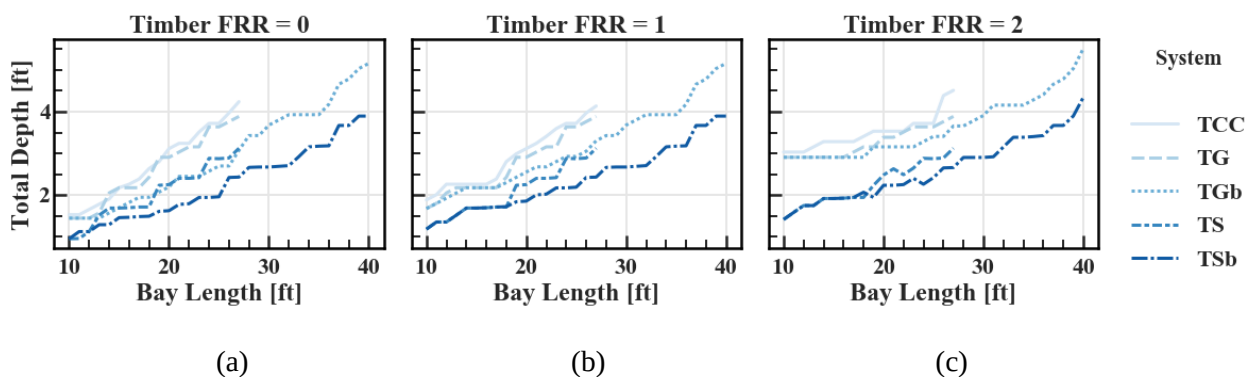


Figure 5-11: Total system depth vs. Bay length for (a) a fully protected option, (b) combined approach option, and (c) a fully exposed option. (Note that system depth is equal to the sum of the CLT thickness and maximum framing depth; 1 m = 3.28 ft)

Not all systems required depth increases to meet fire design requirements. Due to the discrete nature of timber element options, some designs met char requirements with the originally-designed element sizes. Out of the 116 fully exposed option designs with 0% sustainably-sourced timber, 99 required an increase in depth as compared to the fully protected option designs, or 85%. Figure 5-12 shows that the designs which retained the same depth across fire design options included the systems without an infill beam (TCC, TG, and TS) at various spans occurring between 19 to 27 ft. (5.79 to 8.23 m) and systems with an infill beam (TGb and TSb) at spans from 37 to 39 ft. (11.3 to 11.9 m).

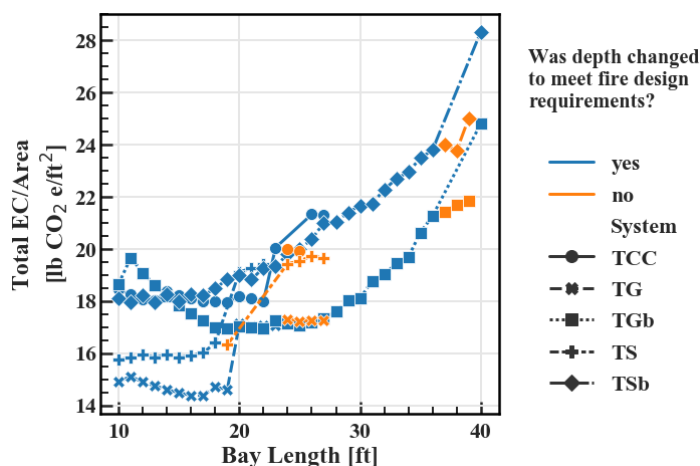


Figure 5-12: Total system EC vs. Bay length for fully exposed option designs, colored by whether or not the depth increased relative to the fully protected option version of the design.
(1 lb CO₂ eq/ft² = 4.88 kg CO₂ eq/m² ; 1 ft = 0.3048 m)

Figure 5-13 shows the same data as in Figure 5-11, but grouped by system then organized (colored) by the fire design configuration. Grouping the data this way provided a means to understand system impacts. This grouping of all fire design configurations for an individual system (Figure 5-13) helps designers compare fire design configurations to each other. In the systems without beams (TCC, TG, and TGb), the depth increases most significantly for the fully exposed option at bay spans below 20 ft. (6.10 m), but less significantly as the bay span increases beyond 20 ft. The selection of fire design configuration has the least impact on depth for the steel hybrid systems (TS and TSb), suggesting greater design flexibility for these systems in meeting different code requirements related to noncombustible fire protection and timber exposure. For example, there is less penalty to system depth in the TS or TSb system if a designer chooses to switch from the fully protected option to the fully exposed option. Based on the results, if the priority is to minimize depth, designers should favor short-spanning steel hybrid systems (TS and TSb) with noncombustible protection.

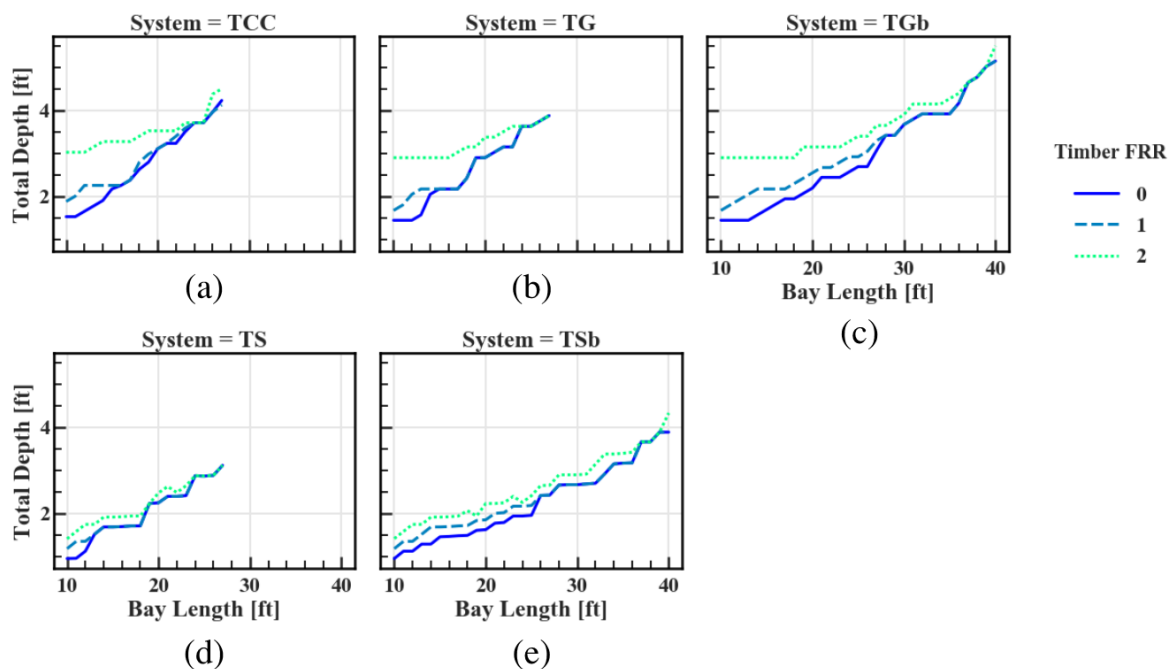


Figure 5-13: Total system depth vs. Bay length for (a) timber-concrete composite floor with timber girders, TCC; (b) timber floor with timber girders, TG; (c) timber floor with timber girders and beams, TGb; (d) timber floor with steel girders, TS; (e) timber floor with steel girders and beams, TSb.

5.1.5.2 Estimated Embodied Carbon Trends

This section presents the results for total system EC, with all values normalized per square foot for easier comparisons. Note that the EC analysis was primarily performed assuming non-carbon-storing timber as previously discussed in the Embodied Carbon section; however, a limited discussion on carbon-storing timber is included to show how the use of more sustainable timber affects the results. Further, while this paper does not provide discussion on uncertainty, it should be noted that there is a level of uncertainty in all values from a combination of the early-stage design approach to modeling, and from EC material data which comes from a variety of sources that may use different assumptions and methodologies.[61] Research is available in the literature which focuses on uncertainty of embodied carbon values for materials, products, and whole building analyses.[230], [249], [250] Therefore, differences between systems and designs may only

be significant when those differences are relatively large, and the results should be understood in that context.

Figure 5-14 shows the overall results for total system EC per square foot for each fire design configuration. In general, EC per square foot increases with bay length, but not necessarily in a linear fashion. Figure 5-14(a) shows that for the fully protected option, all systems can achieve low EC at 15-ft. (4.57 m) spans or less, ranging from 10.5 to 15.8 lbs. CO₂ eq/SF (51.3 to 77.1 kg CO₂ eq/m²) for the 10-ft. (3.05 m) TG and 14-ft. (4.3 m) TS systems, respectively. Beyond 15-ft. spans, the TCC and TS systems become the worst performing systems with the highest EC at a given bay length compared to the other systems. Within the available bay length range (10 to 27 ft. or 3.05 to 8.23 m) for the systems without beams (TCC, TG, and TS), there is a maximum EC of 23.4 lbs. CO₂ eq/SF (114 kg CO₂ eq/m²), which is for the 27-ft. (8.23 m) TCC system. The highest EC for any system and span occurs in the TSb system with 27.8 lbs. CO₂ eq/SF (135 kg CO₂ eq/m²) at the 40-ft. (12.2 m) span, which is 165% greater than the lowest possible EC of 10.5 lbs. CO₂ eq/SF (51.3 kg CO₂ eq/m²) for the 10-ft. (3.05 m) TG system.

Figure 5-14(b) and (c) show results for the combined approach option and fully exposed option, respectively. In Figure 5-14(b), while EC at spans below 14 ft. (4.27 m) tends to increase by selecting the combined approach option over the fully protected option, EC at spans greater than 20 ft. tend to decrease as compared to the fully protected option. Similarly in Figure 5-14(c) for the fully exposed option, EC tends to increase as compared to the fully protected option for shorter spans and decrease for longer spans. For the fully exposed option, the trend lines cover a smaller range in EC as compared to other fire design options, at least for spans below 30 ft. (9.14 m). All systems perform in the range of 14.4 to 20.0 lbs. CO₂ eq/SF (70.3 to 97.6 kg CO₂ eq/m²) for spans up to 25 ft. (7.62 m), and can therefore be considered competitive with each other. Below 20 ft. (6.10 m), the TG system has the lowest EC, while at 20 ft. and above, the TGb system has the lowest EC.

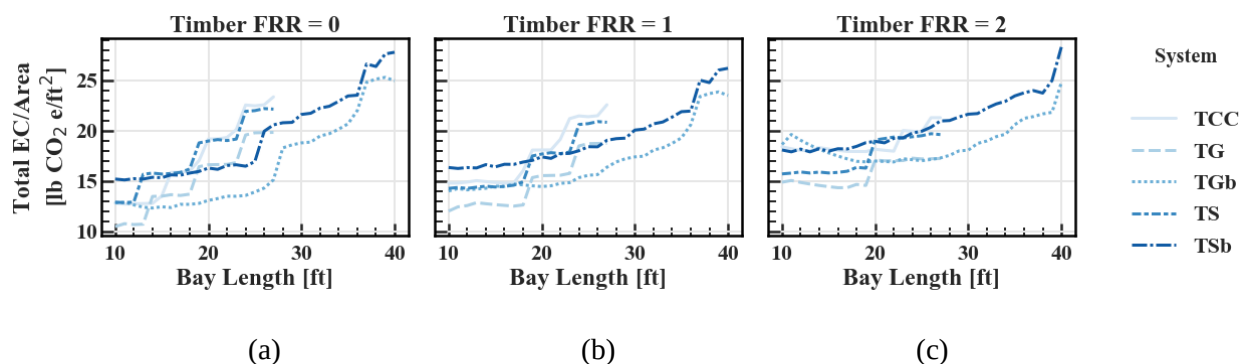


Figure 5-14: Total system embodied carbon per square foot vs. Bay length for (a) a fully protected option, (b) a combined approach option, and (c) a fully exposed option.

Figure 5-15 shows the range of EC possible for each system type with varying levels of sustainably-sourced timber. The data line shown is for 50% sustainably-sourced timber. This shows the importance of knowing what amount of sustainably-sourced timber can be obtained for a project because systems which performed well with 0% sustainable timber often do not perform as well compared to the other systems with 100% sustainable timber and vice versa. This is because non-carbon-storing timber is swapped out with carbon-storing timber, which favors designs with greater amounts of timber, as opposed to non-carbon storing timber which favors the most structurally-efficient designs with the least timber.

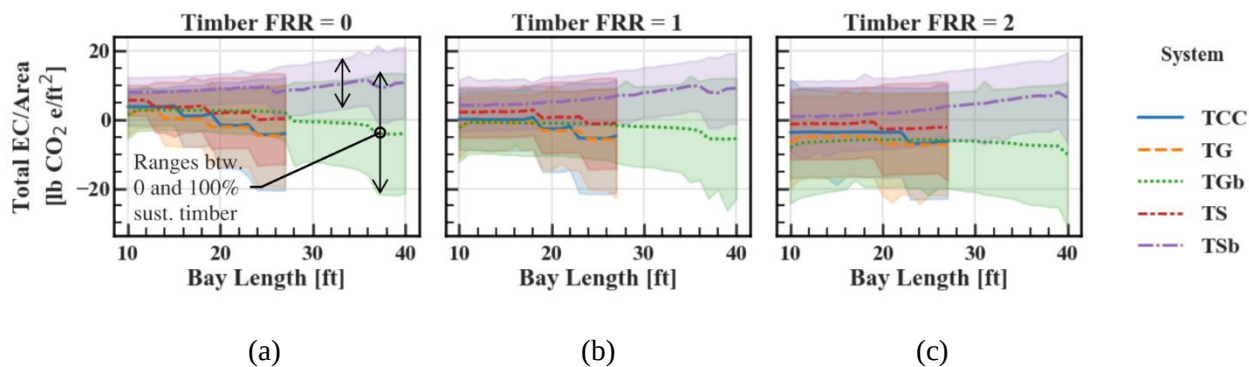


Figure 5-15: Total system embodied carbon per square foot vs. Bay length, shown as a range of values from 0 to 100% sustainably sourced timber for (a) a fully protected option, (b) a combined approach option, and (c) a fully exposed option. (Note that the data lines shown represent the case where 50% of the timber is sustainably sourced.)

As with the discussion of system depth, the results for EC are again repeated, but grouped by system type in Figure 5-16, rather than by fire design strategy as in Figure 5-14. This helps with

system-specific comparisons across the different fire design configurations. The results in Figure 5-16 are again neglecting carbon storage. Trendlines for each system and fire design configuration tend to show stepped behavior, with regular jumps in EC that correspond to increases in CLT panel sizes, as only four discrete options were included in the study, as previously noted in Table 5-4. The jumps in EC tend to be most pronounced and numerous in the systems without beams (TCC, TG, and TS) using the fully protected system. Adding an infill beam helps limit stepping behavior by lowering the CLT span, thus reducing the CLT panel thickness needed. The fully exposed option also reduced stepping behavior as larger CLT panels become required across more of the studied bay spans. Further discussion of the stepped behavior will be provided in the material contributions section of the results and discussion.

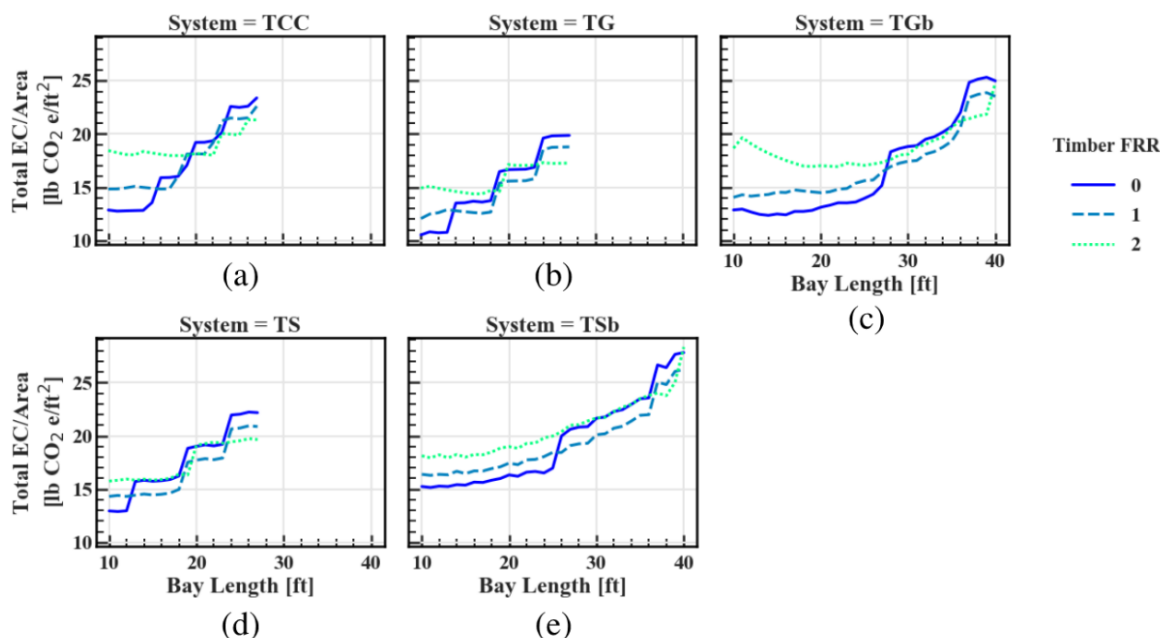


Figure 5-16: Total system embodied carbon per square foot vs. Bay length for (a) timber-concrete composite floor with timber girders, TCC; (b) timber floor with timber girders, TG; (c) timber floor with timber girders and beams, TGb; (d) timber floor with steel girders, TS; (e) timber floor with steel girders and beams, TSb.

In general, all structural system types perform the best for EC with the fully protected option at shorter spans, the combined approach option at mid-range spans, and the fully exposed

option at longer spans. The inflection point where the better fire design configuration changes varies for each system. For the systems studied, each fire design configuration results in the lowest EC for the approximate span ranges shown in Table 5-7. This data is also presented visually and more precisely for each system type in Figure 5-17.

Table 5-7: Approximate bay span ranges where a given fire design configuration results in the lowest EC for the given system when carbon storage is neglected (1 ft = 0.305 m)

System	Timber FRR = 0	Timber FRR = 1	Timber FRR = 2
TCC	10-15 ft (3.0-4.6 m)	16-20 ft (4.9-6.1 m)	21-27 ft (6.4-8.2 m)
TG	10-13 ft (3.0-4.0 m)	14-23 ft (4.3-7.0 m)	24-27 ft (7.2-8.2 m)
TGb	10-27 ft (3.0-8.2 m)	28-36 ft (8.5-11.0 m)	37-40 ft (11.3-12.2 m)
TS	10-12 ft (3.0-3.7 m)	13-23 ft (4.0-7.0 m)	24-27 ft (7.2-8.2 m)
TSb	10-25 ft (3.0-7.6 m)	26-36 ft (7.9-11.0 m)	37-40 ft (11.3-12.2 m)

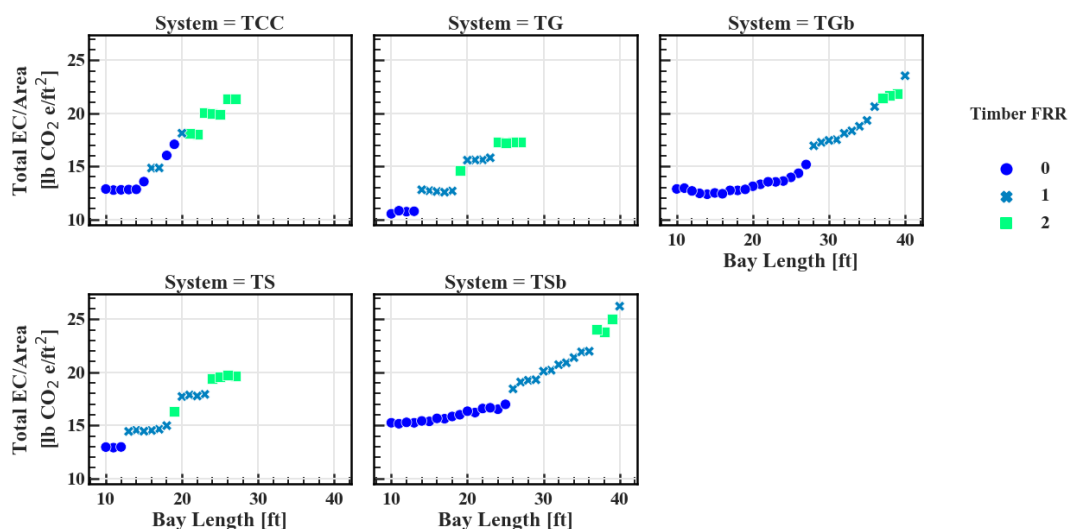


Figure 5-17: Total floor system EC vs. Bay length, filtered to show only the lowest-EC designs for each floor system at each bay length and colored by fire design configuration.

Based on the results, if there is limited availability of sustainably-sourced timber for a project, and if the priority is to minimize EC, designers should favor short-spanning all-timber systems (TG and TGb) using either a fully protected or combined approach option fire design configuration.

5.1.5.3 Material Contributions to System Trends

The discussion here focuses on embodied carbon trends and material contributions to those values. Figure 5-18 helps to further explain the previously discussed “stepping” behavior found in the systems’ embodied carbon plots (Figure 5-16 for example). Here Figure 5-18 shows the same data as in Figure 5-16; however the data is colored by the CLT’s contribution to total EC, and the line styles represent the fire design option. These plots show that the stepped trend line is correlated with increases in CLT EC, or in other words, when CLT panel depth increases the system sees a jump in total floor EC. Because only a limited number of discrete CLT depth options are used in the model, increases to CLT depth drive the EC per square foot significantly upward for non-carbon-storing timber, or downward for carbon-storing timber as shown in Figure 5-19 for 100% sustainably-sourced timber. Most manufacturers have discrete panel depth offerings based on a given ply thickness, such that this stepped trend will be common across manufacturers.

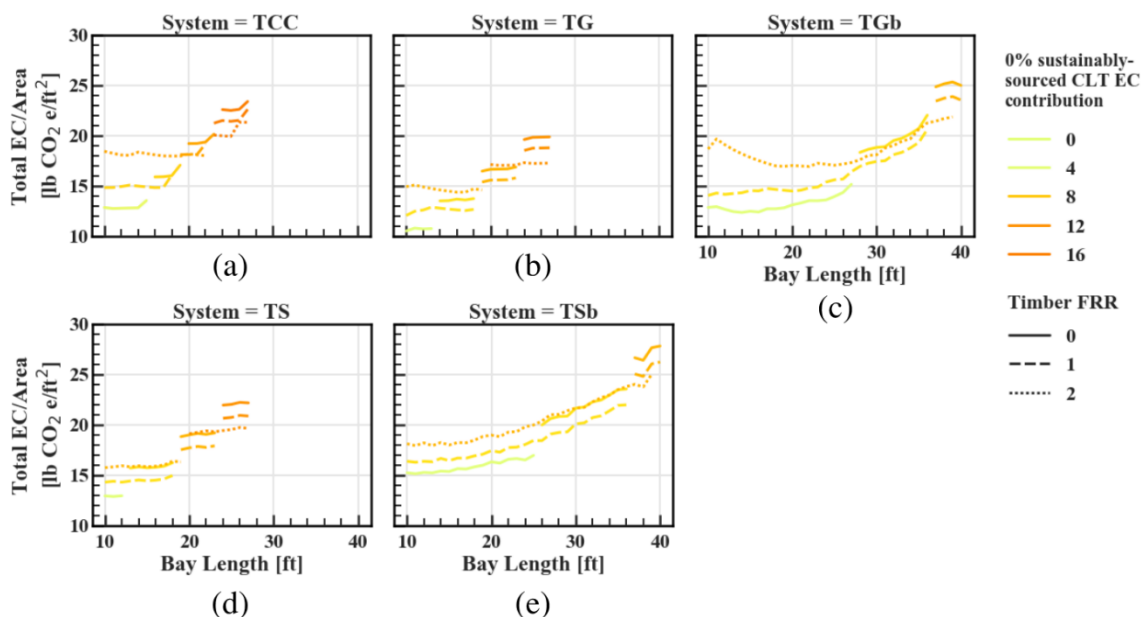


Figure 5-18: Total embodied carbon per square foot vs. Bay length for 0% sustainably sourced timber, and for each floor system type; colored by CLT contribution to EC, with line styles per the fire design configuration.

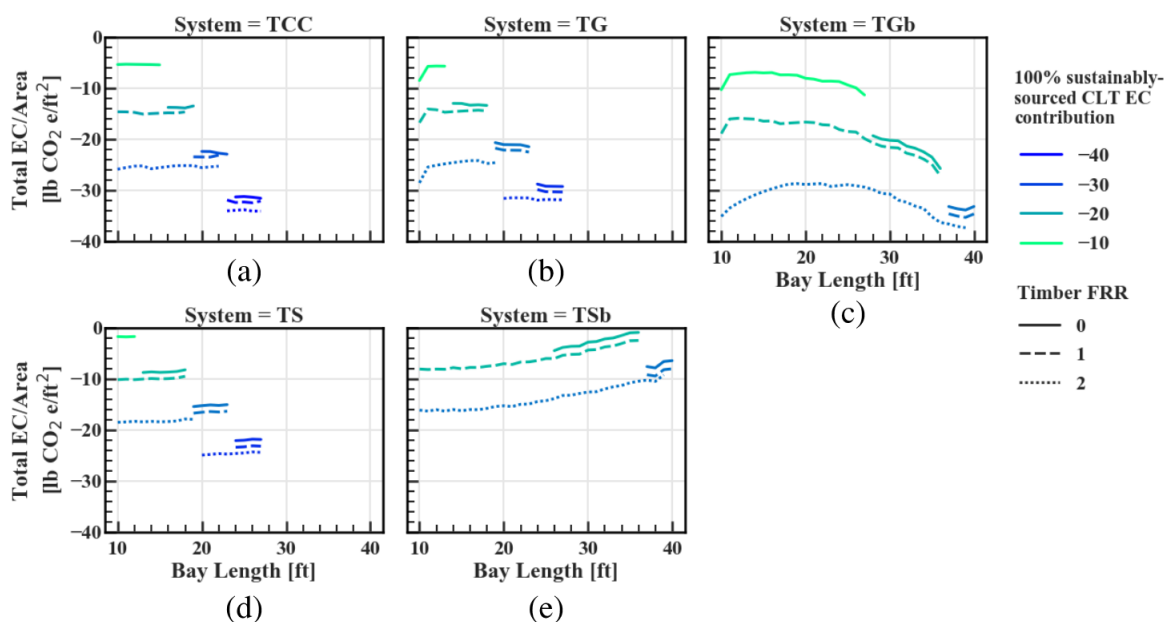


Figure 5-19: Total embodied carbon per square foot vs. Bay length for 100% sustainably sourced timber, and for each floor system type; colored by CLT contribution to EC, with line styles per the fire design configuration.

Further to the results in Figure 5-18 and Figure 5-19, a breakdown of material contributions to EC for a sample 20' bay is shown in Figure 5-20. The breakdown is shown for each system for select variable options, including the fully exposed option (indicated as '2') and the fully protected option (indicated as '0'), and 0, 50, and 100% sustainably-sourced timber. This plot confirms, at least for the 20' bay, that CLT makes up a significant portion of the total EC (net positive or negative) in most cases. Further, for all of the cases shown with non-carbon-storing timber, the fireproofing contribution is traded with added timber contribution when comparing the fully protected option to the fully exposed option. The concrete topping, although not ideal to include because of its high material EC value, tends to contribute only a small portion of the total floor system EC. The TCC system is an exception to this as a thicker concrete layer is often needed to achieve the composite action requirements. Figure 5-20 also shows that with 50% sustainably-sourced timber, only the systems without an infill beam can achieve net carbon storage EC where noncombustible protection is used.

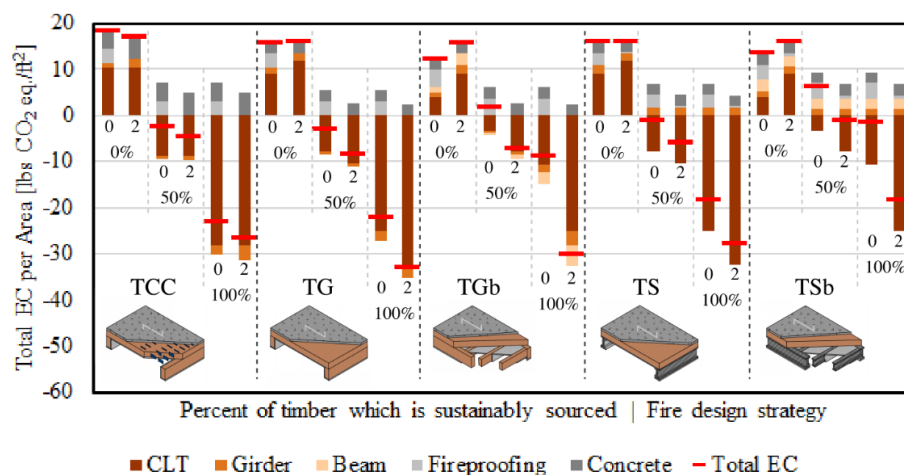


Figure 5-20: Breakdown of system component contributions to total floor system EC for a sample 20-ft bay. Representative data for each system type shows the component breakdown for systems with 0 and 2 hours of timber char, and for 0, 50, and 100% sustainably-sourced timber.

5.1.5.4 Non-Combustible Protection and Timber Char EC Trade-offs

Going beyond material breakdowns, Figure 5-21 shows the change in EC from timber and fireproofing components when switching to the fully exposed option from the fully protected option, again for a sample 20' bay. In other words, if a designer looks at a fully protected option, then decides to switch to the fully exposed option, Figure 5-21 shows how much EC is added or removed through the timber and fireproofing components. In all cases, the fireproofing contribution to EC is removed. EC is added or removed for the non-carbon-storing and carbon-storing timber, respectively, wherever elements are made larger to meet the char method requirements. Figure 5-22 shows the same data, but grouped by sustainable timber sourcing percentage rather than by system as in Figure 5-21.

For the 20' bay, the TS and TG systems with 0% sustainably-sourced timber perform about the same whether the fully exposed or fully protected option is used, trading fireproofing EC for timber EC. The TSb and TGb systems perform better for a fully exposed option only once a 25% or greater timber sourcing option is selected. The TCC system does better with the fully exposed

option in all cases. While Figure 5-21 and Figure 5-22 focuses on the 20' bay, this shows how this data could help a designer understand what EC savings are available based on the amount of sustainably-sourced timber they can obtain and the design choices they wish to make. This further demonstrates that no fire design configuration results in the lowest EC for all designs, and that there are often trade-offs when moving between configurations.

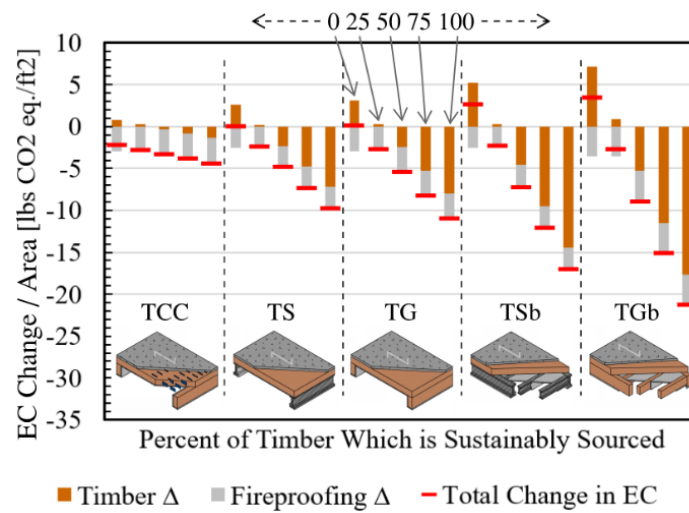


Figure 5-21: Difference in EC for a sample 20-ft bay from extra timber volume for char and removal of noncombustible fireproofing when comparing a fully exposed option to a fully protected option. Representative data for each system type shows the EC differences for each studied level of sustainably-sourced timber.

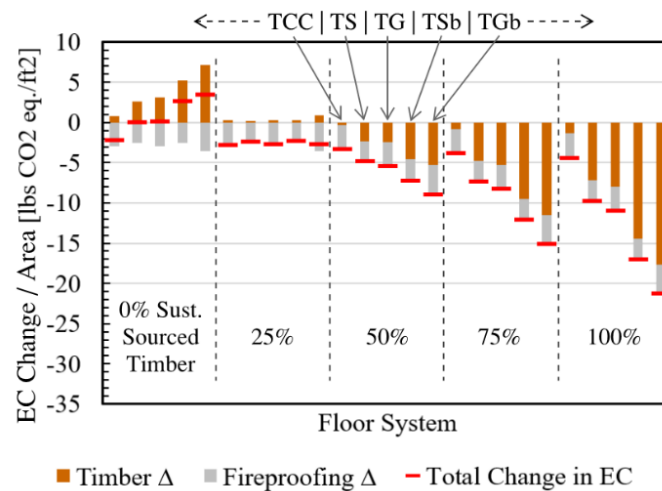


Figure 5-22: The same data shown in Figure 5-21 is repeated here and organized by the percent of sustainably-sourced timber, rather than by system type.

5.1.6 Conclusions and Future Work

This research used parametric models of five mass timber and hybrid mass timber structural floor system types to study the effect of prescriptive fire design requirements and configurations on floor system depth and embodied carbon (EC). The sections below highlight the key conclusions obtained from the results as well as topics of future study related to mass timber structures and EC.

5.1.6.1 Main Conclusions

Throughout the results, different approaches were used to visualize and compare the data from the parametric model. Comparing systems to each other may be helpful earlier in design when even the system may not have been decided yet, or if the building size dictates a specific fire design option. Comparing fire design options for a specific system may be more helpful once a system has been selected and fire design options are being explored. Further, it was helpful to discuss the results in the context of key topics, and therefore, the conclusions are grouped by these topics below:

Structural Floor System Depth Trends

- Regarding floor system depth, only the systems with infill beams (TGb and TSb) achieved spans longer than 27 ft, but required deeper framing sections to achieve spans up to the maximum 40-ft. (12.2 m) spans studied.
- Long-span systems experienced a depth penalty, and the deepest possible design of 66.12 inches (1.68 m) occurred for the 40-ft. (12.2 m) TGb fully exposed option.
- Based on the results, if the priority is to minimize depth, designers should favor short-spanning steel hybrid systems (TS and TSb) with noncombustible protection, which achieved depths as low as 11.5 inches (292 mm) deep for the fully protected 10-ft. (3.05 m) spanning systems.

Estimated Embodied Carbon Trends

While the focus of this research was on non-carbon-storing timber, the availability and use of more sustainably-sourced timber significantly affects total system EC. Designers should try to understand early on what is available for their project, as this will change how design decisions impact total EC. As more sustainable timber is used, fully exposed designs with longer spans tend to result in the lowest EC. Key results regarding EC are below:

- All fully-protected floor systems can achieve low EC at spans of 15 ft. (4.57 m) or less, ranging from 10.5 to 15.8 lbs. CO₂ eq/SF (51.3 to 77.1 kg CO₂ eq/m²).
- All fully-exposed floor systems perform in the range of 14.4 to 20.0 lbs. CO₂ eq/SF (70.3 to 97.6 kg CO₂ eq/m²) for spans up to 25 ft. (7.62 m), and are competitive with each other.
- The fully exposed TG system has the lowest EC for spans below 20 ft. (6.09 m), while at 20 ft. and above, the TGb system has the lowest EC.
- In general, all structural system types perform the best for EC with the fully protected option at shorter spans, the combined approach option at mid-range spans, and the fully exposed option at longer spans.
- Based on the results, if there is limited availability of sustainably-sourced timber for a project, and if the priority is to minimize EC, designers should favor short-spanning all-timber systems (TG and TGb) with either full or partial noncombustible protection.

Material Contributions and Trade-offs

- Sharp changes in EC correspond to increases in CLT panel depth, as CLT is typically available in only a few discrete panel depths for many manufacturers.
- CLT makes up a significant portion of the EC for most designs using non-carbon-storing timber.
- Although concrete has a high material EC value, the concrete topping often contributes to only a small portion of total floor system EC when non-carbon-storing timber is used.
- No fire design configuration results in the lowest EC for all designs, and there are often trade-offs when moving between configurations.

5.1.6.2 Future Work

The authors note that the industry could benefit from additional research in the following topics, which were out of the scope of this paper:

- **Expand fire design and protection options.** This paper includes only drywall and intumescent coating options; however, other options may include spray-on fireproofing, non-structural wood coverings, or mineral wool and fiberglass insulation.
- **Include designs without a concrete topping.** This paper included only designs with a concrete topping. For a project which can source carbon-storing timber, it may be desirable to eliminate concrete wherever possible; however, omission of a concrete topping would affect the design for acoustics and control of walking-induced vibrations, requiring a more in-depth analysis of these performance requirements.
- **Evaluate the relevance of early design stage trends.** While this paper focused on an early-stage design level of detail, it would be helpful to understand how closely the key trends hold true once a project moves into later stages of design.
- **Use data results to develop design tools.** The data discussed in this paper can be used as source data for design tools and guidance that could be used in early-stage design.

The next phase of this study will include studies of other design decisions and features that may affect a mass timber structure's EC, including the following:

- **Study floor assembly acoustic performance.** Compare acoustic performance and EC for a variety of acoustical floor assemblies and levels of performance.
- **Study contribution of connections.** Evaluate whether or not connections contribute significantly enough to EC that they need to be included in the floor systems model at an early-stage level of design.
- **Study floor diaphragm design.** This model focused on floor systems as a gravity structural element only. Future work will evaluate how significantly design for diaphragm behavior affects floor system element sizing, and whether it should be included in the floor systems model.
- **Extrapolate results to a few full building case studies.** Demonstrate how the results so far can be extrapolated to compare options for a full building at the early design stage. This would also include exploring the approximate contributions of portions of the building

which are still commonly built out of concrete or steel even in mass timber buildings, including foundations, parking garages, roof levels, and podiums.

5.1.7 Data Availability Statement

The full data set generated by all floor systems models for and discussed in this paper is available by request from the corresponding author.

5.1.8 Acknowledgements

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5.2 The Impact of Prescriptive Fire Design Provisions on Embodied Carbon for IBC Type IV Construction

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5.2.1 Abstract

Factors such as carbon storage potential, short construction schedules, prefabrication capabilities, and aesthetics are making mass timber a sought-after structural solution. Fire design requirements have been driving as well as impacting designer decisions. These decisions must understand what limitations the mandated codes place on exposed timber, as well as the options for the types of fire protection. This article primarily discusses how the last motivator, aesthetics, affects fire protection design and the carbon storage potential of mass timber. To meet code requirements for different construction types, designers can use noncombustible protection installed directly to the timber, additional sacrificial timber thickness for char design to expose the timber aesthetically, or a combination of both with each contribution adding to the required fire-resistance-rating. While there is wide availability of guidance on these design options, there is little guidance on how these decisions affect a project's sustainability goals for carbon storage. A study of several mass timber structural floor systems in the Residential (R-2) occupancy with sprinklers was carried out using parametric design analysis. This study demonstrates how choices made to achieve required fire-resistance-ratings affect embodied carbon (EC), or the estimated

carbon emissions associated with the harvesting/extraction, transportation of raw materials, and manufacturing of products for the building.

Keywords

Mass timber, hybrid mass timber, embodied carbon, prescriptive fire design, parametric model

5.2.2 Background and Introduction

As of May 2023, 40% of the United States' energy use comes from the building sector. [48], [251] While much of the work to reduce the sector's energy use has focused on operational energy during the occupied phase of a building's life, embodied carbon (EC), or the estimated carbon emissions associated with the materials used in the construction of a building, has not been studied in detail until relatively recently. However, EC is expected to contribute towards 33% of total emissions for buildings constructed over the 30-year period leading to 2050. [5] Material selection plays a vital role in EC contribution.

For some projects, mass timber could be an option to reduce the EC as compared to concrete and steel systems. [6], [7] Many projects that do include mass timber have an interest in exposing the timber for aesthetics, [3] and for its biophilia benefits, [229] both of which have been shown to improve occupant wellness. [3], [229] Exposed mass timber elements can be designed safely by various means such as prescriptive and performance methodologies. US design standards currently focus on prescriptive means that consider a mass timber element's ability to maintain strength at the section's interior via the development of a protective char layer during a fire. [105] However, while timber may be selected (at least partially) for its assumed carbon storage benefits, no literature was found at the time of writing which includes an analysis of how fire safety design affects a design's EC. This paper focuses on prescriptive methodologies; however Hens et. al.

present an in-depth discussion regarding following prescriptive versus performance-based design methodologies in early design. [86]

5.2.3 Mass Timber in the United States

As of February 2022 in North America, there are 9 mass timber projects of 8 stories or higher under construction and 26 projects proposed. [4] Mass timber projects in the United States are increasing in height compared to early projects built as shown in Table 5-8. [4] Many of these taller mass timber projects built in the US are centered on Residential occupancies. Timber is often exposed on the interior where possible to achieve aesthetic goals and biophilia benefits for occupants. Most of the tallest projects in the US are not all-timber, but rather incorporate a concrete core, steel bracing, or similar. Mass timber has been used in some overbuild projects because it is lightweight, which can reduce the amount of structural renovation work required for the existing building and reduce cost due to lighter equipment needs during construction. [252]

Table 5-8: Recent tall representative mass timber buildings constructed in the United States (Data retrieved from the “State of Tall Timber 2022” by the Council on Tall Buildings and Urban Habitat (CTBUH) [4], the CTBUH database [26], the WoodWorks Innovation Network [253], and other project websites where noted for a given project)

Project Name	Year Completed	Construction Type	Structure	Height (ft (m))	Stories	Location	Building Use
<i>Ascent</i>	2022	Special approvals	Timber over podium with concrete core	284 (87)	25	Milwaukee, WI	Residential
<i>1510 Webster</i>	Under construction	Type IV-A	Timber over podium with concrete core	187 (57)	18	Oakland, CA	Residential
<i>Return to Form</i> [254]	2024; permitting in process	Type IV-B (2024 IBC)	Timber over podium with concrete core	~175 (~50)	14	Denver, CO	Residential
<i>503 on Tenth</i> [255]	2023; under construction	Type IV-B	All-Timber	164 (50)	10	Portland, OR	Office

Project Name	Year Completed	Construction Type	Structure	Height (ft (m))	Stories	Location	Building Use
<i>INTRO Residential Tower</i> [256]	2022	Special approvals	Timber over podium with concrete core	130 (40)	9	Cleveland, OH	Mixed-Use
<i>Carbon 12</i> [257]	2018	Type III-A	Timber with steel braced frames	95 (29)	8	Portland, OR	Residential
<i>Glisan Tower</i> [258], [259]	Under construction	Type IV-B	Timber with steel braced frames	94 (29)	8	Portland, OR	Mixed-Use
<i>Heartwood</i> [260], [261]	Under construction	Type IV-C	Timber with steel braced frames	80 (24)	8	Seattle, WA	Residential
<i>Platte Fifteen</i> [198], [262]	2019	Type III-B	Timber with concrete core and steel-braced glulam frame	70 (21)	5	Denver, CO	Office

5.2.4 Mass Timber in the Building Code

The 2021 International Building Code (IBC) includes several sections that define mass timber building elements and how they are permitted to be used within different construction types. Included in the 2021 edition, three new construction types were established: Type IV-A, IV-B, and IV-C. These three are intended to allow the construction of larger and taller mass timber buildings than previously allowed. In addition to these three new construction types, the old Heavy Timber construction type (Type IV), has been renamed IV-HT. The A, B, and C types are in order from greatest to least fire resistance requirements. [1]

Mass timber elements are now specifically noted to belong to Type IV construction, which prescribes the minimum element sizes defined in IBC Section 2304.11 for heavy timber and shown in Figure 5-23. IBC 2021 further describes mass timber elements as consisting of solid, built-up, panelized, or engineered wood products, [34] which is consistent with definitions of mass timber commonly used in practice. Type IV construction more generally includes

buildings with mass timber, noncombustible building elements, or a combination of both, including for all wall construction. [34]

This article focuses on the Residential (R-2) occupancy, for which the IBC-allowed building heights and areas per Section 506.2 are summarized in Figure 5-24 for Type IV construction. The Residential R-2 occupancy includes buildings with greater than two dwelling units and permanent residents, [34] and was selected for this research because 65% of mass timber projects over eight stories worldwide include Residential occupancies. [3], [4]

IBC construction types not only define the limits on building height and area, but they also are used to define the Fire Resistance Ratings (FRRs) required for the various structural and non-structural building elements. The FRRs for IBC 2021 Type IV construction per Section 601 are summarized in Figure 5-25. For mass timber elements, the FRR may be provided by the charring of the timber, noncombustible protection, or a combination of both methods per Section 602.4. [34] Noncombustible protection is a newly defined term in the 2021 IBC and is the additional FRR time attributed to the noncombustible material when applied to mass timber building elements. A general summary of the main requirements for noncombustible protection is provided in Table 5-9 and Table 5-10. These options for meeting FRR are discussed further in the section, Overview of Fire Performance Design. Section 2303 further describes the minimum standards and testing that structural mass timber elements must meet. IBC Section 602.4 also defines for each construction type the requirements for minimum amounts of noncombustible protection and allowable unprotected areas for mass timber elements, which is dependent on the construction type. [34]

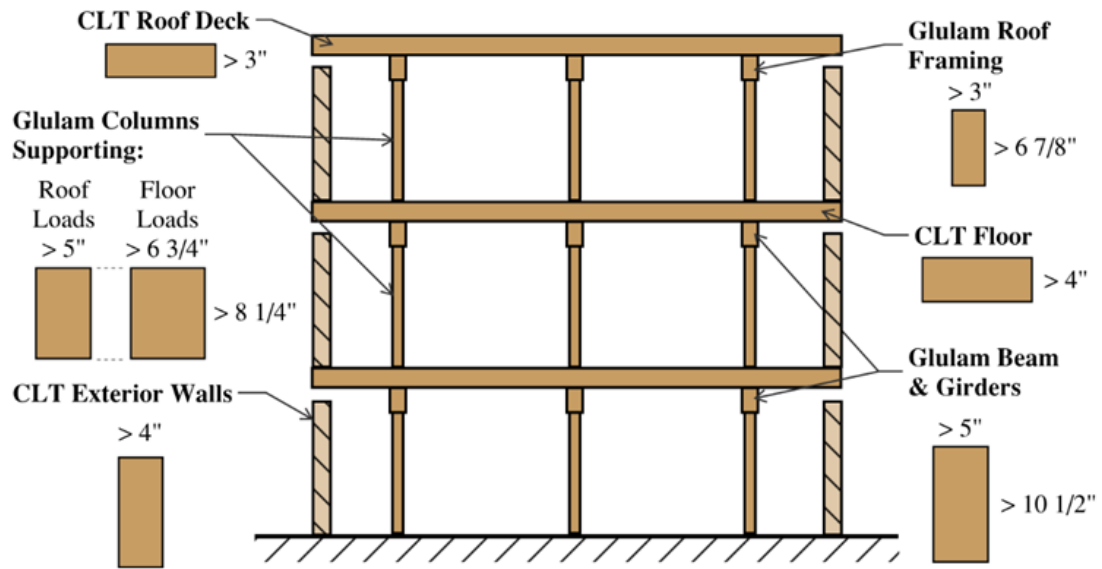


Figure 5-23: Minimum element sizes for CLT and Glulam mass timber (Sizes shown are per IBC 2021: Table 2304.11 for columns, beams, girders, and roof framing; Section 2304.11.2 for CLT walls; Section 2304.11.3 for CLT floors; and Section 2304.11.4 for roof decks; 1 in = 25.4 mm)

Representative Mass Timber Building Sizes, Residential Occupancy (R-1, R-2, NFPA-13 Sprinklered, W=>30', 100% open space)

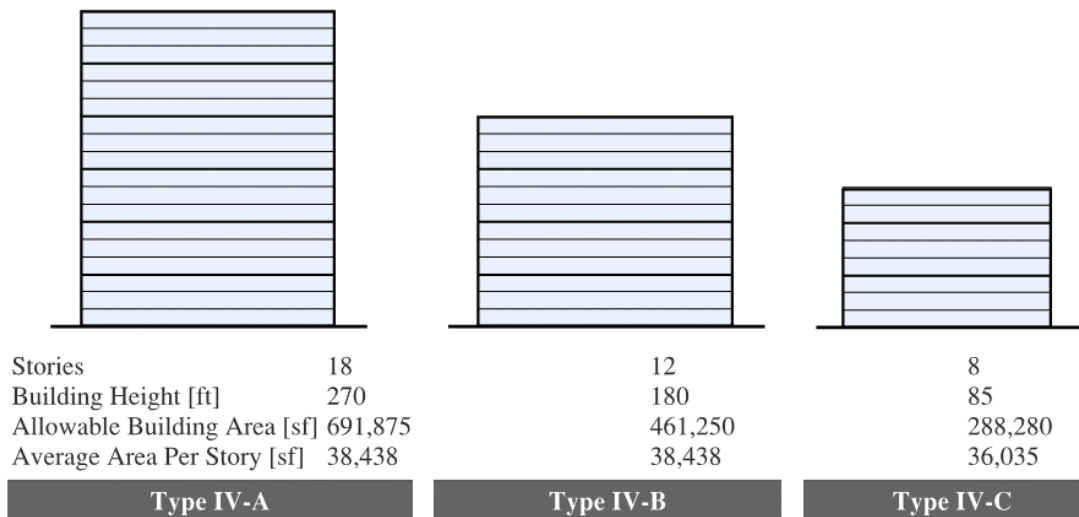


Figure 5-24: New mass timber building categories appearing in the 2021 IBC and their maximum allowed stories, heights, and areas for R-2 with automatic sprinklers provided throughout. (Figure adapted from Breneman et al. (2019) [1] and based on data from the 2021 IBC Table 506.2 and Section 506.2.1 assuming type SM sprinklers [34]; 1 ft = 0.305 m; 1 ft² = 0.093 m²)

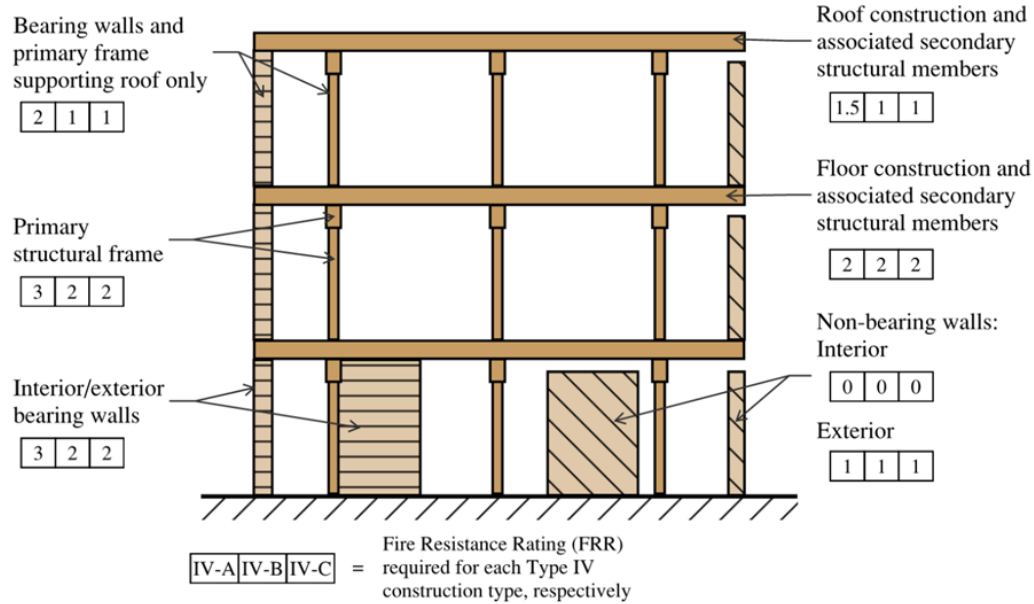


Figure 5-25: Fire resistance ratings for Type IV construction (Based on Table 601 from the 2021 IBC)

Table 5-9: Required noncombustible protection and allowable unprotected mass timber in Type IV construction (Based on 2021 IBC Section 602.4.)

Construction Type	Noncombustible Protection Time (minutes)			Noncombustible Material above Floors	Allowable Unprotected Mass Timber	Separation Distance Between Unprotected Surfaces
	Exterior Side of Walls	Protected Interior Surfaces	Concealed Spaces			
IV-A	≥ 40	≥ 80	≥ 80	≥ 1 inch (25.4 mm)	None	N/A
Ceilings: 20% of floor area ^a						
IV-B	≥ 40	≥ 80	≥ 80	≥ 1 inch (25.4 mm)	Walls: 40% of floor area Ceilings & Walls: sum of proportion of total and allowable for both not to exceed 1.0	≥ 15 feet (4.6 meters)
Columns & beams (not part of walls): 100%						
IV-C	≥ 40	0	≥ 40	0	All Elements	0

^a Note that the 2024 IBC will allow Type IV-B construction to have an area of exposed mass timber ceilings equal to 100% of the floor area.

Table 5-10: Minimum protection time required from noncombustible materials (Based on 2021 IBC Section 722.7.1(1))

Required FRR of Building Element	Minimum Noncombustible Protection (minutes)
1	40
2	80
3+	120

Looking beyond the 2021 IBC, design strategies and requirements vary by code/reference standard and may include either prescriptive requirements with specific codified design requirements, or performance-based design (PBD) methodologies that set performance requirements, or a combination of both. [205], [244], [245] Table 5-11 summarizes the requirements and guidance included in the most relevant codes and guides in use in the U.S.

Table 5-11: Prescriptive and performance guidance available in different codes and guidelines

Code/ Guideline	Prescriptive Guidance		Performance-based Guidance	
2021 International Building Code (IBC) [34]	Ch. 7 & 9; § 602 & 504	Various rule-based requirements including: • Fire and smoke control • Occupant and fire department notification • Active fire protection equipment and systems • Fire and gas detection	§ 104	An option for PBD is provided which includes the allowance of alternative materials, design and methods of construction, and equipment.
		Requirements for mass timber construction, including FRRs, exterior and interior protection, and concealed spaces. Provisions based on building occupancy, height, and area.		Limited other guidance is provided.
2021 ICC Performance Code for Buildings and Facilities (ICCPC) [263]	N/A		Ch. 6	Considers: • Sources of Fire Ignition • Limiting Fire Impact Looks at fire prevention, fire impact management, and means of egress.
2021 International Fire Code (IFC) [264]	Ch. 7 & 9	Similar fire protection and life safety provisions as in the IBC	§ 104	Similar to IBC. This provides a pathway for following PBD.

Code/ Guideline	Prescriptive Guidance		Performance-based Guidance	
<i>2021 National Fire Protection Association Fire Code (NFPA) [265]</i>	Ch. 12-14 & 20	Provides several chapters which set forth prescriptive requirements for topics such as: • Fire protection systems • Means of egress • Occupancy fire safety	Ch. 5	Provides information for how a PBD approach may be used. This sets performance requirements and defines design scenarios and input data to be used in the design and modelling process.
<i>2018 National Design Specification for Wood Construction (NDS) [140]</i>	§ 16.2	Design procedures provided for exposed wood members, which includes calculation process for: • Char rate and depth • Effective char depth • Strength and design of members using reduced cross sections	§ 16.3	Statement on wood connections, which should be protected from fire exposure for the required FRR
<i>Technical Report No. 10: Calculating the Fire Resistance of Exposed Wood Members (TR 10) [238]</i>	Pt. 3	Technical guidance for calculating the fire resistance of exposed wood members, using prescriptive design procedures set forth in the NDS.	§ 3.4	Statement on wood connections, similar to the NDS.
<i>2021 Fire Design Specification (FDS) [141]</i>	Ch. 3	Supplemental provisions to the NDS which incorporates equations and procedures from both the NDS and TR 10. Chapter included for: • General requirements for fire design • Ignition and flammability • Fire resistance	§ 3.9	Statement on wood connections, similar to the NDS. Further, the FDS allows protection of connections to be determined through testing.

This article focuses on prescriptive requirements due to their popularity and familiarity with building designers and code reviewers. The goal of codified design requirements is to produce buildings with a minimum standard of fire safety performance. Building codes do not offer guidance to improve designs beyond code minimum, and do not set minimum targets for embodied carbon. Other resources are available which provide more in-depth discussion of the mass timber requirements in the building code, such as "Mass Timber Buildings and the IBC", written by ICC and AWC, and published by ICC. [266]

5.2.5 Overview of Fire Performance Design

Both passive and active methods of fire protection exist for mass timber construction, [138] where active strategies include those which must be activated in the event of a fire, such as sprinklers, while passive strategies related to the design of assemblies and construction which are inherently fire-resistive. This article focuses on the US code-based passive prescriptive methods used for mass timber structural elements due to their relation to the EC of the structure, but assumes that sprinklers are provided for the R-2 occupancy to maximize the allowable building height and areas. [34] Passive strategies include:

- The **char method**, which involves designing the timber to achieve a required FRR, including the loss of cross-section due to charring.
- **Noncombustible protection**, which typically consists of gypsum wallboard (GWB) installed directly against mass timber elements to protect them from fire.

Both passive methods may be used on their own, or in combination by summing the contribution of each for a total FRR. [34], [140] Combining the two methods may be realistic when the code requires baseline noncombustible protection. Beyond meeting the baseline, combining the contribution time is appropriate if the designer wants to minimize the number of layers of GWB protection to reduce installation time, or the designer is trying to optimize the amount of timber and GWB for the lowest EC in cases when more sustainable timber cannot be sourced. Figure 5-26 shows examples of how these strategies may be used to achieve a 2-hour FRR.

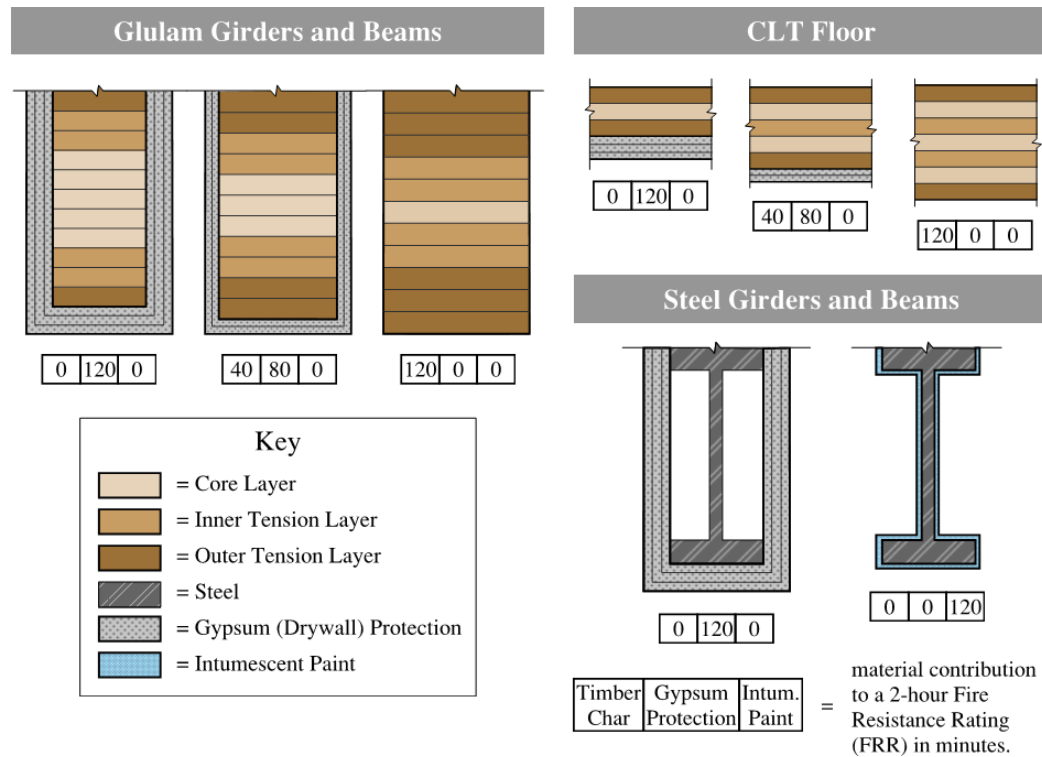


Figure 5-26: Conceptual examples of potential strategies to achieve a 2-hr rating for Glulam, CLT, and steel sections. (Not To Scale: Number of laminations are purely conceptual and intended to be representative. Figure adapted from figures in The CLT Handbook (2019 Canadian Edition) and The 2018 Fire Design Specification for Wood Construction. [105], [141])

5.2.5.1 Char Method

The char method is based on the properties of large timber elements in a fire. While light-framed timber elements may either burn all the way through or fail too soon for 2-hour FRRs, mass timber includes large enough dimensions that an outer layer of char will form, which then protects the inner timber and allows the element to retain some of its original strength. With this inherent fire resistance, mass timber can be sized up to allow for a sacrificial thickness for char. [105] Lumber grades in mass timber layups should be selected based on the geometry and loading expectations after a portion of the element has charred. [141] See Figure 5-27 for an example of how the char method may be implemented for a CLT panel. The 2018 National Design

Specification for Wood Construction (NDS) and The 2021 Fire Design Specification for Wood Construction (FDS) include a calculation-based method, which estimates the effective char depth for an FRR up to 2 hours. The effective char zone is then assumed to contribute nothing to strength, and the remaining section is used to calculate the new properties to use in design checks. The FDS also allows a designer to use the properties of a CLT panel whose number of laminations do not exceed the uncharred laminations in the remaining section, as shown in Figure 5-27. [139], [140] The calculation methods can be applied regardless of wood species, but vary slightly for different structural product types, such as for Glulam versus CLT. See Chapter 16 of the 2018 NDS for the relevant design procedures, or Chapter 3 of the 2021 FDS for the same set of procedures plus additional commentary and design guidance.

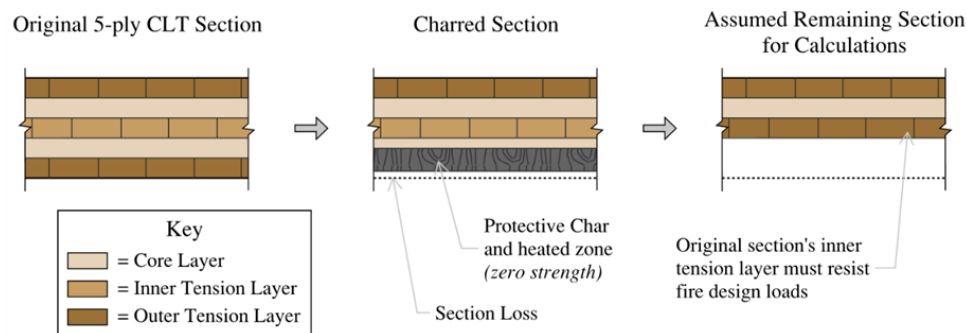


Figure 5-27: Example of charring process and remaining section for use in calculations. (Figure adapted from figures in The CLT Handbook (2019 Canadian Edition) and The 2021 Fire Design Specification for Wood Construction. [105], [141])

5.2.5.2 Use of Noncombustible Protection

The use of noncombustible protection, currently limited in the IBC to GWB, is permitted to provide a FRR based on the number of layers and FRR of the individual layers. In a fully protected strategy, the intent is that the noncombustible protection provides the full required fire rating, and therefore multiple layers may be required depending on the rating. Various codes and standards differ on the allowed protection times from noncombustible protection, as summarized

in Table 5-12. This research uses the values for GWB from the 2021 FDS to simplify calculations and because differences in EC estimates based on the 2021 IBC vs the 2021 FDS are negligible. Per the 2021 FDS, 1/2-inch (13 mm) and 5/8-inch (16 mm) GWB provides 30 and 40 minutes respectively of protection.

Table 5-12: Protection times in minutes contributed by noncombustible protection by code.

Product	2021 IBC	2021 FDS	2019 CLT Handbook; CAN Edition	2013 CLT Handbook; US Edition
½" Type X GWB (13 mm)	25 minutes	30 minutes	15 minutes	N/A
5/8" Type X GWB (16 mm)	40 minutes	40 minutes	30 minutes	30 minutes
3.5" Mineral wool batt, ≥ 2.5 pcf (89 mm, 40 kg/m ³)	N/A	19 minutes	N/A	N/A
1.5" Mineral wool batt, ≥ 2.5 pcf (38 mm, 40 kg/m ³)	N/A	17 minutes	N/A	N/A
Fiberglass batts, ≥ R-13 (RSI 2.3)	N/A	3 minutes	N/A	N/A

5.2.6 Methodology

The impact of all of these code requirements on actual design decisions is complex to model, because a variety of factors (such as load requirements, bay size, and fire protection strategy) might affect the benefits of one particular design strategy. In this paper, we thus model possible options across a range of key parametric design variables to make their impact clear. Options are then evaluated using design space exploration (DSE). Parametric design and analysis are increasingly used in architecture to explore a range of designs and possibilities. This gives designers greater flexibility during early design compared to traditional design methods. [179] This research uses the same concepts of parametric analysis, but instead applies them to parametric models evaluating the performance of mass timber floor systems over a range of

designs possibilities. This is similar to the methods used by Jelusic and Kravanja (2017), Mayencourt and Mueller (2019), and Hens et al. (2020). [86], [181], [182]

5.2.6.1 Parametric Modeling

The parametric model for this research consists of models for several different floor systems, which by varying bay length, system type, fire design method, and sustainable timber sourcing results in numerous design configurations. The modeled floor systems are shown in Figure 5-28, and are discussed in more depth by Leonard et. al. [203] and in Chapter 3 of this dissertation.

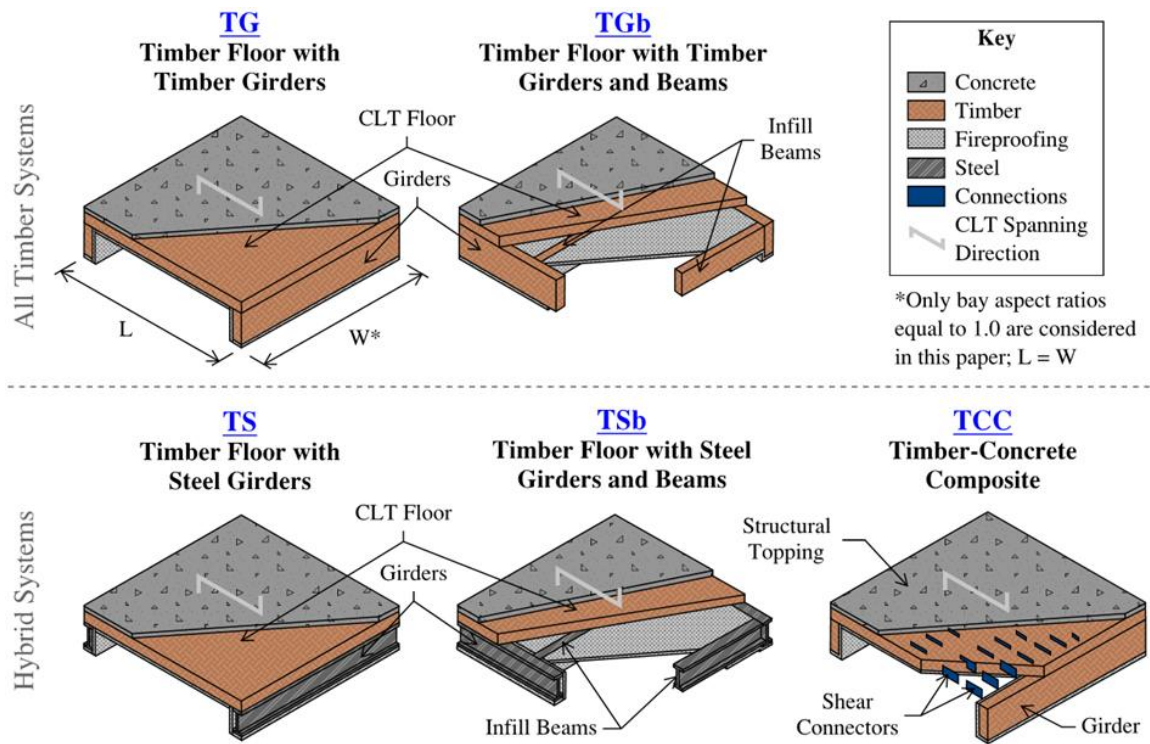


Figure 5-28: Studied floor systems

Five floor system types were modeled for a range of bay lengths, different bay aspect ratios, varying sustainable timber sourcing assumptions, and different fire protection strategies, as summarized in Table 5-13. However, this paper focuses on the results for only bay aspect ratios equal to 1, and for systems with only 1 infill beam within the center of the bay where infill beams are provided. This was to limit the number of variables and complexity of the models so that data analysis could focus on the effects of different fire design strategies. The parametric models are built using a combination of grasshopper, custom python components, and spreadsheet-based models and databases. Table 5-13 summarizes the variables use within the model and the ranges or options for each.

Table 5-13: Summary of variables and their ranges or options in the parametric model

Variable	Range or Options to Change in Model	Justification
<i>Bay Length</i>	10 to 40 feet, in 1-foot increments (3 to 12 meters, in 0.3-meter increments)	Range covers most bay lengths currently used in mass timber Residential occupancy projects
<i>Fire Design Configurations to Achieve FRR</i>	The following strategies will be clarified in Figure 5-29: • Fully protected option (2 configurations) ○ Type IV-A requirements ○ Type IV-B and IV-C requirements • Combined approach option (2 configurations) ○ Type IV-A requirements ○ Type IV-B and IV-C requirements • Fully exposed option (2 configurations) ○ Type IV-B requirements ○ Type IV-C requirements	Options cover the options for Residential R-2 occupancy within the mass timber construction types.
<i>Percent of Sustainably-Sourced Timber (SST)</i>	0%, 25%, 50%, 75%, and 100%	Options based on assumed timber-sourcing capabilities for a typical project
<i>System Type</i>	• Timber Floor with Timber Girders (TG) • Timber Floor with Timber Girders and Beams (TGb) • Timber Floor with Steel Girders (TS) • Timber Floor with Steel Girders and Beams (TSb) • Timber-Concrete Composite Floor with Timber Girders (TCC)	Systems were selected to cover a variety of all-timber and hybrid timber options, and were selected in part due to the feasibility of modeling the system parametrically at an early design stage.

5.2.6.2 Prescriptive Fire Provision Modeling

Figure 5-29 shows how mass timber elements can be designed to achieve the IBC 2021 fire protection requirements depending on the construction type of the project (options along vertical side of table), and the designer's project goals for the fire design of the timber (options along top side of table.) As this article will also consider hybrid systems consisting of a CLT floor panel and steel beams, an option for the steel fire protection is noted in the table as well; however, other configurations may be possible, and further study of the steel fire design is beyond the scope of this article.

At steel framing, fire protection is provided by intumescent paint at conditions where the timber is exposed, and by GWB encasement where the timber has at least some GWB protection. Based on publicly available product data, it was determined that intumescent paint applied at 0.55 lbs per square foot of steel surface area (2.7 kg/m^2) provides 2 hours of protection. [59], [216], [217] Additional modeling procedures and prescriptive fire modeling details are summarized by Leonard and Solnosky. [203]

The previous section summarized how fire protection for mass timber is treated in the code, and how designers can safely design their timber structures to meet the requirements of fire design while in some cases still allowing for exposed timber to meet carbon reduction, aesthetic and biophilic design goals. Depending on the selected strategies and construction type, fire performance design can significantly affect element sizing, use and noncombustible protection, and therefore the total EC of a design.

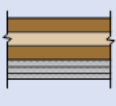
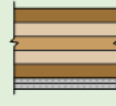
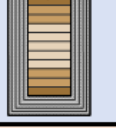
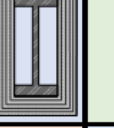
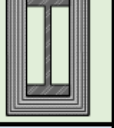
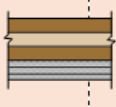
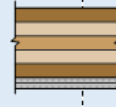
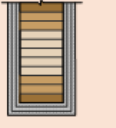
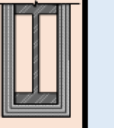
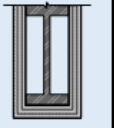
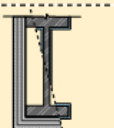
Constr. Type	Element (FRR)	Fully Protected Timber		FRR From Combined Method		Timber Exposed at Max Allowed	
		TG, TGb, TCC	TS, TSb	TG, TGb, TCC	TS, TSb	TG, TGb, TCC	TS, TSb
IV-A	CLT (2-hr)	2 hours of non-combustible protection (drywall) 		80 minutes of protection from drywall + 40 minutes from mass 		N/A	
	Framing (3-hr)	3 hours of protection from drywall 		2 hrs drywall + 1 hr timber 	3 hrs from drywall 		
IV-B	CLT (2-hr)	2 hours of protection from drywall 		80 min. drywall + 40 min. timber with 2 hrs from drywall on steel 		2 hrs from timber for 20% of bay area + 80/40 min. from drywall/ timber for 80% of bay area 	
	Framing (2-hr)					2 hrs from timber at 20% area + 80/40 from drywall/ timber for 80% area 	2 hrs from int. paint on 20% + 2 hrs from drywall for 80% area 
IV-C	CLT (2-hr)					2 hrs from timber 	
	Framing (2-hr)					2 hrs from timber 	2 hours of protection from intumescent paint 

Figure 5-29: Prescriptive fire design options used for each Type IV construction type in the parametric model. Each color block represents a distinct fire design configuration for the all-timber and hybrid timber-steel system types.

5.2.6.3 Structural Design

Each structural element in the model is sized using a custom python code created by the authors for this research. Sizing is based on the Allowable Stress Design (ASD) methodology for both steel and timber, and is performed to meet the applicable codes and standards for the limit states summarized in Table 5-14. Most system types are designed following NDS and AISC guidance as noted in Table 5-14; however the Timber-Concrete Composite (TCC) system was designed following the Canadian guide, “Design Guide for Timber-Concrete Composite Floors in Canada” by FP Innovations because design guidance specific to the US is limited for TCC floors. The custom code determines required capacities for a given design and selects the lowest weight structural element from a database. This approach is used for each limit state in the order shown in Table 5-14 and is resized and rechecked against other limit states as needed until all requirements are met. The assumptions included in each model type are summarized in Table 5-15.

Table 5-14: Limit states included in the structural sizing code

Element	Shear	Flexure	Deflections	Vibrations	Fire Design	Code and Standards
<i>CLT Floor Panel</i>	✓	✓	✓ (including creep)	✓	✓	2018 National Design Spec for Wood Construction [140];
<i>Glulam Framing</i>	✓	✓	✓	✓ (supporting element for CLT)	✓	2021 Fire Design Spec for Wood Construction [141]; The 2013 and 2019 CLT Handbooks [42], [105]
<i>Steel Framing</i>	✓	✓	✓	✓ (supporting element for CLT)	N/A	AISC Steel Construction Manual [237] and AISC Specification for Structural Steel Buildings [236]
<i>Timber-Concrete Panel</i>	✓	✓	✓ (including creep)	✓	✓	Design Guide for Timber-Concrete Composite Floors in Canada [120]

Table 5-15: Structural design assumptions

Item	Assumed Condition	Additional Comments
Boundary Conditions	Pinned connections	Chosen to be able to initially assume simple connections.
Number of Spans	Maximum permitted based on manufacturing and transportation limits	This allows the model to take advantage of additional allowable span, such as for vibrations in multi-span conditions
Span Length	Equal to bay length	Conservative for timber as NDS defines span length as distance between faces of supports
Bay Location	Center bay	For EC accounting, perimeter girders and beams are considered to be shared with the adjacent bay
Live Load	40 psf residential + 20 psf allowance for partitions = 60 psf (2.87 kN/m ²)	Based on ASCE 7-10 for a Residential occupancy, private rooms and corridors serving them. Live load reduction is neglected due to small tributary area in designs.
Superimposed Dead Load	20 psf + 19 psf for a 1.5" (38 mm) nonstructural concrete topping = 39 psf (1.87 kN/m ²)	20 psf is for mechanical, utilities, finishes, and other items
Steel Shapes	W-Shapes only	Shapes obtained from the AISC steel shapes database [20]

5.2.6.4 Embodied Carbon Evaluation

To estimate embodied carbon of each design, material take-offs are pulled from the model for the structural elements, the concrete topping, and noncombustible protection. The weights of all the materials are multiplied by their respective EC factors, summed together, and divided by the bay area to normalize the total value per square foot. A rough estimate is also added for columns, with timber columns assumed in the TCC, TG, and TGb systems, and steel columns assumed in the TS and TSb systems. Structural material values are obtained from a combination of Industry-wide EPDs or the average of multiple manufacturer-specific EPDs. Timber EC values are considered and modeled both with and without biogenic carbon storage as the recognition and quantification of carbon storage is still in development. Net carbon storage is based on the sum of A1-A3 impacts, biogenic carbon stored in the timber, and assumed emissions due to 100% landfilling using the EPA's Waste Reduction Model (WARM) [218]. The floor

systems model for this research varies the specific proportion of Sustainably-Sourced Timber (SST) and adjusts the EC values linearly, as carbon storage may only be claimed for SST. [61] The results discussed later focus on partial SST because 100% responsible and certified timber materials may not be available for use on a typical project. [240] Fire protection material EC values are gathered from environmental product declarations (EPDs) and other resources such as product technical data. Values assumed in this research are summarized in Table 5-16.

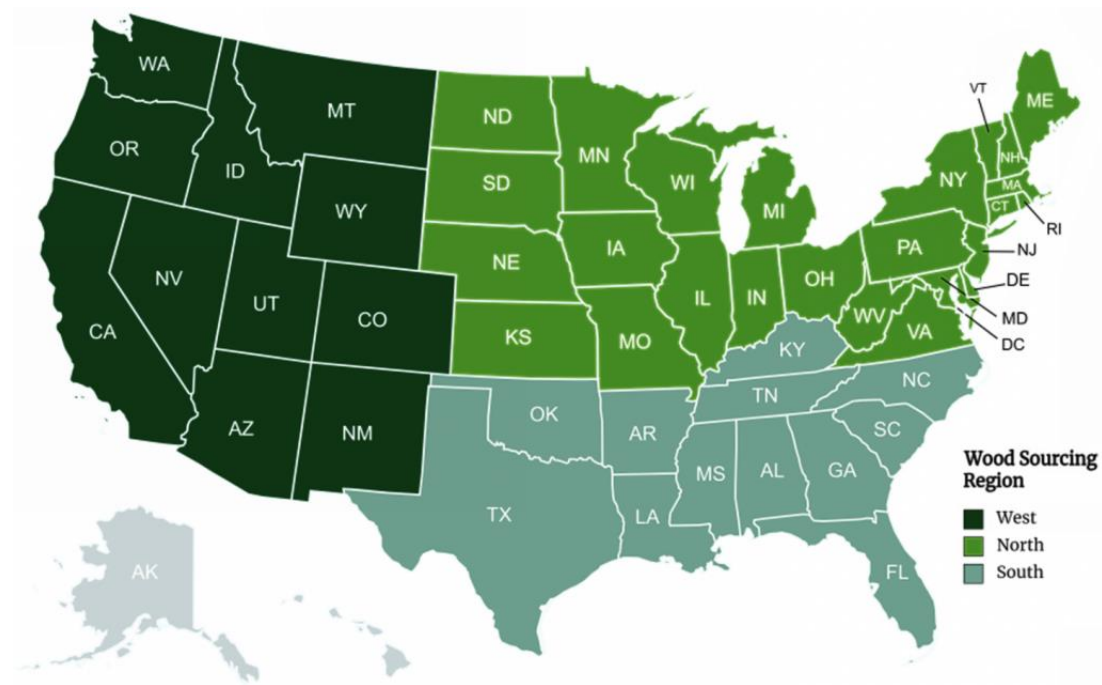
Table 5-16: Embodied carbon of common structural and building materials
(1 lb CO₂ eq/lb = 1 kg CO₂ eq/kg)

Embodied Carbon of Structural Materials (lb CO₂ e/lb)			
<i>Material</i>	<i>EC value</i>	<i>Material Assumptions</i>	<i>Data Source</i>
Timber	CLT	0.27	Average of five North American CLT EPD's following ISO 21930:2017 A and B [64], [207]–[210]
	Glulam	0.25	American Wood Council EPD for North American Glued Laminated Timber [65]
	CLT	-1.19	Carbon storage is neglected
	Glulam	-1.04	Carbon storage is included (linear interpolation used for values between 0 and 100% carbon storage)
Reinforced Concrete	0.17	25% Cement replacement with fly ash	Same as for neglected carbon storage case, based on biogenic carbon accounting and EPA WARM model [218]
Steel (section)	1.22	93% Recycled steel content	NRMCA Industry-wide LCA report and CRSI EPD for reinforcing steel [211], [212]
Gypsum Wallboard (drywall)	0.28	Type X: a 10% waste factor is applied to the total combined EC takeoff for GWB and joint compound	AISC industry EPD [213]
Joint Compound	1.19	Conventional ready-mixed	Industry-wide GWB EPD [214]
Intumescent Paint (for steel)	2.31	Solvent-based with 40.7 SF/gallon (1 m ² / liter) coverage to achieve 1 hour of fire protection	Industry-wide joint compound EPD [215]
			“A brief guide to calculating embodied carbon” by ISE [59]; Hilti All Weather High Build CFP-SP AWHB intumescent steel fire proofing – product data sheet (PDS) [216]; FlameOFF Fire Barrier Paint – PDS [217]

5.2.6.5 Wood Materials

To inform the values of SST for modeled design examples, an additional discussion of wood sourcing is included. The American Wood Council created a web-based Wood Sourcing Tool, which provides the percentages of non-controversial, responsible, and certified-sourced forest products by region or mill number. [240] Regional values are based on average mill data for the region. The regional data from the tool is summarized in Figure 5-30. Note that all U.S.-sourced wood is considered non-controversial, meaning there is a low chance of illegally-sourced wood. Most of the U.S.-source wood is responsible based on a combination of independent certification standards and areas with known implementation of best practices as evaluated by the National Association of State Foresters. [267] The greatest variation in sourcing appears in the “Certified” category, which is based on internationally-recognized certification program. It would be conservative to base the modeled SST inputs on the “Certified” category data; however, the paper authors anticipate that many “Responsible” sources have the potential to be recognized as “Certified” in the future if those sources either seek further certification or gain recognition for their own certification processes.

The results section of this paper will first compare a variety of SST options including 0, 25, 50, 75, and 100%, followed by a more in-depth analysis based on a 50% average for the U.S. generally. A design example considers 75% SST to offer an analysis of an alternate carbon storage assumption.



Forest Products Sourcing Data	West	North	South
Non-Controversial Sources	100%	100%	100%
Responsible Sources	95%	97%	95%
Certified Sources	73%	21%	30%

Figure 5-30: Forest product sourcing map for the United States and corresponding data by sourcing category and region. Data from the AWC’s “Wood Sourcing Tool” [240] at <https://awc.org/wood-sourcing/>

Further, while a variety of species and grades are available for structural mass timber elements, only a single species and grade were considered in this research. This decision was made to limit model complexity and focus on how prescriptive fire design and floor system design affects EC. Designers should understand, however, that species, grade, and timber sourcing can have a significant effect on the embodied carbon of the mass timber elements. Figure 5-31 uses CLT product data and EPDs from a range of manufacturers and demonstrates the wide variation in EC per unit of bending strength per square foot of panel. The relationships between relative grade strength and EC changes when different levels of SST are considered. Figure 5-32 includes a conceptual visualization of the unit considered on the vertical axis of the Figure 5-31 plots. Table 5-17 summarizes the selected wood properties and range of sizes used in the database from which

the parametric model selects elements. Designers should also consider the impact of A4-associated embodied carbon, as longer transportation distances may overcome benefits in A1-A3 EC when comparing some products. EC from the A4 module is out of the scope of this study.

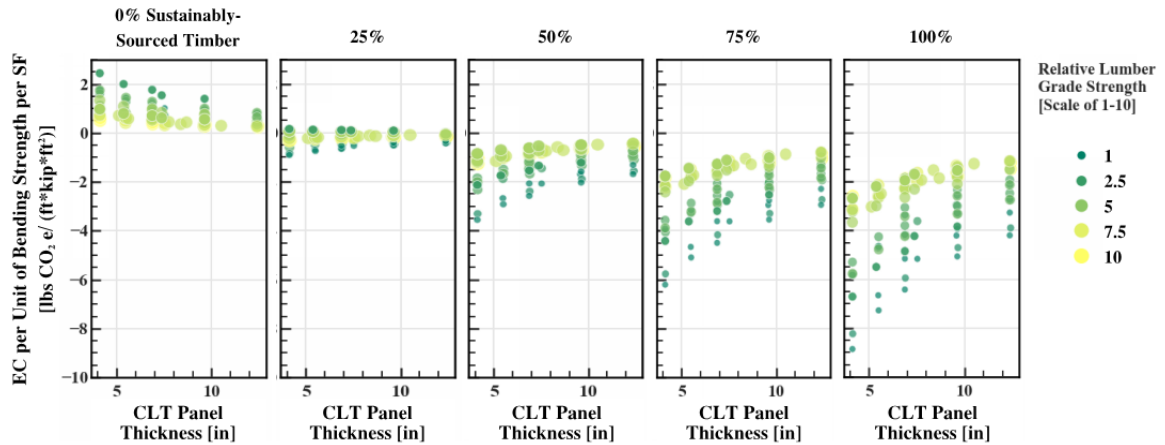


Figure 5-31: EC per Unit of Bending Strength per 1 SF panel versus CLT Panel Thickness; a relative lumber grade strength rating of 1 represents the weakest grade, and a rating of 10 represents the strongest grade (Strength and grade data obtained from manufacturer technical guides [39]–[41], [239]; EC data based on manufacturer EPDs, or ICE V3.0 values where EPDs are not available [61])
 (1 lb CO₂ eq/(ft-kip*ft²) = 3.6 kg CO₂ eq/(kN-m*m²); 1 inch = 25.4 mm)

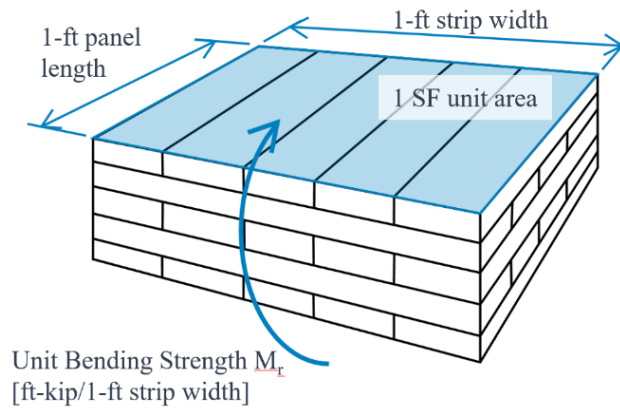


Figure 5-32: Representative example of 1 unit of bending strength for a 1 SF panel. This is the normalized unit for the data shown in Figure 5-31. (1 ft = 0.305 m.; 1 ft² = 0.093 m²; 1 ft-kip = 1.36 kN-m)

Table 5-17: Structural design assumptions for timber components

Item	Assumed Condition	Additional Comments
CLT Panels	Spruce-Pine-Fir and Douglas Fir	Uses Structurlam Grade V2M1.1 as a baseline reference. Panel layup options include 3, 5, 7, and 9 plies, with 1-3/8" (35 mm) plies.
	Density = 26 pcf (1.24 kN/m ²)	<i>Note: Panels with thinner, 5/8" (16 mm), tangential plies were found in initial analysis to be inefficient for the char design methods used in the model, and are therefore not considered in this research.</i>
Glulam Framing	Douglas Fir	Uses Structurlam Grade Series 24F-V8 as a baseline reference. Size options include those ranging from 5.125" (130 mm) wide x 11.75" (298 mm) deep to 20" (508 mm) wide x 56.75" (1441 mm) deep.
	Density = 35 pcf (1.68 kN/m ²)	

5.2.6.6 Design Space Exploration Methods

This research uses Design Space Exploration (DSE) to explore the resulting data for trends, and to help understand how design choices affect the performance of a variety of designs. [179] In this manner, design performance can be mapped against design variables during analysis. [183] Because of the fast computational time of the model, the full design space was sampled for all the variables and ranges listed in Table 5-15, resulting in 2,480 designs, 1,854 of which could be designed to meet all the design requirements, which accounts for 75% of the original design space.

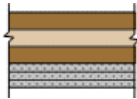
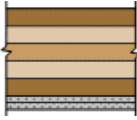
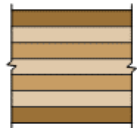
5.2.7 Results and Discussion

The results of the previously discussed modelling are included in the following section. The analysis is intended to help understand how data extracted from a parametric model can be used to understand trends in prescriptive fire design options and EC and to help guide early design decisions. Results are separated by construction type, as this is typically known early in

design; however, there are similarities between construction types, which will be noted where applicable. The results and discussion section discusses within the context of the three fire design configurations noted in Figure 5-29. Key terminology for each configuration is summarized in Table 5-18. Further, use of the term “system” is in reference to the five main floor system types described in Figure 5-28. The terms “non-carbon-storing” and “carbon-storing” timber in this section refer to timber with positive and negative material EC values, respectively. The carbon storage concept is used generally in this paper to compare different assumptions about sustainable timber sourcing, and further discussion and study of actual amounts of claimable carbon storage are beyond the scope of this work. Based on material EC data per Table 5-16, CLT and Glulam are carbon-storing when the percentage of SST is greater than 19% and 20%, respectively.

Prior to more a specific presentation of the results based on construction type is a summary overview of the results. Generally, the greatest differences occur across the SST and floor system variations. Further, differences between fire design configurations are clearer than between construction types. Although differences between construction types are subtle, the authors have chosen to separate discussion later in this section by construction type to offer a stand-alone analysis for single construction types of interest. Figure 5-33 looks closer at a variety of SST proportions, using the data from Type IV-C as an example. Similar trends and comparisons exist from a high-level perspective at Type IV-A and Type IV-B as well. Each column of plots in the figure is for the noted floor system, and data is colored based on the fire design configuration.

Table 5-18: Summary of terminology used to describe fire design configurations to achieve required FRR

Fire Design Configurations	Configuration Icon	Short-hand labels	Simple text description
<i>Full FRR from noncombustible protection</i>		Protected	Fully protected method
<i>Combined: portion of FRR from each method</i>		Combined	Combined approach method
<i>Full FRR from char method at max area permitted</i>		Exposed	Fully exposed method

Per Figure 5-33, at 0% SST, the trends are intuitive, with EC increasing as bay size increases. This will be true for any non-carbon-storing design. By 25% SST, the designs are approaching carbon-storing designs, and the EC versus bay size trends have nearly flattened out for most systems. At 50% SST, many designs have become carbon-storing except for most of the steel hybrid designs (TS and TSb), and most systems see reduced EC and increased carbon storage as bay size increases, except for the TSb system. The steel hybrid designs become mostly carbon-storing by 100%; however, the TSb system still sees an increasing trend line for EC versus bay size. Some key takeaways for designers include the following:

- At 25% SST, the different fire design configurations are generally competitive with each other, allowing design flexibility.
- For most systems and designs, as more SST is used, designs become carbon-storing and can store more carbon by increasing bay size.
- For steel-hybrid designs with infill framing, smaller bays provide reduced EC no matter the SST proportion, and most designs aren't carbon-storing until 100% SST is used.
- Fully protected designs tend to have lower EC over exposed designs in low-SST options, and vice versa for high-SST options.

Note that per the representative construction type comparisons in Figure 5-34 that differences across construction types are marginal for similar fire design strategies.

While the focus of this analysis is on EC, given the trend at higher proportions of SST of reduced EC for larger bays, competing objectives must be considered. In a carbon-storing design, if minimizing EC and maximizing carbon storage of the floor structure are the only goals, then the largest designs using the greatest amount of timber should be used. However, larger bays require deeper structural elements, which can increase floor-to-floor heights, building heights, envelope area and related operating energy, project costs, constructability, and more. Figure 5-35 includes multi-objective plots for Type IV-C with 0, 50, and 100% SST showing EC versus depth. The non-carbon-storing designs can achieve both low EC and low structural depth by reducing bay size. As designs become carbon-storing, in most cases, the EC and depth objectives begin to compete with each other. It is up to the designer to consider architectural design needs to optimize the amount of EC given system depth constraints. As previously noted, the TSb system is the only one which maintains a positive trend between EC and depth even at 100% SST. Note similarly per Figure 5-36 that differences across construction types are again marginal for similar fire design options.

The remainder of this paper focuses on the EC objective; however, all objectives should be considered during design. The following sections will study the 50% SST option in further detail, per the previous discussion of wood sourcing materials. Note that the general trends and results at 50% SST will be similar at higher proportions of SST, but exaggerated and to a greater degree as the timber stores more carbon.

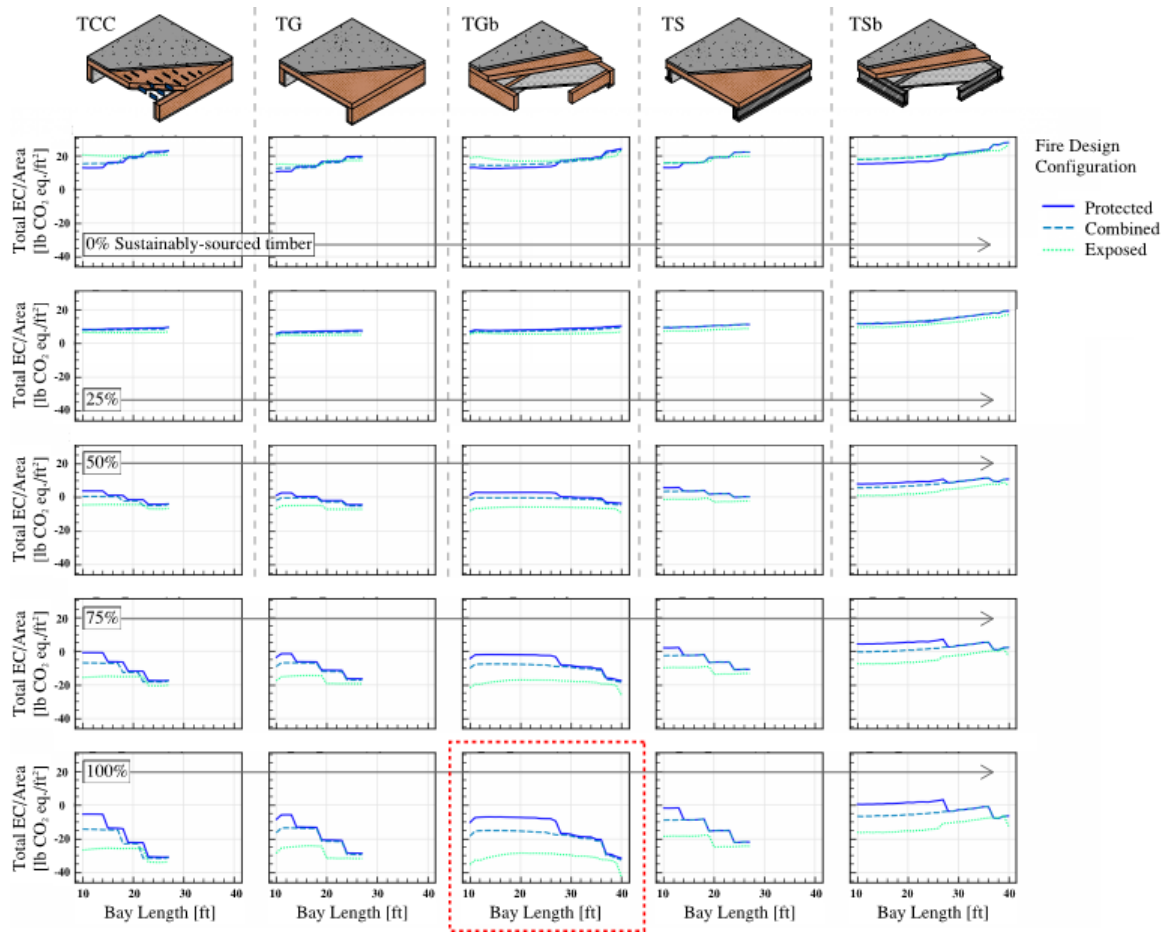


Figure 5-33: Sample of results for Type IV-C construction for all floor systems and select timber-sourcing options; Plot outlined in red dashed box shown for all three construction types in Figure 5-34 (1 lb CO₂ eq/ft² = 4.88 kg CO₂ eq/m²; 1 foot = 0.305 m)

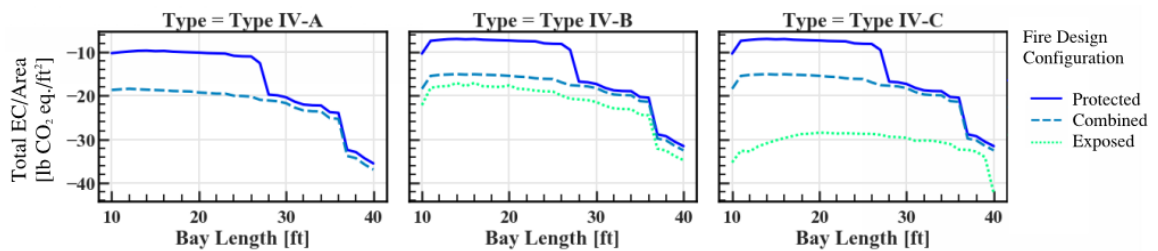


Figure 5-34: Example comparison plot between construction types IV-A through C for the TGb system at 100% sustainably-sourced (1 lb CO₂ eq/ft² = 4.88 kg CO₂ eq/m²; 1 foot = 0.305 m)

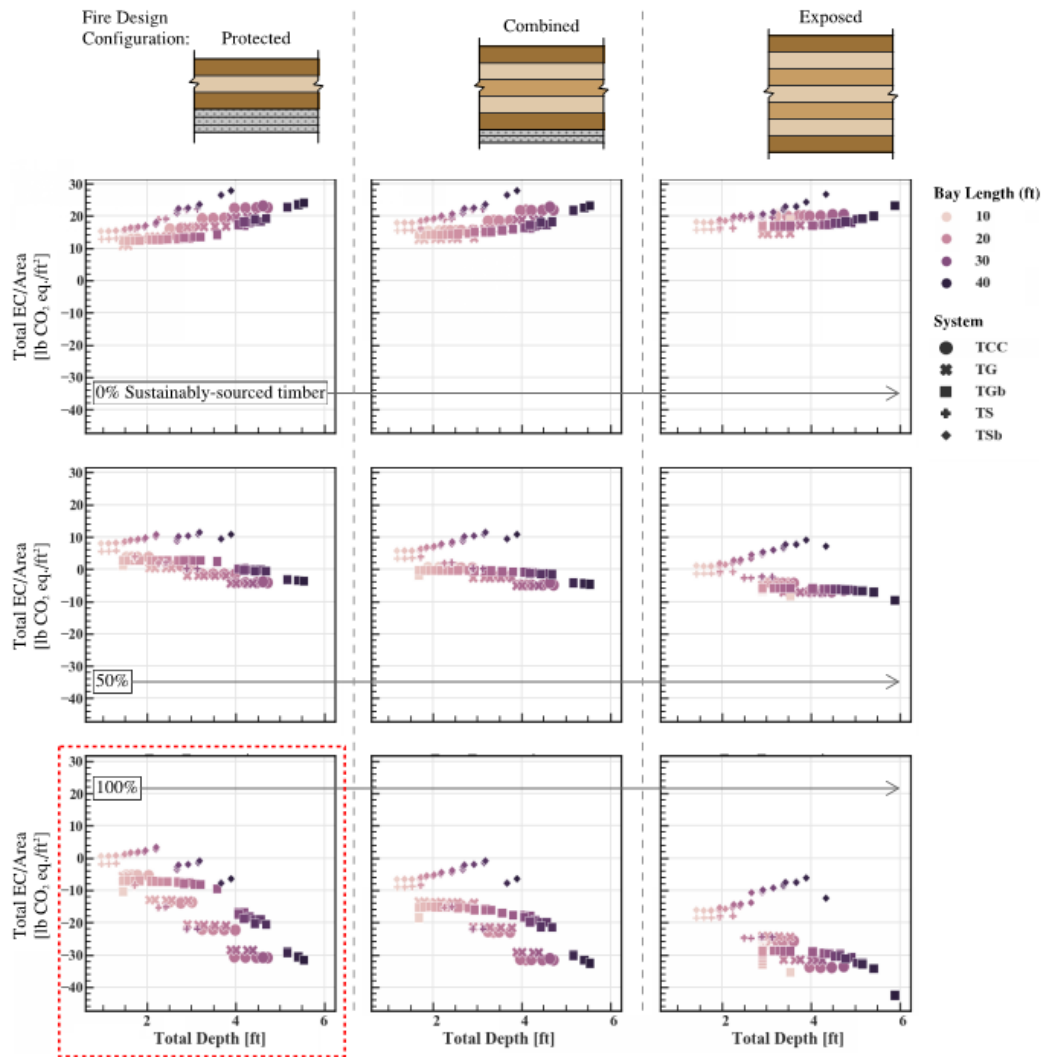


Figure 5-35: Sample of data from Type IV-C showing multi-objective plots of EC versus System Depth; Plot outlined in red dashed box shown for all three construction types in Figure 5-36

(1 lb CO₂ eq./ft² = 4.88 kg CO₂ eq./m²; 1 foot = 0.305 m)

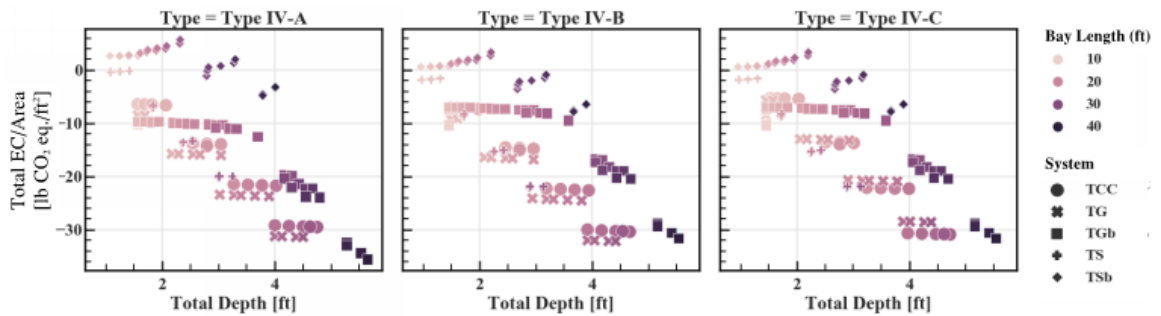


Figure 5-36: Example comparison plot between construction types IV-A through C for the protected fire design option at 100% sustainably-sourced (1 lb CO₂ eq./ft² = 4.88 kg CO₂ eq./m²; 1 foot = 0.305 m)

5.2.7.1 Type IV-A Construction

Type IV-A allows mass timber elements to achieve the required FRR either by noncombustible materials alone (fully protected method), or a combination of noncombustible materials and design for timber char (combined approach method). Type IV-A does not allow any exposed timber. Note again that the plots in this section are for 50% SST.

Figure 5-37 includes a plot for each fire design configuration, with the data colored and styled based on the floor system type. Some annotations which are applicable to all construction types in this paper are provided on these plots, but are omitted from future plots for clarity. Note that the data trends do not follow a smooth path; rather, there is a stepping behavior that occurs. Further review of the data finds that steps correspond to different required minimum CLT thicknesses, and that the CLT panel drives the stepped changes in EC. Further, designs in these plots can be divided into “carbon-storing” and “non-carbon-storing” designs as annotated for the protected configuration plot. Future plots will clarify this division with a bold horizontal red line at EC equal to zero. Figure 5-37 is most helpful in comparing Systems to each other for a given fire design configuration. Below are the key points from each plot:

- For the fully protected method:
 - The TCC and TG systems offer the lowest EC at most bay spans through their 27-foot (8.3 m) limit.
 - The TS system is competitive with the other systems considering some uncertainty is involved. (Note that an in-depth analysis of uncertainty is out of the scope of this paper.)
 - The TCC, TG, TGb, and TS systems each become carbon-storing above 15 ft (4.6 m), 13 ft (4.0 m), 27 ft (8.2 m), and 19 ft (5.8 m), respectively.
- For the combined approach method:
 - The TCC, TG, and TGb systems are all competitive at various spans.
 - The TS system is no longer competitive at most spans.
 - Carbon-storing designs exist at all spans for various floor system types.

Figure 5-38 presents the same data as Figure 5-37, but sorts the data into plots for each System. Therefore, this figure is most helpful in comparing fire design configurations to each other for a given System. This plot is again annotated with notes applicable to all construction types, which will be omitted from future plots for clarity. Below are key points from Figure 5-38:

- In all cases, the combined method offers the lowest EC.
- The protected method becomes competitive with the combined method for spans above 27 feet (8.3 m) for the systems with infill beams (TGb and TSb), and above about 14 feet (4.3 m) for the systems without infill beams (TCC, TG, and TS).
- In some cases, the use of the combined method pushes a design from being non-carbon-storing to carbon-storing, for example for the TGb system.

Based on the previous plots, below is a non-exhaustive set of decisions that will contribute to minimizing EC for Type IV-A construction when 50% SST is used.

- Use the combined method for fire design for any bay size and System type.
- Design a TCC, TG, or TGb system for spans up to 27 feet (8.3 m), and design a TGb system for spans over 27 feet (8.3 m) whenever architectural depth requirements allow it.
- Depending on the depth restrictions, either shorter bay spans and/or the TSb system should be used to avoid the high EC of the long-span TS system.
- Choosing longer spans will minimize the EC for a given system for all but the TS system.

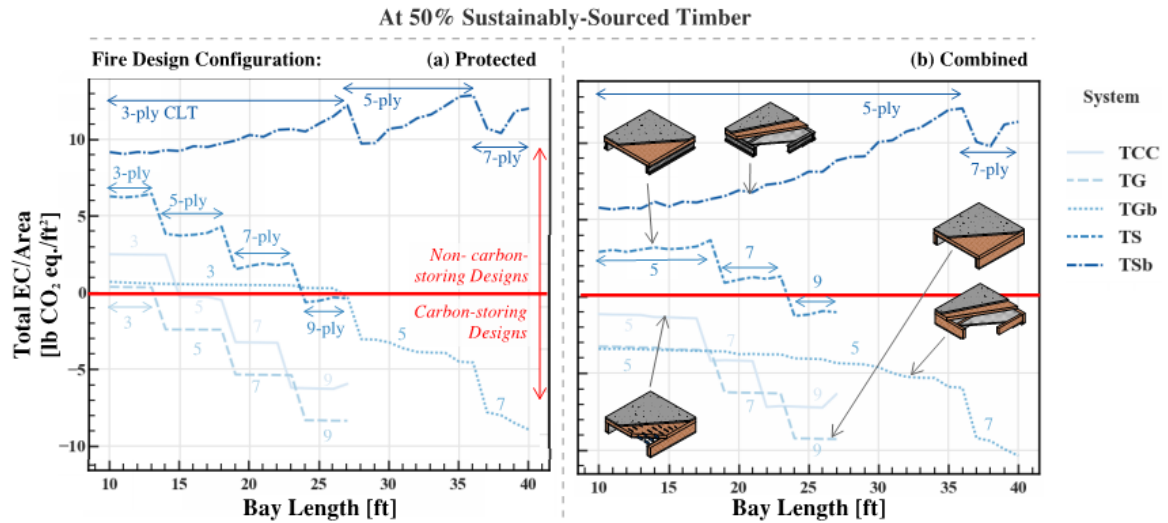


Figure 5-37: EC versus Bay Size for Type IV-A Construction with 50% SST;
 EC = 0 is denoted by a thick horizontal line; (a) Fully protected (b) Combined approach
 (1 lb CO₂ eq/ft² = 4.88 kg CO₂ eq/m²; 1 foot = 0.305 m)

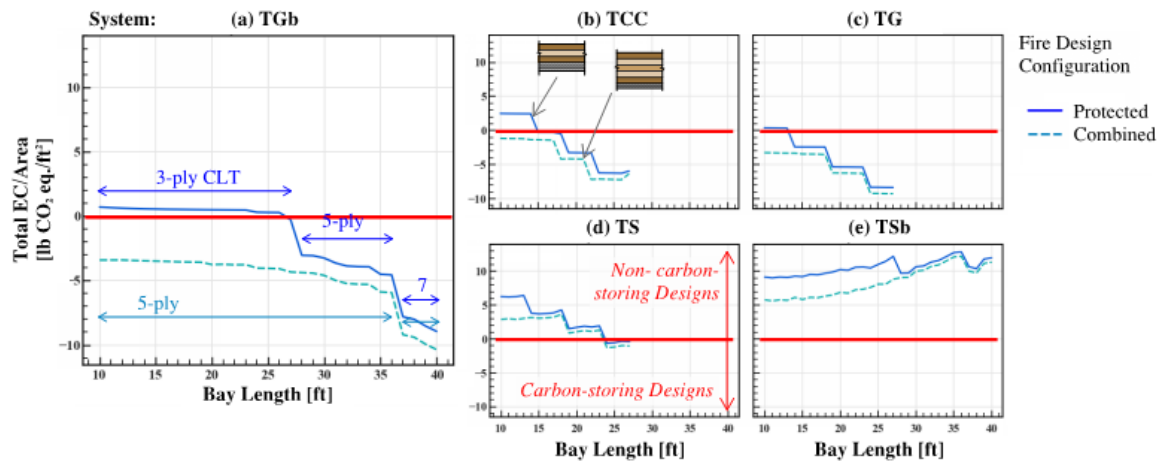


Figure 5-38: EC versus Bay Size for Type IV-A Construction with 50% SST. (a) All-timber system with infill framing, (b) Timber-concrete-composite system, (c) All timber system, (d) Steel-hybrid system, (e) Steel-hybrid system with infill framing
 (1 lb CO₂ eq/ft² = 4.88 kg CO₂ eq/m²; 1 foot = 0.305 m)

5.2.7.2 Type IV-B Construction

Type IV-B allows mass timber elements to achieve the required FRR by any of the three fire design configurations. However, there are limits and conditions set on the wall and ceiling area of timber which may be exposed, as summarized in Table 5-9. Note again that the plots in this section are for 50% SST.

Figure 5-39 is presented similarly as Figure 5-37, and some similar stepping behavior occurs relating to the required minimum CLT thickness. In Type IV-B construction, both the exposed and combined fire design methods provide carbon-storing design options at most spans. Below are the key points comparing Systems to each other in each plot:

- For the fully protected method:
 - The TCC and TG systems offer the lowest EC at most bay spans through their 27-foot (8.3 m) limit.
 - Carbon-storing designs only exist for the TCC and TG systems with bay spans above 13 feet (4.0 m) and the TGb system with bay spans above 26 feet (7.9 m).
- For the combined approach method:
 - The TCC, TG, and TGb systems are all competitive at various spans.
 - The TS system is no longer competitive at most spans.
 - Carbon-storing designs exist at all spans for various floor system types.
- For the exposed method:
 - There is a clear division between steel-hybrid designs being mostly non-carbon-storing and all others being carbon-storing.
 - The TCC, TG, and TGb systems are competitive at small spans from about 10-17 feet (3.1-5.2 m).

Below are key points comparing fire design configurations to each other in each plot in Figure 5-40:

- In all cases, the combined and exposed methods offers the lowest EC and are generally competitive with each other.

- The protected method becomes competitive with the exposed and combined methods for spans above 27 feet (8.3 m) for the systems with infill beams (TGb and TSb), and above about 14 feet (4.3 m) for the systems without infill beams (TCC, TG, and TS).

Based on the Type IV-B plots, below is a non-exhaustive set of decisions that will contribute to minimizing EC for Type IV-B construction when 50% SST is used.

- Use the combined or exposed method for fire design for any bay size and System type.
- Design a TCC, TG, or TGb system for spans up to 27 feet (8.3 m), and design a TGb system for spans over 27 feet (8.3 m) whenever architectural depth requirements allow it.
- Depending on the depth restrictions, either shorter bay spans and/or the TSb system should be used to avoid the high EC of the long-span TS system.
- Choosing longer spans will minimize the EC for a given system for all but the TS system.

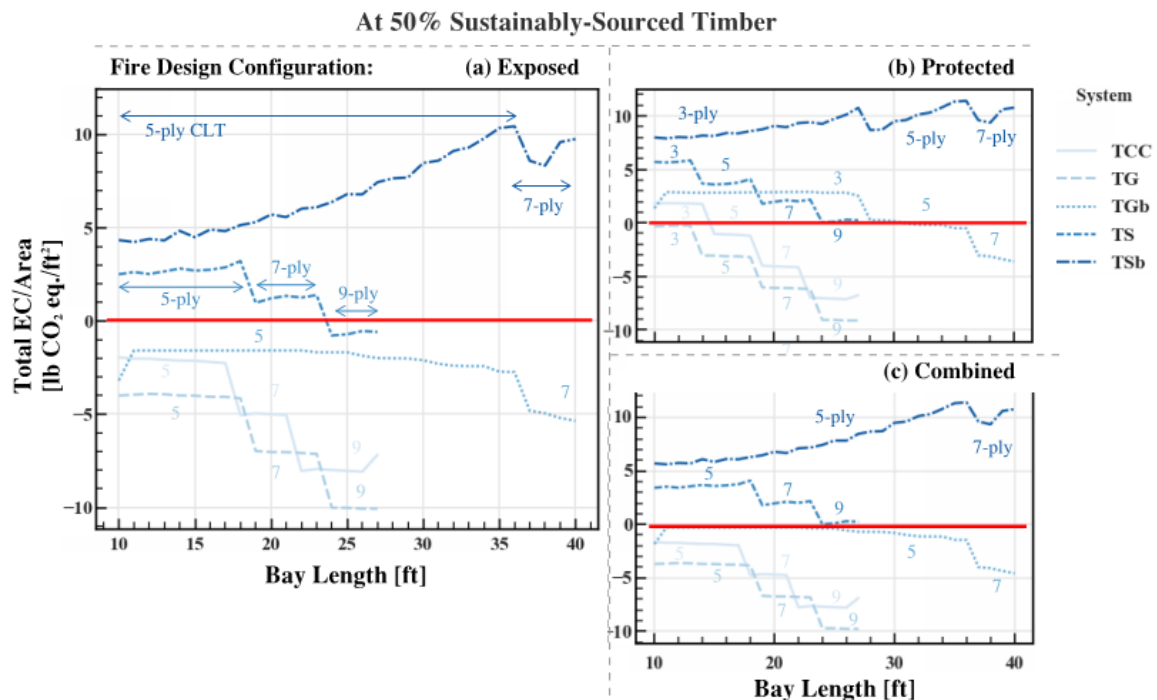


Figure 5-39: EC versus Bay Size for Type IV-B Construction with 50% SST;
 EC = 0 is denoted by a thick horizontal line;
 (a) Exposed method (b) Fully protected method (c) Combined approach method
 (1 lb CO₂ eq./ft² = 4.88 kg CO₂ eq./m²; 1 foot = 0.305 m)

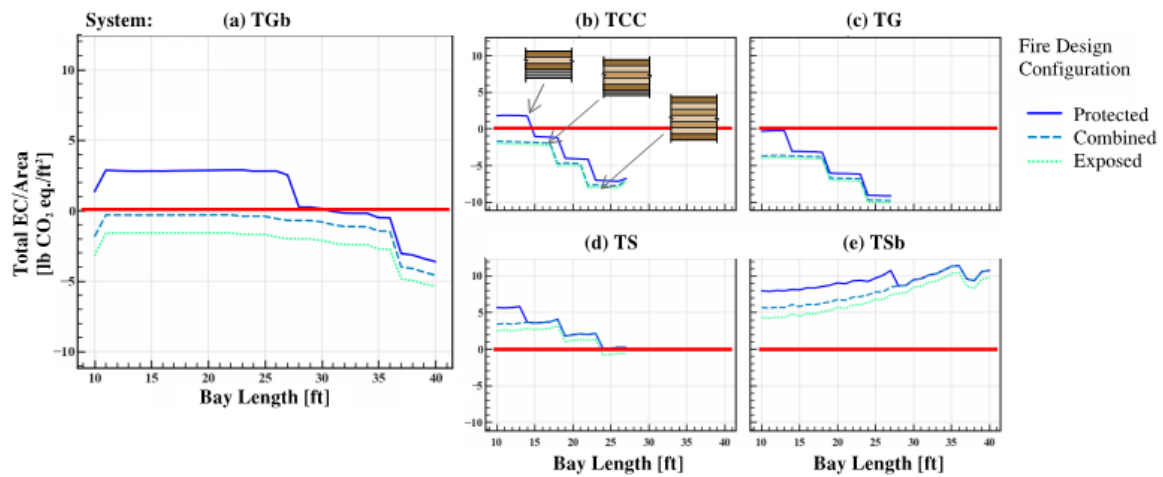


Figure 5-40: EC versus Bay Size for Type IV-B Construction with 50% SST. (a) All-timber system with infill framing, (b) Timber-concrete-composite system, (c) All timber system, (d) Steel-hybrid system, (e) Steel-hybrid system with infill framing
 (1 lb CO₂ eq/ft² = 4.88 kg CO₂ eq/m²; 1 foot = 0.305 m)

5.2.7.3 Type IV-C Construction

Type IV-C allows mass timber elements to achieve the required FRR by any of the three fire design configurations, and the timber is permitted to be fully exposed. Note again that the plots in this section are for 50% SST.

Figure 5-41 is presented similarly as Figure 5-37, and some similar stepping behavior occurs relating to the required minimum CLT thickness. In Type IV-C construction, both the exposed and combined fire design methods provide carbon-storing designs at all spans. All systems using the exposed method are fully carbon-storing, except for the TSb system. Below are the key points comparing Systems to each other in each plot:

- For the fully protected method:
 - The TCC and TG systems offer the lowest EC at most bay spans through their 27-foot (8.3 m) limit.
 - Carbon-storing designs only exist for the TCC and TG systems with bay spans of 18-27 feet (5.5-8.3 m) and the TGb system with bay spans of 31-40 feet (9.4-12.2 m).

- For the combined approach method:
 - The TCC, TG, and TGb systems are all competitive at various spans.
 - The TS system is no longer competitive at most spans.
 - Carbon-storing designs exist at all spans for various floor system types.
- For the exposed method:
 - All systems (except for the TSb) are carbon-storing, which allows greater design flexibility.
 - The TCC, TG, and TGb systems are competitive at all applicable spans.

Below are key points comparing fire design configurations to each other in each plot in Figure 5-42:

- In all cases, the exposed method offers the lowest EC.
- The protected and combined methods become competitive each other for spans above 27 feet (8.3 m) for the systems with infill beams (TGb and TSb), and above about 14 feet (4.3 m) for the systems without infill beams (TCC, TG, and TS).

Based on the Type IV-C plots, below is a non-exhaustive set of decisions that will contribute to minimizing EC for Type IV-C construction when 50% SST is used.

- Use the exposed method for fire design for any bay size and System type.
- Design a TCC, TG, or TGb system whenever architectural depth and structural requirements permit.
- Depending on the depth restrictions, either shorter bay spans and/or the TSb system should be used to avoid the high EC of the long-span TS system.
- Choosing longer spans will often minimize the EC for a given system for all but the TS system, and in the case of the exposed option for non-TS systems.

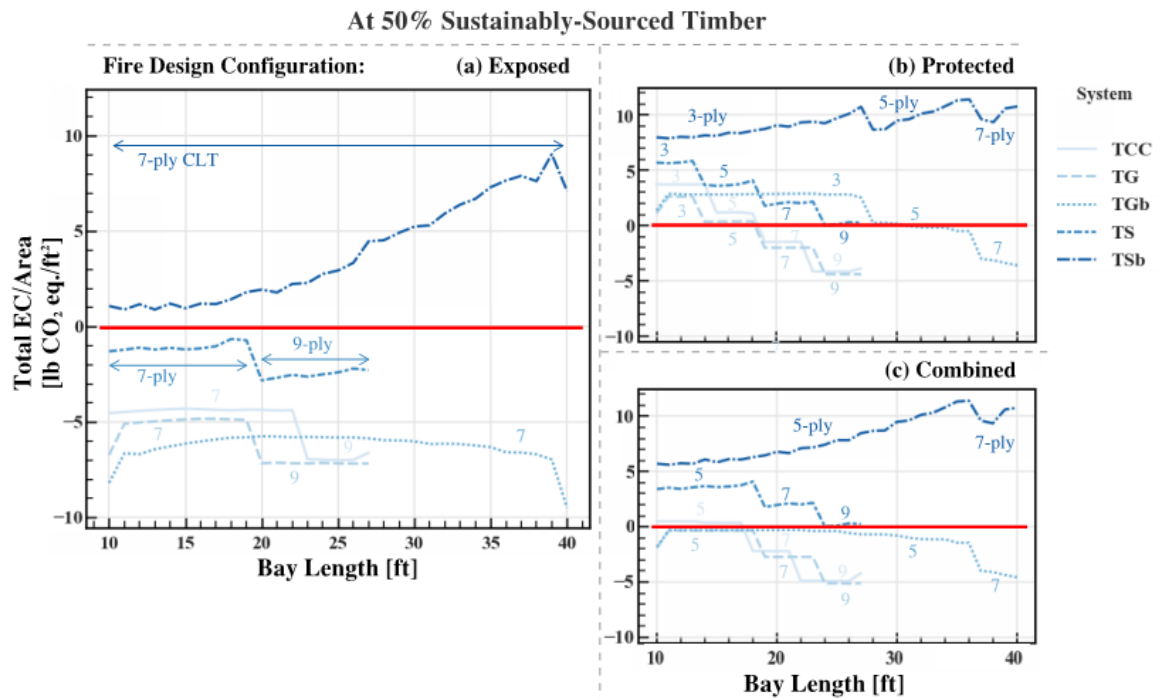


Figure 5-41: EC versus Bay Size for Type IV-C Construction with 50% SST;
 EC = 0 is denoted by a thick horizontal line;
 (a) Exposed method (b) Fully protected method (c) Combined approach method
 (1 lb CO₂ eq/ft² = 4.88 kg CO₂ eq/m²; 1 foot = 0.305 m)

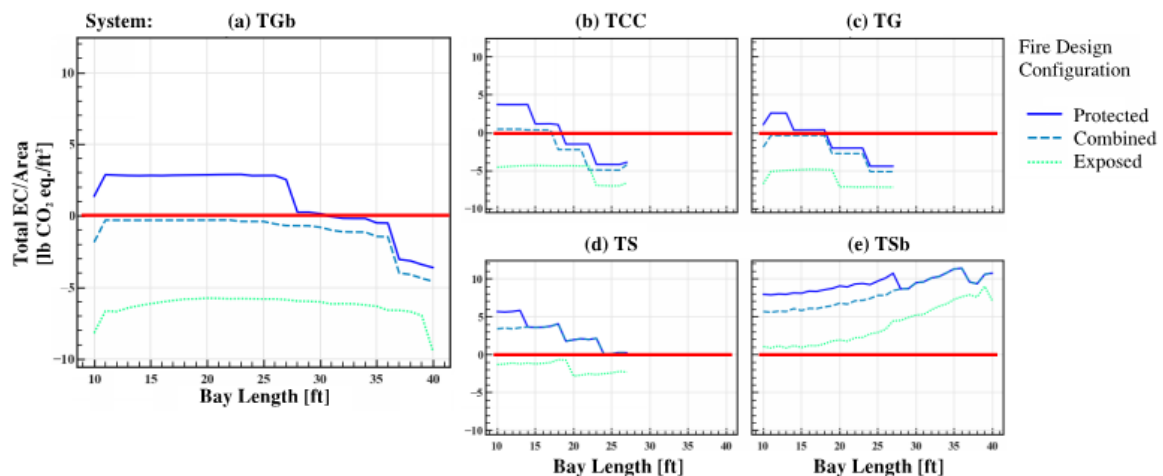


Figure 5-42: EC versus Bay Size for Type IV-C Construction with 50% SST. (a) All-timber system with infill framing, (b) Timber-concrete-composite system, (c) All timber system, (d) Steel-hybrid system, (e) Steel-hybrid system with infill framing
 (1 lb CO₂ eq/ft² = 4.88 kg CO₂ eq/m²; 1 foot = 0.305 m)

5.2.8 Design Example

A hypothetical design example was created to demonstrate how the floor system data may be used to guide early-stage design decisions. In this example, design goals are described below and summarized in Figure 5-43.

- 8-story Type IV-C construction with a Residential (R-2) occupancy
- 15-25' (4.6-7.6 m) bay span with a maximum total system depth of 3' (0.91 m)
- Coordinate with MEP services and provide fast construction schedule
- Project located in the West Region (Assume 75% SST per the AWC Wood Sourcing Tool)
- Reduce EC and expose CLT ceilings

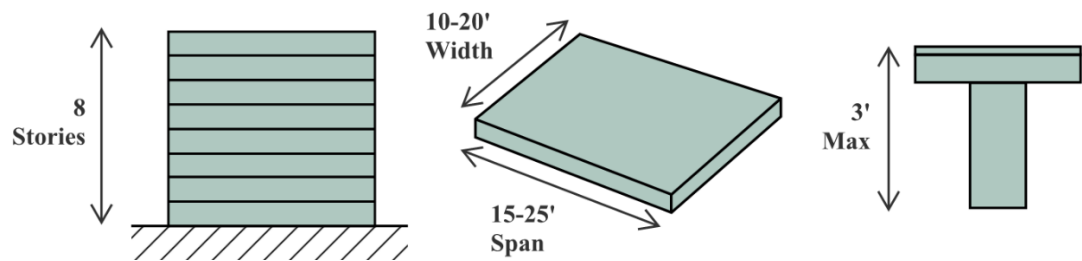


Figure 5-43: Hypothetical design example dimensional criteria (1 ft = 0.305 m)

Figure 5-44 shows the filtered data for Type IV-C construction with bay spans from 15 to 25 feet (4.6 to 7.6 meters). The plots are arranged by fire configuration and the data is colored and styled by system. The shaded regions with each data line represent the range of values with different bay aspect ratios and numbers of infill beams. This figure shows that differences in EC are significant across different fire design configurations, with the exposed option offering the greatest carbon storage. The exposed TG and TGb systems are selected for further comparison. The authors anticipate that these systems may be relatively deep, and therefore the TS system will also be considered to offer potential low-depth options.

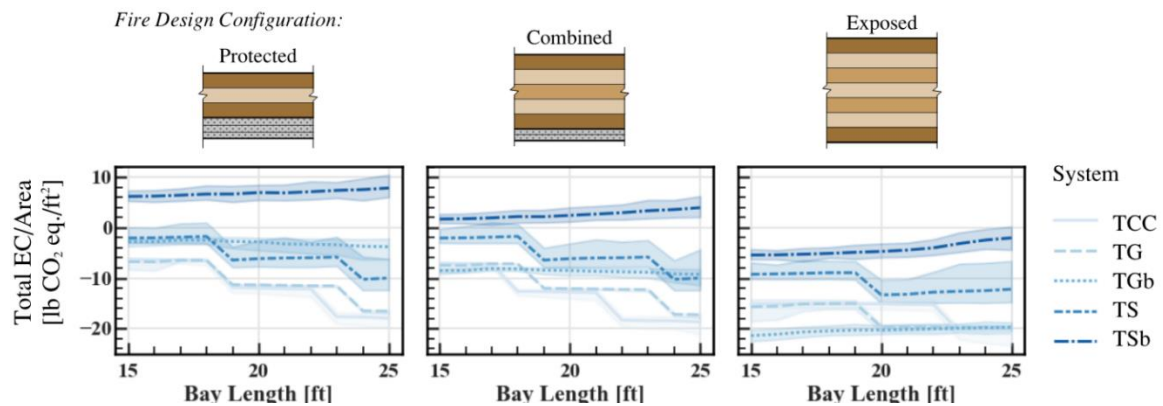


Figure 5-44: EC versus Bay Length for Type IV-C design options comparing fire design configurations. Data style and hue is determined by System type. Shaded regions around each plotted line represents the range of values for different bay aspect ratios and numbers of infill beams

(1 lb CO₂ eq/ft² = 4.88 kg CO₂ eq/m²; 1 foot = 0.305 m)

Figure 5-45 further filters the data to show only the TG, TGb, and TS systems for the exposed fire design configuration. Based on the dataset, only the data for one infill beam for the TGb system is shown because fewer infills tends to result in the lowest EC as compared to including more infill beams. Data lines are colored based on bay aspect ratio, and generally show negligible differences between EC for different bay aspect ratios. For the design goals, only ratios of 1 and 1.5 will be considered further. Also, because EC is similar between the TG and TGb systems, only the TG system will be considered out of those two because the preference is to have no infill beams for coordination with services.

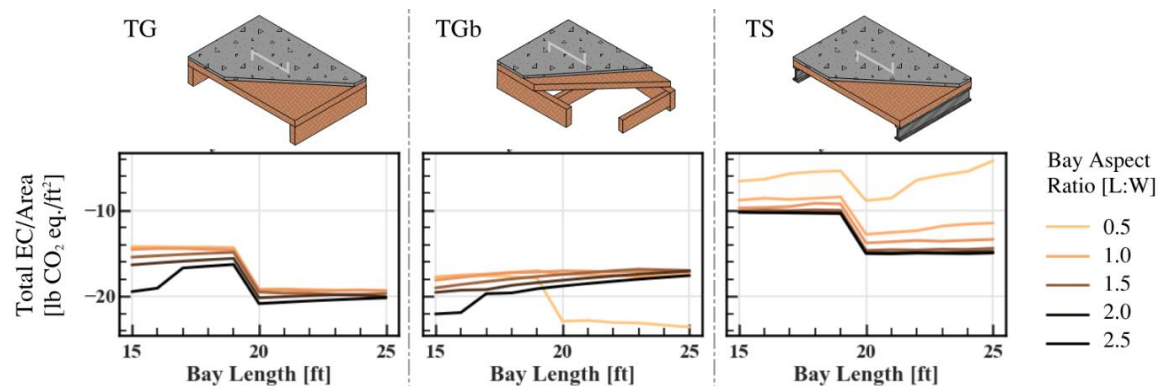


Figure 5-45: Comparison between designs filtered to include only exposed fire configurations, the TG and TS systems, and the TGb system with only 1 infill beam. Data colored by bay aspect ratio

(1 lb CO₂ eq/ft² = 4.88 kg CO₂ eq/m²; 1 foot = 0.305 m)

Finally, Figure 5-46 shows a reduced filtered dataset, which becomes a chart of design options to select from to take further into design refinement. This chart shows that there are trade-offs between system depth and EC for 75% SST. While the TG system maximizes carbon storage, the TS system offers much shallower options. While these example requirements led to the options in Figure 5-46, this is an iterative process, and other data visualizations may be considered to refine early design decisions. Further, other disciplines out of the scope of the paper should be considered as well.

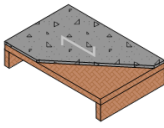
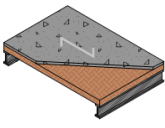
System	Bay Span [ft]	Bay Width [ft]	Aspect Ratio [W:L]	Assembly Depth [ft]	EC (lbs CO ₂ eq./ft ²)	System	Bay Span [ft]	Bay Width [ft]	Aspect Ratio [W:L]	Assembly Depth [ft]	EC (lbs CO ₂ eq./ft ²)
 TG	15	10	1.5	2.9	-15.4	 TS	15	10	1.5	1.6	-10.1
	16	10.7	1.5	2.9	-15.3		17	11.3	1.5	1.7	-10.0
	17	11.3	1.5	2.9	-15.1		16	10.7	1.5	1.7	-10.0
	18	12	1.5	2.9	-15.0		19	12.7	1.5	1.9	-10.0
	19	12.7	1.5	2.9	-14.9		18	12	1.5	1.9	-9.9
	15	15	1	2.9	-14.5		15	15	1	1.9	-9.7
	16	16	1	2.9	-14.4		16	16	1	1.9	-9.7
	17	17	1	3.0	-14.4		17	17	1	1.9	-9.5
	20	13.3	1.5	3.1	-19.5		18	18	1	1.9	-9.2
	18	18	1	3.3	-14.5		20	13.3	1.5	2.2	-14.7
	20	20	1	3.4	-19.3		19	19	1	2.2	-9.2
	19	19	1	3.5	-14.6		20	20	1	2.5	-13.8
Color Code Key  Longest span to Shortest  Deepest assembly to Shallowest  Highest EC to Lowest Red Text = Max total depth exceeded											

Figure 5-46: Table of final design options for consideration with depth and EC data;
 (1 lb CO₂ eq/ft² = 4.88 kg CO₂ eq/m²; 1 foot = 0.305 m)

5.2.9 Conclusions

This research uses parametric modeling and design space exploration to understand how prescriptive fire design methods affect the EC of various mass timber and hybrid mass timber floor systems. The results section of this paper provided a stand-alone section for each construction type which outlines some of the design and EC trends for each type, as well as what

design decisions will lead to reduced EC. Summarized here are trends that are shared or similar between all three construction types. Regarding sustainable timber sourcing:

- As more SST is used, most designs become carbon-storing, and all designs see reductions in EC.
- At 25% SST, the different fire design configurations are generally competitive with each other, allowing design flexibility.
- Fully protected designs tend to have lower EC over exposed designs in low-SST options, and vice versa for high-SST options.
- In carbon-storing designs, longer spans tend to result in lower EC, but will typically have greater maximum assembly depth as a trade-off.

Regarding the designs considered in the results section for 50% SST:

- The TCC and TG systems offer the lowest-EC options.
- Maximizing char design and minimizing noncombustible protection results in the lowest-EC designs at comparable bay sizes.
- Roughly considering that some uncertainty exists, for some spans and construction types, all three fire design configurations are competitive with each other, allowing some design flexibility.
- Infill beams are required to span longer than 27 feet (8.3 m).
- Depending on the depth restrictions, either shorter bay spans and/or the TSb system should be used to avoid the high EC of the long-span TS system.
- Choosing longer spans will often minimize the EC for a given system for all but the TS system, and in the case of the exposed option for non-TS systems.

5.2.10 Limitations and Future Work

The research discussed in this paper is based on a narrow scope, which allows for more in-depth modeling and analysis, but which results in many limitations. This work focuses on floor systems as a first step to understanding how parametric frameworks can help understand EC for mass timber structures. Floor systems were selected because they contribute a significant portion

of EC to the overall mass timber structure. Future work in this area could benefit from similar studies of lateral systems, foundations for mass timber structures, and columns.

Further, due to the nature of parametric modelling, which often depends on simplified models with key variables to limit the analysis time and data quantity, only an early-stage design level of detail is modeled. For the type of data and modeling capabilities that currently exist, the authors found that early-stage design is a more appropriate application than attempting to inform later stages of the design process.

Connections are currently neglected in the model, and additional work is needed to understand how much connections contribute to the embodied carbon of a floor system and building. Connections have not been included at this stage because of the early-stage design focus. As noted in Table 5-15, pinned connections are assumed in the model to allow for theoretically simpler connections which are less likely to have a large contribution to floor system EC as compared to fixed connections.

To limit the complexity of the model and the number of variables considered, only a single wood species was included for each timber element. This was done because the species was found to have a significant effect on embodied carbon of the timber elements, and so a median grade was selected to allow for simpler comparisons of the fire design aspects, which is the focus of this paper.

5.2.11 Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

5.2.12 Acknowledgements

The authors would like to thank Kenneth Bland and the American Wood Council for providing a review of this article. We especially appreciate Kenneth's guidance on the building code summary, fire design overview, literature review, and sustainability metrics for mass timber. The authors would also like to thank M. Kevin Parfitt, Dr. Ali Memari, and Corey Gracie-Griffin for their general advisement on this work. This research is supported in part by the Graduate Assistance in Areas of National Need (GAANN) Fellowship and the J. Roger Glunt Graduate Fellowship in Housing, hosted by the Pennsylvania Housing Research Center (PHRC). Neither fellowship had any role or input in the planning and implementation of this research and the paper results do not reflect the views of these organizations.

5.3 Chapter Conclusions

Both papers appearing in this chapter presented the results of a study of the impacts of fire design provisions on structural design goals and embodied carbon (EC). Both papers studied the floor systems with different timber carbon-storage assumptions, which significantly affects the findings and trends in EC. Therefore, designers should try to understand early on how sustainably-sourced the available timber for their project is. Without assuming carbon-storing timber, there are many cases where fire design using noncombustible protection offers competitive or reduced EC as compared to exposed designs using char. As more sustainable timber is used and more carbon storage is assumed, the protected systems at longer spans offer reduced-EC design options. In general, all structural system types perform the best for EC with the fully protected option at shorter spans, the combined approach option at mid-range spans, and the fully exposed option at longer spans. Further, considering the same spans and fire design options, differences between mass

timber construction types are marginal, giving designers flexibility in applying guidance across the construction types.

Another unique design consideration for mass timber system in addition to fire design includes designing for acoustic performance. All mass timber floor assemblies will require some amount of acoustic treatment to meet code minimum requirements for acoustic insulation (STC and IIC) between dwelling spaces. While this chapter assumed code minimum acoustic insulation in the models, the next chapter seeks to understand the impacts of acoustic insulation on structural design and EC goals.

Chapter 6

Acoustic Assemblies for Mass Timber Floors

The previous chapters focused on a more generalized set of mass timber floor system models that could be applicable to a variety of scenarios. To manage the complexity inherent in a parametric model with a variety of variables, some assumptions were made, including an assumption of code-minimum acoustic insulation. However, acoustics can be a common complaint or challenge of mass timber projects, and additional acoustic materials and products are often required for mass timber floor system design. Adding more material to improve acoustic insulation often adds embodied carbon, depth, or a combination of both.

This chapter includes a paper which originally appeared in the proceedings of the 2023 World Conference on Timber Engineering (WCTE 2023). [268] The paper includes modeling methods, results and discussion, and a summary of key findings. The content is largely the same as in the original paper, with only some minor revisions. While this chapter may serve as a standalone analysis and discussion of acoustic insulation, its results may contribute in a supplemental manner to the floor system models from Chapters 4 and 5.

Following is a discussion of author contributions. The first author and dissertation writer, Samantha Leonard, performed the majority of data collection, all of the data analysis and paper drafting, and most of the final paper revisions. Morgan Prichard aided in the data collection process. Mohamad Eddin and Jonathan Broyles provided initial input on the research topic and goals, occasional feedback during data gathering and analysis, and feedback for the draft paper. Nathan Brown and Sylvain Ménard provided feedback intermittently and for the draft paper. Broyles contributed to revisions for the final paper, and Eddin presented the work at WCTE 2023.

6.1 Trade-offs in embodied carbon and acoustic insulation for mass timber floor assemblies

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6.1.1 Abstract

Mass timber structural systems are increasingly used in the design of low and mid-rise buildings. One of the primary motivators for using mass timber structures is their low embodied carbon emissions (EC), which reduces a building's carbon footprint. Despite this advantage, criticism of mass timber structures in multi-story buildings is often poor air-borne and impact sound insulation. In response, this paper studies common mass timber floor assemblies for their EC and sound insulation performance. EC data is used along with previous experimental acoustic data to evaluate how acoustic insulation affects the sustainability of mass timber floors. This study found that there is no clear relationship between EC and acoustic insulation; while high-EC assemblies exist, there are many low-EC assemblies at all levels of acoustic insulation. Trade-offs instead occur in the types of assemblies that can achieve performance goals and their depth or visible finish. While other factors such as cost or structural requirements may control assembly selection, designers seeking to reduce EC should consider room design needs and select acoustic insulation strategies with favorable EC-to-acoustic insulation ratios.

6.1.2 Introduction

Mass timber structures are increasingly gaining interest among building owners and developers due to their potential to positively affect the triple bottom line: sustainability, society, and economy. [45] Mass timber structural elements have been shown to require less energy during manufacturing compared to traditional structural materials such as steel and concrete, [6] can improve occupant wellness, [37] and have the potential to revitalize local economies in forested regions. [46]

However, the relatively lightweight mass timber floor structures often pose challenges for serviceability requirements such as sound insulation. [194], [269] The 2021 IBC requires that projects meet specific acoustic performance standards for floor and wall assemblies separating dwelling units. [34] The two main acoustic insulation performance quantifiers in North America are Sound Transmission Class (STC), a measure of a floor or wall assembly's ability to prevent airborne-based sound transmission between spaces, and Impact Insulation Class (IIC), a measure of a floor assembly's ability to insulate a space from impact noise (i.e., footfall) from above. [270]

Lab-based measurements for mass timber floor systems constructed using Cross Laminated Timber (CLT), a panelized mass timber product, have demonstrated that bare CLT alone cannot meet typical code requirements for acoustic insulation. [271] While several recommendations exist to improve the acoustic performance of a CLT floor system, not every recommendation improves the same acoustical phenomena. Common examples of acoustical treatments include using dense-porosity surfaces that reflect sound, adding mass to reduce vibration amplitudes, including sound-dissipating layers in the assembly to absorb sound, and providing acoustic separation between finishes and the structure to improve sound insulation.

[194], [272] These strategies complicate how acoustical performance can be improved for mass timber structures.

As sound insulation performance requirements can have significant effects on the floor assembly construction, designers require guidance during project decision-making. Many organizations offer resources with data on mass timber floor assembly acoustic performance, such as the FPInnovations CLT Handbook chapter on acoustics and the WoodWorks Inventory of Acoustically-Tested Mass Timber Assemblies (WW Inventory herein). [194], [196] However, there is limited guidance on how decisions related to sound insulation performance affect a mass timber floor system's carbon produced during material extraction, transportation, and manufacturing, also known as embodied carbon (EC).

Salles E Portugal et al. studied concrete versus cork flooring materials for their environmental impact. [273] Broyles et al. conducted design optimization of concrete floor slabs for embodied carbon and acoustic performance. [235], [274] Tomas M. Echenagucia et al. researched the acoustic optimization of a concrete structure for a concert hall space. [275] Mirdad et al. analyzed 28 mass timber-concrete composite floors for EC and STC and found that increasing timber thickness is generally more beneficial for sound insulation and EC than increasing concrete thickness; however, IIC was omitted, and the types of assemblies are limited. [276] Ilgin et al. reviewed 13 tall mass timber building case studies for various architectural design features, including finding an average floor-to-floor height of 3 m, which is affected by floor assembly construction. [277] Beyond these papers, current literature review did not find a comparison of acoustic performance and embodied carbon for a wide range of mass timber floor assembly types. This study builds on the existing WW Inventory by adding EC data for each assembly. By pairing acoustic insulation ratings and EC data sets, these performance objectives can be compared for a range of assembly types and configurations. The resulting findings are intended to aid early design decision making.

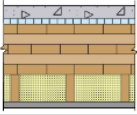
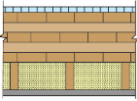
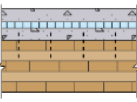
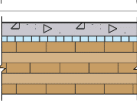
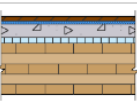
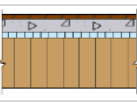
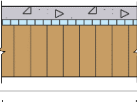
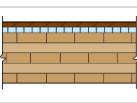
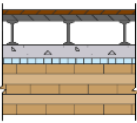
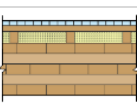
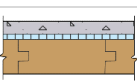
6.1.3 Methods

The studied assemblies for this research come from the WW Inventory, which is the most comprehensive database of mass timber assembly acoustic performance test results found during the literature review process. This study calculated EC for the assemblies based on the inventory's description of their construction, and EC is compared to the inventory's acoustic performance test ratings during the data analysis process.

6.1.3.1 Assembly construction

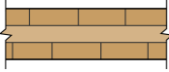
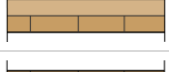
The WW Inventory included descriptions and test data for 349 mass timber floor assemblies. The inventory organized floor assemblies into six categories, which was further divided into twelve total categories in this study. The categories included in this study are summarized in Table 6-1. Assemblies include features such as: structural or non-structural toppings, exposed mass timber panel ceilings, suspended acoustic ceilings, and raised access floors. A variety of materials and products appear in the assemblies, including those of the following types: mass timber panel, concrete or gypsum topping, acoustic mats or systems, acoustic accessories, board-type products such as gypsum board and plywood, insulation, flooring, and acoustical underlayment. Assembly descriptions and typical material properties are used to estimate total assembly depth. In the final EC database, 92 out of 349 assemblies meet the 2021 IBC requirements, have both STC and IIC data, and have sufficient information to estimate EC.

Table 6-1: Categories used in this research, based on the WW Inventory. Symbols are referred to later in the results plots. The final main EC database is discussed further in section 2.3.

Symbol	Assembly Category & Symbol	Typical Assembly Construction	Number of Assemblies	Code-compliant w/ STC/IIC data	In Final Main EC Database
	Mass timber with ceiling side concealed, with or without finish floor		59	39	25
	Mass timber with ceiling side concealed, with or without finish floor, no topping		31	22	17
	CLT-concrete composite		10	10	6
	Mass timber with concrete or gypsum topping		59	16	7
	Mass timber with concrete or gypsum topping w/ finish floor		81	17	13
	GLT decking		5	1	1
	NLT decking		25	8	5
	CLT without concrete or gypsum topping		30	5	3
	Mass timber with raised access floor		15	7	7
	Mass timber with raised wood sleepers		15	5	5
	Mass timber with raised wood sleepers, no topping		4	2	2
	T&G decking		15	5	1
Total			349	137	92

Most assemblies in the full WW Inventory (266 out of 349, or 76 percent) use five-ply CLT panels, which can typically span about 4 to 5.5 meters. [39] Table 6-2 shows typical maximum allowable spans for the mass timber panels which appear in the inventory. Spans are based on IBC 2021 residential occupancy loads but can vary depending on factors such as wood species, structural loading requirements, and project-specific fire resistance rating requirements. Mass timber panel structural spans are often controlled by criteria to limit walking-induced floor vibrations. More in-depth calculations of span limits for individual assemblies are out of this paper's scope.

Table 6-2: Typical allowable spans for mass timber panels appearing in the WW Index, based on publicly-available manufacturer technical guides [39], [278], [279] STC and IIC data is from the WW Inventory. [196]

Mass Timber Panel	Panel Depth (mm)	Span (m)	Assumed Panel Construction	STC	IIC
3-ply CLT	104.8	4.0		38	22
5-ply CLT	131.8	4.8		39	22
5-ply CLT	137.2	4.8		41	27
5-ply CLT	174.6	5.5		41	25
7-ply CLT	228.6	7.0		44	30
GLT	88.9	3.7		35	20
2x4 NLT w/ Plywood	88.9	3.7		29	-
2x6 NLT w/ Plywood	139.7	5.2		34	33

6.1.3.2 Acoustic performance data

Acoustic performance test data for most assemblies consists of one STC rating and one IIC rating (270 assemblies). Some assemblies include only STC or IIC (57 assemblies), while 33 assemblies include one or more of the following ratings: Apparent Sound Transmission Class (ASTC), Apparent Impact Insulation Class (AIIC), Field Impact Insulation Class (FIIC), Field Sound Transmission Class (FSTC), and Normalized Noise Isolation Class (NNIC). Where ASTC, AIIC, FSTC, FIIC, or NNIC ratings are provided in lieu of STC and IIC, an estimated STC and IIC rating were calculated to provide a comparable rating to other assemblies. It is assumed that these metrics generally result in a lower rating by about five points due to field conditions, [280] and therefore five points were added to these values to estimate equivalent STC and IIC ratings. The WW Inventory assembly ratings are obtained from various manufacturer and third-party test reports for testing performed in accordance with the ASTM E 90 and ASTM E 492 test standards. [281], [282] A limitation of this data is that there are often rating discrepancies between labs, bringing into question the expected sound insulation performance of an assembly. [283] Additionally, construction quality can vary the acoustic insulation performance, [284] as air leaks can reduce performance. [285]

Table 6-3 summarizes the standards and methods used in the WW Inventory assembly data. For the purposes of evaluating and comparing designs, levels of acoustic performance are defined per Table 6-4, based on the performance divisions used by Long. [280]

Table 6-3: Test standards and methods used to quantify sound insulation of assemblies in the WW Inventory.

Standard (Short Name)	Standard (Long Name)	Number of Assemblies
<i>ASTM E 492</i> [282]	Standard test method for laboratory measurement of impact sound transmission through floor-ceiling assemblies using the tapping machine	176
<i>ASTM E 90</i> [281]	Laboratory measurement of airborne sound transmission loss of building partitions and elements	170
<i>Modified ASTM E 90/E 492</i>	Floor zone testing procedures	68
<i>ISO 12354 (ISO 15712-1)</i> [286]	Building acoustics — Estimation of acoustic performance of buildings from the performance of elements — Part 1: Airborne sound insulation between rooms	36
<i>ASTM E 1007</i> [287]	Standard test method for field measurement of tapping machine impact sound transmission through floor-ceiling assemblies and associated support structures	26
<i>Multiple Methods</i>	Combination of ASTM E 492 and ASTM E 1007 [23, 28]	20
<i>ASTM E 336</i> [288]	Standard test method for measurement of airborne sound attenuation between rooms in buildings	19
<i>Legacy from CLT handbook</i> [194]	Various European standards	11

Table 6-4: Acoustic performance tier requirements

Performance Tier	STC/ IIC	Description
<i>Non-code-compliant</i>	<50	Clearly hear normal activities of neighbor
<i>Code Minimum</i>	50	Normal activities of neighbors somewhat muted
<i>Good</i>	55-59	
<i>Better</i>	60-64	
<i>Best</i>	65+	Cannot hear normal activities of neighbors

6.1.3.3 Embodied carbon estimation

The assemblies studied include between 1 and 9 floor materials and components. Embodied carbon material values are obtained for each material from either the Inventory of Carbon and Energy (ICE) V3.0 database, [61] product environmental declaration (EPD) sheets, or industry wide EPDs. The ICE database is a collection of EC factors that relate a construction material quantity to its corresponding carbon emissions, using a cradle-to-gate life cycle assessment

(LCA). EPDs are often created by manufacturers or third-party groups and are independently validated per ISO 14025:2006. Additionally, technical product data sheets and NRC test reports were referenced to clarify typical information about some material types, and to help inform property assumptions. Note that the analysis includes only the cradle-to-gate LCA boundaries (A1-A3).

From the perspective of calculating embodied carbon, all the materials included in the studied assemblies can be classified based on their coverage, resulting in three coverage categories: area, linear, and discrete. Each material in the WW Inventory had typical properties such that EC per area could be calculated for each material. Most materials in the inventory are area-based, meaning they are installed to cover the full area of the floor. EC per area for these materials is calculated per Equation 1:

$$EC_i = EC_f * t_{i,typical} * \rho \quad (6-1)$$

Where:

EC_i = EC per area for a given assembly layer of typical thickness

[kg CO₂ eq./m²]

EC_f = EC factor per mass for a given assembly component [kg CO₂ eq./kg]

$t_{i,typical}$ = the baseline layer thickness assumed for the EC_i value [m]

ρ = component density [kg/m³]

Acoustic accessories include both linear- and discrete-based materials, where linear includes items like wood furring or resilient channels, and discrete includes those such as acoustic clips or rubber isolators. EC for linear and discrete materials can be calculated per Equations 2 and 3, respectively, to determine an equivalent EC per area. Based on Equations 1 through 3, representative assembly material values are summarized in Table 6-5.

$$EC_i = \frac{EC_f * A_{i,typical} * \rho}{S} \quad (6-2)$$

Where:

$A_{i,typical}$ = the baseline component cross sectional area assumed for the
EC_i value [m²]

S = component spacing [m]

$$EC_i = \frac{EC_f * m_{i,typical}}{S_{\perp} * S_{\parallel}} \quad (6-3)$$

Where:

$m_{i,typical}$ = the baseline component mass assumed for the EC_i value [kg]

$S_{\perp}$ = spacing perpendicular to a reference span direction [m]

$S_{\parallel}$ = spacing parallel to a reference span direction [m]

Table 6-5: Embodied carbon of representative mass timber assembly materials (kg CO₂ eq. per m² per typical thickness/unit/spacing)

Coverage Category	Material Type	Material	EC _i (kg CO ₂ eq. per m ²)	Ref
Area	Mass Timber Panel	CLT (5-ply)	23.9	[64]
		GLT (88.9 mm)	14.3	[65]
	Concrete or Gypsum Topping	NW Concrete (38.1 mm)	12.4	[61]
		LW Concrete (76.2 mm)	12.0	[289]
	Acoustic Mats or Systems	Dimpled Rubber Mat (25.4 mm)	13.7	[290]
		Raised Access Floor	52.5	[291]
	Board-type Products	Gypsum (15.9 mm)	1.79	[292]
		Plywood (19 mm)	7.3	[61]
	Insulation	Fiberglass (92 mm)	0.90	[293]
		Mineral Wool (30 mm)	1.1	[294]
	Finish Flooring	Carpet	12.9	[295]
		Hardwood Flooring	3.5	[61]
	Acoustical Underlayment	Flat Rubber Mat (17 mm)	21.8	[290]
		Foam Mat	3.5	[296]
Linear	Acoustic Accessories	Resilient Channels	1.66	[297]
Discrete		Wood Furring	0.35	[61]
		Sound Isolation Clips	5.35	[61]

In some cases, EC information was not available for materials or products, or there was not enough information in an assembly description to reasonably estimate EC. As a result, only 217 out of 349 assemblies were included in the EC database. 92 of those 217 assemblies meet the 2021 IBC and have both STC and IIC data. Each studied assembly is evaluated for EC by a

summation of each material's EC material value. The unit of comparison is kg CO₂ eq. per m². Because the layer EC values were first calculated based on typical properties per Equations 1-3, atypical conditions must be accounted for in each assembly estimate. While some modifications were made as needed depending on whether a layer was area, linear, or discrete-based, the general equation to estimate the full assembly EC is summarized and simplified in Equation (4):

$$EC = \sum_{i=1}^n EC_i * \frac{d_{i,actual}}{d_{i,typical}} \quad (6-4)$$

Where:

EC = total assembly EC per area [kg CO₂ eq./m²]

$d_{i,actual}$ = the actual property (thickness, density, area, spacing, or mass) of the given component if different than typical [mm, kg/m³, mm², m, kg]

$d_{i,typical}$ = the baseline property assumed for the EC_i value [mm, kg/m³, mm², m, kg]

6.1.4 Results and discussion

6.1.4.1 Results

After obtaining the total EC for the corresponding timber floors in the WW Inventory, the EC is plotted against the air-borne (STC) and structure-borne (IIC) acoustic performance. Figure 6-1 shows STC versus EC, assigning to each data point a hue based on assembly depth and a marker style based on whether the mass timber panel is exposed aesthetically to the underside. Similarly, Figure 6-2 compares the same data set, but for IIC versus EC. Horizontal lines in both Figure 6-1 and Figure 6-2 depict the lowest rating of each acoustic performance tier per Table 6-4.

Figure 6-1 shows that there is no clear relationship between STC and EC; all STC performance tiers can be achieved with similar levels of EC (between about 30 to 50 kg CO₂ eq./m²) if the right assembly is selected. While low-EC options exist, there are numerous

assemblies with significantly higher EC (by 2 to 4 times, upwards of 100 to 125 kg CO₂ eq./m²) which should be avoided if possible. Interestingly, these high-EC assemblies occur more frequently in the lower performance tiers for this data set. Figure 6-1 also finds that while low-depth options exist at all performance tiers (200 to 300 mm), the highest STC-rated assemblies made use of deep assemblies (of 400 to 450 mm) and concealed ceilings (i.e. underside acoustic treatment is required such that the ceiling cannot be exposed aesthetically.) Some assemblies with exposed ceilings achieve great STC performance but are limited to a maximum of STC-66 within this data set.

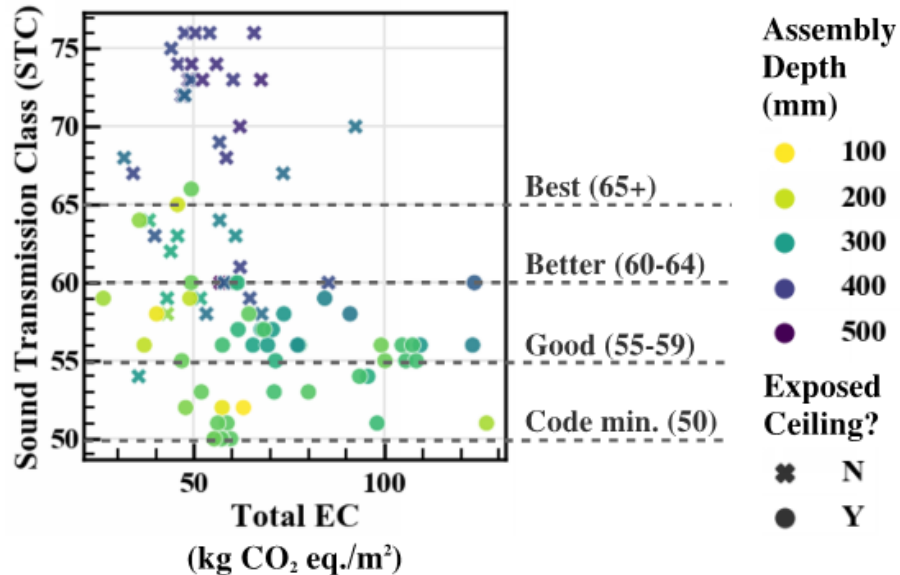


Figure 6-1: STC versus EC for all studied code-compliant assemblies. Horizontal lines depict acoustic performance tiers.

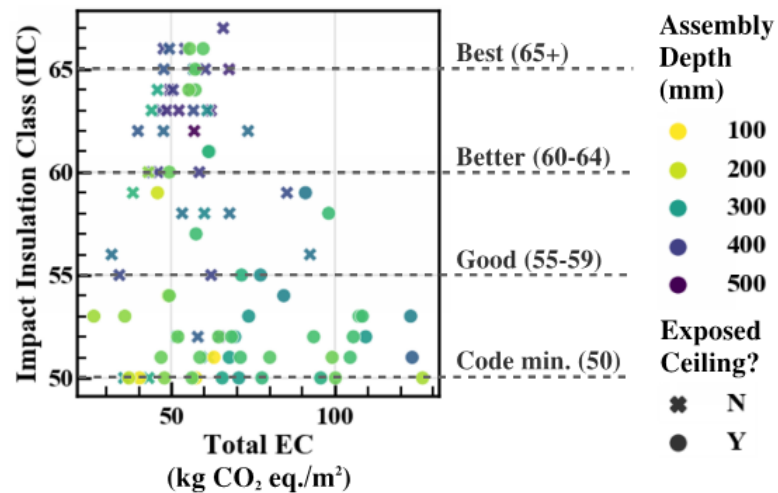


Figure 6-2: IIC versus EC for all studied code-compliant assemblies. Horizontal lines depict acoustic performance tiers.

Figure 6-2 shows some trends for IIC versus EC similar to those for STC versus EC.

There is again no clear relationship between IIC and EC, and while high-EC options exist especially at lower performance tiers, there are low-EC options at all performance tiers. Further, there are similarly relatively low-depth options (200 to 300 mm) at all performance tiers; however, the highest IIC-ratings are not limited to the deepest assemblies. Note that maximum IIC ratings are lower than the maximum STC ratings for assemblies in this data set, which is consistent with the difficulty of achieving higher IIC ratings in general. Figure 6-1 and Figure 6-2 show several assemblies at a given performance rating with different EC values. While designers should attempt to select the lowest-EC option that meets their project's IIC and STC requirements, other factors out of the scope of this study, such as structural requirements, cost, aesthetics, and scheduling, may restrict assembly selection.

Figure 6-3 and Figure 6-4 use the full database of assemblies with both STC and IIC test data and sufficient EC data, including non-code-compliant assemblies. These were included here to better understand the relationship between STC and IIC amongst the assemblies included in the WW Inventory, as well as to visualize how estimated EC (Figure 6-3) and approximate allowable span (Figure 6-4) are represented within the data set.

Figure 6-3 shows that STC and IIC have a hyperbolic relationship. Many more of the assemblies in this data set met code for STC than for IIC, as it is often more difficult to achieve higher IIC ratings. The lowest-EC assemblies with 15 to 20 kg CO₂ eq./m² often do not meet code. Relatively low-EC assemblies of 40 kg CO₂ eq./m² occur at all combined STC and IIC performance tiers (i.e. both STC and IIC are rated at the same performance tier for an assembly.) Assemblies with concealed ceilings generally achieve the best combined STC and IIC performance.

Figure 6-4 shows the same data as Figure 6-3, but with data points assigned a hue based on approximate allowable span per Table 6-2 and a marker based on the presence of a topping. All acoustic performance tiers for STC and IIC have options that can span upwards of 6 meters. Longer spans are likely possible at higher acoustic performance using similar assemblies to the 6-meter-spanning assemblies; however, the number and types of longer-spanning assemblies was limited in the WW inventory.

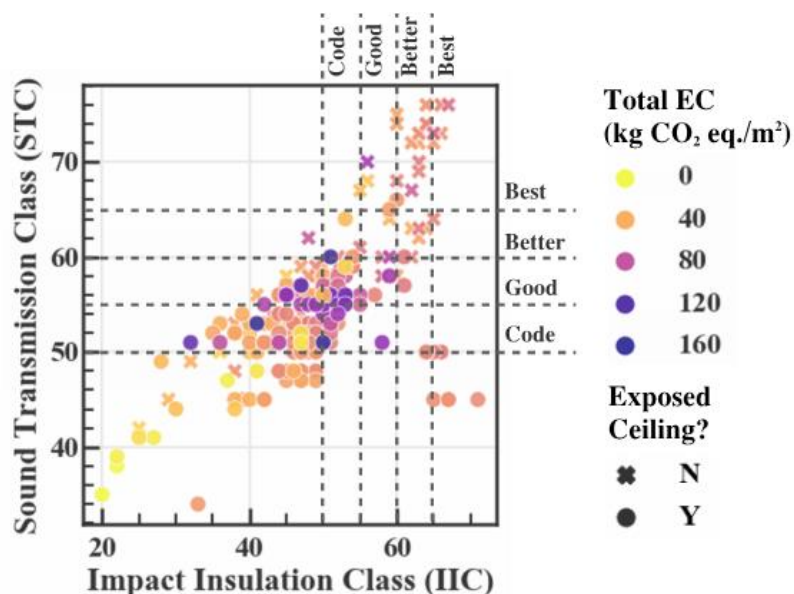


Figure 6-3: STC versus IIC for all studied assemblies, including non-code-compliant assemblies.

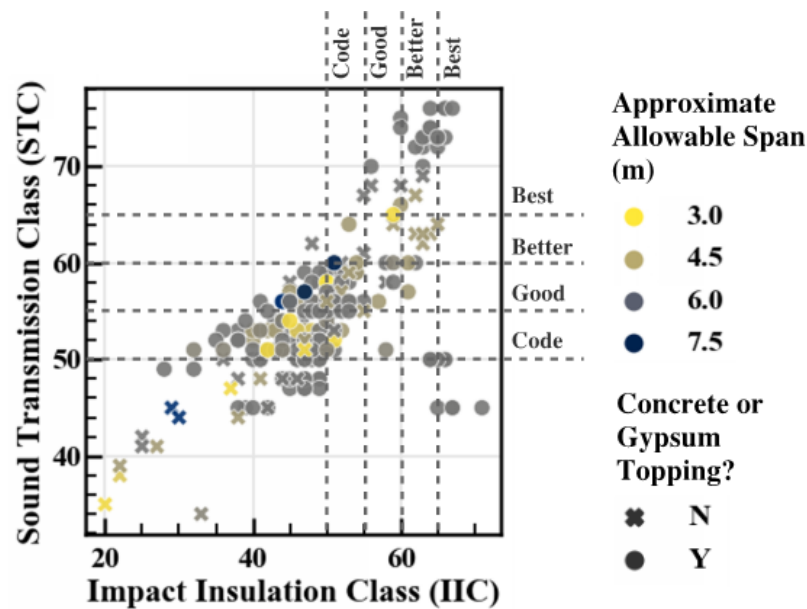
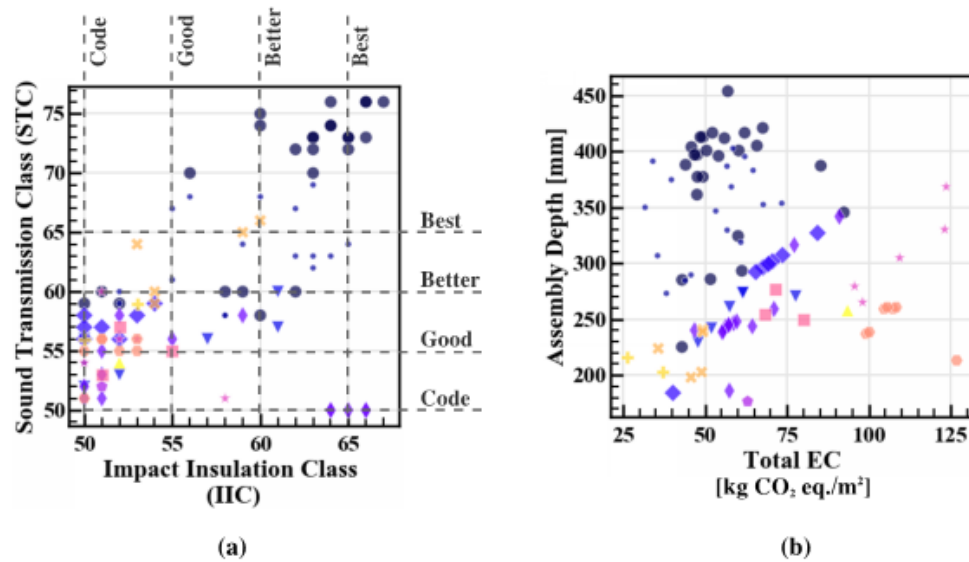


Figure 6-4: STC versus IIC for all studied assemblies, including non-code-compliant assemblies.

Figure 6-5(a) and (b) take the data from Figure 6-3 and removes the non-code-compliant assemblies for closer analysis of STC versus IIC (Figure 6-5 (a)) and Depth versus EC (Figure 6-5 (b)). In each plot, both marker hue and style are assigned based on the assembly category per Table 6-1. Per Figure 6-5, although many concealed-ceiling assemblies are the deepest assemblies, averaging around 400 mm, these represent most of the best-performing assemblies for STC and IIC while maintaining relatively low EC, with several options in the range of 45 to 50 kg CO₂ eq./m².

Figure 6-5 also shows that for categories that include versions both with and without a concrete or gypsum topping (Ceiling Side Concealed and Raised Wooden Sleepers), those with a topping tended to achieve higher STC and IIC ratings with limited impact to EC. This is likely because the concrete and gypsum toppings are most often paired with an acoustical mat, which together can be a relatively efficient use of material to improve acoustic insulation. While STC and IIC are generally related in Figure 6-5(a), some assemblies with flooring can have a high IIC rating even if STC is low.



Assembly Category	
● Ceiling Side Concealed	★ NLT Decking
• Ceiling Side Concealed (no Topping)	■ No Concrete/Gypsum Topping
▼ CLT-Concrete Composite	○ Raised Access Floor
◆ Concrete/Gypsum Topping	✱ Raised Wooden Sleepers
◇ Concrete/Gypsum Topping w/ Flooring	✱ Raised Wooden Sleepers (no Topping)
● GLT Decking	▲ T&G Decking

Figure 6-5: (a) STC versus IIC for all studied code-compliant assemblies; (b) Assembly depth versus EC per unit of floor area for all studied code-compliant assemblies

Further, there is no relationship between EC and assembly depth, according to Figure 6-5 (b). Low-EC options of 30 to 40 kg CO₂ eq./m² occur at a variety of assembly depths. This is likely because many assemblies use separation and air gaps between assembly components to improve acoustic performance, which makes efficient use of the materials in such assemblies.

Although Figure 6-1 through Figure 6-5 indicate no clear relationship between sound insulation and EC, or between assembly depth and EC, options exist with higher EC. While it may be possible for designers to simply select the lowest-EC option that meets their project's STC and IIC requirements, there are most likely other factors that have the potential to control assembly selection, such as structural performance requirements, cost, scheduling, and material availability. Except for the approximate allowable spans shown in Figure 6-4, these factors are

out of the scope of this research. However, by understanding the material efficiency of the components and systems used to improve sound insulation versus their EC, general recommendations and guidance can be provided to help reduce EC during early design decisions. Approximate component and system contributions to EC, STC, and IIC are shown in the bar chart in Figure 6-6.

Figure 6-6 shows that increasing gypsum in an assembly that already has some gypsum does not add much EC but does not help STC or IIC either. Additionally, adding a separation between layers via wood furring provides the best STC and IIC improvement per amount of added EC. However, the most significant takeaway is that suspended channels and other means of providing acoustical separation between assembly layers provide high improvements to STC and IIC with relatively low EC impact to the assembly. This further validates that the typical recommendation of providing acoustic separation between layers is a materially-efficient and effective approach to improving sound insulation in an assembly.

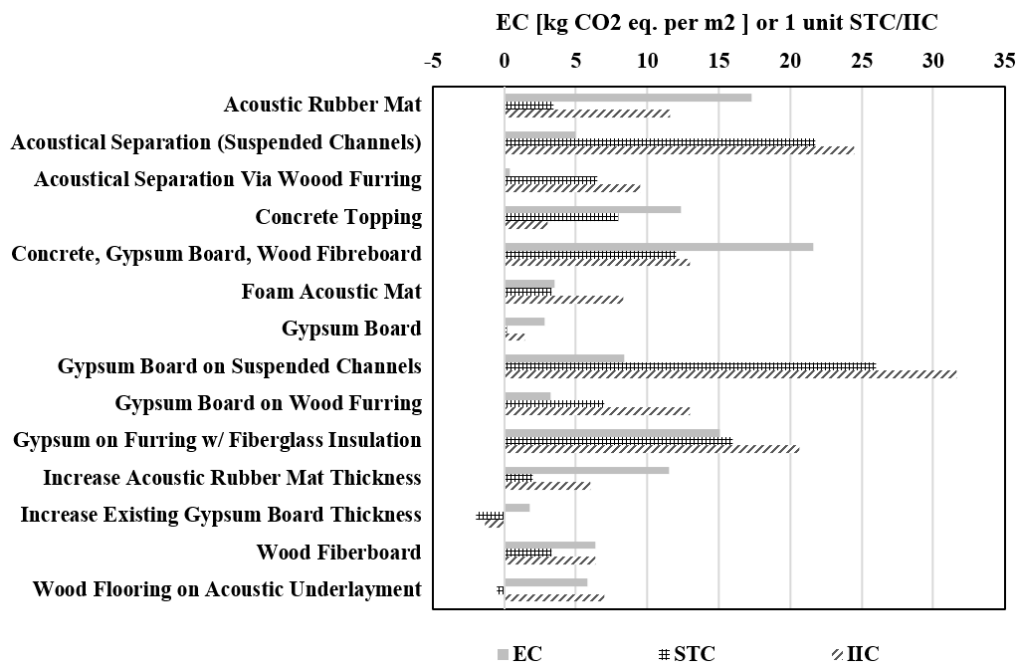


Figure 6-6: EC per floor area of various materials or systems of materials and the difference in STC and IIC as compared to existing baseline assemblies without the given material or system. (Based on a selective set of assemblies with 5-ply CLT panel and 38-mm concrete topping)

6.1.4.2 Discussion

Previous studies have shown that many mass timber floor systems without acoustic treatments have unsatisfactory air-borne and structure-borne sound insulation performance. However, adding materials and components to improve sound insulation can affect the EC of mass timber floor assemblies. By combining existing acoustic test results with EC data for a variety of assemblies, comparisons can be made to understand different assembly types and trade-offs with improved sound insulation. Because of data limitations due to lab-to-lab differences in STC and IIC results, as well as the limited availability of EC data, the findings of this research are most helpful during early design when more general and broad design decisions occur. Further analysis is needed to refine the design in the later stages of a project. This research finds that:

- Although adding acoustic treatments or systems to assemblies results in many with high EC, there is no clear relationship between STC and EC or between IIC and EC; relatively low-EC options exist at all acoustic performance tiers.
- In this data set, deeper assemblies are needed to achieve the best STC values, but low-depth options exist for all IIC tiers.
- One trade-off to achieve the best acoustic performance is that a designer may need to sacrifice exposed timber ceilings for underside acoustic treatment, which affects the architecture and results in greater assembly depth.
 - Because separations and air gaps are often used to achieve improved IIC and STC, these assemblies can still have relatively low EC.
 - Note that underside treatments including gypsum board can provide other benefits such as fireproofing, which eliminates the need for char design. The reduction in structural depth by eliminating char design may partially or completely offset the depth of underside acoustic treatment.
- The best EC per STC or EC per IIC from separating components aligns with typical recommendations to improve sound insulation per the CLT handbook. [194]
- An in-depth structural analysis was excluded; however, there are a wide variety of assemblies in this data set that can span up to 6 meters at all acoustic performance tiers.

- Experimental measurements were not taken from the same lab, which could have significant variability in results from lab to lab.
- More holistic studies including other building disciplines (for example, fire proofing, thermal insulation, cost, scheduling, etc.) may continue to reveal what the best assemblies are and for what design scenarios are best.
- There are many buildings for which code will not allow exposed timber ceilings depending on the Construction Type per the 2021 IBC, and in most cases, a non-combustible topping is required for mass timber floors. [34]

6.1.5 Conclusions

This study extended the WW inventory that compiled the sound insulation performance of mass timber assemblies by extracting material information and adding EC data. The results showed that there was no direct correlation between EC and acoustic insulation. As a result, designers may select a floor assembly which meets project-specific goals for EC, STC, and IIC. Where several assemblies have similar acoustic performance, but different EC, other factors not in this study's scope may control the design selection. These additional factors include, but are not limited to, structural design requirements, cost, scheduling, and fire resistance requirements. Although this study helps extend existing research on the performance of mass timber assemblies within the built environment, a comprehensive database including additional considerations could improve initial assembly selection.

This chapter is the last of the main chapters on various aspects of mass timber design. The next chapter compiles the results of this and the previous chapters 3 through 5 into a more practical chapter offering design guidance based on the results.

6.1.6 Data availability

The WoodWorks Inventory of Acoustically-Tested Mass Timber Assemblies is publicly available at no cost from <https://www.woodworks.org/resources/inventory-of-acoustically-tested-mass-timber-assemblies/>. EC data generated for this paper, building on the WW Inventory data, is available by request from the corresponding author. Components and data sources in Table 6-5 are only representative. Data available from the corresponding author includes EPDs, technical data sheets, and reports for the components listed below. Most EPDs are manufacturer-specific, and as such, a multitude of manufacturers are listed below as data sources for this research; however, it is not the authors' intent to promote specific manufacturers or products.

- CLT – average of Product EPDs from various North American manufacturers: Smartlam, [smartlam.com], Structurlam [structurlam.com], Nordic Structures [nordic.ca/en/products], Vaagen [vaagentimbers.com], Kalesnikoff [kalesnikoff.com]
- Glue Laminated Timber (GLT) – Industry-wide EPD, [awc.org/wp-content/uploads/2021/11/AWC_EPD_NorthAmericanGluedLaminatedTimber_20200605.pdf]
- Mass Plywood Panel (MPP) – Product EPDs from Freres, [frereswood.com]
- Lightweight Concrete – Paper by Kanavaris et al. [289]
- Gypsum-based Toppings – USG Product EPD, [www.usg.com]
- Acoustic ceilings, sound reduction board, and other generic gypsum-, cement-, or fiber-based boards – Product EPDs by USG, [usg.com]
- Flooring Underlayment and Acoustic Membranes: Product EPDs by Autex Acoustics, [autexacoustics.com], Fermacell [fermacell.com/en], Isolon [isolon.lv/en], QT Sound Control, [qtsoundcontrol.com/], and Sto [stocorp.com]; Technical product data by AcoustiTech [acousti-tech.com/en], Kinetics [kineticsnoise.com/], Maxxon [maxxon.com], Pliteq [pliteq.com], Regupol [regupol.us], Soprema [soprema.us], and Sto [stocorp.com].
- Proprietary Subflooring – Product EPD by HuberWood, [huberwood.com/advantech]
- Raised Access Floor – Product EPD by Teccrete, [globalifs.com/raf-teccrete]

- Metal Channels, Studs, and Ceiling Framing – Product EPDs by Cemco [cemcosteel.com], and Clark Dietrich [clarkdietrich.com]; Design guide by USG. [298]
- Insulation – Product EPDs and Technical data sheets by Johns Manville [jm.com/en/], Owens Corning [owenscorning.com/en-us/insulation], and Rockwool [rockwool.com/north-america/].
- Bamboo Plywood – Product EPD by Plyboo, [plyboo.com]
- Roof Board – Product EPD by Georgia Pacific, [buildgp.com/densdeck]
- Sand – Report by the National Stone Sand & Gravel Association. [299]
- Flooring – Product EPDs by Mannington Commercial [manningtoncommercial.com] and Tarkett [home.tarkett.com/en_EU]; Industry-wide EPDs by TCNA [tcnatile.com] and RFCi [armstrongflooringpartner.force.com/ArmstrongConnect/s/article/Environmental-Product-Declaration-EPD-Luxury-Vinyl-Tile].

The ICE v3.0 database values were used for Nail Laminated Timber (NLT), tongue and groove (T&G) decking, wood subfloor, cement mortar, normal weight concrete, sound isolation clips, wood furring, wood board products such as plywood, hardwood flooring, and laminate flooring. [61] Finally, NRC reports on sound insulation research and assembly test results were used to clarify assembly construction where relevant. [300], [301]

6.1.7 Acknowledgements

The authors would like to thank Ryan Solnosky, M. Kevin Parfitt, Dr. Ali Memari, and Corey Gracie-Griffin for their advisement on this work. This research is supported in part by the Graduate Assistance in Areas of National Need (GAANN) Fellowship and the J. Roger Glunt Graduate Fellowship in Housing, hosted by the Pennsylvania Housing Research Center (PHRC). Neither fellowship had any role or input in the planning and implementation of this research, and the included results do not reflect the views of these organizations.

Chapter 7

Design Guidance for Mass Timber Floors

Previous chapters focused on various broad aspects of mass timber floor design, including structural metrics (Chapter 4), fire design strategies (Chapter 5), and acoustic insulation (Chapter 6). This chapter seeks to formulate the findings from those chapters into a designer forward chapter here which highlights specific design guidance and recommendations resulting from those previous findings in a user-friendly format for those without parametric models available.

This chapter is an extended version of a conference paper which is under review following an accepted abstract to the 7th Residential Building Design & Construction Conference (RBDCC) by the Pennsylvania Housing Research Center (PHRC), which will take place in March 2024. Publication of the conference paper is expected post-conference. It is anticipated that this chapter and conference paper will also form the basis for a journal paper.

This chapter is also related to ongoing work for the AIA Upjohn research initiative grant, which is partially funding the remainder of the research for this dissertation. The work for this grant, led by the PI Corey Gracie-Griffin, includes two main deliverables: a web-based parametric interactive design tool and a supplemental design guide. The following chapter serves as an initial draft of the content planned for the design guide, with the exception of any comparisons to steel floor system baselines, which are out of the scope of this dissertation. AIA has not yet had any role or input in the planning and implementation of the research for this dissertation and the chapter here; however, future work includes planned round tables with stakeholders and opportunities for feedback to continue to improve and expand upon the work documented in this dissertation.

7.1 U.S. design guidance for CLT floor systems with residential occupancy loads

7.1.1 Abstract

With the recent expansion of mass timber structural usage for multi-family and mid- to high-rise apartment buildings over that of light framed construction because of their prefabrication capabilities, low embodied carbon (EC), aesthetics, ability to go taller, and for the potential to reduce construction schedules. Because modern mass timber structures are relatively new, practitioners are still learning how to properly select systems, navigate mass timber design provisions, and understand how design decisions affect the final design performance. While there are numerous design guides and tools available for mass timber, few offer guidance at the early design stage when many key decisions are made. Further, none of the available tools link early-stage design guidance with decision effects on various design goals, such as reducing EC, limiting structural depth, and more. Based on parametrical modeling of mass timber floors, this chapter includes design guidance for early decision making to inform design goals of EC, fire design, acoustic insulation, and structural depth and mass.

7.1.2 Introduction

Mass timber construction has increased in the U.S. for several reasons, including but not limited to, innovations in engineering wood products like cross-laminated timber (CLT) [3], embodied carbon (EC) reduction goals [6], [7], aesthetic preferences for exposed timber structures [3], [105], and potential wellness benefits from biophilia [229]. These mass timber structures are also typically lighter than conventional construction solutions like reinforced concrete. As such they reduce the size, cost, and installation needs for foundations. [44] While there are many available

resources to guide mass timber design, as summarized later in this chapter, there are limited resources to help with early design guidance at the intersection of EC and other projects goals like fire design, acoustic insulation, and floor system depth.

7.1.2.1 Cross Laminated Floors

CLT panels are manufactured by structurally gluing together layers of dimensional lumber which are oriented orthogonally to each other. CLT panels typically consist of three to seven equal-thickness layers, but some manufacturers have additional panel options which vary layer quantity, thickness, and even orientation to obtain different panel properties. Panel length is limited by a manufacturer's press size. [104] CLT is well-suited to prefabrication and CNC machining, and due to the crosswise layup, CLT demonstrates both dimensional stability and two-way spanning behavior. [104], [187] Where mass timber framing is used with a CLT floor panel, glued-laminated timber (Glulam) girders and beams are often used. Figure 7-1 presents a summary of common and non-common CLT floor system options. Highlighted in green are the systems which appear in this guide.

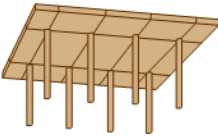
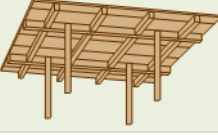
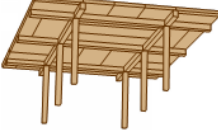
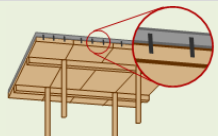
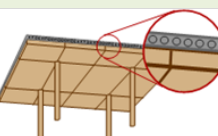
System	Variation	Schematic	Applicability	Typical Span
<i>Post and Panel</i>	Point supported panels		Hotel, Dormitories, Micro Apartments	8 – 14 ft (2.4 – 4.2 m)
	Stressed skin lattice		Hotel, Dormitories, Micro Apartments (increase span compared to typical point-supported)	15 – 25 ft (4.6 – 7.6 m)
<i>Post-Beam-Panel</i>	Girder and deck		Office, Residential (minimize cost)	12 – 20 ft (3.6 – 6 m)
	Staggered deck		Office, Residential (long-span bays, minimize material, possible services over beams)	15 – 25 ft (4.6 – 7.6 m)
<i>Post, Beam, Purlin, Panel</i>	Beams and girders		Office, Residential (minimize floor panel depth)	25 – 35 ft (7.6 – 9.1 m)
	Two-way beams		Office, Residential (square bays, minimize beam sizes)	12 – 20 ft (3.6 – 6 m)
<i>Steel-timber hybrid</i>	Non composite framing (girders or girders & beams)		Office, Public Buildings, Post Disaster Status	15 – 35 ft (4.6 – 9.1 m) (for CLT)
	Proprietary flush beams		Office, Residential (long span and shallow depth)	20 – 40 ft (6 – 12 m)
<i>Timber-concrete composite</i>	Shear connectors with beams		Office, Residential	20 – 30 ft (6 – 9.1 m)
	Point-supported voided concrete timber composite		Office, Residential (eliminate beams, reduce mass)	20 – 30 ft (6 – 9.1 m)

Figure 7-1: Summary of representative mass timber floor system options. Summary and figures adapted from the Structurlam Mass Timber Technical Guide [39] and Elsa Lam for Canadian Architect [109]

7.1.2.2 Design Guidance Organization

This chapter presents resulting design guidance from the parametric modeling-based research detailed back in Chapters 4-6 in this dissertation. Design guidance in this chapter focuses on CLT floor systems designed and built in the U.S. with residential occupancy loads; however, the results may be used for any other occupancies with loads similar to the residential, within about 5-10 psf, to make rough early design comparisons. This set of design recommendations includes a summary of helpful resources, discussion of methods, and the following guideline sections:

- Overview of Floor Systems (§ 7.1.5)– Broad guidance on design considerations for mass timber is included here, as well as an overview summary of each included floor system.
- Fire Design Guidance (§ 7.1.6) – Comparisons are made between fire design options using timber char, noncombustible protection, or a combination of both.
- Acoustic Insulation Design Guidance (§ 7.1.7) – While all other guidance sections assume code minimum acoustic insulation, here other acoustic performance levels are evaluated and recommendations for improving acoustic insulation are made.
- Structural and Embodied Carbon Design Guidance (§ 7.1.8) – Recommendations are presented that balance system depth, mass, and EC while considering structural performance.
- Embodied Carbon Assessment (§ 7.1.9) – Guidance on how to read and EPD and what to consider when making timber carbon storage assumptions are included.

Finally, two design examples are provided to demonstrate how this guide may be used for hypothetical scenarios situated in early design.

7.1.3 Resources

Table 7-1 includes a summary of the various resources available for mass timber, including educational materials, handbooks, codes, specifications, and more.

Table 7-1: Summary of representative mass timber resources

Resource	Documents/Versions/Organizations	Comments
<i>Codes and Specifications</i>	• International Building Code (IBC), [34] • National Design Specification for Wood Construction (NDS), [140] • Fire Design Specification for Wood Construction (FDS), [141] • The American Institute for Timber Construction (AITC) Timber Construction Manual [302] • American Wood Council's (AWC) Technical Report No. 10 on "Calculating the Fire Resistance of Exposed Wood Members," [238]	Mass timber design is codified in the IBC. Specifications such as the NDS, FDS, and Timber Construction Manual provide technical insights into timber behavior that the IBC excludes. Some codes have supplemental information and reports that provide useful design procedures, such as AWC's TR No. 10, which accompanies the NDS.
<i>CLT Handbook</i>	• 2013 U.S. Edition [16] • 2019 Canadian Edition [4]	The handbooks cover manufacturing, structural design for gravity and lateral loads, structural design for connections and long-term loads, vibration performance, fire design, sound insulation, enclosure design, environmental performance, and lifting and handling of panels. While the 2013 edition is starting to become dated, many useful structural equations apply and have U.S. units for ease of use. The 2019 edition is more recent but includes SI units in equations, which may require conversion for use in the U.S.
<i>U.S. Mass Timber Construction Manual</i>	• 1st Edition [303]	This guide covers all topics related to the construction of mass timber buildings, including preconstruction and planning, moisture control, installation of panels and connections, acoustic assemblies, finishing, and close-out.
<i>Design Guide for Timber-Concrete Composite Floors in Canada</i>	• 1st Edition [120]	This guide focuses on structural design of TCC floors, including design for short- and long-term deflection, vibration performance, ultimate limit state design, and fire resistance. A useful design example demonstrates the calculation procedures. While targeted for a Canadian audience, this is the most useful guide for this system type at the time of this writing.

Resource	Documents/Versions/Organizations	Comments
<i>AISC Design Guide 37: Hybrid Steel Frames with Wood Floors</i>	• 2022 Publication [122]	This hybrid steel-timber design guide provides calculation procedures for both composite and non-composite floor systems with timber floors and steel framing. Other covered topics include fire design, acoustics, and sustainability.
<i>Mass Timber Design Manual</i>	• 2021 Publication [44]	This design manual presents an introduction to a variety of design disciplines for mass timber, as well as links to additional papers and documents with more information. Included are discussions of products, design applications, tall timber design, and sustainability. Case studies and code summaries are also provided.
<i>Mass Timber Building Science Primer</i>	• 2021 Publication [28]	This primer provides broad discussion of mass timber buildings as a system and the roles of different disciplines in mass timber building design and construction. Included is in-depth discussion and guidance for enclosure design and moisture management during construction.
<i>Educational Organizations</i>	• WoodWorks • The American Wood Council (AWC) • Think Wood • Naturally Wood • The Canadian Wood Council (CWC)	WoodWorks has published several indices with assembly-level design data, including an index of connections [159] and test data for acoustic insulation [196] and fire resistance. [304]
<i>Manufacturer Resources</i>	• Technical design guides with span tables • Sample specifications • Product catalogues • Product certificates • Educational material • Environmental Product Declarations (EPDs)	Most manufacturers of mass timber products provide technical guides on their website with useful information about mass timber design, structural requirements, span tables, and more, with a focus on their proprietary products. While span tables may not cover all assumptions or design options that a designer would want to consider, they provide a useful option for initial sizing of members.
<i>Software</i>	• Structural design software • LCA and EC software	There are a variety of software programs available which perform some aspects of wood design and carbon accounting. See Tables 3-8 and 3-9 at the end of Chapter 3 of this dissertation for a summary of structural design software and life cycle analysis (LCA)/EC software.

7.1.4 Methods

Design guidance presented in this chapter is informed by a mass timber floor design dataset generated through parametric modelling. Chapter 3 of this dissertation more thoroughly describes the modeling and analysis process; however, a brief summary is provided here for convenience, as well as a discussion of key assumptions, variables, and equations. Multiple systems were modeled, including mass timber, steel-hybrid mass timber, and timber-concrete composite systems. Each system model used automated procedures in Grasshopper and/or Excel to select the lowest-EC element that meets all design limit states for a given bay geometry. Limit states include shear, flexure, fire design, deflections, and control of walking-induced vibrations. The models generated data for structural depth and mass, element sizing, and material take-offs, which were used to estimate EC. The generated dataset was used to inform design recommendations.

7.1.4.1 Parametric Modeling

The mass timber floor systems appearing in this guide were modeled parametrically for the following variables: bay span, system type, fire design method, and level of assumed timber carbon storage. Floor systems include mass timber, steel-hybrid mass timber, and timber-concrete composite systems. The studied systems are described in section 7.1.5 and are discussed in more depth by Leonard et. al. [203] Modeled designs can be studied for the impact of design variables on performance objectives or metrics, as depicted in Figure 7-2. The parametric modelling methodology is further described by Leonard and Solnosky. [201] Table 7-2 summarizes the ranges and options for each variable, which combined generate a set of possible designs.

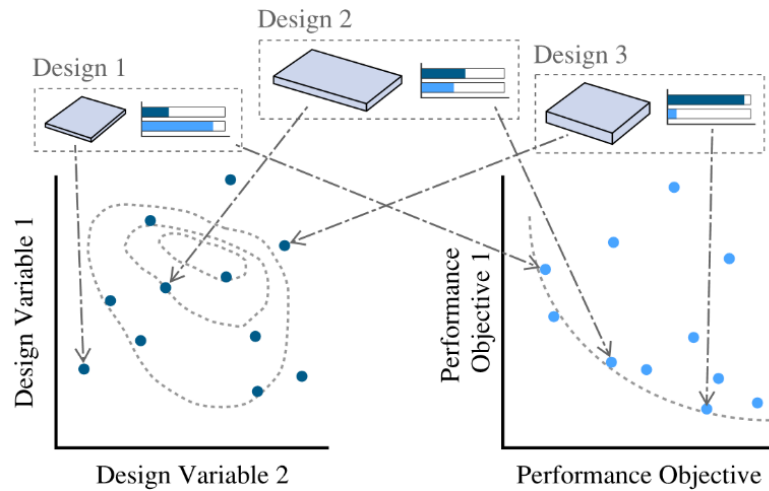


Figure 7-2: Conceptual depiction of design space exploration (figure adapted from N. Brown, 2020)

Table 7-2: Summary of variables and their ranges or options in the parametric model

Variable	Range or Options to Change in Model	Additional Notes
<i>Bay Length</i>	10 to 40 feet, in 1-foot increments (3 to 12 meters, in 0.3-meter increments)	Covers most bay lengths currently used in mass timber residential occupancy projects.
<i>Bay Aspect Ratio</i>	0.5, 0.75, 1.0, 1.5, 2.0, 2.5	Concrete systems designed only for square bays (bay aspect ratio = 1.0)
<i>Fire Design Configurations to Achieve FRR</i>	• 2 hours from char method • 2 hours from noncombustible protection • Combined: 1 hour from each method	Cover a range of strategies for a 2-hr FRR, a common FRR required by IBC Type IV construction.
<i>Percent of Sustainably-Sourced Timber (SST)</i>	0%, 25%, 50%, 75%, and 100%	Based on assumed timber-sourcing capabilities for a typical project.

7.1.4.2 Embodied Carbon (EC) Evaluation

EC is estimated for each design by multiplying a design's material takeoffs by each material's respective EC factor. Material EC factors were collected for the LCA modules A1-A3 from environmental product declarations (EPDs) reported by specific manufacturers. Timber EC

values and assumptions regarding carbon storage can vary widely within the industry, and therefore extreme values were determined for cases both with and without carbon storage for timber. Additional information on reading EPDs and timber carbon storage assumptions is included in section 7.1.9. Material EC factors are summarized in Table 7-3. In this work, the phrase “sustainably-sourced timber” (SST), is used generally to refer to different levels of carbon storage, where 0% SST includes no carbon storage, 100% SST includes full carbon storage, and other assumptions in between are based on linear interpolation.

Table 7-3: Embodied carbon of common structural and building materials [lb CO₂ eq/lb]
(1 lb CO₂ eq/lb = 1 kg CO₂ eq/kg)

Material Information		EC Material Coefficients	
Material	Material Assumptions	EC Value	Data Source
Cross Laminated Timber (CLT)	Carbon storage is neglected	0.27	Average of five North American CLT EPD's following ISO 21930:2017 A and B [64], [207]–[210]
	Carbon storage is included ¹	-1.19	
Glued Laminated Timber (Glulam)	Carbon storage is neglected	0.25	American Wood Council EPD for North American Glued Laminated Timber [93]
	Carbon storage is included ¹	-1.04	
Reinforced Normal Weight Concrete (Slab)	3001-4000 psi	0.17	Based on a combination of plain concrete and reinforcing steel values (~5% of total mass is reinforcing steel)
	4001-5000 psi	0.20	
	5001-6000 psi	0.21	
	6001-8000 psi	0.23	
Normal Weight Concrete with WWR (Topping)	3001-4000 psi	0.15	Combination of plain concrete and reinforcing steel values (~3% of total mass is reinforcing steel)
	3001-4000 psi	0.13	
Plain Normal Weight Concrete	4001-5000 psi	0.16	NRMCA EPD for concrete with 25% cement replacement with fly ash [211]
	5001-6000 psi	0.17	
	6001-8000 psi	0.19	
Reinforcing steel	98% Recycled steel content	0.85	Concrete Reinforcing Steel Institute (CRSI) EPD [212]
Steel (section)	93% Recycled steel content	1.22	AISC Industry-wide EPD for Hot-rolled structural sections [213]
Gypsum Board (drywall) ²	Type X:	0.28	Industry-wide gypsum board EPD [214]
Joint Compound ²	Conventional ready-mixed	1.19	Industry-wide joint compound EPD [215]
Intumescent Paint (for steel)	Solvent-based	2.31	Technical guides and product data sheets [59],[216],[217]

¹ Linear interpolation used for values between 0 and 100% carbon storage, carbon storage value based on assuming 100% landfilling at EOL based on the EPA Waste Reduction Model (WARM) [218]

² A 10% waste factor is applied to the total combined material takeoff for drywall and joint compound

7.1.4.3 Structural Design

Designs were automatically sized for structural performance in the parametric model following an Allowable Stress Design (ASD) methodology. All elements were designed for flexure, shear, deflections, long-term loading, and control of walking-induced vibrations per the codes and guides summarized in Table 7-4. See Figure 7-3 for a flow chart of the limit state check process, Table 7-5 for key equations used in the analysis, and Table 7-6 for key design assumptions. Due to the early-stage design scale of modeling, some timber-specific limit states were modeled simply for analysis, including using the simplified approaches to control of walking-induced vibrations given in the CLT Handbook [105] and the WoodWorks U.S. Mass Timber Floor Vibration Design Guide [167]; as well as designing for fire following code-prescriptive options. See Chapter 3 for additional information on vibration and fire design.

Table 7-4: Limit states included in the structural sizing code.

Element	Shear	Flexure	Deflections	Vibrations	Fire Design	Code and Standards
<i>CLT Floor Panel</i>	✓	✓	✓ (including creep)	✓	✓	2018 National Design Spec for Wood Construction [140]; 2021 Fire Design Spec for Wood Construction [141]; The 2013 and 2019 CLT Handbooks [42], [105]
<i>Glulam Framing</i>	✓	✓	✓	✓ (as a supporting element for CLT)	✓	AISC Steel Construction Manual[237] and AISC Specification for Structural Steel Buildings[236]
<i>Steel Framing</i>	✓	✓	✓	✓ (as a supporting element for CLT)	N/A	

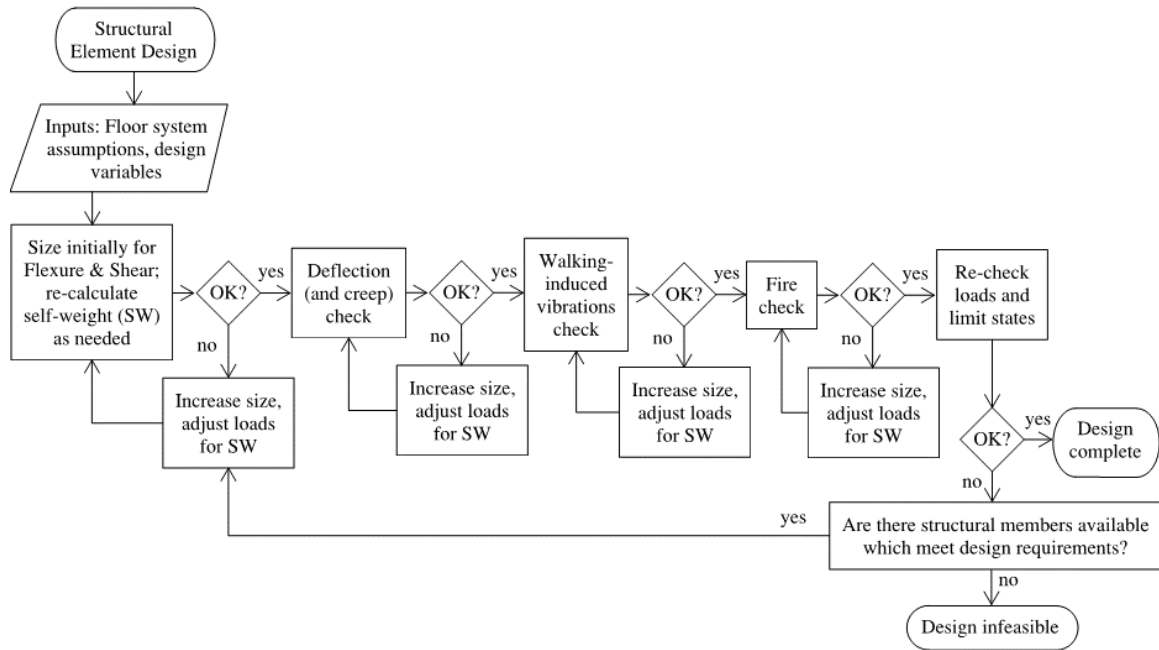


Figure 7-3: Limit states flow chart

Table 7-5: Key equations used during each limit state design check

Limit State	Key Equations
Flexure	$M_{max} = 0.125 * w * L^2$ $F_b S_{eff} \geq M_{max}$
Shear	$V_{max} = 0.625 * w * L$ $V_s \geq V_{max}$
Deflections	$\Delta = \frac{wL^4}{185EI_{app}}$
Control of walking-induced vibrations	$L \leq 0.11 \frac{\left(\frac{(EI)_{eff}}{10^6}\right)^{0.29}}{m^{0.12}}$ OR $f_n = \frac{3.54}{\sqrt{\Delta}} \geq 3 \text{ Hz}$
Fire design	$M'_f = K * F_b S_{eff} * C_L \geq M_{max}$ $V'_f = K * V_s * C_L \geq V_{max}$

Table 7-6: Structural design assumptions

Item	Assumed Condition
Boundary Conditions	Pinned connections, assume simple connections. Actual connections are not included in the model or EC calculations.
Number of Spans	Maximum permitted based on manufacturing and transportation limits
Span Length	Equal to bay length (Conservative as compared to distance between faces of supports)
Bay Location	Center bay with identical bays on each side around it
Live Load	40 psf residential + 20 psf allowance for partitions = 60 psf (2.87 kN/m ²) (ASCE 7-10: residential occupancy, private rooms and corridors serving them)
Superimposed Dead Load	20 psf + 19 psf for a 1.5" (38 mm) nonstructural concrete topping = 39 psf (1.87 kN/m ²) (20 psf is estimate for mechanical, utilities, finishes, and more)
Steel Shapes	W-Shapes only
CLT Panels	Spruce-Pine-Fir and Douglas Fir Density = 26 pcf (1.24 kN/m ³) Structurlam Grade V2M1.1 as a baseline reference. Panel layup options include 3, 5, 7, and 9 plies, with 1-3/8" (35 mm) plies.
Glulam Framing	Douglas Fir Density = 35 pcf (1.68 kN/m ²) Structurlam Grade Series 24F-V8 as a baseline reference. Size options include those ranging from 5.125" (130 mm) wide x 11.75" (298 mm) deep to 20" (508 mm) wide x 56.75" (1441 mm) deep.

7.1.5 Overview of Floor Systems

Using the discussed methods and assumptions, data was collected parametrically to inform design guidance for five mass timber floor systems. Data was also collected for two concrete floor systems to provide a baseline comparison. This section summarizes the floor systems which appear in the design guidance sections of this paper and provides an overall discussion of holistic considerations and high-level initial design recommendations.

7.1.5.1 Floor System Summary and Comparison

Figure 7-4 depicts the studied mass timber and concrete floor systems. The acronyms included in the figure will be used herein to refer to each floor system type. The 5 mass timber floor systems can be broken down into 2 all-timber (TG and TGb) and 3 hybrid (TS, TSb, TCC) classifications. These 5 may alternatively be broken down into categories based on including infill beams with girders (TGb and TSb) or girder only (TGb and TSb) configurations. All mass timber systems' floors consist of CLT. The framing for all-timber systems uses rectangular Glue-laminated Timber (Glulam) and the hybrid steel systems use A992 steel W-shapes. Except for the TCC system, all mass timber floors include a non-structural concrete topping to improve performance for serviceability requirements, including acoustic insulation and design for the control of walking-induced vibrations.

Data for the concrete baselines was generated using a model originally established by Broyles et. al. Here two common concrete systems were selected for comparison as a detailed study of concrete floors is out of the scope of this chapter; however, there are significant opportunities to use optimized concrete floor structures to reduce their EC and mass per the study by Broyles et. al. [235]

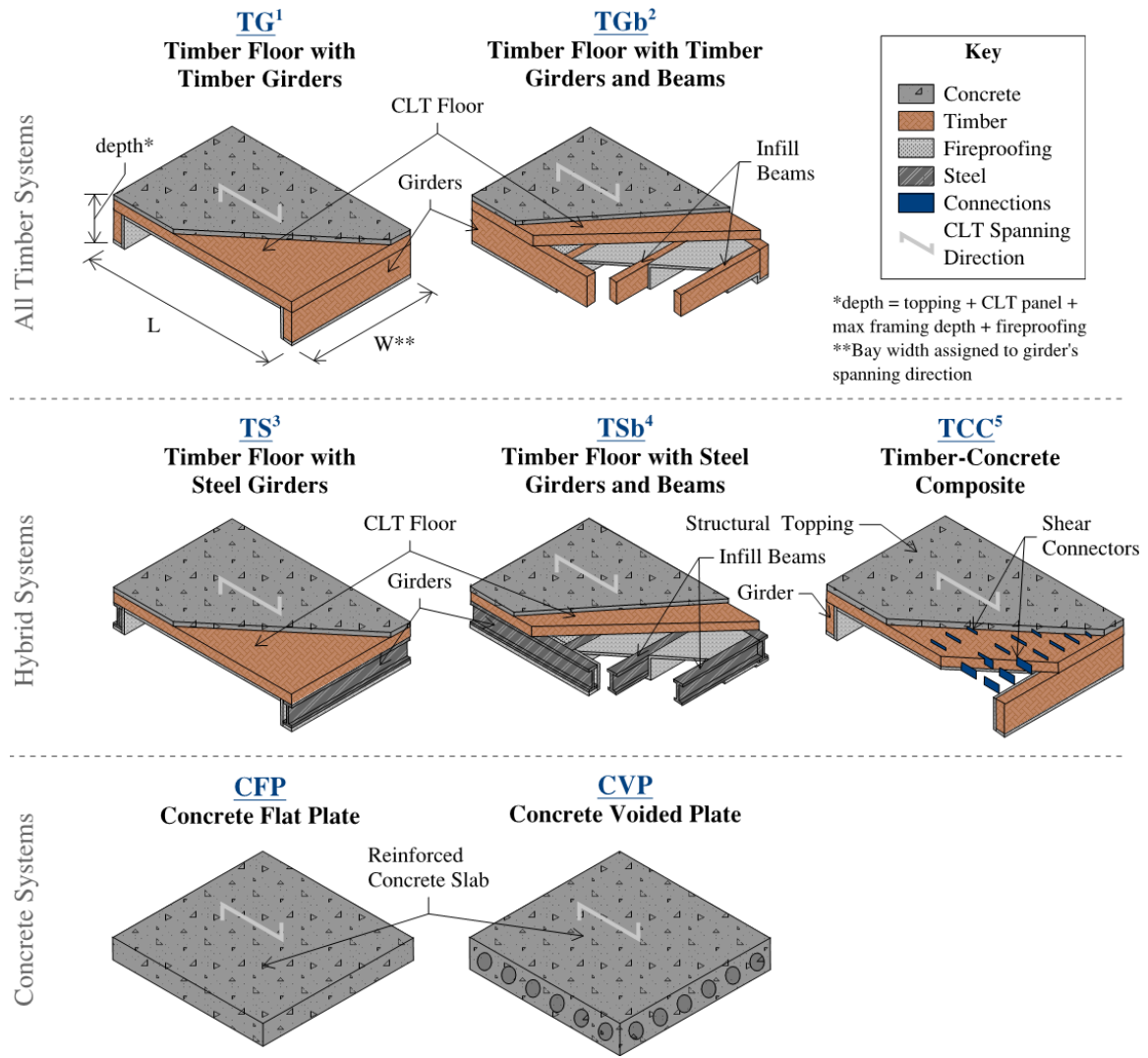


Figure 7-4: Included mass timber, hybrid timber, and concrete baseline floor systems. Representative configurations are shown for mass timber systems. The concrete baselines consider only square bays. These systems related to those in Figure 7-1 per the included footnotes.

¹ Post-Beam-Panel - girder and deck

² Post, Beam, Purlin, Panel - beams and girders

^{3,4} Steel-timber Hybrid - non composite framing

⁵ Timber-concrete Composite - shear connectors with beams

7.1.5.2 Holistic System Considerations

Throughout this guide, a consistent focus centers on depth, mass, and EC of floor systems because these 3 metrics contribute significantly to the overall building's performance and assembly configuration. Many other holistic considerations that are important yet are out of the scope of this paper can all affect building height, mass, and total energy use. These holistic concepts are discussed generally in Table 7-7. Many of Table 7-7's considerations are discussed more thoroughly in the cited applicable resources as noted in Section 7.1.3.

Table 7-7: Holistic design consideration summary

Discipline	Considerations	Ref
Structural	Gravity Systems - Projects currently commonly use CLT floor panels in a post-girder-panel configuration with beams positioned either below or flush with the floor panel. - Columns typically bypass the floor panel to avoid compression perpendicular to the grain. - Other common floor systems include: - post-girder-beam-panel - steel-hybrid systems - timber-concrete composite systems	[39], [108]
	Lateral Systems - Mass timber lateral systems are more suitable for relatively shorter projects. - Options include shear walls, braced frames, and post-tensioned systems. - Taller structures have commonly used concrete core walls.	[108]
	Fire Design - Common prescription fire design options include: - designing for sacrificial char depth - the use of noncombustible covers.	[139]
	Connections - Connections can be designed for exposed or concealed conditions and may affect the selected design configuration. - Connections can greatly affect overall building structural behavior. - Connections can be the most expensive part of a mass timber structure.	[160]
Serviceability	Vibrations - Because mass timber structures are lightweight, they are susceptible to vibration control issues due to both wind and human activities. - To control walking-induced vibrations in floor systems, the floor system supporting elements often require increased stiffness.	[168], [108]
	Acoustic Insulation - Mass timber floors alone do not meet code-required acoustic insulation levels for dwelling spaces. - Additional floor assembly layers designed for acoustic insulation are required.	[194]

Discipline		Considerations	Ref
Architecture	<i>Space planning</i>	• Mass timber tends to be better suited for small, regularly sized and spaced bay sizes. • Spaces with open floor plans and potential future tenant changes will require special consideration. • Taller structures will impose larger column size requirements and may benefit from steel hybrid options to reduce impacts to useable floor area.	[108], [25]
	<i>Aesthetics</i>	• The underside of the mass timber floor structure may be exposed aesthetically in certain conditions. • Designers must coordinate with code requirements, fire ratings, char design, panel fabrication quality, and construction moisture management.	[34], [105]
	<i>Integration of Services</i>	• Depending on the aesthetic design intent, special coordination of MEP services like ductwork, wiring, and plumbing may be required.	[108]
Construction Management	<i>Scheduling</i>	• Mass timber structures tend to have quick construction schedules. • Building enclosure design and construction scheduling should consider quick dry-in times to reduce exposure to the elements.	[44], [105]
	<i>Cost</i>	• The cost of a mass timber project can vary widely depending on the knowledge and experience of the project team. • There will typically be a cost premium for teams designing and constructing their first mass timber project. • As the industry gains experience with mass timber construction, premiums are expected to go down.	[188]
	<i>Installation</i>	• Mass timber elements are typically prefabricated for the project using CNC machining. • Prefabricated elements can be installed with less labor in the field as compared to conventional construction. • More design is required upfront due to the challenge of resolving issues in the field for prefabricated components. • Additional consideration is required for installation details of hybrid systems.	[188], [191]
	<i>Embodied Carbon</i>	• The partial or full substitution of conventional building materials with mass timber can reduce overall EC when used appropriately. • Designers should seek to limit impacts of deep mass timber systems on building height, lateral system demands, building enclosure area, and operational energy.	[6]
Other	<i>Building Enclosure</i>	• Wood structures can be appropriately protected from degradation due to water damage by implementing commonly used best practices in current building enclosure design practice. • One such approach is the use of a drained and ventilated rainscreen cladding system which includes two water control layers for redundancy and directs water away from the building to reduce the risk of moisture intrusion.	[192], [193]

Most importantly, operational carbon is not included in this guidance. In this section, depth is considered a rough proxy for the effect of the floor system design on operational carbon, as deeper floor structures tend to increase total building height (or reduce the number of floors than can be included in a height-limited area), thereby increasing both building enclosure area and operational energy usage during the occupied phase of a building's life cycle, as well as lateral system demands and sizing. Designers with sustainability goals should seek to select systems with a balance of low floor system EC and low depth to limit impacts on total building EC and operational energy.

To further the discussion of height, some considerations on the challenges of building taller with mass timber are presented here. As previously mentioned, one of these is depth, such that mass timber systems tend to require deeper elements, and as a result there are limits on space available in the ceiling plenum, or system coordination becomes inhibited. Therefore, to resolve this, wood structures may have fewer stories, as compared to buildings of similar height in concrete or steel. In some cases, creative detailing and design can mitigate the impact of floor system depth on overall building height, such as placing the top of girders and floor panels flush with each other, placing deep girders at interior partitions, and running mechanical equipment between girders and beams. [159], [305] See Figure 7-5 for conceptual sketches of these options.

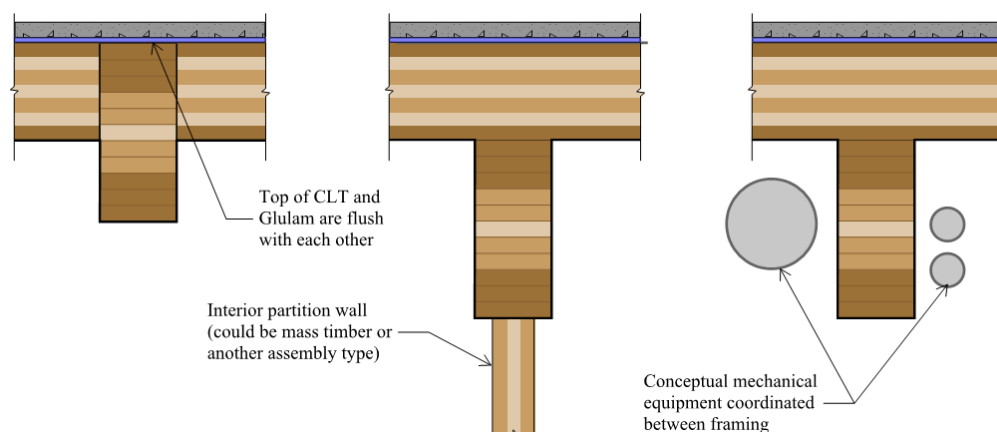


Figure 7-5: Conceptual figures of options to mitigate impacts of mass timber framing depth

Table 7-8 presents approximate estimates of the number of stories that mass timber buildings can be built to within the IBC 2021 Type IV height and story requirements, based on various design combinations. These are based on estimating plenum depth for TG system with 3, 5, 7, and 9-ply CLT panel options by adding an estimated space for HVAC, considering equipment coordinated below either the floor panel or the framing. Note that there are some cases where additional acoustic treatment can affect the number of stories that will fit in the permitted height. For example, for the D.C. height restriction, if a 5-ply panel is required, increasing the acoustic insulation could potentially reduce the number of possible stories from 11 to 10.

Additional challenges of building taller, which are out of the scope of this research due to the focus on gravity floor systems, are discussed here. First, although timber has similar proportional strength to stiffness properties relative to its weight as compared to steel [306], its low stiffness means that tall timber buildings often require very large frame and lateral system elements. [307] Further, tall timber lateral systems encounter challenges related to drift and connection design, and in many cases the lateral system and connections may drive the design of tall timber buildings. [306], [307]. Finally, while current design often designs to match forms of steel and concrete structures, different forms in timber may be needed, especially when designing taller. [308] The scope of this chapter focuses on traditional floor system typologies, as development of new mass timber typologies is still in progress.

Table 7-8: Number of stories by construction type and design type. An example of a location with additional height restrictions is included (Washington D.C.)

Type	Max Allowable Height [ft (m)]	Max Stories Allowed	Floor Plenum Depth [in (mm)]*	Number of stories for design (shaded values exceed max permitted)**			
				For code acoustic insulation		With high acoustic insulation***	
				Stories	Fl-to-fl height	Stories	Fl-to-fl height
IV-A	270 (82)	18	CLT Panel & Mech	24 (610)	24	23	11.3
				27 (686)	24	23	11.6
				30 (762)	23	22	11.8
				33 (838)	22	22	12.1
			CLT, Girder, & Mech	38 (965)	22	21	12.5
				45 (1140)	21	20	13.1
				58 (1470)	19	19	14.2
				67 (1700)	18	18	14.8
IV-B	180 (55)	12	CLT Panel & Mech	24	16	15	11.3
				27	16	15	11.6
				30	15	15	11.8
				33	15	14	12.1
			CLT, Girder, & Mech	38	14	14	12.5
				45	14	13	13.1
				58	13	12	14.2
				67	12	12	14.8
IV-C	85 (26)	8	CLT Panel & Mech	24	7	7	11.3
				27	7	7	11.6
				30	7	7	11.8
				33	7	7	12.1
			CLT, Girder, & Mech	38	6	6	12.5
				45	6	6	13.1
				58	6	6	14.2
				67	5	5	14.8
Ex.							
Wash. D.C. IV-B	130 (40)	12	CLT Panel & Mech	24	11	11	11.3
				27	11	11	11.6
				30	11	10	11.8
				33	11	10	12.1

* Depths based on CLT panel depths for 3, 5, 7, and 9-ply panels respectively for each category, the average girder depth for the modeled TG floors for each designed panel depth where applicable, an assumed 18-inch (457 mm) depth for mechanical equipment, [309] and 2 inches for a concrete topping and basic acoustic mat.

** Based on an assumed common 9'-0" floor to ceiling height [310]

*** Assumed 4" of depth added for raised wooden sleepers to provide high acoustic insulation value

7.1.5.3 High Level System Comparisons

This section includes general high-level comparisons of depth, mass, and EC for the included systems. An initial comparison to concrete baseline systems is included; however, following that is an exclusive discussion of the mass timber and hybrid mass timber systems. Most plots in this section use 75% SST unless otherwise noted, based on responsible timber sourcing data for the U.S. [240] The “Embodied Carbon Alternatives” section later in this chapter includes limited comparisons to other SST values and discusses SST assumption decision-making in greater detail. Figure 7-6 presents summary data comparing all floor systems to each other. EC data is based on assuming 75% SST. The trend lines in Figure 7-6 represent mean values, and the shaded bands represent a 95% confidence interval. Specific values will be included more thoroughly in the design guidance sections. Representative key conceptual considerations are summarized in Table 7-9.

Figure 7-7 presents mean values for representative design spans for the depth, mass, and EC of each system. Data is included for all fire design strategies, and therefore represents something roughly between the exposed and protected fire design options. The data is presented this way to guide early general decisions between system types regardless of eventual fire design strategy. Data will be broken out by fire design strategy later in section 7.1.6. The data in Figure 7-7 is color-coded by performance, with more saturated colors representing better values within each metric. Data for both 0 and 75% SST is shown, and economical spans are bolded in each system.

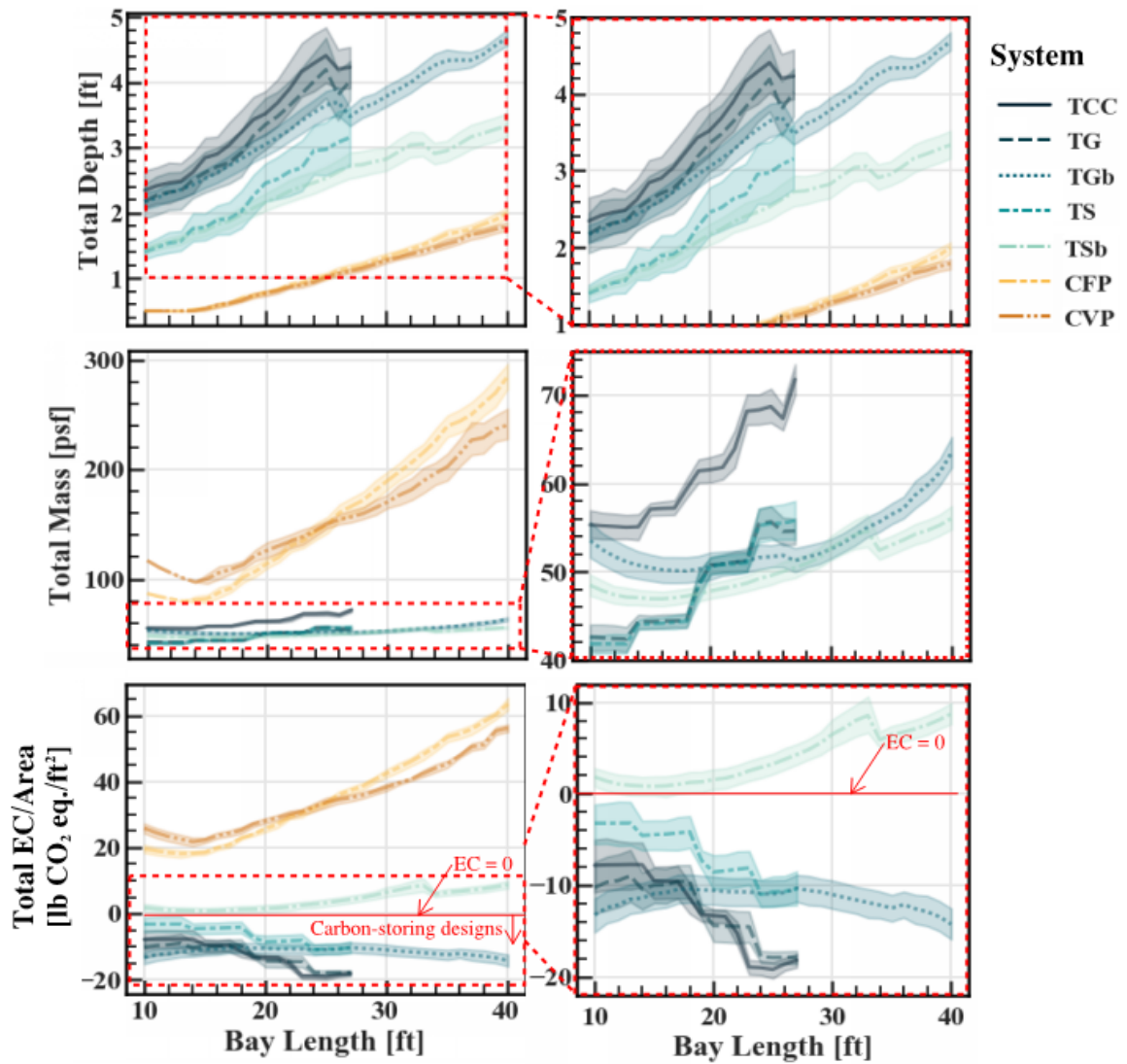


Figure 7-6: Depth, EC, and Mass vs Bay Length for all considered systems, including concrete baselines. The full dataset for all designs is used. The trend lines represent an average for each system, and the shaded regions represent typical ranges of values for each, excluding outliers and extreme ends of the design range. (a) The full metric range on the y-axis is presented (b) The y-axis is expanded to focus on the mass timber systems. (1 ft = 3.05 m; 1 psf = 4.88 kg/m²)

Table 7-9: Key overall design considerations

Main Considerations	Sub-considerations
Research studied a bay range of 10-40 feet (3.1-12.2 m)	The all-timber-framed systems (TG, TGb, and TCC) are limited to about 27-ft (8.2 m) spans due to vibration control limitations.
Mass timber systems are deeper than baseline concrete systems.	- The all-timber systems are 2-3 feet (0.6-0.9 m) deeper. - The hybrid steel-timber systems are 1-2 feet (0.3-0.6 m) deeper.
Mass timber systems are significantly lighter than the baseline concrete systems.	- The CFP and CVP systems' mass varies greatly depending on bay size, with a range of about 80 to 280 psf (390-1370 kg/m²). - The CFP and CVP systems' mass increases at a rate of about 8 and 5.5 psf (39 and 27 kg/m²), respectively, per additional 1-foot of span after the first 15 feet (4.6 m). - The mass timber systems fall within a range of about 40 to 75 psf (200-370 kg/m²).
At 75% SST, the concrete baselines are not competitive for EC.	- The concrete system EC has a range of 16-55 lbs CO₂ eq. / ft² (78-268 kg/m²), and varies significantly with bay size. - Except for the TSb system, all mass timber systems are carbon-storing.
The steel-hybrid mass timber systems (TS and TGb) are shallower as compared to the all-timber-framed systems (TG, TGb, and TCC).	- The steel-hybrid systems have a depth range of about 1-3 feet (0.3-0.9 m). - The all-timber-framed systems have a depth range of about 2-5 feet (0.6-1.5 m).
The TCC system is the heaviest as compared to the other mass timber floors due to the thicker structural concrete topping provided for composite action with the timber floor.	- Below about 18-20 feet (5.5-6.1 m), the TG and TS systems are the lightest, ranging from about 40-50 psf (195-244 kg/m²). - Above about 18-20 (5.5-6.1 m) feet, the TGb and TSb systems are the lightest, ranging from about 48-56 psf (234-273 kg/m²).
EC for the mass timber systems varies greatly by bay size and system type.	- At spans below about 15 feet (4.6 m), the TGb system stores the most direct EC, about 10-14 lbs CO₂ eq. / ft² (49-68 kg CO₂ eq./m²). - At spans greater than 15 feet (4.6 m), the TCC and TG systems store the most direct EC, about 15-20 lbs CO₂ eq. / ft² (73-98 kg CO₂ eq./m²).

0% Sustainably-Sourced Timber															
Span	TCC			TG			TGb			TS			TSb		
	Depth	Mass	EC	Depth	Mass	EC	Depth	Mass	EC	Depth	Mass	EC	Depth	Mass	EC
10	2.3	55.3	16.3	2.2	42.6	13.6	2.2	53.5	19.0	1.4	41.8	15.0	1.4	48.5	20.1
12	2.5	55.1	16.2	2.3	42.4	13.3	2.3	51.7	17.9	1.5	41.8	15.0	1.6	47.4	19.3
14	2.6	55.1	16.2	2.5	44.4	14.0	2.4	50.7	17.3	1.8	44.0	16.1	1.7	47.1	19.2
16	2.9	57.2	17.2	2.7	44.4	13.9	2.6	50.2	16.9	1.9	44.2	16.3	1.8	46.9	19.1
18	3.2	59.4	18.3	2.9	44.5	14.0	2.8	50.1	16.9	2.0	44.4	16.5	2.0	47.2	19.4
20	3.5	61.6	19.3	3.4	50.8	16.7	3.1	50.6	17.0	2.5	50.7	19.5	2.2	47.8	19.8
22	3.9	63.9	20.5	3.6	51.1	16.8	3.3	51.1	17.3	2.6	50.9	19.6	2.3	48.4	20.3
24	4.3	68.3	21.6	4.0	55.4	18.7	3.5	51.6	17.5	3.0	55.2	21.7	2.5	49.2	21.2
26	4.2	67.3	21.3	3.8	54.6	18.6	3.7	51.9	17.7	3.1	55.5	22.0	2.6	50.0	22.0
28	-	-	-	-	-	-	3.6	51.7	17.7	-	-	-	2.7	50.9	22.9
30	-	-	-	-	-	-	3.8	52.6	18.1	-	-	-	2.8	52.7	24.7
32	-	-	-	-	-	-	4.0	54.1	18.7	-	-	-	3.0	54.2	26.3
34	-	-	-	-	-	-	4.3	55.7	19.3	-	-	-	2.9	52.4	23.8
36	-	-	-	-	-	-	4.3	57.2	19.8	-	-	-	3.1	53.6	24.8
38	-	-	-	-	-	-	4.4	59.8	20.5	-	-	-	3.2	54.7	25.8
40	-	-	-	-	-	-	4.7	63.5	21.8	-	-	-	3.3	56.0	27.1

75% Sustainably-Sourced Timber															
Span	TCC			TG			TGb			TS			TSb		
	Depth	Mass	EC	Depth	Mass	EC	Depth	Mass	EC	Depth	Mass	EC	Depth	Mass	EC
10	2.3	55.3	-7.8	2.2	42.6	-10.2	2.2	53.5	-13.2	1.4	41.8	-3.2	1.4	48.5	1.8
12	2.5	55.1	-7.7	2.3	42.4	-9.5	2.3	51.7	-12.1	1.5	41.8	-3.2	1.6	47.4	1.1
14	2.6	55.1	-7.7	2.5	44.4	-10.4	2.4	50.7	-11.4	1.8	44.0	-4.5	1.7	47.1	0.9
16	2.9	57.2	-9.6	2.7	44.4	-9.9	2.6	50.2	-10.8	1.9	44.2	-4.4	1.8	46.9	0.9
18	3.2	59.4	-11.4	2.9	44.5	-9.6	2.8	50.1	-10.4	2.0	44.4	-4.1	2.0	47.2	1.2
20	3.5	61.6	-13.3	3.4	50.8	-14.4	3.1	50.6	-10.5	2.5	50.7	-8.5	2.2	47.8	1.5
22	3.9	63.9	-15.2	3.6	51.1	-14.5	3.3	51.1	-10.7	2.6	50.9	-8.2	2.3	48.4	2.0
24	4.3	68.3	-19.0	4.0	55.4	-17.8	3.5	51.6	-10.9	3.0	55.2	-11.0	2.5	49.2	2.9
26	4.2	67.3	-18.6	3.8	54.6	-17.8	3.7	51.9	-10.8	3.1	55.5	-10.7	2.6	50.0	3.8
28	-	-	-	-	-	-	3.6	51.7	-10.6	-	-	-	2.7	50.9	4.8
30	-	-	-	-	-	-	3.8	52.6	-11.0	-	-	-	2.8	52.7	6.5
32	-	-	-	-	-	-	4.0	54.1	-11.6	-	-	-	3.0	54.2	8.0
34	-	-	-	-	-	-	4.3	55.7	-12.2	-	-	-	2.9	52.4	5.9
36	-	-	-	-	-	-	4.3	57.2	-12.1	-	-	-	3.1	53.6	6.7
38	-	-	-	-	-	-	4.4	59.8	-12.9	-	-	-	3.2	54.7	7.5
40	-	-	-	-	-	-	4.7	63.5	-14.2	-	-	-	3.3	56.0	8.7

Key	Deepest to Shallowest	Heaviest to Lightest	Highest to Lowest	Bold values = Economical spans by system type
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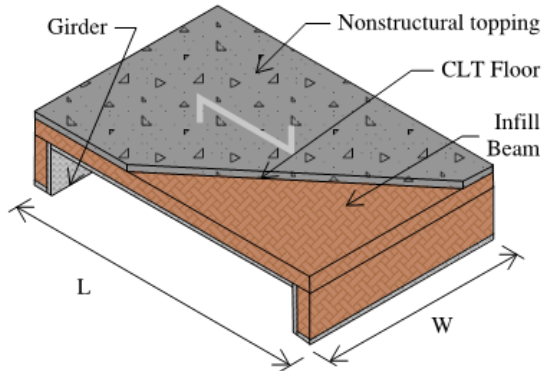
Figure 7-7: Summary values for representative designs, average over all three fire design configurations.

More saturated cell colors represent improved performance. Economical spans determined based on WoodWorks guidance [311] and model results. **Units:** Depth [feet], Mass [lbs / ft²], EC [lbs CO₂ eq./ft²]

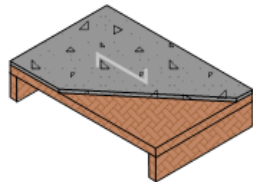
7.1.5.4 Summary Design Guidance by System

1-page Summary charts (Figure 7-8 through Figure 7-12) were created for each mass timber system that describe: a given system's design in further detail, notes key design guidance, and more refined summary data plots. Gray-shaded regions of the bay aspect ratio diagram and data plots on the summary pages are used to highlight recommended spans and configurations for those metrics. The plots use the full dataset but break it out into protected and exposed fire design strategies. The summary charts are intended to act as initial starting points for understanding the pros and cons of each system and the ranges of expected values for meeting depth, mass, and EC design goals.

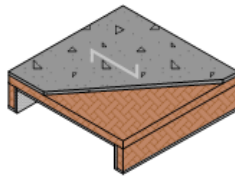
Sample bay design configurations



Rectangular bay, gypsum board protection



Rectangular bay, exposed structure

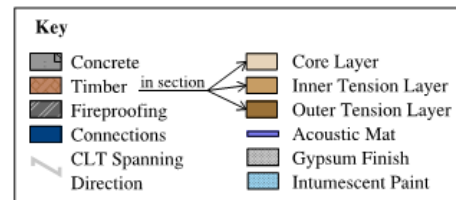
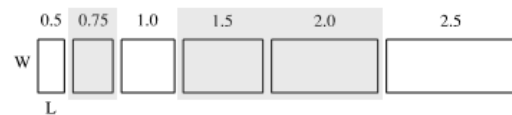


Square bay, gypsum board protection

System Description

CLT floor panels span between Glulam girders located at each end of the bay, and the girders span the bay width. Non-structural concrete topping is provided for acoustic insulation and to control walking-induced vibrations. In protected designs, drywall is installed directly against the underside of the CLT panels and wraps the girders.

Bay aspect ratio configurations: [L:W]



Key Design Guidance

Gray-shaded areas in the plots below represent recommended spans or bay configurations. General guidance is summarized below:

- Where a low-depth floor is the priority, select the protected fire design option and minimize bay size.
- Where a low-mass floor is the priority, select spans between 10 and 20 feet (3.1 and 6.1 m).
- Where EC reduction is a primary goal, consider selecting the exposed design and small bay spans of 10 to 15 ft (3.1 to 4.6 m) to limit impacts of floor system depth on floor height, envelope area, operational energy usage, and mass per SF.
- Because all designs are carbon-storing, consider prioritizing depth and mass to limit holistic impacts on foundations, the lateral system design, construction, and more.

Summary Plots

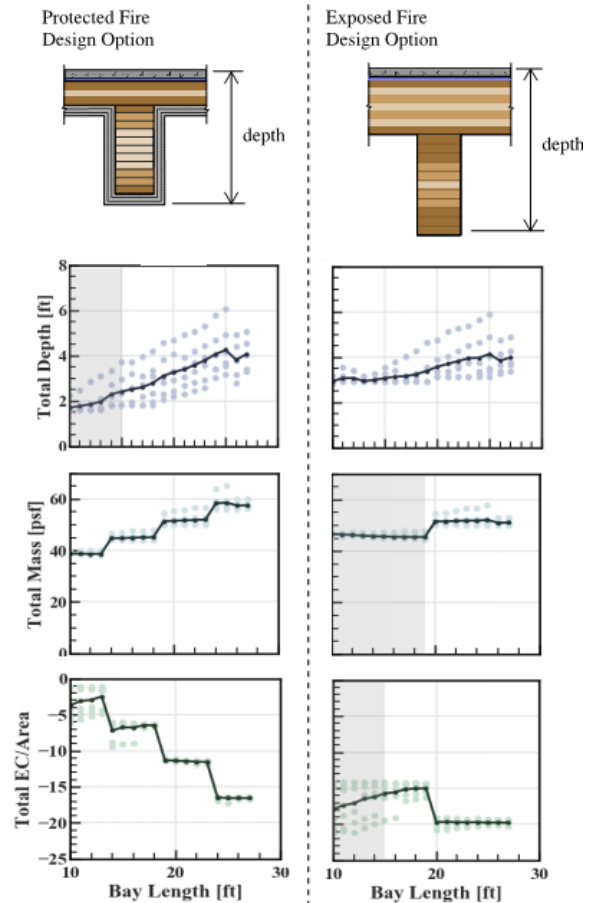
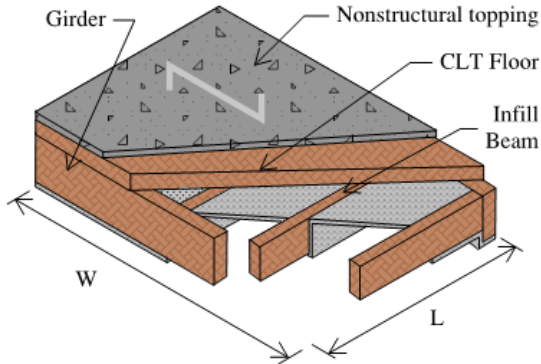
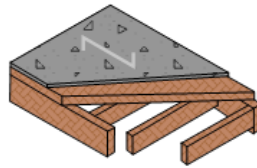


Figure 7-8: TG System Overview

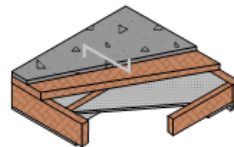
Sample bay design configurations



Rectangular bay, gypsum board protection, multiple infill beams



Rectangular bay, exposed structure, multiple infill beams

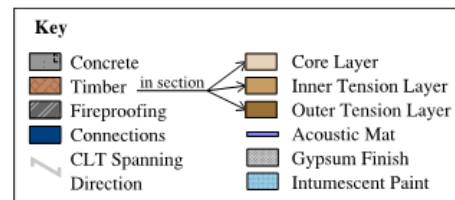
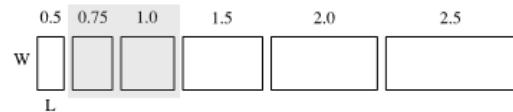


Square bay, gypsum board protection, single infill beam

System Description

In this system, CLT floor panels span between infill beams spaced throughout the bay. Glulam infill beams span between girders located at each end of the bay, and Glulam girders span the bay width. Non-structural concrete topping is provided for acoustic insulation and to control walking-induced vibrations. Where non-combustible protection is used, drywall is installed directly against the underside of the CLT panels and wraps the girders and beams.

Bay aspect ratio configurations: [L:W]



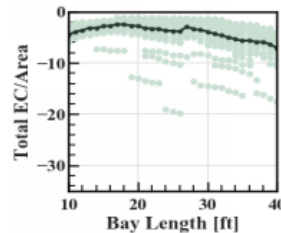
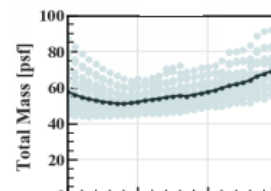
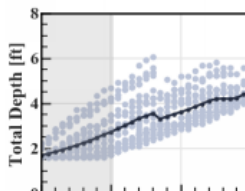
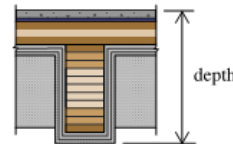
Key Design Guidance

Gray-shaded areas in the plots below represent recommended spans or bay configurations. General guidance is summarized below:

- Where a low-depth floor is the priority, select the protected fire design option and minimize bay size.
- Where a low-mass floor is the priority, select spans between 15 and 25 feet (4.6 and 7.6 m).
- Where EC reduction is a primary goal, consider selecting the exposed design and small bay spans of 15 to 20 ft (4.6 to 6.1 m) to limit impacts of floor system depth on floor height, envelope area, operational energy usage, and mass per SF.
- Because all designs are carbon-storing, consider prioritizing depth and mass to limit holistic impacts on foundations, the lateral system design, construction, and more.

Summary Plots

Protected Fire Design Option



Exposed Fire Design Option

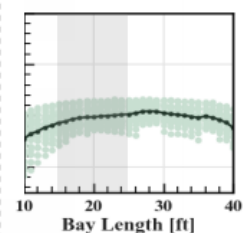
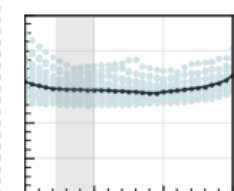
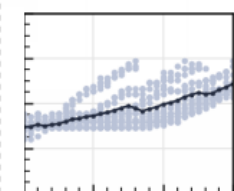
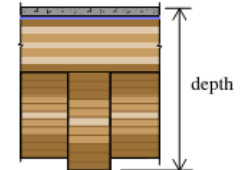
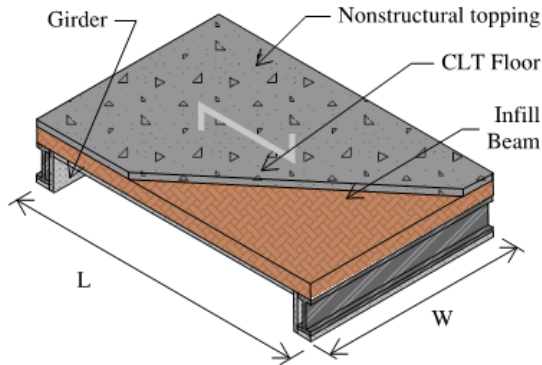
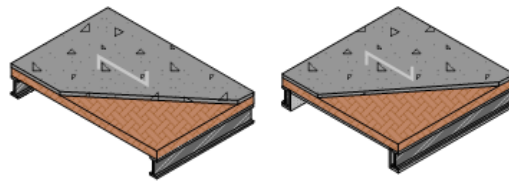


Figure 7-9: TGb System Overview

Sample bay design configurations



Rectangular bay, gypsum board protection



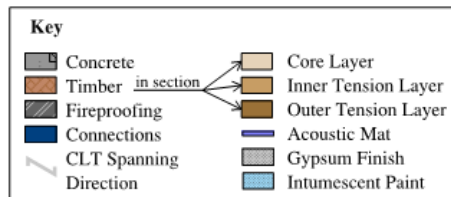
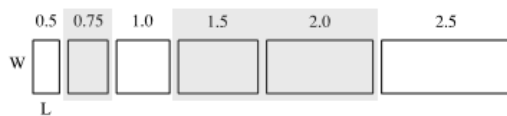
Rectangular bay, exposed structure

Square bay, gypsum board protection

System Description

CLT floor panels span between girders located at each end of the bay, and girders span the bay width. Non-structural concrete topping is provided for acoustic insulation and to control walking-induced vibrations. In protected designs, drywall is installed directly against the underside of the CLT panels and wraps the girders. In exposed designs, the steel is protected with an intumescent coating.

Bay aspect ratio configurations: [L:W]



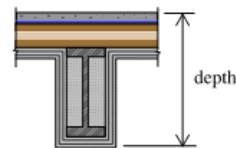
Key Design Guidance

Gray-shaded areas in the plots below represent recommended spans or bay configurations. General guidance is summarized below:

- Where a low-depth floor is the priority, select either fire design option and minimize bay size.
- Where a low-mass floor is the priority, select spans between 10 and 20 feet (3.1 and 6.1 m).
- Where EC reduction is a primary goal, consider selecting the exposed design and small bay spans of 10 to 20 ft (3.1 to 6.1 m) to limit impacts of floor system depth on floor height, envelope area, operational energy usage, and mass per SF.
- Because most designs are carbon-storing, consider balancing depth, mass, and EC goals to limit holistic impacts on foundations, the lateral system design, construction, and more.

Summary Plots

Protected Fire Design Option



Exposed Fire Design Option

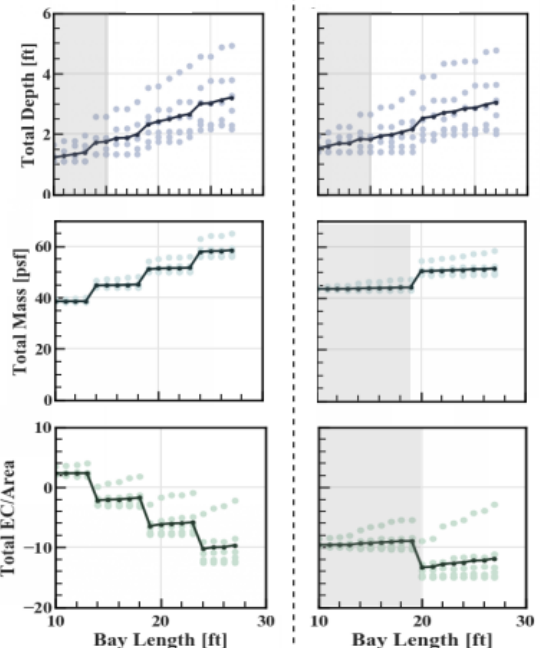
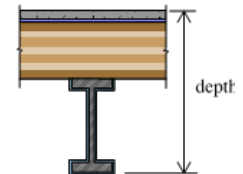
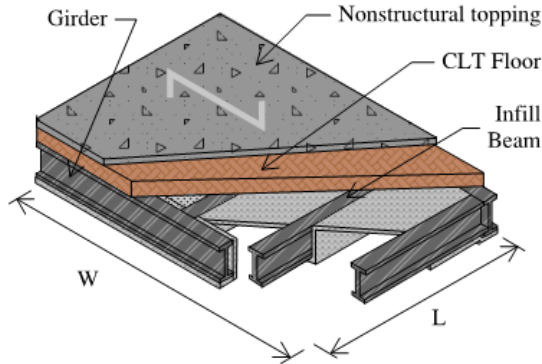
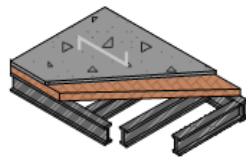


Figure 7-10: TS System Overview

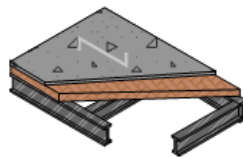
Sample bay design configurations



Rectangular bay, gypsum board protection, multiple infill beams



Rectangular bay, exposed structure, multiple infill beams

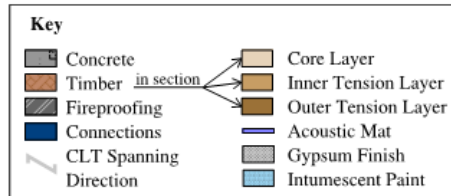
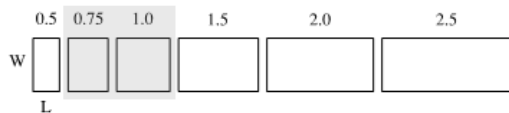


Square bay, exposed structure, single infill beam

System Description

CLT floor panels span between infill beams spaced throughout the bay. Infill beams span between girders located at each end of the bay, and girders span the bay width. Non-structural concrete topping is provided for acoustic insulation and to control walking-induced vibrations. In protected designs, drywall is installed directly against the underside of the CLT panels and wraps the girders and beams. In exposed designs, the steel is protected with an intumescent coating.

Bay aspect ratio configurations: [L:W]



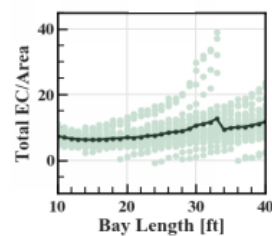
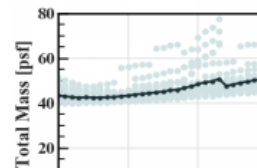
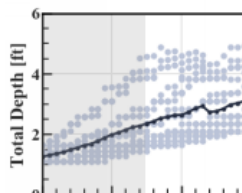
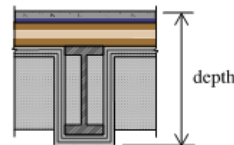
Key Design Guidance

Gray-shaded areas in the plots below represent recommended spans or bay configurations. General guidance is summarized below:

- Where a low-depth floor is the priority, select either fire design option and minimize bay size.
- Where a low-mass floor is the priority, select spans between 15 and 25 feet (4.6 and 7.6 m).
- Where EC reduction is a primary goal, consider selecting the exposed design and small bay spans of 10 to 20 ft (3.1 to 6.1 m) to obtain a carbon-storing floor system.
- Because most designs are not carbon-storing, depth, mass, and EC can all be reduced together by selected relatively small bay spans.

Summary Plots

Protected Fire Design Option



Exposed Fire Design Option

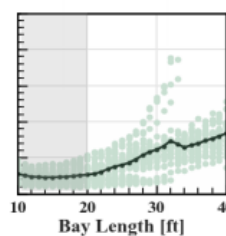
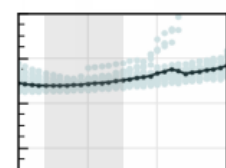
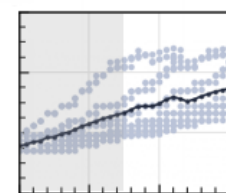
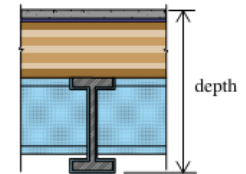
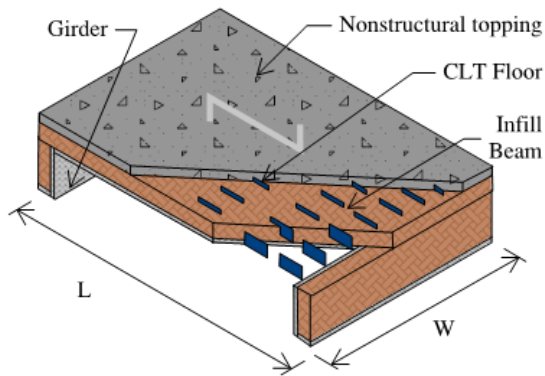
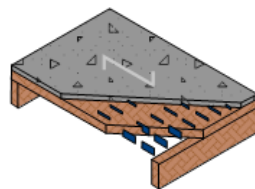


Figure 7-11: TSb System Overview

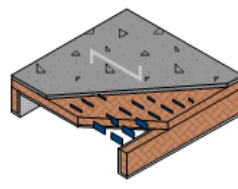
Sample bay design configurations



Rectangular bay, gypsum board protection



Rectangular bay, exposed structure

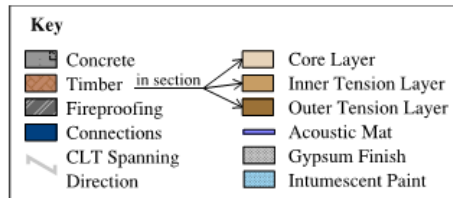
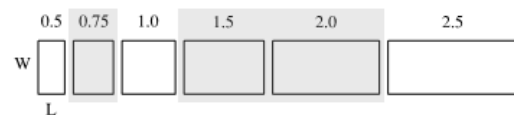


Square bay, gypsum board protection

System Description

CLT floor panels span between Glulam girders located at each end of the bay, and the girders span the bay width. The concrete topping is connected to the CLT floor panels to act compositely through the use of steel shear connectors. The concrete topping helps to improve acoustic insulation and to better control walking-induced vibrations. In protected designs, drywall is installed directly against the underside of the CLT panels and wraps the girders.

Bay aspect ratio configurations: [L:W]



Key Design Guidance

Gray-shaded areas in the plots below represent recommended spans or bay configurations. General guidance is summarized below:

- Where a low-depth floor is the priority, select the protected fire design option and minimize bay size.
- Where a low-mass floor is the priority, select spans between 10 and 20 feet (3.1 and 6.1 m).
- Where EC reduction is a primary goal, consider selecting the exposed design and small bay spans of 10 to 15 ft (3.1 to 4.6 m) to limit impacts of floor system depth on floor height, envelope area, operational energy usage, and mass per SF.
- Because all designs are carbon-storing, consider prioritizing depth and mass to limit holistic impacts on foundations, the lateral system design, construction, and more.

Summary Plots

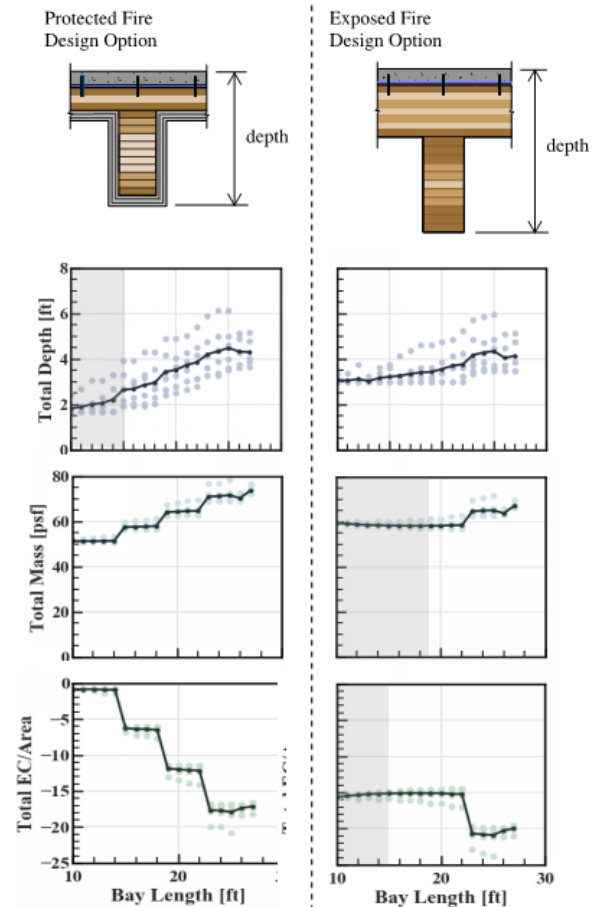


Figure 7-12: TCC System Overview

7.1.6 Fire Design Guidance

7.1.6.1 Prescriptive Fire Design Options

The provided guidance for incorporating fire design strategies is based on 2021 IBC prescriptive options to protect the timber with noncombustible materials, design for timber char, or by combining both methods. Figure 7-13 illustrates these options for various mass timber and hybrid mass timber floor system elements. Figure 7-14 demonstrates the timber char design concept, in which fire design calculations consider only an estimated remaining section after char thickness is removed, and Table 7-10 includes rules of thumb for char design. A “Design Strength to Member Strength” conversion factor is used in structural calculations.

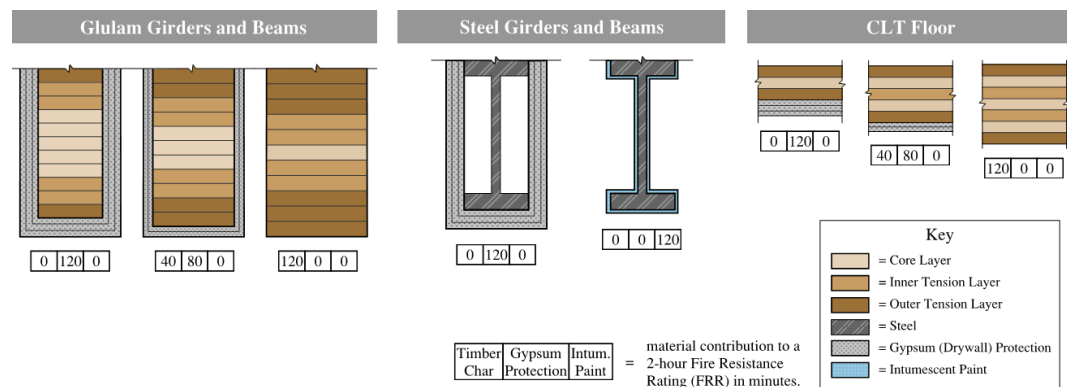


Figure 7-13: Conceptual examples of potential strategies to achieve a 2-hr FRR for Glulam, CLT, and steel sections. Figure adapted from figures in The CLT Handbook and The 2018 FDS. [105], [141]

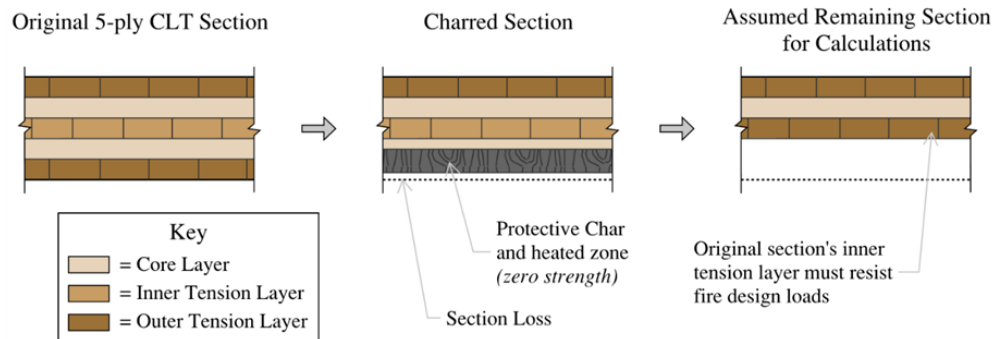


Figure 7-14: Example of charring process and remaining section for use in calculations. (Figure adapted from figures in The CLT Handbook (2019 Canadian Edition) and The 2021 Fire Design Specification for Wood Construction. [105], [141])

Table 7-10: Rules of thumb for char depth and initial sizing of CLT and Glulam

Element	Fire Design Configuration (FRR = 2 hours)			
	80 minutes from noncombustible protection 40 minutes from timber char		2 hours from timber char	
	Effective char depth inches (mm)	Min. element size inches (mm)	Eff. char depth inches (mm)	Min. element size inches (mm)
CLT Panel 1-3/8" (35 mm) plies	1.3 (33)	6.875 (175) 5-ply panel (2 sacrificial plies*)	4.1 (103)	9.625 (245) 7-ply panel (4 sacrificial plies*)
Glulam	1.3 (33)	Must be calculated	3.2 (81)	Must be calculated

* Sacrificial plies are selected conservatively based on selecting the next smallest panel and its properties based on the last untouched lamination parallel to bending.

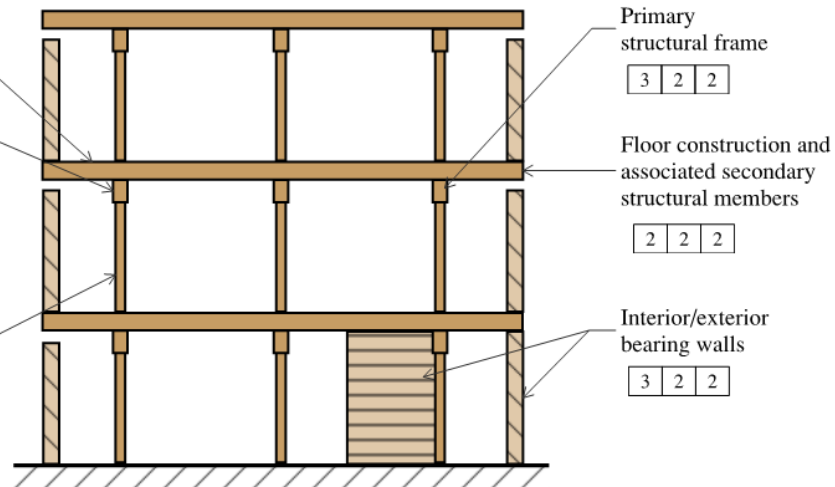
7.1.6.2 Mass Timber Building Fire Protection Provisions Summary

The 2021 IBC includes many requirements for mass timber, fire resistance ratings, fire protection, and more. See Chapter 5 of this dissertation for a detailed discussion of mass timber in the code. Figure 7-15 and Figure 7-16 summarize the most relevant requirements that designer need to be concerned with in the early stages. The following 2021 IBC code sections are primary provisions for determining the requirements related to construction types IV-A, IV-B, and IV-C:

- § 506.2.1: Allowable building height and area
- § 601: Minimum fire resistance ratings
- § 722.7.1(1): Minimum protection time from noncombustible materials
- § 722.7.1(2): Protection provided by noncombustible materials
- § 2304.11: Minimum element sizes for CLT and Glulam

Minimum Element Sizes:

CLT Floor	> 4"
Glulam Beam & Girders	> 5"
	> 10 1/2"
Glulam Columns Supporting Floor Loads:	> 6 3/4"
	> 8 1/4"

Minimum Fire Resistance Rating (FRR):


IV-A | IV-B | IV-C = FRR (hours) required for each Type IV construction type, respectively;

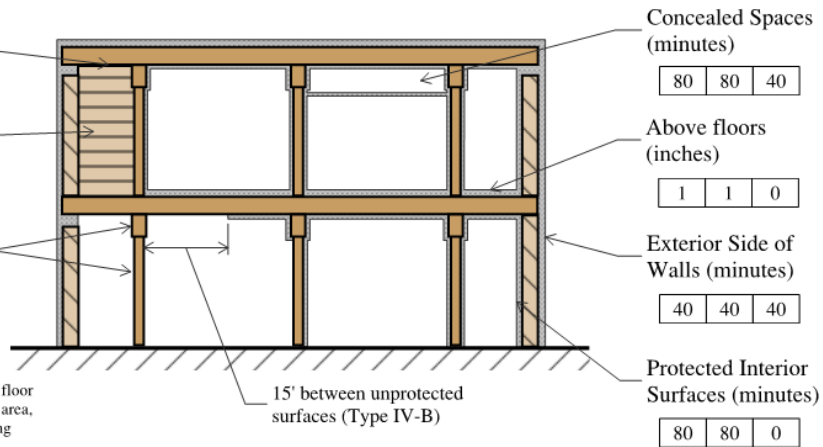
Minimum noncombustible protection*:
80 minutes for 2-hr FRR
120 minutes for 3-hr FRR

*Protection provided by:
1/2" Type X GWB = 25 minutes
5/8" Type X GWB = 40 minutes

Figure 7-15: Minimum element sizes and FRR for mass timber (Sizes shown are per IBC 2021: Table 2304.11 for columns, beams, girders, and roof framing; Section 2304.11.2 for CLT walls; Section 2304.11.3 for CLT floors; and Section 2304.11.4 for roof decks; 1 in = 25.4 mm)

Allowable Unprotected Mass Timber (%):

Ceilings	0	20*	100
Walls	0	40*	100
Columns & Beams	0	100	100

Minimum Noncombustible Protection:


* For Type IV-B, 20% and 40% of the floor area is used to determine unprotected area, and both are combined per the following equation:

$$(U_{ic}/U_{ac}) + (U_{iw}/U_{aw}) \leq 1.0$$

U_{ic} Total unprotected ceiling area
 U_{ac} Allowable unprotected ceiling area
 U_{iw} Total unprotected wall area
 U_{aw} Allowable unprotected wall area

IV-A | IV-B | IV-C = Mass timber protection requirements by Type-IV construction type

Figure 7-16: Mass timber protection requirements. (Note that the 2024 IBC will allow Type IV-B construction to have an area of exposed mass timber ceilings equal to 100% of the floor area.)

7.1.6.3 Fire Design Analysis Overview

Designs were parametrically modeled for each floor system using the three fire design strategies shown in Figure 7-13 and by performing material takeoffs and EC estimates per the previously discussed research methods. Figure 7-17 offers a broad overview of the resulting data when filtered by bay area range categories and selecting the best-performing design for each system within that category for each performance metric.

Key takeaways represented in Figure 7-17 comparing fire design options include:

- When designing with 0% SST and a 2-hr FRR, to reduce depth, mass, and EC:
 - For systems with infills (TGb or TS), select the protection option.
 - For systems without infills (TCC, TG, or TS), select protected designs for bays less than about 400 ft² and exposed designs for bays greater than 900 ft².
- Consider that smaller bays tend to be more controlled by strength requirements (fire design, flexure, or shear), while larger bays tend to be more controlled by serviceability requirements (control of walking-induced vibrations or deflections).
- When designing with 75% SST, the exposed designs offer the lowest floor system EC in most cases, with as much as 20 lbs CO₂ eq. /ft² (98 kg CO₂ eq. /m²) savings as compared to the protected systems, particularly for bay spans below 20 feet (6.1 m) or for systems with infill beams.
 - Designers should aim to select low-EC designs within reasonable limits on depth.
 - The protected TSb system has the highest EC, and can reach upwards of 30-40 lbs CO₂ eq. /ft² (146-195 kg CO₂ eq. /m²).

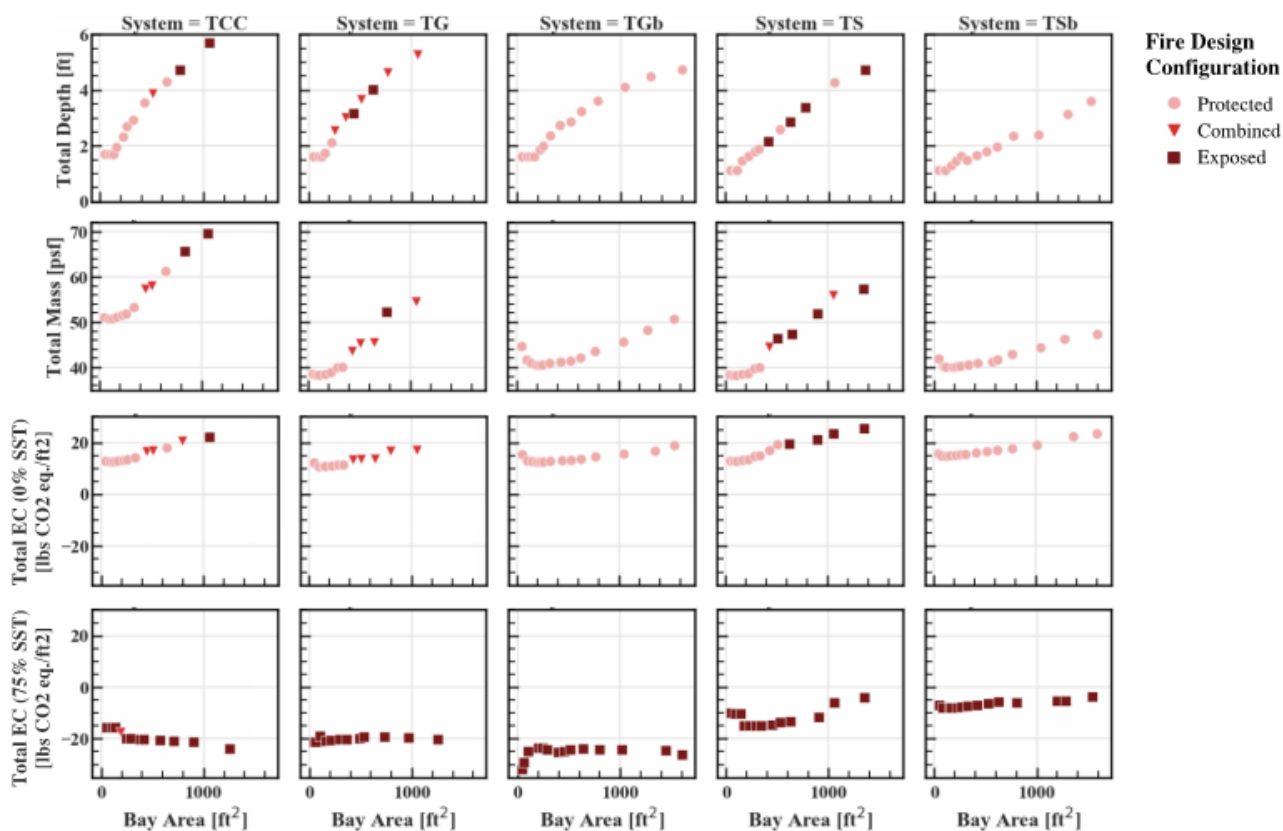


Figure 7-17: Design objectives vs bay area for systems with 0 and 75% SST. Data points represent the best-performing design for a given metric within bay area range categories, and are colored by fire design configuration.

The bay size types which informed the selection of data points in Figure 7-17 are defined in Table 7-11, and are based on the available data within each category, the ability of systems to achieve various bay sizes, and the representation of bay sizes and ranges.

Table 7-11: Defined bay area categories and sub-categories (1 ft² = 0.093 m²)

Bay Size Types	Small Bay < 250 ft ²	Medium 250 - 500 ft ²	Large 500 - 1000 ft ²	Extra-Large < 1000 ft ²
Sub-types [ft ²]	< 50	250 – 300	500 – 600	1000 – 1250
	50 – 100	300 – 400	600 – 750	1250 – 1500
	100 – 150	400 – 500	750 – 1000	> 1500
	150 – 200			
	200 – 250			

7.1.6.4 Fire Design Summary Guidance

An analysis of the model results for different fire design options found that fire design can significantly affect depth, mass, and EC. Box and whisker plots can help visually present the data for a set of design options. Figure 7-18 summarizes the data that can be extracted from a box and whisker plot. Figure 7-19 through Figure 7-21 provide a useful summary of representative design options and ranges. Each performance metric including depth (Figure 7-19), mass (Figure 7-20), and EC (Figure 7-21) is represented in a box and whisker plot for each system for the exposed and protected fire design options, and for each bay size category.

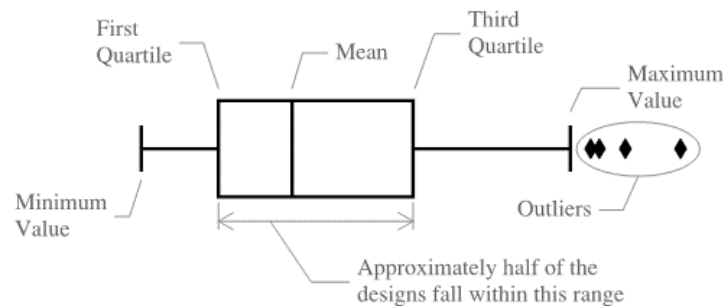


Figure 7-18: How to read a box and whisker plot

Listed here are specific key design guidance on fire design configurations given the results in Figure 7-19 through Figure 7-21:

- For the data shown for 75% SST, most designs are carbon-storing regardless of the fire design strategy.
 - However, if a carbon-storing floor system is desired, then avoid selecting the protected TSb system for all bay size ranges, the exposed TSB system for small and medium bays, and the protected TS system for small bays.
- To limit depth to below 4 ft, plan to design either small and medium Glulam-framed systems (TCC, TG, and TGb) or small, medium, and large steel-framed systems. (Sizes defined per Table 7-11.)
- To reduce mass, note that infill beams tend to be better-suited for larger bays and for protected systems.

- For small bays, systems with infill beams tend to be approximately 5-10 psf (24-49 kg/m²) heavier than those without because infills do not necessarily help further reduce CLT sizing at small spans.
- Systems with exposed infills tend to be approximately 10-15 psf (49-73 kg/m²) heavier than protected infill designs because of the increased surface area that needs to meet char thickness design requirements.

Designs which rely on noncombustible protection for their FRR may require a significant amount of drywall beyond just a finish layer for aesthetics. For this body of work, two layers of ½” (12.7 mm) Type X drywall provide 60 minutes (1 hour) of protection and 3 layers of 5/8” (15.9 mm) Type X drywall provide 120 minutes (2 hours) of protection. [139] Many of the designs covered in this guide require a 2-hour FRR, and therefore require 3 layers of drywall, which adds to installation time on site.

Figure 7-22 provides a chart of representative mean values for each system for both exposed and protected designs within each sub-category of bay size. The data in this chart is for 75% SST, and is averaged over different design options for spans, number of infill beams, and bay aspect ratio. Data is color-coded by performance metric, with more saturated colors representing better values within each metric. Figure 7-22 can serve as a starting point to compare the two main fire design strategies. Based on these plots, the following design scenarios offer a balanced performance between depth, mass, and EC:

- For TCC: Protected designs which have a bay area < 150 ft² (13.9 m²)
- TG: Protected designs which have a bay area < 200 ft². (18.6 m²)
- TGb: Protected designs which have a bay area < 250 ft². (23.2 m²)
- TS: Protected designs < 100 ft² (9.0 m²) or between 200 – 500 ft² (18.6-46.5 m²) and Exposed designs less than 500 ft² (46.5 m²)
- TSb: Exposed designs less than 400 ft² (37.2 m²)

There are some limitations to this work:

- Fire design follows code-prescriptive options, rather than performance-based design methodologies.
- CLT char design assumes a conservative approach based on selecting the panel properties of a panel based on the removal of all plies with any char and up to the first ply parallel to bending.
- Glulam design assumes a balanced layup with sufficient inner ply strength for char design and the removal of sacrificial plies.
- Note that more refined calculations of remaining capacity may be performed in later stages of design using the full remaining sections, rather than the conservative assumptions.
- Balanced layups for Glulam may not be required in some cases.

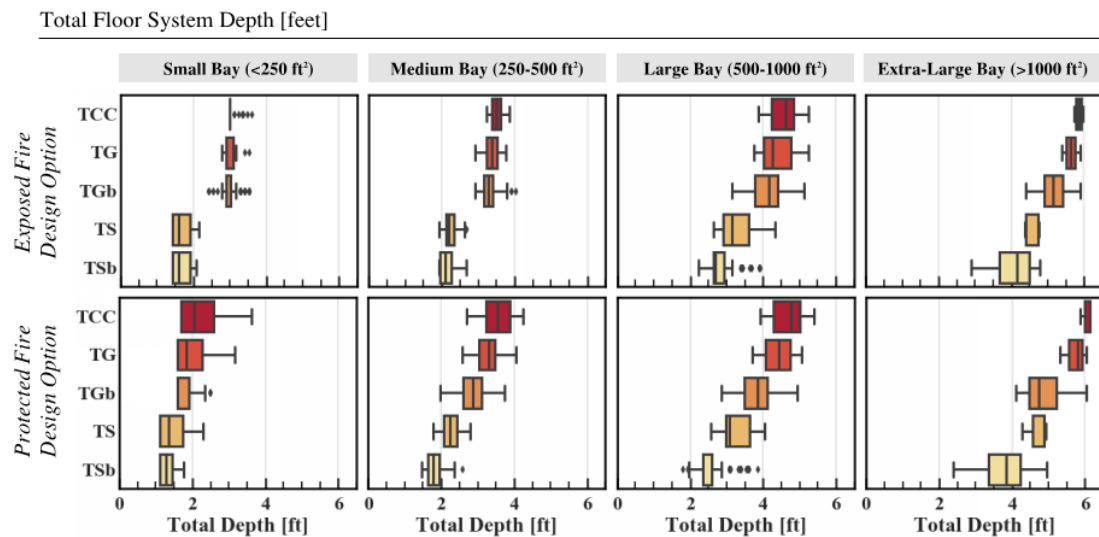


Figure 7-19: Box and whisker plots with depth data for exposed and protected fire design configurations, separated by ranges of bay sizes and by System.

Total Floor System Mass [lbs./ft²]

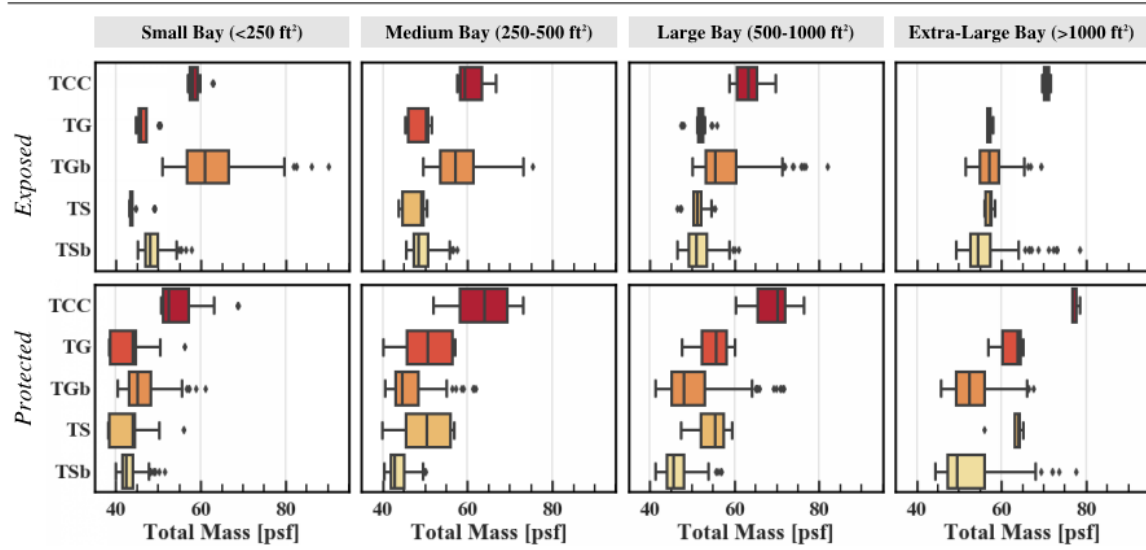


Figure 7-20: Box and whisker plots with mass data for exposed and protected fire design configurations, separated by ranges of bay sizes and by System.

Estimated Embodied Carbon - 75% Sustainably-Sourced Timber [lbs. CO₂ eq./ft²]

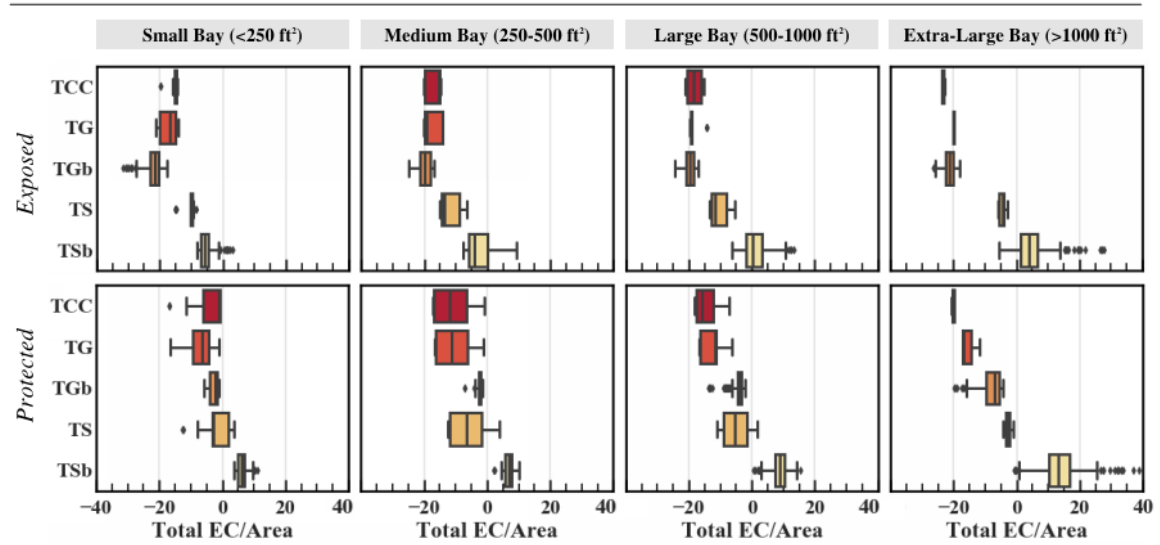


Figure 7-21: Box and whisker plots with EC data for exposed and protected fire design configurations, separated by ranges of bay sizes and by System.

Exposed Fire Design Strategy															
Area Range (SF)	TCC			TG			TGb			TS			TSb		
	Depth	Mass	EC	Depth	Mass	EC	Depth	Mass	EC	Depth	Mass	EC	Depth	Mass	EC
0-50	3.1	57.7	-14.9	3.0	47.0	-16.7	2.9	72.1	-27.0	1.4	45.2	-11.3	1.4	49.3	-5.4
50-100	3.0	57.9	-15.0	3.0	45.4	-16.1	3.0	64.7	-24.6	1.4	43.2	-10.1	1.4	48.0	-6.1
100-150	3.0	58.6	-15.2	2.9	46.1	-19.4	3.0	61.3	-21.2	1.5	43.2	-10.0	1.6	52.0	-4.1
150-200	3.0	59.2	-15.5	3.0	45.9	-20.9	3.0	59.9	-20.7	1.8	43.3	-9.8	1.8	47.7	-6.0
200-250	3.2	59.3	-16.4	3.0	47.8	-17.4	3.1	60.1	-20.4	2.0	46.3	-12.2	1.9	48.0	-5.1
250-300	3.6	60.4	-16.9	3.2	48.2	-17.4	3.1	58.3	-20.3	2.1	46.8	-12.2	2.0	48.0	-4.7
300-400	3.4	60.6	-17.1	3.4	48.5	-17.3	3.2	57.7	-19.9	2.2	47.2	-11.7	2.1	49.0	-2.9
400-500	3.7	60.8	-17.1	3.4	49.2	-17.5	3.4	57.7	-19.5	2.5	48.1	-11.7	2.3	50.2	-0.8
500-600	4.1	61.1	-17.3	3.9	50.2	-17.6	3.7	57.5	-19.6	2.9	49.4	-10.7	2.6	50.9	0.5
600-750	4.6	63.1	-18.6	4.3	50.6	-17.9	4.1	58.0	-19.7	3.1	49.9	-10.7	2.8	51.6	1.4
750-1000	4.9	64.6	-19.3	4.9	53.6	-19.4	4.5	56.6	-20.0	3.8	53.3	-9.9	3.1	51.7	1.1
1000-1250	5.8	70.5	-23.4	5.6	57.0	-20.0	4.9	56.8	-20.7	4.4	56.4	-5.2	3.6	52.7	1.9
1250-1500	-	-	-	-	-	-	5.2	57.4	-21.5	4.7	57.9	-3.4	4.1	54.1	2.9
>1500	-	-	-	-	-	-	5.5	59.8	-22.9	-	-	-	4.4	59.5	8.8

Protected Fire Design Strategy															
Area Range (SF)	TCC			TG			Tgb			TS			TSb		
	Depth	Mass	EC	Depth	Mass	EC	Depth	Mass	EC	Depth	Mass	EC	Depth	Mass	EC
0-50	2.4	57.0	-6.2	2.1	44.8	-6.8	1.6	47.8	-4.4	1.7	44.8	-3.0	1.1	43.8	6.4
50-100	1.9	54.9	-4.5	1.8	42.7	-5.6	1.6	52.1	-5.0	1.3	42.7	-1.9	1.2	42.4	5.7
100-150	1.7	51.3	-1.2	1.7	39.8	-5.6	1.8	44.3	-2.2	1.2	39.7	0.7	1.1	46.2	7.7
150-200	1.7	51.1	-0.8	1.6	38.6	-5.7	1.6	45.2	-2.2	1.1	38.4	2.0	1.5	42.1	5.9
200-250	3.0	61.3	-9.9	2.6	48.0	-9.4	2.1	44.8	-2.0	1.9	47.9	-5.5	1.6	42.4	6.0
250-300	3.3	62.1	-10.1	2.9	49.0	-10.0	2.4	44.4	-2.2	2.0	48.9	-5.9	1.7	42.4	6.3
300-400	3.4	63.2	-11.0	3.3	50.2	-10.6	2.8	45.5	-2.3	2.2	49.9	-6.0	1.8	43.4	6.7
400-500	4.0	65.4	-12.5	3.7	52.3	-12.0	3.1	47.5	-2.6	2.5	52.0	-6.9	2.0	44.4	7.3
500-600	4.2	65.4	-12.3	3.9	51.5	-10.5	3.5	49.1	-3.3	2.8	51.3	-4.3	2.2	45.2	7.9
600-750	4.7	68.8	-14.8	4.4	54.5	-12.8	3.8	50.6	-4.1	3.2	54.2	-6.2	2.4	46.1	8.7
750-1000	5.1	71.5	-16.4	4.9	58.0	-14.5	4.1	50.2	-5.3	3.8	57.5	-5.7	2.8	46.8	9.4
1000-1250	6.0	77.3	-20.2	5.7	61.8	-15.3	4.6	51.8	-7.1	4.5	61.0	-2.9	3.3	48.5	10.5
1250-1500	-	-	-	-	-	-	4.9	53.6	-8.9	4.9	64.7	-2.7	3.8	50.7	11.5
>1500	-	-	-	-	-	-	5.3	56.0	-10.4	-	-	-	4.2	56.6	17.2

Key		Deepest to Shallowest		Heaviest to Lightest		Highest to Lowest
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Figure 7-22: Summary values for representative designs assuming 75% SST. More saturated cell colors represent improved performance. **Units:** Depth [feet], Mass [lbs / ft²], EC [lbs CO₂ eq./ft²]

7.1.7 Acoustic Insulation Design Guidance

7.1.7.1 Overview of Mass Timber Acoustic Insulation

After following design decisions related to fire, designers should next consider project-specific acoustic insulation requirements. Because mass timber floors are lightweight as compared to traditional steel and concrete construction, it can be challenging to meet acoustic insulation needs. [194], [269] For this design guidance creation, the baseline mass timber models assume code minimum acoustic insulation, and if a building only needs to meet code, then the guidance on structural design and EC may be followed more directly. If, however, acoustical performance beyond code minimum is required, then this section provides a useful summary and comparison of acoustic assembly options to start with. This research is based on a tested database for two acoustic insulation metrics [270]:

- **Sound Transmission Class (STC)** is a measure of a floor or wall assembly's ability to limit airborne sound transmission across the assembly. (Figure 7-23a)
- **Impact Insulation Class (IIC)** is a measure of a floor assembly's ability to limit structure-borne transmission of impact noise like footfall to the space directly below the assembly. (Figure 7-23b)

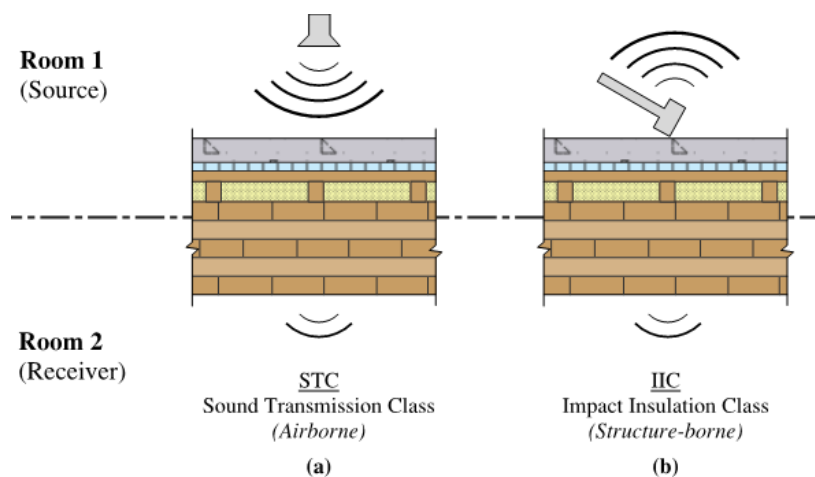


Figure 7-23: Illustration of (a) STC and (b) IIC

The 2021 IBC requires a minimum STC-50 and IIC-50 for floor and wall assemblies separating dwelling spaces. [34] For comparison, a tested bare 5-ply CLT floor panel achieves only around STC-40 and IIC-25. [196] The baseline mass timber models in this research assume that a non-structural concrete topping and acoustic mat are included to meet code for acoustics. Higher tiers of performance are described in Table 7-12 to establish baseline metrics. [280]

Table 7-12: Acoustic performance tier requirements

Performance Tier	STC/ IIC	Description
Non-code-compliant	<50	Clearly hear normal activities of neighbor
Code Minimum	50	Normal activities of neighbors
Good	55-59	somewhat muted
Better	60-64	Cannot hear normal activities of neighbors
Best	65+	

Common recommendations for improving acoustic insulation of mass timber floors include the following [194], [272]:

- Include dense-porosity surfaces to reflect sound,
- Increase floor mass to reduce vibration amplitudes,
- Include sound-dissipated layers,
- Provide acoustic separation between finishes and the structure.

7.1.7.2 Acoustic Insulation Analysis Overview

This research included a study which supplemented the WoodWorks Inventory of Acoustically-Tested Assemblies [196] with EC, depth, and mass data for the included assemblies. Due to the limitations of lab-to-lab testing consistency, the findings are applicable only to early design decision-making, where more refined analysis is expected during later design stages. Refer to Chapter 6 of this dissertation for additional information regarding the methods used in this study. Figure 7-24 includes a general overview of the data and multi-objective plots comparing (a) STC vs IIC and (b) Depth vs EC. The data for these assemblies include the baseline CLT floor panel,

as well as other non-CLT floor panel options. General considerations illustrated in Figure 7-24a and Figure 7-24b include:

- Include a concrete or gypsum topping with an acoustic mat to achieve higher STC and IIC with limited impact to EC.
- Include soft flooring materials like carpet tile to improve IIC.
- Consider an assembly with underside treatment, i.e. a concealed ceiling to meet very high STC and IIC requirements.
- To minimize depth and EC, consider assemblies with raised wooden sleepers.

As an initial starting point, Figure 7-25 includes representative bare CLT panels that document their mass, EC, depth, and lab-tested STC and IIC. Additional assembly layers and components must be added to these bare panels to achieve code-minimum or better acoustic insulation.

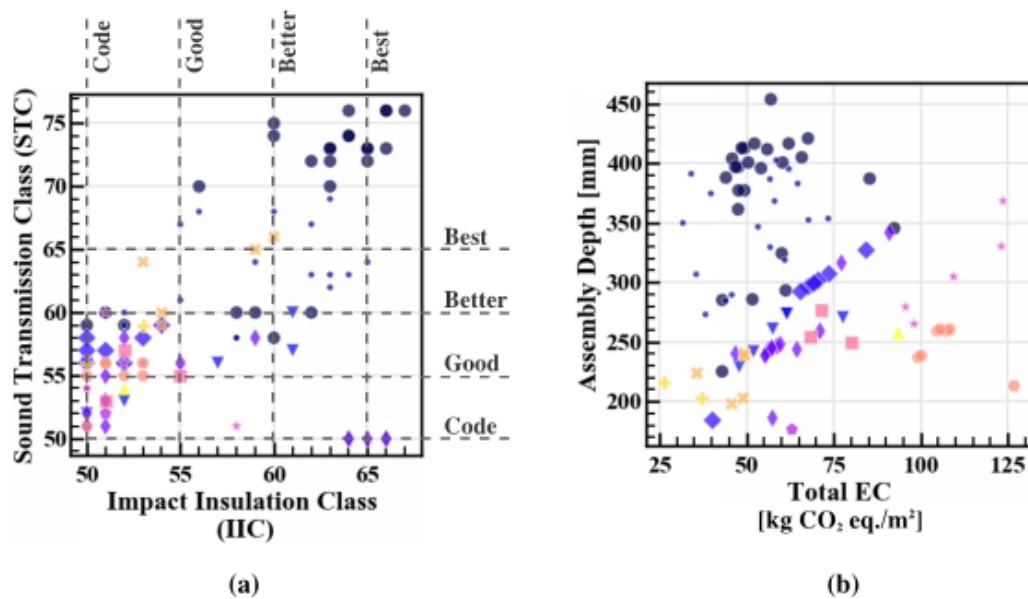
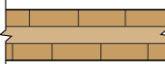
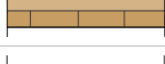


Figure 7-24: (a) STC vs IIC for all studied code-compliant assemblies; (b) Depth vs EC for all studied code-compliant assemblies

Mass Timber Panel	Span ft (m)	Depth in (mm)	Mass psf (kg/m ²)	EC *	EC	Panel Construction	STC	IIC
				(0% SST)	(100% SST)			
				<i>lbs CO₂ e/ft²</i>	<i>(kg CO₂/m²)</i>			
3-ply CLT	13 (4.0)	4.1 (105)	8.9 (19.6)	2.4 (11.7)	-10.6 (-51.6)		38	22
5-ply** CLT	16 (4.8)	5.2 (132)	11.3 (24.8)	3.0 (14.8)	-13.4 (-65.4)		39	22
5-ply** CLT	16 (4.8)	5.4 (137)	11.7 (25.8)	3.2 (15.4)	-13.9 (-67.9)		41	27
5-ply** CLT	18 (5.5)	6.9 (175)	15.0 (33.0)	4.0 (19.7)	-17.8 (-86.8)		41	25
7-ply CLT	23 (7.0)	9 (229)	19.5 (43.0)	5.3 (25.7)	-23.2 (-113.24)		44	30

* EC values for a different timber carbon storage SST assumption can be made through linear interpolation between the values for 0 and 100% SST.

** These panels are very similar, with variations in ply thickness. Differences in STC and IIC data may be partially attributed to lab-to-lab result variability.

Figure 7-25: Performance metrics for bare mass timber panels appearing in the WW Index [11], and based on publicly-available manufacturer technical guides [18–20].

7.1.7.3 Acoustic Summary Guidance

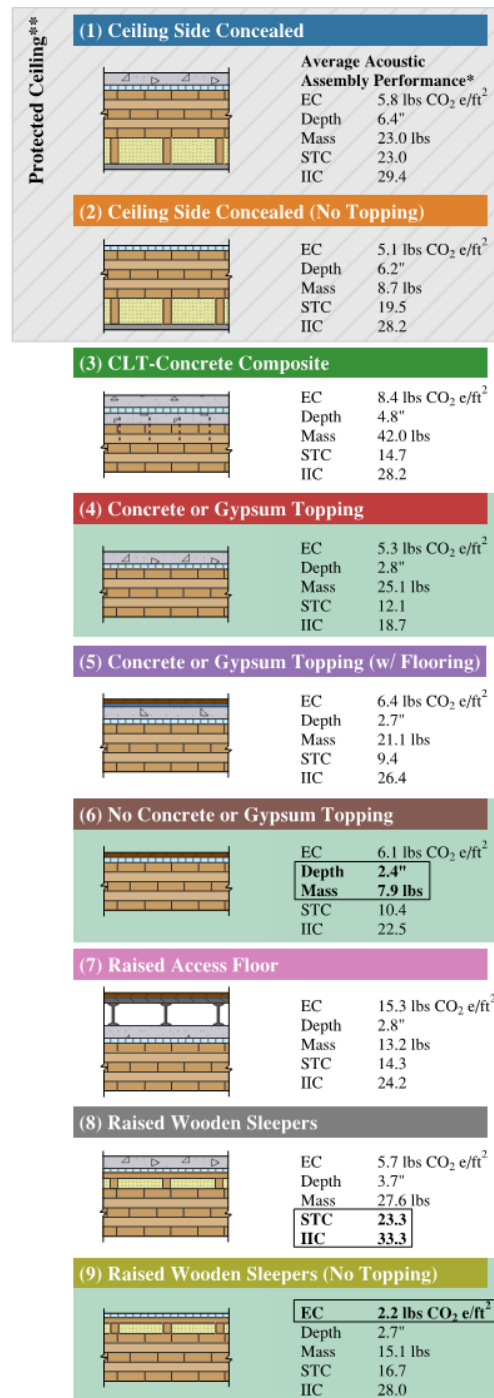
Figure 7-26 provides a useful summary of acoustic assembly options for CLT floor systems, their average performance metrics, and comparisons of each performance metric amongst the assembly options. Figure 7-26b includes the mean EC, depth, mass, STC, and IIC that each assembly added as compared to bare CLT floor performance per Figure 7-25. To make use of these summary Figures, these mean values can be added to a bare panel being considered for a project to estimate total performance. Based on Figure 7-26, key design recommendations and considerations are as follows:

- The assemblies which have the best balance of all five metrics here all have exposed ceilings and include the following, which are highlighted in green in Figure 7-26a:
 - Concrete or gypsum topping
 - No concrete or gypsum topping
 - Raised wooden sleepers with no topping
- To minimize additional system mass and depth, avoid using concrete or gypsum-based toppings.
- To maximize acoustic insulation (STC and IIC), use raised wooden sleepers.
- To maximize IIC, consider the concrete or gypsum topping assembly with flooring.
- To meet other specific needs, outliers may be considered in early design with care. For example, very high IIC performance occurs for some of the “Concrete or Gypsum Topping with Flooring” assemblies. Using a higher or lower value for an assembly will affect the other metrics.
- Many high-performing options for STC and IIC exist within the concealed ceiling assembly categories.

There are some limitations to this work:

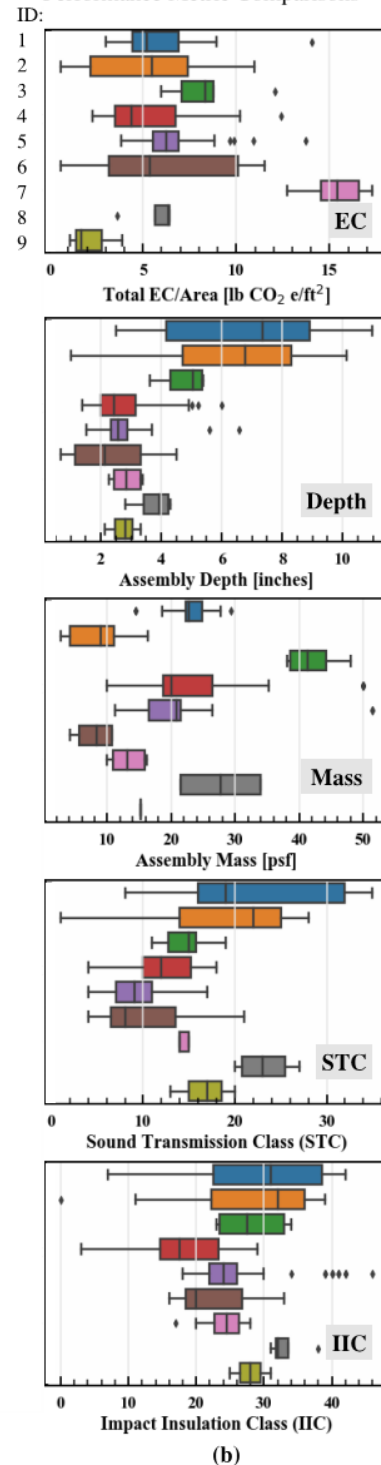
- The analysis is based on actual tested assemblies, and therefore includes only those assemblies represented within the test database.
- Many assemblies do not include the flooring, and there is limited data for mass timber panels other than 5-ply CLT.
- Reported results for the same assembly can vary widely across different labs.
- Lab tests for acoustic performance may not predict in-situ field performance, which relies heavily on the quality of installation and detailing.
- The main parametric model for the five studied floor systems does not incorporate varying loads to accommodate heavier acoustic assemblies.

Acoustic Insulation Assemblies



(a)

Performance Metric Comparisons



(b)

Figure 7-26: Summary design data for acoustic CLT floor assemblies. (a) Summary of additive mean values not including the bare CLT floor for each category. Green-shaded categories have the best balance of all five metrics (b) Box and whisker plots of data for additive values.

*Mean metric values do not include the bare CLT floor but may be added to data for bare floors per Figure 7-25.

**Gray-shaded region includes categories with underside acoustic treatment

7.1.8 Structural and Embodied Carbon Design Guidance

Critical to mass timber floor construction is structural performance, while the consideration of fire and acoustic performance is needed, having starting guidance for structural design is equally important. This section provides additional data visualizations and design guidance specific to the structural and embodied carbon performance goals in a designer friendly format that complements Chapter 4. Although fire design guidance was previously discussed in a specific section, this section will continue to break down data discussions into the different fire design options where relevant.

7.1.8.1 Structural Performance by Fire Design Strategy

Structural performance can vary significantly with fire design configuration depending on the bay span and system. Figure 7-27 shows the total assembly depth versus bay length for each system, with the data divided by fire design configurations, and Figure 7-28 enlarges a subset of the same data for 10 to 20-foot spans. The trend lines represent mean values, while the bands around each trend line represent a confidence interval of 95%. Below are key considerations for structural design:

- Consider that smaller bays less than 20 ft (6.1 m) tend to be more controlled by strength requirements (fire design, flexure, or shear), while larger bays greater than 20 ft (6.1 m) tend to be more controlled by serviceability requirements (control of walking-induced vibrations or deflections).
- Exposed designs are significantly deeper for the all-timber systems at spans below about 20 feet, but (6.1 m) become competitive at longer spans.
 - Exposed all-timber system depths range from about 3 feet (0.9 m) deep at 10-ft (3.1 m) spans to 3.5-ft (1.1 m) deep at 20-ft (6.1 m) spans.
 - Protected all-timber system depths range from about 2-ft (0.6 m) deep at 10-ft (3.1 m) spans to 3 ft deep (0.9 m) at 20-ft (6.1 m) spans.

- Above 20 feet (6.1 m) spans, the TG and TCC systems have less variability between fire design options.
 - TCC systems range from about 3.5 ft (1.1 m) deep at 20 feet (6.1 m) to 4.5 ft (1.4 m) deep at their 27-ft (8.2 m) maximum span.
 - TG systems range from about 3.5 (1.1 m) ft deep at 20 feet (6.1 m) to 4-ft (1.2 m) deep at their 27-ft (8.2 m) maximum span.
- Above 25 (7.6) feet spans for the TGB system, the exposed designs average about a half-foot deeper than the protected designs.
 - Exposed designs range from 4-5 feet (1.2-1.5 m) between the 25- and 40-ft (7.6- and 12.2-m) bay spans.
 - Protected designs range from about 3.5 to 4.5 ft (1.1 to 1.4 m) between the 25- and 40-ft (7.6- and 12.2-m) bay spans.
- Protected designs are often marginally shallower than exposed designs for most bay lengths in the steel-hybrid systems.
 - Average depths for the TS system range from about 1.5 to 3 ft (0.5 to 0.9 m) for the 10- to 27-ft (3- to 8.2-m) span range.
 - Average depths for the TSb system range from about 1.5 to 3.5 ft (0.5 to 1.1 m) for the 10- to 40-ft (3- to 12.2-m) span range, with exposed designs generally being about a half-foot deeper than protected designs.

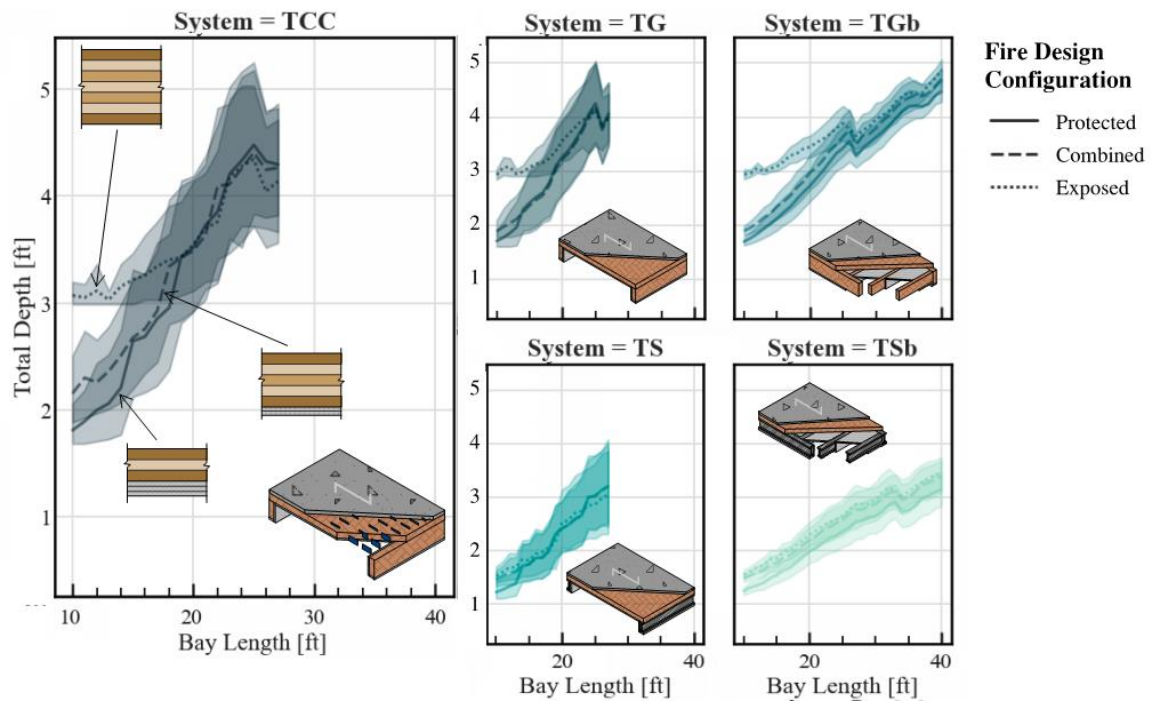


Figure 7-27: Depth versus bay length for different systems with varying fire design configurations for 10 to 40 ft (3.1 to 12.2 m) bay spans and 75% SST.

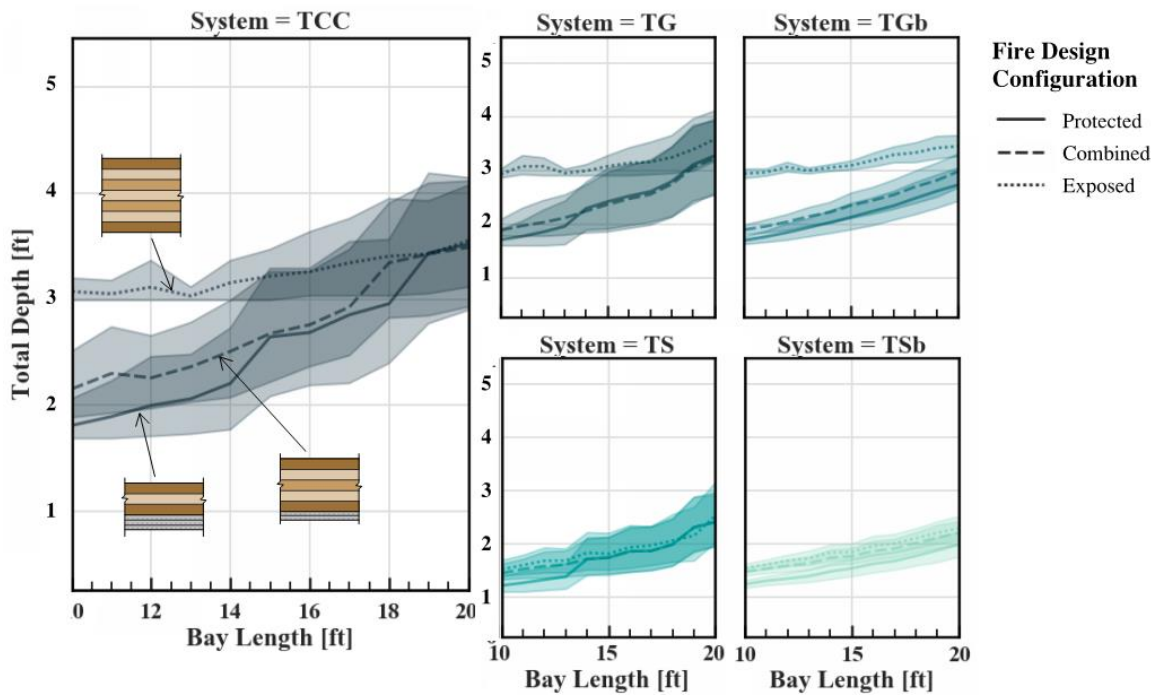


Figure 7-28: Depth versus bay length for different systems with varying fire design configurations for 10 to 20 ft (3.1 to 6.1 m) bay spans and 75% SST.

Figure 7-29 shows similar data but it was divided into plots by fire design configuration rather than by system for an alternate comparative visualization. This figure also includes EC and mass versus bay span. Below are key design considerations:

- In all cases, the TSb system offers the lowest depth, but the highest EC.
- The TSb system does not become carbon-storing except for the exposed option with spans below about 28 ft (8.5 m).
- The TCC and TG systems are generally the deepest systems and have the lowest EC.
- Adding infills helps reduce depth for protected systems, but is less significant in reducing depth for exposed systems.
- Exposed designs generally result in deeper designs with lower EC and higher mass.

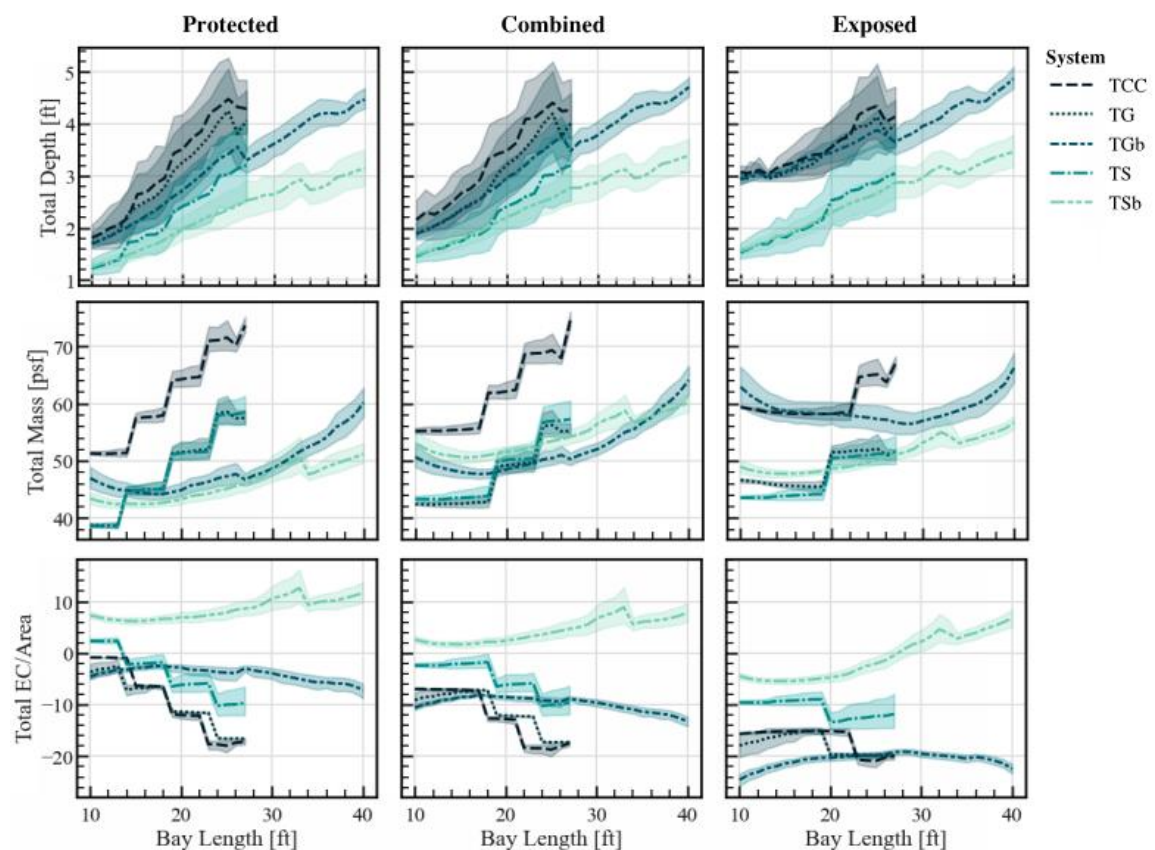


Figure 7-29: Floor system data separated by fire design configuration and shown for each system and performance metric. EC assumes 75% SST and is in units of lbs CO₂ eq./ft².

7.1.8.2 Infill Beams

For some projects, designers may want to include infill beams for a number of reasons including but not limited to aesthetics and span capabilities. Figure 7-30 presents a comparison of varying the number of infill beams in the TGb and TSb systems. In many cases, the number of infill beams does not significantly affect the performance metric, including for the depth of the TGb and TSb systems, and the EC of the TGb system. In cases where the number of infill beams makes a difference, providing one infill beam is typically the best option. In the TSb system at higher bay spans, the use of one infill helps maintain a low EC at or close to net zero for the floor system as compared to using more infills, especially as the bay spans longer. The TSb and TGb system mass may be reduced by up to about 16 and 20%, respectively, if infill beams are limited to one infill. Below is the resulting design guidance based on this analysis and previous discussion of systems including infill beams:

- Provide infill beams for systems spanning longer than about 27 feet (8.2 m).
- Where feasible, limit TSb and TGb designs to a single infill beam.
- Provide infill beams to reduce system mass in protected designs with bays greater than 250 ft² (23 m²). (The medium bay area category or larger)
- Incorporate infill beams where feasible to reduce depth of their counterpart versions (i.e. add infills to the TG or TS systems to reduce depth.)

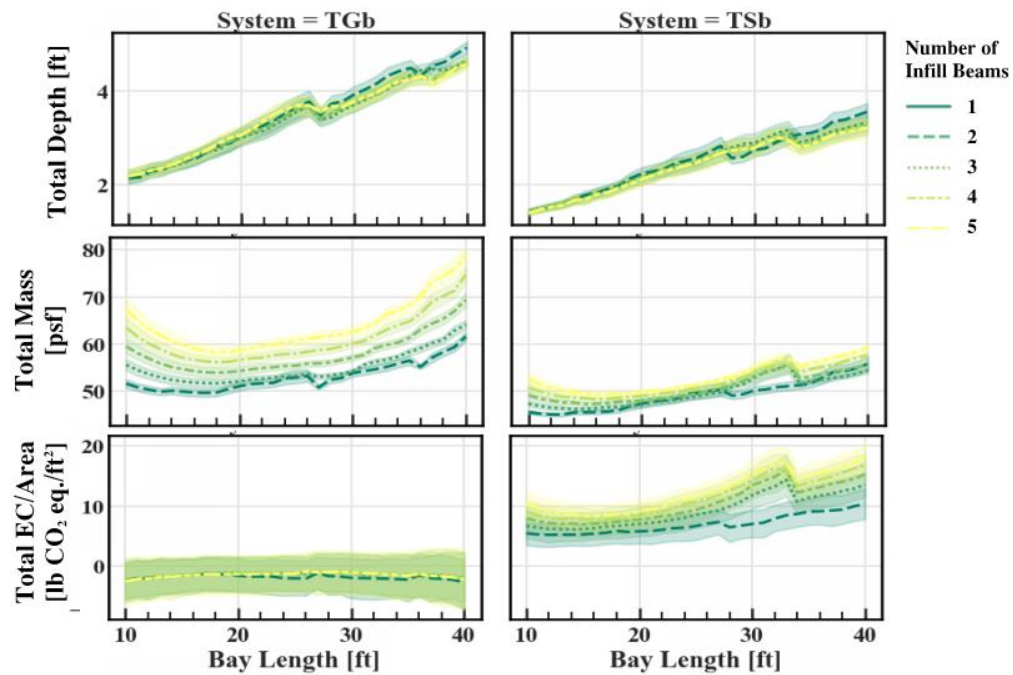


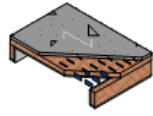
Figure 7-30: Design objectives versus bay length for floor systems with infill beams and 75% SST.

7.1.8.3 Structural Summary Guidance

This section so far has discussed structural performance and EC trends for mass timber floors. Figure 7-31 provides a useful summary of depth, mass, and EC for all systems and representative concrete floor comparison data. Figure 7-31a provides average performance metric values for each system, broken down by fire design configuration, while Figure 7-31b shows box and whisker plots for the performance metrics at the exposed and protected design options. Depending on the design type, note that there can be a large variability in performance metrics, offering designers a range of options to meet their goals. A good starting point is to consider systems which meet design goals and compare the available options within those systems. For example, if reducing depth is very important, consider steel-hybrid systems and compare the performance metrics across fire design options and bay sizes.

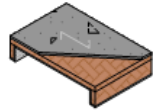
Mass Timber Structure Types

Timber-Concrete Composite



Average Assembly Metrics*			
Metric	Exposed	Combined	Protected
Depth [ft]	3.5	3.3	3.2
Mass [lbs/ft ²]	60.3	61.5	61.1
EC [lbs CO ₂ e/ft ²]	-16.6	-11.9	-9.1

Timber Floor & Timber Girders



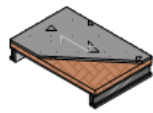
Average Assembly Metrics*			
Metric	Exposed	Combined	Protected
Depth [ft]	3.4	2.9	2.9
Mass [lbs/ft ²]	48.4	47.2	48.1
EC [lbs CO ₂ e/ft ²]	-17.7	-11.0	-9.3

Timber Floor & Timber Girders, Beams



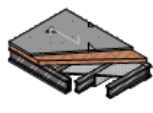
Average Assembly Metrics*			
Metric	Exposed	Combined	Protected
Depth [ft]	3.7	3.3	3.1
Mass [lbs/ft ²]	59.0	51.6	48.1
EC [lbs CO ₂ e/ft ²]	-20.7	-9.7	-3.9

Timber Floor & Steel Girders



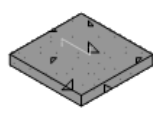
Average Assembly Metrics*			
Metric	Exposed	Combined	Protected
Depth [ft]	2.3	2.2	2.2
Mass [lbs/ft ²]	47.0	48.4	48.3
EC [lbs CO ₂ e/ft ²]	-10.8	-5.0	-3.9

Timber Floor & Timber Girders, Beams



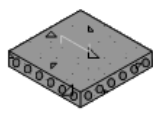
Average Assembly Metrics*			
Metric	Exposed	Combined	Protected
Depth [ft]	2.6	2.5	2.2
Mass [lbs/ft ²]	50.8	54.2	45.7
EC [lbs CO ₂ e/ft ²]	-1.1	4.3	8.4

Concrete Flat Plate



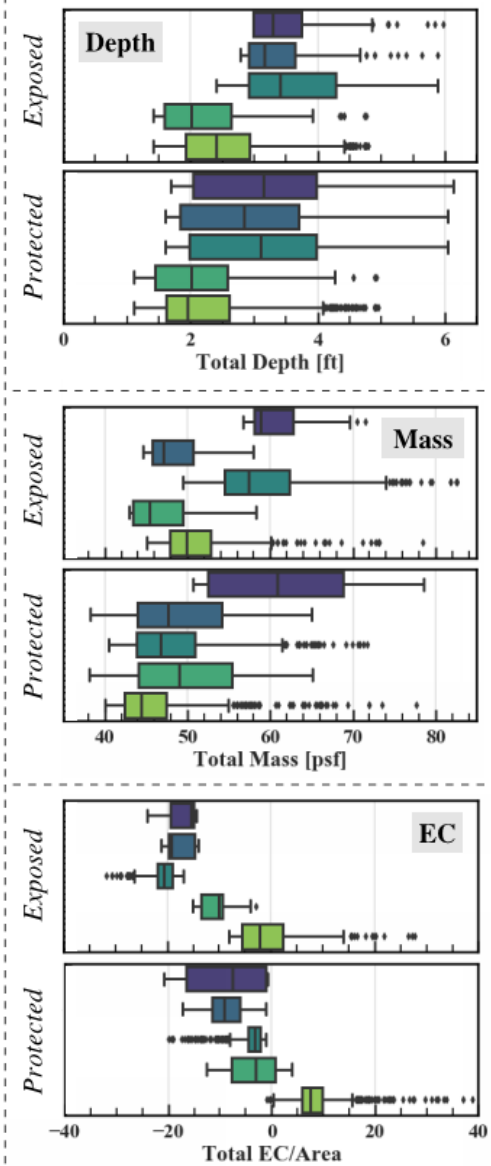
Average Assembly Metrics*			
Metric	Exposed		Protected
Depth [ft]	1.1		1.1
Mass [lbs/ft ²]	159.4		159.4
EC [lbs CO ₂ e/ft ²]	35.3		36.1

Concrete Voids Plate



Average Assembly Metrics*			
Metric	Exposed		Protected
Depth [ft]	1.0		1.0
Mass [lbs/ft ²]	154.0		154.0
EC [lbs CO ₂ e/ft ²]	34.1		35.0

Performance Metric Comparisons



(a)

(b)

Figure 7-31: Summary design data for CLT floor systems. (a) Summary of mean values for each system. Green-shaded categories have the best balance of all three metrics (b) Box and whisker plots of design data. *Mean metric values represent the mean of all designs in a given category, including varying infills and aspect ratio.

7.1.8.4 Bay Geometry

So far, this section has included summary charts to aid decision-making, while the following sections seek to offer more specific early design estimates for depth, mass, and EC. This section provides additional plots, equations, and charts that can be used to provide quick estimates of performance metrics for early designs based on bay area. Plots and equations are first shown for assembly depth. Then enlarged plots are shown for mass and EC.

Assembly Depth

Figure 7-32 includes plots for depth versus bay area, and in general a roughly quadratic trend line can be observed for all systems regardless of bay aspect ratio. Based on this observation, equations for estimating depth were developed using the “statsmodels” package in Python. Depth equations for each system and fire design option are provided in Table 7-13, both based on the entire span range available for a system, as well as for the economical span ranges previously noted in Figure 7-7.

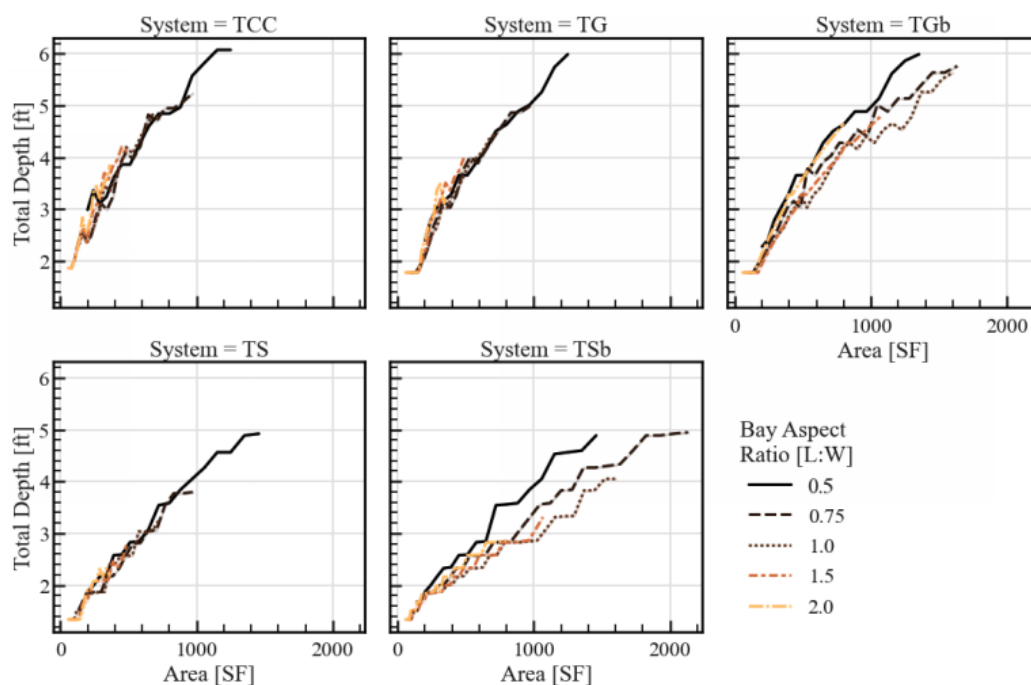


Figure 7-32: Depth versus bay area for each system for the protected fire design option. Data styled and color by bay aspect ratio.

Table 7-13: Early-stage design equations for approximating total assembly depth

		System	Full Span Length Range*	Economical Span Length Range*
Fire Design Approach	Protected	<i>TCC</i>	$D = -2.82\text{e-}06 A^2 + 7.13\text{e-}03 A + 1.25$	$D = -2.84\text{e-}06 A^2 + 6.99\text{e-}03 A + 1.17$
		<i>TG</i>	$D = -2.32\text{e-}06 A^2 + 6.47\text{e-}03 A + 1.15$	$D = -2.06\text{e-}06 A^2 + 6.26\text{e-}03 A + 1.11$
		<i>TGb</i>	$D = -1.45\text{e-}06 A^2 + 4.79\text{e-}03 A + 1.18$	$D = -7.19\text{e-}07 A^2 + 3.93\text{e-}03 A + 1.35$
		<i>TS</i>	$D = -8.47\text{e-}07 A^2 + 4.00\text{e-}03 A + 0.92$	$D = -3.77\text{e-}07 A^2 + 3.20\text{e-}03 A + 1.2$
		<i>TSb</i>	$D = -3.57\text{e-}07 A^2 + 2.46\text{e-}03 A + 0.97$	$D = -1.15\text{e-}07 A^2 + 1.90\text{e-}03 A + 1.09$
	Combined	<i>TCC</i>	$D = -2.12\text{e-}06 A^2 + 6.07\text{e-}03 A + 1.59$	$D = -2.25\text{e-}06 A^2 + 6.01\text{e-}03 A + 1.54$
		<i>TG</i>	$D = -1.93\text{e-}06 A^2 + 5.91\text{e-}03 A + 1.27$	$D = -1.33\text{e-}06 A^2 + 5.45\text{e-}03 A + 1.27$
		<i>TGb</i>	$D = -1.48\text{e-}06 A^2 + 4.80\text{e-}03 A + 1.38$	$D = -7.55\text{e-}07 A^2 + 3.88\text{e-}03 A + 1.59$
		<i>TS</i>	$D = -5.65\text{e-}07 A^2 + 3.53\text{e-}03 A + 1.08$	$D = -3.77\text{e-}07 A^2 + 3.20\text{e-}03 A + 1.2$
		<i>TSb</i>	$D = -4.01\text{e-}07 A^2 + 2.50\text{e-}03 A + 1.21$	$D = -1.68\text{e-}07 A^2 + 1.95\text{e-}03 A + 1.34$
	Exposed	<i>TCC</i>	$D = 6.96\text{e-}07 A^2 + 1.73\text{e-}03 A + 3.01$	$D = 3.23\text{e-}06 A^2 + 1.60\text{e-}04 A + 3.17$
		<i>TG</i>	$D = 1.12\text{e-}06 A^2 + 1.32\text{e-}03 A + 2.77$	$D = 4.08\text{e-}06 A^2 + -7.53\text{e-}04 A + 2.98$
		<i>TGb</i>	$D = -1.04\text{e-}07 A^2 + 2.11\text{e-}03 A + 2.64$	$D = 8.11\text{e-}07 A^2 + 1.34\text{e-}03 A + 2.65$
		<i>TS</i>	$D = -5.03\text{e-}07 A^2 + 3.32\text{e-}03 A + 1.17$	$D = -4.62\text{e-}07 A^2 + 3.27\text{e-}03 A + 1.17$
		<i>TSb</i>	$D = -4.27\text{e-}07 A^2 + 2.53\text{e-}03 A + 1.29$	$D = -1.98\text{e-}07 A^2 + 2.01\text{e-}03 A + 1.41$

D = full floor system depth = topping + CLT panel + framing + fireproofing

$A = L * W = L^2 / AR$

Where;

L = bay span

W = bay width

AR = bay aspect ratio = L / W

* Economical spans assume: TCC & TG = 10-20 ft; TGb = 20-30 ft; TS = 18-26 ft; TSb = 30-40 ft

Area Density and Embodied Carbon

Figure 7-33 through Figure 7-38 include plots for mass per square foot, or area density, and EC of each system for protected designs and exposed designs. Enlarged versions of these plots for printing and measuring appear in Appendix B of this dissertation. The plots show each performance metric versus bay area, with separate trend lines based on different bay aspect ratios. Designers may estimate area density and EC of an initial design by finding the appropriate plot and trendline, reading it based on the anticipated bay area. Where a specific bay aspect ratio isn't included, linear interpolation between the two nearest included aspect ratios is permitted.

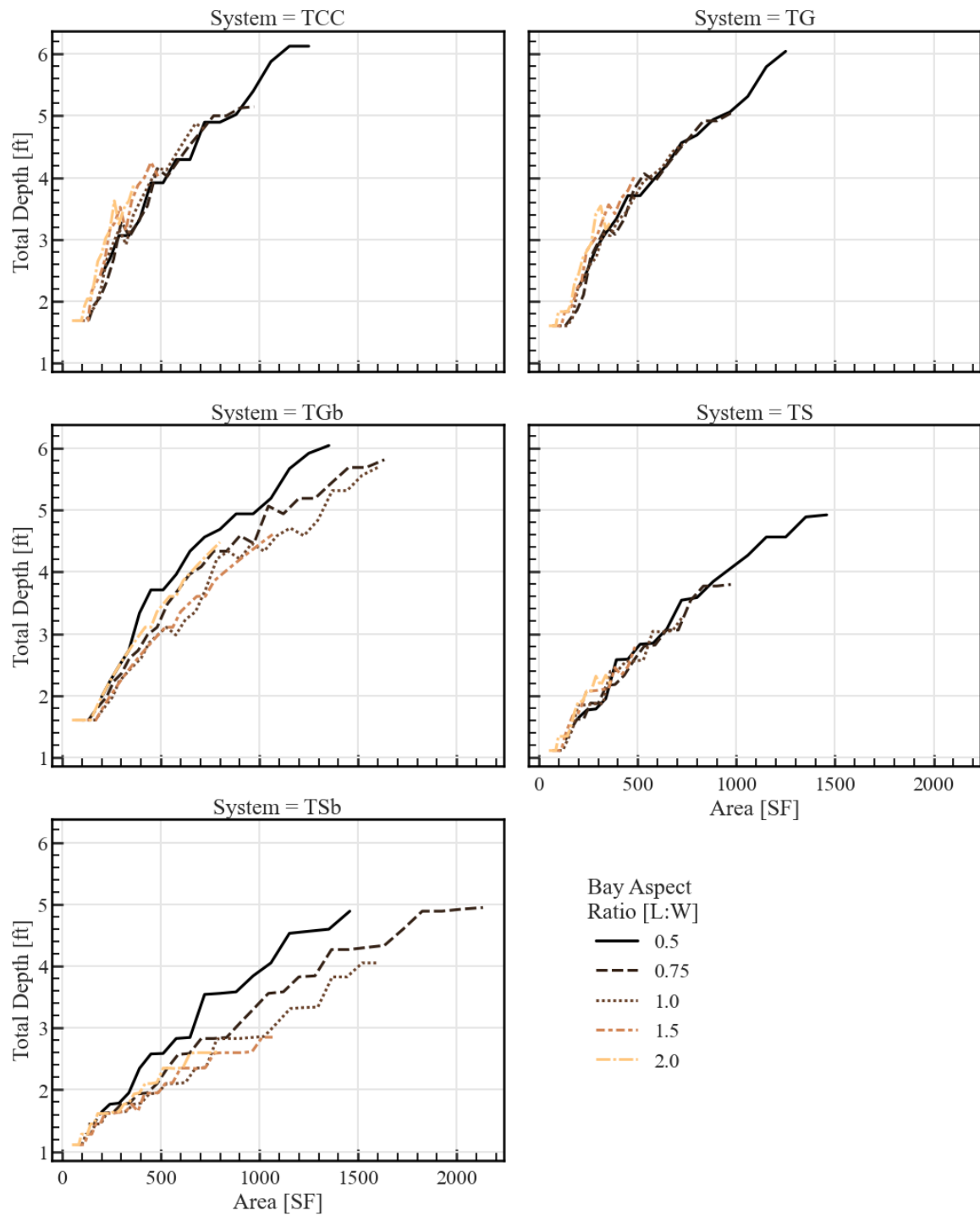


Figure 7-33: Depth versus bay area for protected designs (with a single infill beam where applicable)
 [1 ft = 0.305 m; 1 ft² = 0.093 m²]

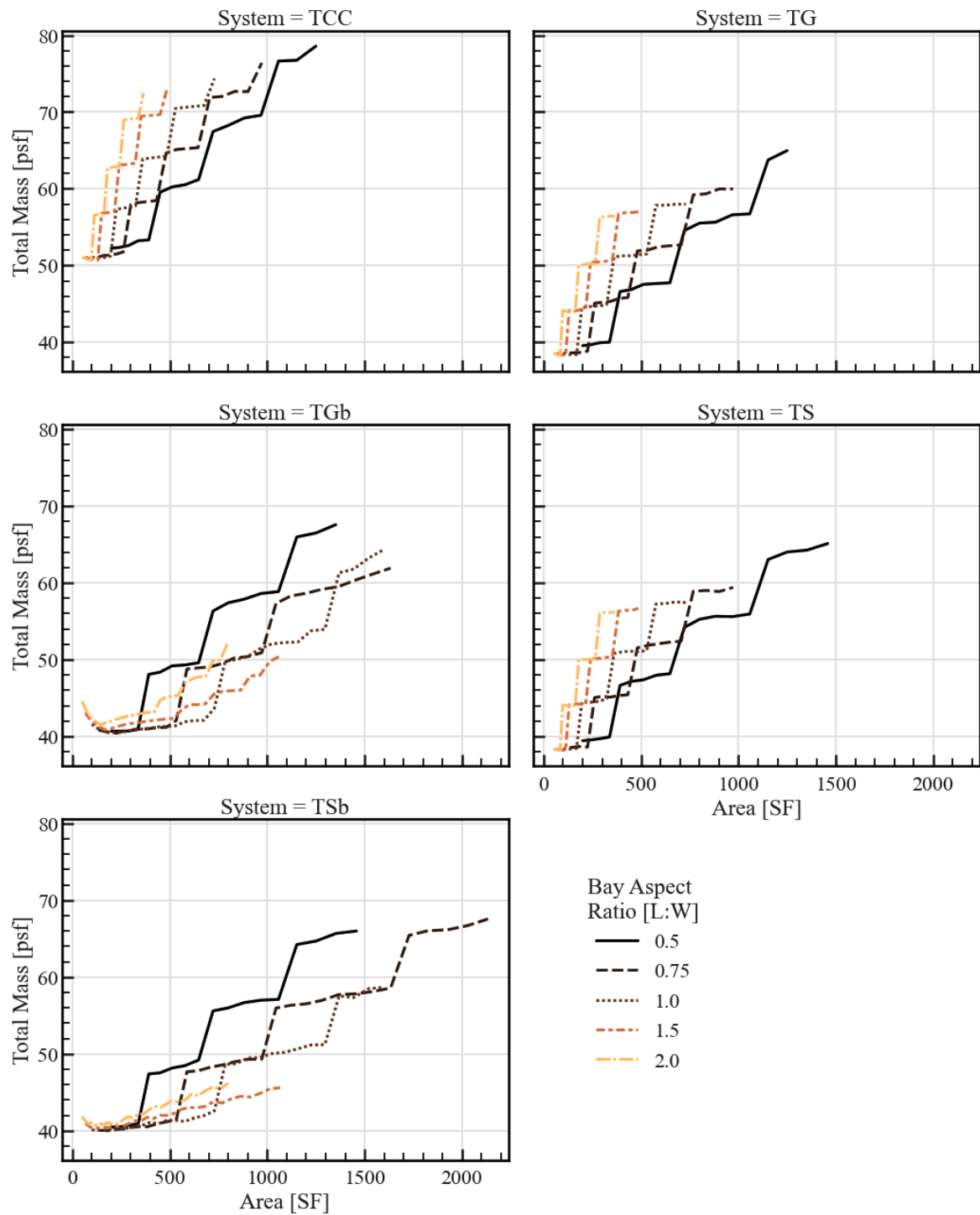


Figure 7-34: Mass versus bay area for protected designs (with a single infill beam where applicable)
 [1 psf = 4.88 kg/m²; 1 ft² = 0.093 m²]

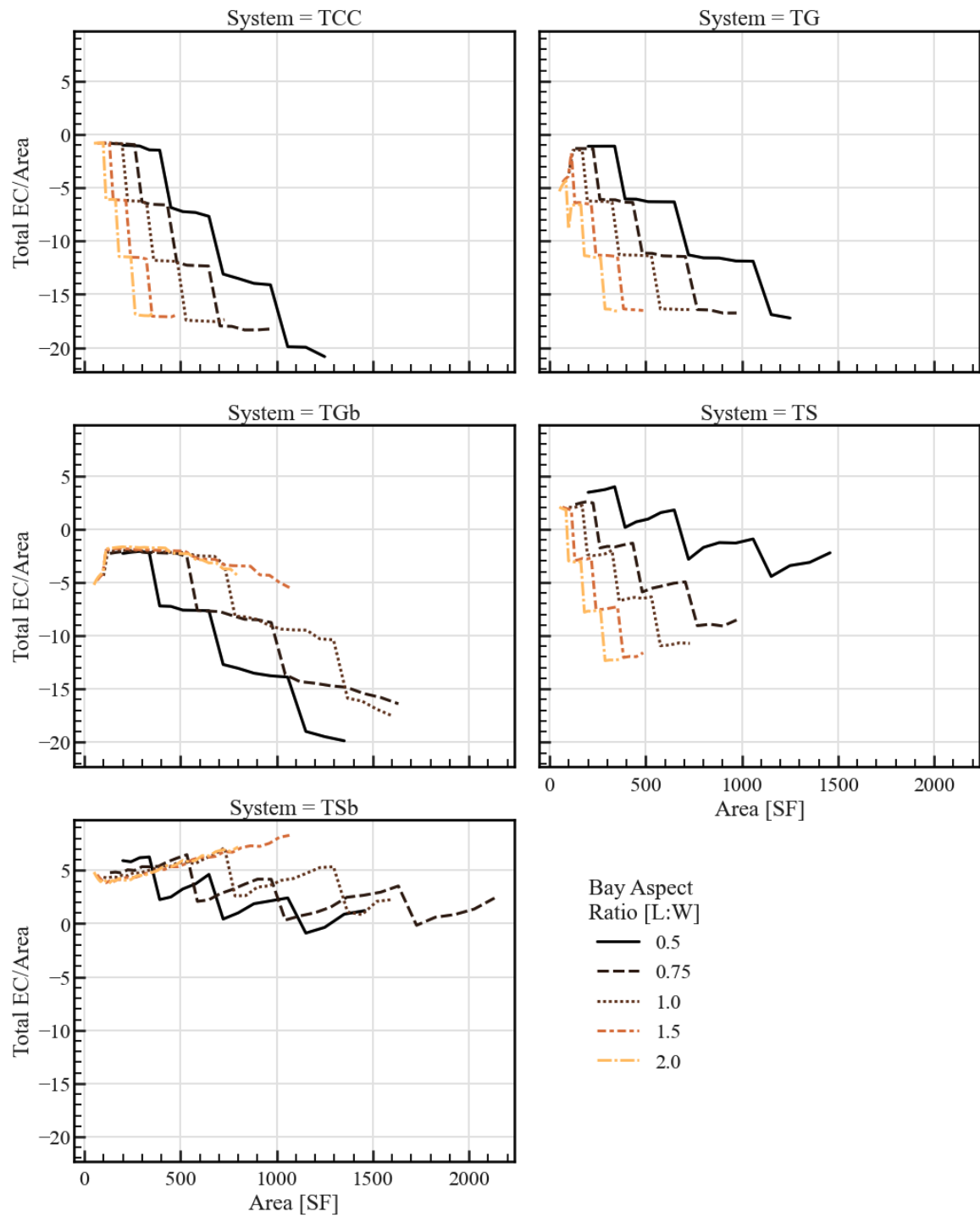


Figure 7-35: EC versus bay area for protected designs with 75% SST (with a single infill beam where applicable) [1 lb CO₂ eq. / ft² = 4.88 kg CO₂ eq. /m²; 1 ft² = 0.093 m²]

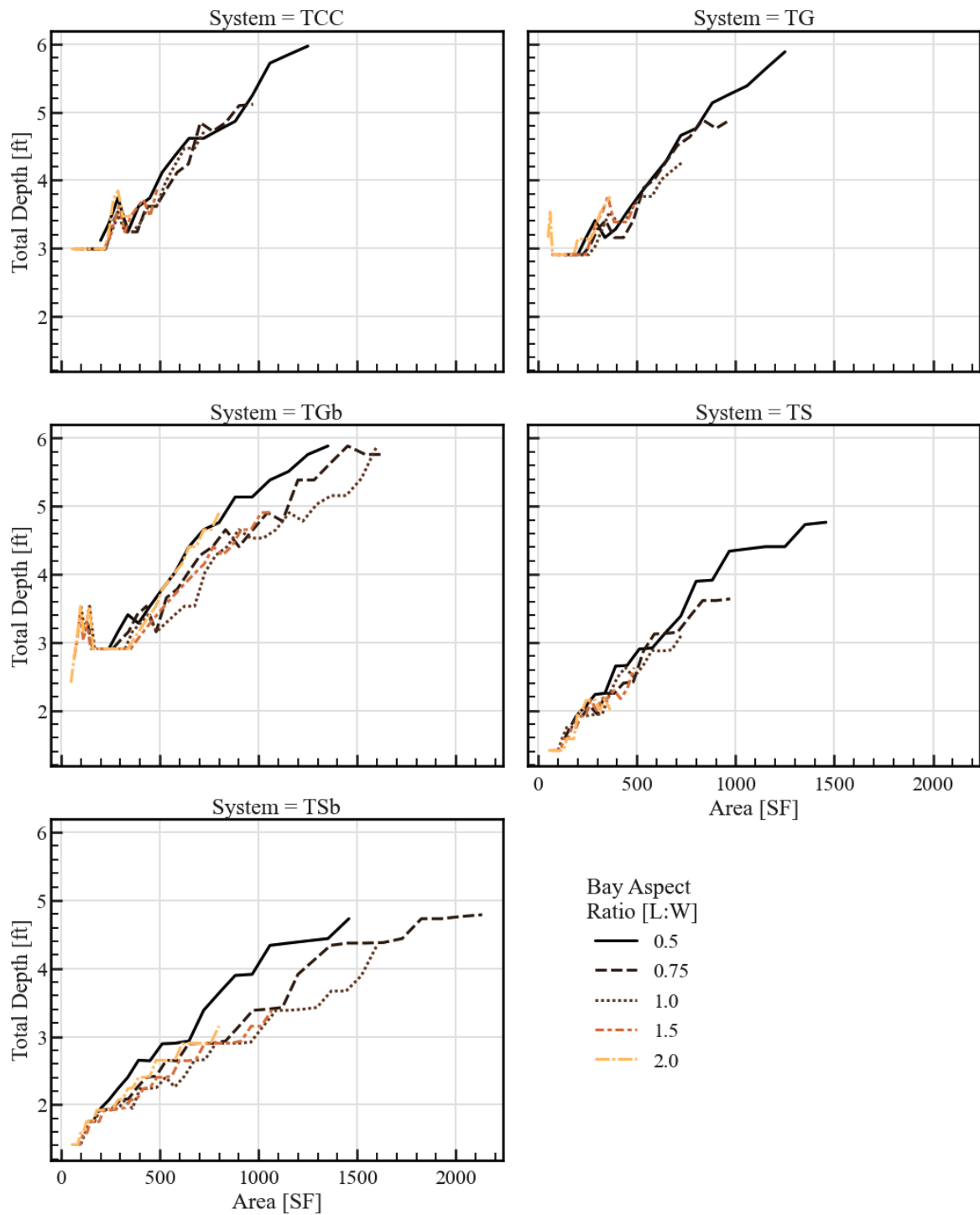


Figure 7-36: Depth versus bay area for exposed designs (with a single infill beam where applicable)
 [1 ft = 0.305 m; 1 ft² = 0.093 m²]

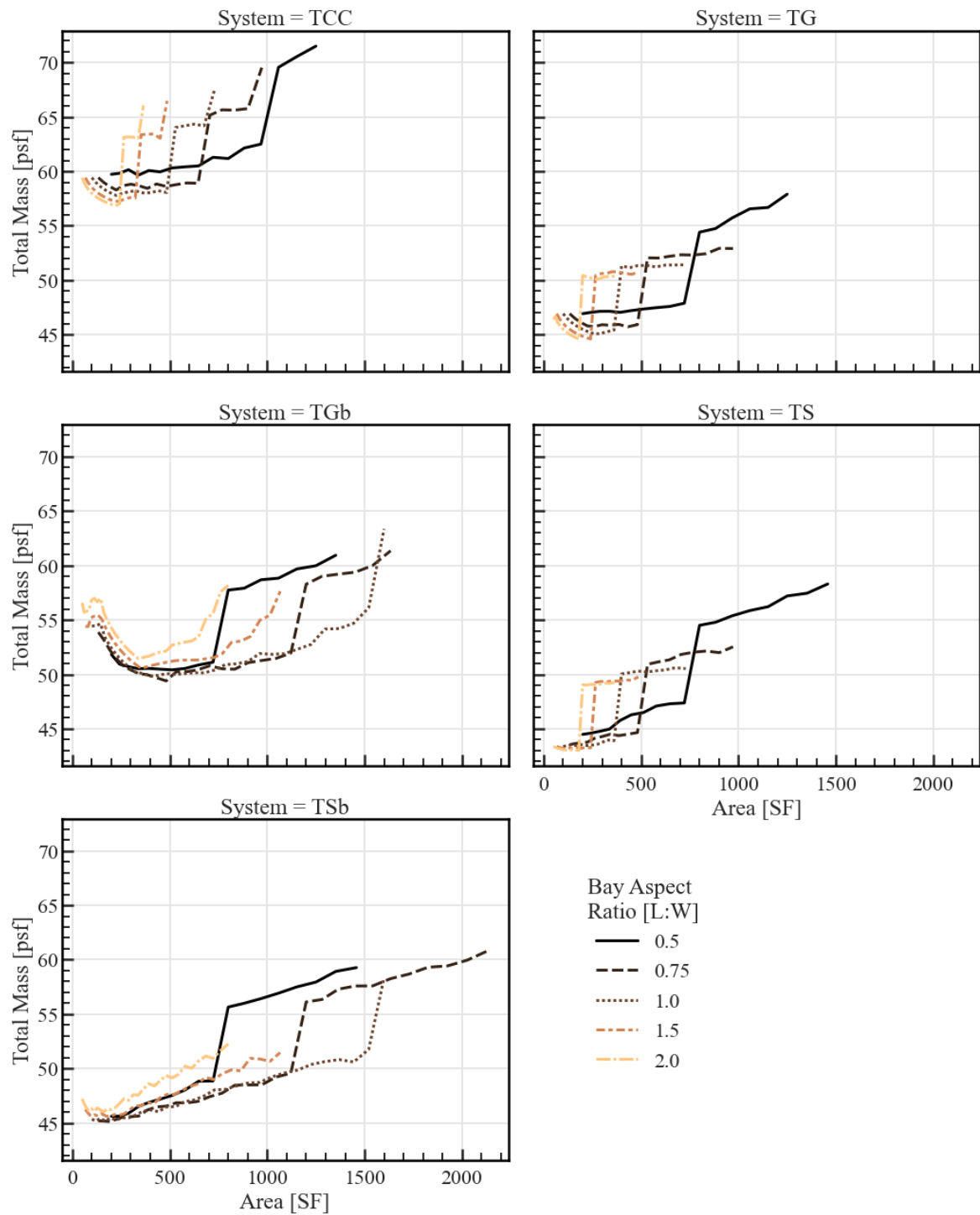


Figure 7-37: Mass versus bay area for exposed designs (with a single infill beam where applicable)
 [1 psf = 4.88 kg/m²; 1 ft² = 0.093 m²]

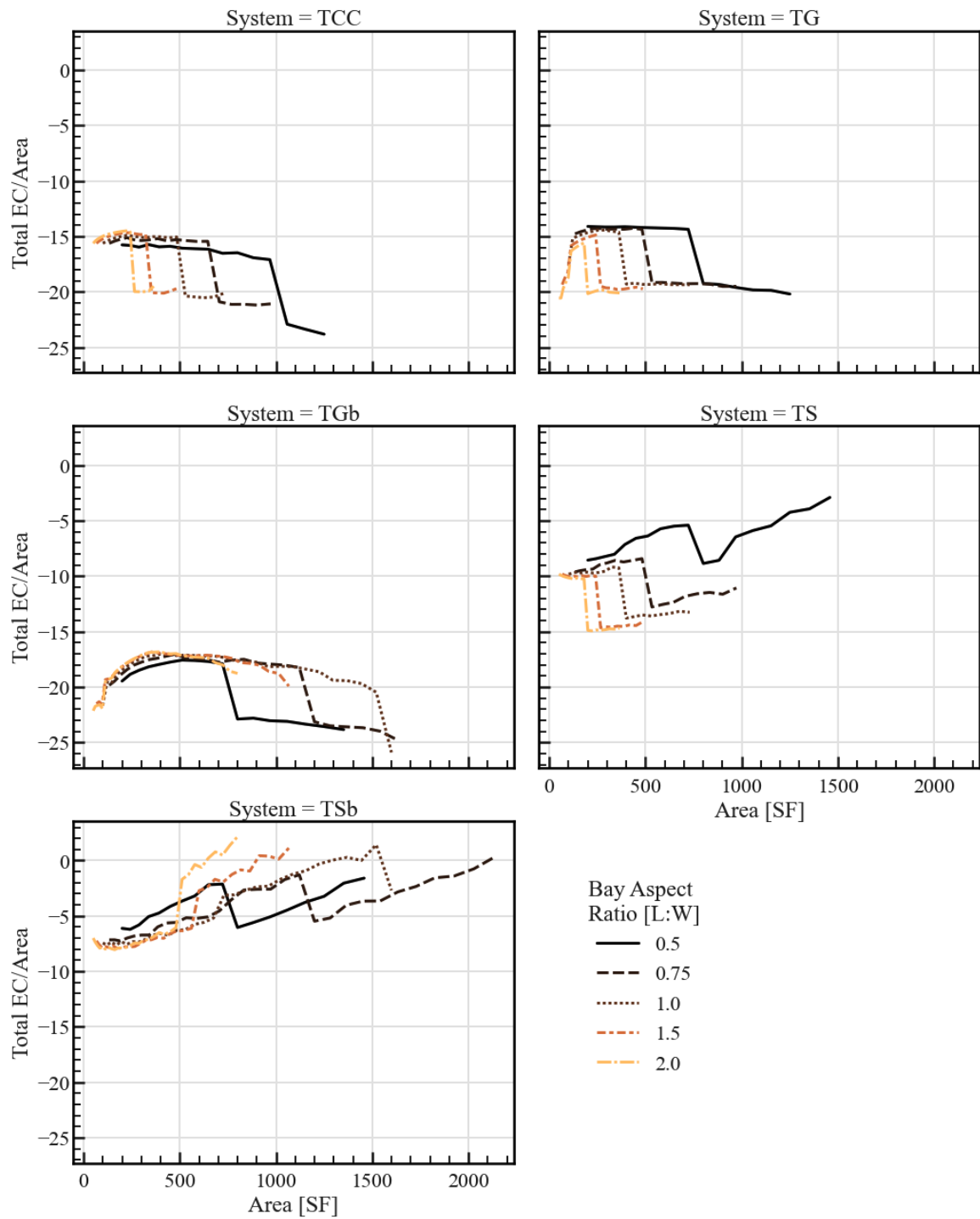


Figure 7-38: EC versus bay area for exposed designs with 75% SST (with a single infill beam where applicable) [1 lb CO₂ eq. / ft² = 4.88 kg CO₂ eq. /m²; 1 ft² = 0.093 m²]

7.1.8.5 *Element Contributions*

Finally, a discussion of element contributions to depth, mass, and EC is provided. By understanding element-level contributions, designers seeking to refine performance metrics may consider material and product choices to improve their designs. Figure 7-39 includes example material breakdowns for each performance metric for each bay length for all studied systems. Data is for designs with 75%SST, 0 to 1 infill beams, a bay aspect ratio of 1.5, and exposed mass timber with the char fire design method. Below are key considerations for designers based on this example:

- While the CLT panels contribute very little to total depth (often less than 30%), they make up a large portion of the system mass and carbon storage (50% of more).
- Further, while the concrete topping makes up only a negligible contribution to total depth, it contributes significantly to mass and somewhat to EC.
 - The concrete topping contributes only 1.5-2.5 inches (38-64 mm) to system depth.
 - Toppings add 20-30 psf (98-146 kg/m²) of mass and 3-4 lbs CO₂ eq./ft² (14-20 kg/m²) of EC.
- A designer seeking to reduce mass would ideally look for solutions that minimize or eliminate the need for a concrete topping while balancing serviceability requirements for vibrations and deflections, as well as to select lighter weight CLT options.
 - Reducing or eliminating the topping may allow increased floor excitation due to walking-induced vibrations, and should be carefully studied.
 - Where concrete toppings will be removed from a design, consider designing for spans below 20 feet (6.1 m).
- The lightest systems are not entirely ideal as they tend to have issues with acoustic insulation and walking-induced vibrations.
- Designers seeking to increase carbon storage who are working on an assumption similar to 75% SST should prioritize CLT panel products with high carbon storage.

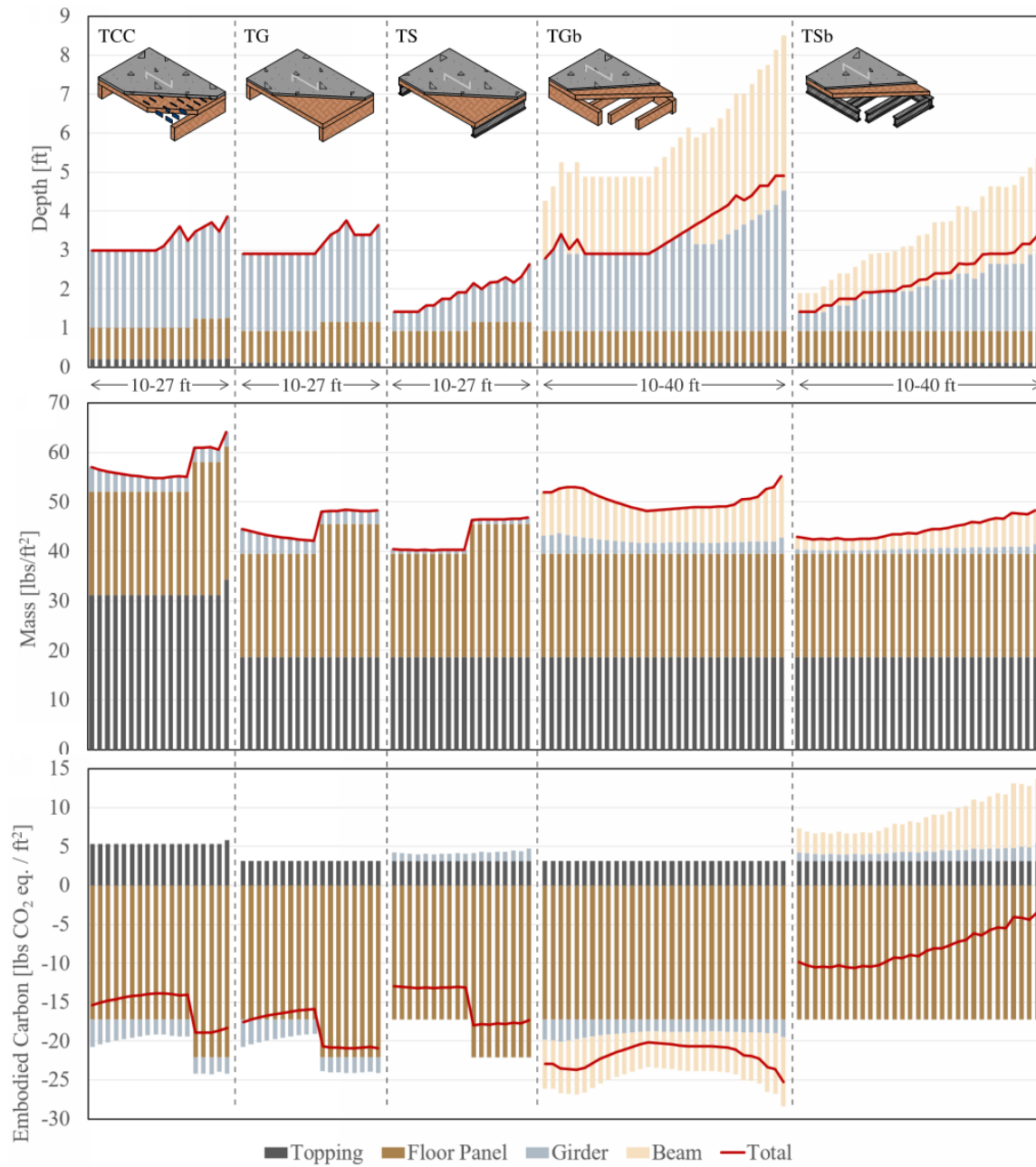


Figure 7-39: Material contributions to performance metrics for exposed designs with a bay aspect ratio of 1.5, 1 infill beam where applicable, and 75% SST. The max of either girder or beam depth is used to determine total system depth. A bar breakdown is shown for 1-ft span increments.

7.1.9 Embodied Carbon Assessment

While there are several indicators used to assess the sustainability of materials, embodied carbon (EC) is a widely used and recognized indicator of environmental impact. EC is also useful in early design to provide initial comparisons between options before enough building information is available or decided upon to perform a full building LCA.

7.1.9.1 Gathering Embodied Carbon Data

As previously mentioned, the material EC factors collected for this research come from EPDs, which can be obtained from online databases, directly from manufacturer websites, or by calling a manufacturer to request a copy if one is available. EPDs report environmental impact data for a declared unit of a product or material, as defined within the EPD. The EC value for the product in an EPD can be found in the LCIA results summary under the Global Warming Potential (GWP) impact indicator, which is in units of kg CO₂ equivalent. In the example in Figure 7-40, the data is shown for each A1-A3 module individually, and as a sum total. A1-A3 boundaries were chosen because EPDs most commonly report these modules, and analysis beyond A1-A3 requires a more in-depth, project-specific LCA study. More refined LCAs are expected for design refinement, but are typically too complex and detailed for early-stage design.

The example table in Figure 7-40 also shows a GWP value which includes biogenic carbon. In this case, biogenic carbon has a net zero impact on overall GWP. This is common for mass timber EPDs, which additionally report the A5, C3, and C4 LCA modules and assume that all stored carbon will eventually be emitted back to the atmosphere, resulting in net zero biogenic carbon. This additional data is reported in a biogenic carbon inventory in EPDs, as shown in the

example in Figure 7-41. The carbon accounted in the C3/C4 module and highlighted in red in Figure 7-41 is what this chapter has referred to as the stored carbon for timber materials.

Core Mandatory Impact Indicator			Total	A1	A2	A3
Global warming potential – TRACI 2.1	GWP _{TRACI}	kg CO ₂ e	124.02	61.61	40.80	21.61
Global warming potential – w/ biogenic CO ₂	GWP _{BIO}	kg CO ₂ e	124.02	(1,211.74)	40.80	1,294.96
Depletion potential of the stratospheric ozone layer	ODP	Kg CFC11e	2.63E-06	1.59E-06	1.72E-09	1.04E-06
Acidification potential of soil and water sources	AP	kg SO ₂ e	1.33	0.59	0.54	0.20
Eutrophication potential	EP	kg Ne	0.20	0.11	0.03	0.06
Formation potential of tropospheric ozone	SFP	kg O ₃ e	29.66	11.69	13.81	4.15
Abiotic depletion potential (ADP _{fossil}) for fossil resources;	ADP _f	MJ, NCV	1,873.86	974.87	584.75	314.24
Fossil fuel depletion	FFD	MJ Surplus	262.39	135.00	86.42	40.98

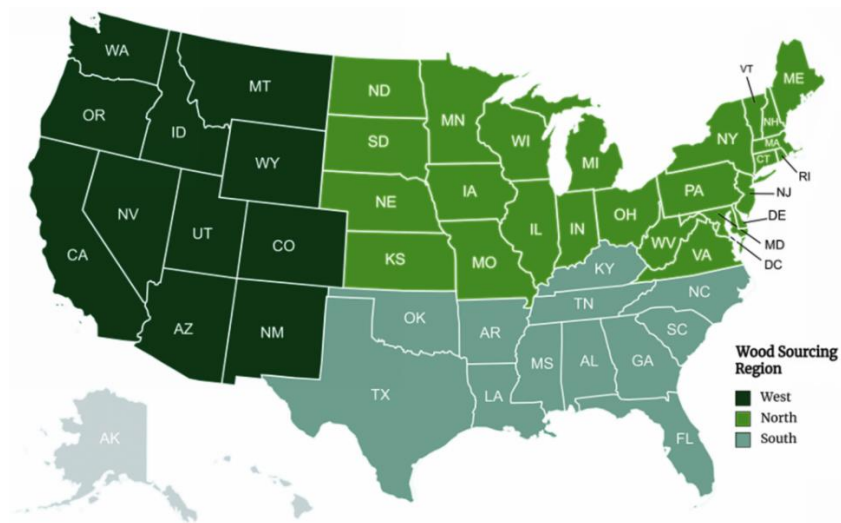
Figure 7-40: Example EPD data summary table for CLT. GWP impact indicators highlighted in red. Data retrieved from Structurlam's CLT EPD. [64]

Additional Inventory Parameters			Total	A1	A2	A3	A5	C3/C4
Biogenic Carbon Removal from Product	BCRP	kg CO ₂	(969.71)	(969.71)	-	-	-	-
Biogenic Carbon Emission from Product	BCEP	kg CO ₂	874.83	-	-	-	-	874.83
Biogenic Carbon Removal from Packaging	BCRK	kg CO ₂	-	-	-	-	-	-
Biogenic Carbon Emission from Packaging	BCEK	kg CO ₂	-	-	-	-	-	-
Biogenic Carbon Emission from Combustion of Waste from Ren. Sources Used in Production	BCEW	kg CO ₂	94.88	-	-	94.88	-	-
Net biogenic carbon emission		kg CO ₂	0.00					

Figure 7-41: Biogenic carbon inventory parameters for CLT. Timber “carbon storage” EC value is highlighted in red. Data retrieved from Structurlam's CLT EPD. [64]

7.1.9.2 Timber Carbon Storage

While mass timber EPDs currently account biogenic carbon as net zero, there may be cases when it is useful to quantify and compare designs based on carbon storage. Per commentary in the ICE database [61], an inventory of EC data, mass timber EC values may include carbon storage if sustainably-sourced timber (SST) is used and end of life (EOL) impacts are considered. For the A1-A3 scope of this chapter, carbon storage is calculated based on approximate levels of SST. A starting point for selecting a SST assumption can be based on the AWC wood sourcing web tool. This tool presents sustainable timber sourcing data by region, and indicates that most U.S.-sourced wood is responsible wood, or approximately 95-97% per Figure 7-42. Many of the charts and plots previously shown in this chapter are for 75% SST, which is meant to conservatively represent the sustainability of responsibly-sourced wood. Data from AWC’s tool for the three regions is summarized in Figure 7-42.



Forest Products Sourcing Data	West	North	South
Non-Controversial Sources	100%	100%	100%
Responsible Sources	95%	97%	95%
Certified Sources	73%	21%	30%

Figure 7-42: Forest product sourcing map for the United States and corresponding data by sourcing category and region. Data from the AWC’s “Wood Sourcing Tool” [240] at <https://awc.org/wood-sourcing/>

To demonstrate the significance of selecting a carbon storage assumption for timber EC, Figure 7-43 depicts EPD data from a range of manufacturers and lumber grades for CLT. Data is plotted as EC per unit of bending strength versus panel thickness for a range of SST assumptions, with points colored by relative lumber grade strength. The relative scale shown in Figure 7-43 was developed by arranging the CLT panels in order of strength based on their specified lumber grades, and assigning a rating from 1 (weakest) to 10 (strongest). CLT grades are defined in ANSI/APA PRG 320: Standard for Performance-Rated Cross-Laminated Timber. [312] The relationships between panel thickness, grade strength, and EC vary depending on SST.

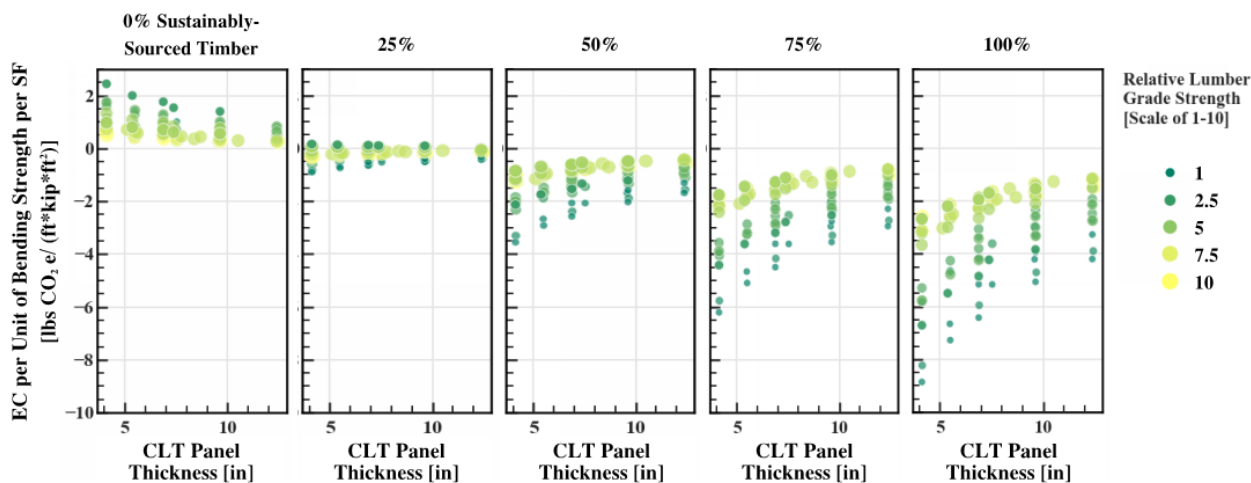


Figure 7-43: EC per Unit of Bending Strength per 1 SF panel versus CLT Panel Thickness; a relative lumber grade strength rating of 1 represents the weakest grade, and a rating of 10 represents the strongest grade (Strength and grade data obtained from manufacturer technical guides [39]–[41], [239]; EC data based on manufacturer EPDs, or ICE V3.0 values where EPDs are not available [61])
 $(1 \text{ lb CO}_2 \text{ eq}/(\text{ft} \cdot \text{kip} \cdot \text{ft}^2) = 3.6 \text{ kg CO}_2 \text{ eq}/(\text{kN} \cdot \text{m} \cdot \text{m}^2); 1 \text{ inch} = 25.4 \text{ mm})$

Further, Figure 7-44 shows the systems plot of EC versus bay length from Figure 7-6 for varying levels of SST. Below are key design considerations for the systems included:

- Most systems do not become fully carbon-storing until 75% SST is used.
- When 0% SST is assumed, the concrete baseline floors may be competitive with the mass timber floors at small bay spans of 12-18 feet (3.7-5.5 m).
- Steel-timber systems with infill beams never become fully carbon-storing across the entire range of bay spans, even when 100% SST is used.

- Direct EC of the floor system design increases with mass for non-carbon-storing designs, and decreases with mass for carbon-storing designs.
 - Note that increased mass affects other parts of the building and other disciplines, so mass and EC should be optimized with other design objectives to represent full building impacts.

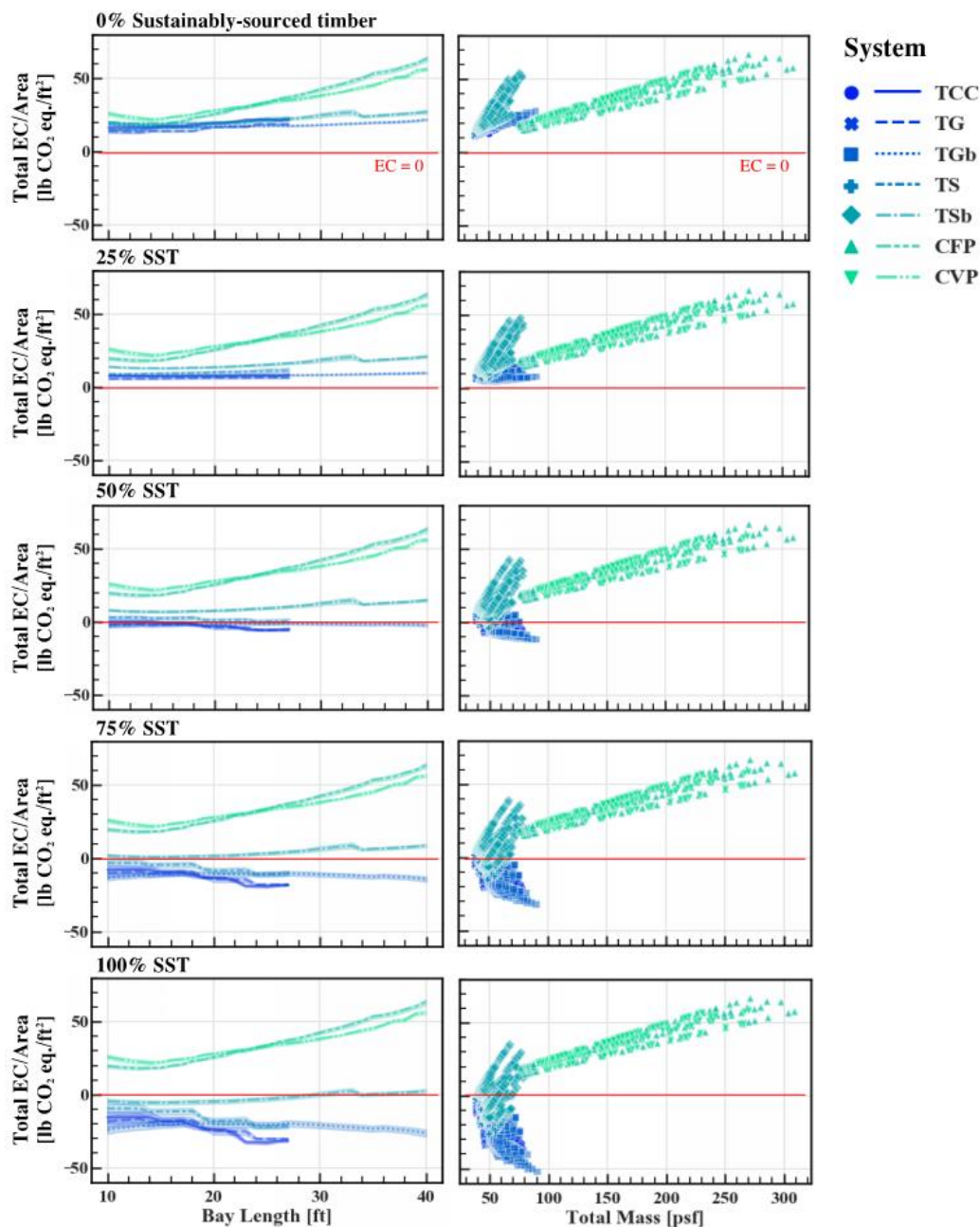


Figure 7-44: EC versus bay length and mass for a range of SST assumptions. Averages are shown for the full dataset.

7.1.10 Design Example

Hypothetical design examples were created to demonstrate how these early-stage guides may be used to inform early-stage design decisions. The examples show a sampling of the charts and plots from sections 7.1.5 through 7.1.9 being used to inform design decisions and establish a starting point for design. The process shown in these examples is linear for the sake of brevity and clarity; however, this can be an iterative process, and different sets of tables and plots may be used as appropriate to inform decision making.

The first example uses 75% SST for a small to medium bay size with exposed CLT ceilings and better acoustic insulation. The second design example assumes 0% SST for a medium to large bay size with code minimum acoustic insulation and no set preference for the fire design strategy.

7.1.10.1 Design Example A

For this example, design goals are described below and summarized in Figure 7-45.

- 8-story Type IV-C construction with a residential (R-2) occupancy
- Project located in the West Region of the U.S.
- Target a 15-25' (4.6-7.6 m) bay span with a maximum total system depth of 3' (0.91 m) as set by the architecture of the project (possible bay area range: 150-500 ft² (15-46 m²))
- Promote easy MEP service coordination and provide for a fast construction schedule.
- Reduce EC and expose CLT ceilings
- Target “better” acoustic insulation with STC and IIC in the range of 60-64

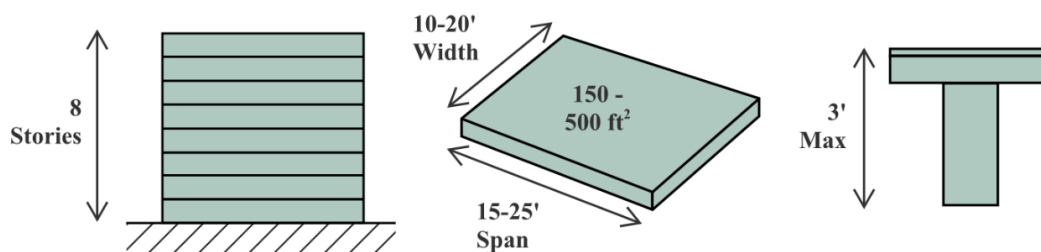


Figure 7-45: Hypothetical design example dimensional criteria (1 ft = 0.305 m)

Because the project is located in the Western region of the U.S., it was initially assumed that the wood will also be sourced from the west. Per Figure 7-46, approximately 75% SST is assumed based on the certified wood sourcing data.

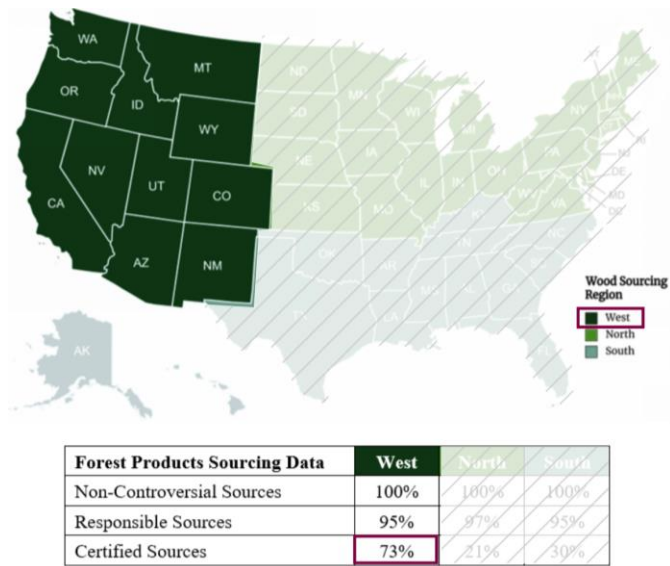


Figure 7-46: Marked up wood sourcing map and table for hypothetical example located in the West region of the U.S. (From Figure 7-41)

Based on MEP coordination needs, assume that a system without infill beams is required for the project (due to less possible clashes). Based on the desire to expose the ceiling, the possible bay area range, and the selection of systems without infills, Figure 7-47 is marked up for the remaining options. Because the values in this figure are mean values, those designs which are close to and below 3 feet (0.9 m) are selected for additional consideration. Based on Figure 7-47, the TS system could work well with any size in the bay area range for example, while the TCC and TG systems could work well at smaller bay areas below 250 and 300 ft² (23 and 28 m²).

Exposed Fire Design Strategy												
Area Range (SF)	TCC			TG			TGB			TS		
	Depth	Mass	EC	Depth	Mass	EC	Depth	Mass	EC	Depth	Mass	EC
0-50	3.1	57.7	-14.9	3.0	47.0	-16.7	2.9	72.1	-27.0	1.4	45.2	-11.3
50-100	3.0	57.8	-18.0	3.0	45.4	-18.1	3.0	64.7	-24.6	1.4	43.2	-10.1
100-150	3.0	58.6	-15.2	2.9	46.1	-19.4	3.0	61.3	-21.2	1.5	43.2	-10.0
150-200	3.0	59.2	-15.5	3.0	45.9	-20.9	3.0	59.9	-20.7	1.8	43.3	-9.8
200-250	3.2	59.3	-16.4	3.0	47.8	-17.4	3.1	60.1	-20.4	2.0	46.3	-12.2
250-300	3.6	60.4	-16.9	3.2	48.2	-17.4	3.1	58.3	-20.3	2.1	46.8	-12.2
300-400	3.4	60.6	-17.1	3.4	48.5	-17.3	3.2	57.7	-19.9	2.2	47.2	-11.7
400-500	3.7	60.8	-17.1	3.4	49.2	-17.5	3.4	57.7	-19.9	2.5	48.1	-11.7
500-600	4.1	61.1	-17.3	3.9	50.2	-17.6	3.7	57.5	-19.6	2.9	49.4	-10.7

Figure 7-47: Marked-up fire design plot. Red-line strikethroughs are for design categories which are too deep. Dark red boxes outline ranges of interest for each system under consideration. (From Figure 7-22)

Units: Depth [feet], Mass [lbs / ft²], EC [lbs CO₂ eq./ft²]

In considering the acoustic insulation goals for the project, first select a bare panel for baseline values. Because of the exposed ceiling, a 7-ply CLT panel is likely the minimum size needed due to char design per Table 7-10. A larger panel may be needed; however, no STC or IIC data is available, so the data for the 7-ply panel may be used conservatively per Figure 7-48. Therefore, to meet minimum goals of STC- and IIC-60, additional floor assembly layers need to add STC-16 and IIC-30 to the bare 7-ply CLT panel values of STC-44 and IIC-30.

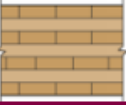
Mass Timber Panel	Span ft (m)	Depth in (mm)	Mass psf (kg/m ²)	EC *	EC	Panel Construction	STC	IIC
				(0% SST) lbs CO ₂ e/ft ² (kg CO ₂ /m ²)	(100% SST)			
3-ply CLT	13 (4.0)	4.1 (105)	8.9 (19.6)	2.4 (11.7)	-10.6 (-51.6)		38	22
5-ply CLT	16 (4.8)	5.2 (132)	11.3 (24.8)	3.0 (14.8)	-13.4 (-65.4)		39	22
5-ply CLT	16 (4.8)	8.4 (137)	11.7 (25.8)	3.2 (15.4)	-13.9 (-67.9)		41	27
5-ply CLT	18 (5.5)	6.8 (175)	15.0 (33.0)	4.0 (19.7)	-17.8 (-86.8)		41	28
7-ply CLT	23 (7.0)	9 (229)	19.5 (43.0)	5.3 (25.7)	-23.2 (-113.24)		44	30

Figure 7-48: Marked up chart with bare CLT panel data (From Figure 7-25)

Per, Figure 7-49 acoustic goals may be met by incorporating a raised wooden sleeper acoustic assembly, either with or without a topping. Note that this chapter only includes systems with a concrete topping; however, projects may consider the elimination of the topping during design refinement. While the acoustic assembly without a topping does not meet the necessary additive IIC-30, floor finish options like engineered wood or carpet may be considered to gain additional IIC performance. At this time, assume that raised wooden sleepers with a topping are used. This assembly category often includes infill insulation between sleepers and an acoustic mat between the subfloor and concrete topping.

Because the structural model includes the topping for depth, mass, and EC, assume that the values for the raised wooden sleeper assembly without a topping can be added to the results from the parametric model to estimate the impacts of the acoustic assembly selection on the full floor design for those metrics. Therefore, use the following average baseline values for the selected acoustic assembly, which can be added to the parametric model results for depth, mass, and EC, and which can be added to the bare CLT floor test data for STC and IIC from Figure 7-48:

- EC = 2.2 lbs CO₂ eq./ft² (10.7 kg CO₂ eq./m²)
- Depth = 2.7" (68.6 mm)
- Mass = 15.1 lbs (6.8 kg)
- STC = 23.3
- IIC = 33.3

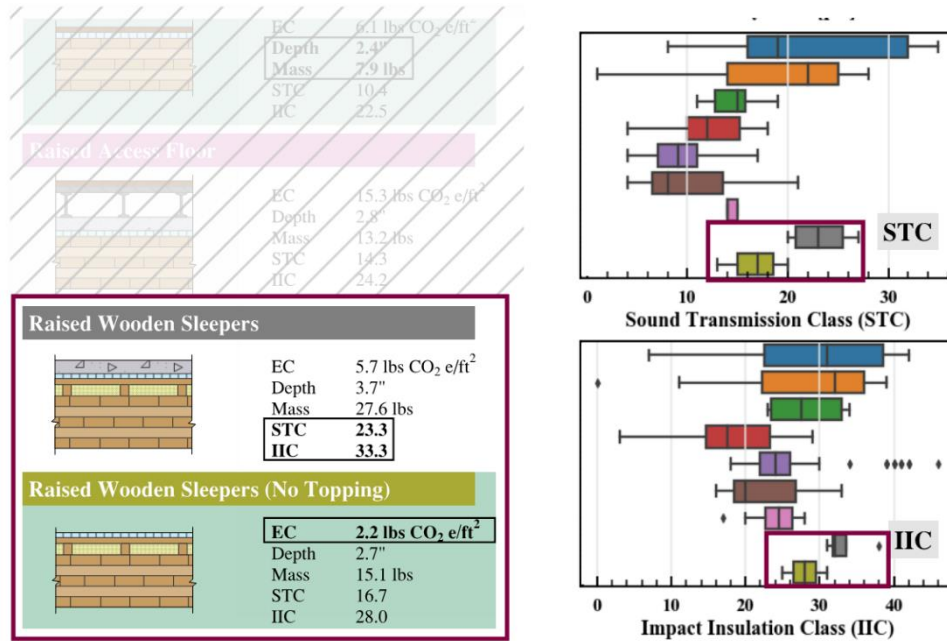


Figure 7-49: Marked up acoustic design summary. Red-boxed areas represent best assembly options to meet project requirements. Values are for the acoustic assembly only, and do not include the CLT floor panel so they can be added to the parametric model results. (From Figure 7-26)

The decisions so far result in the following options to study more closely, all of which will use the exposed fire design method and the raised wooden sleeper acoustic assembly:

- A TCC system with a bay area of 150-250 ft² (14-23 m²).
- A TG system with a bay area of 150-300 ft² (14-28 m²).
- A TS system with a bay area of 150-500 ft² (14-46 m²).

Next, the equations for depth can be used to estimate the maximum bay area that can be designed given the 3-ft (0.9 m) depth limit imposed on the project. Per the equations in Figure 7-50, the maximum areas for each considered system can be found. An economical span is preferred, so those equations will be used, keeping in mind that the final selected span needs to be within the economical span range.

		System	Full Span Length Range*	Economical Span Length Range*
Fire Design Approach	Protected	TCC	$D = -2.82\text{e-}06 A^2 + 7.13\text{e-}03 A + 1.25$	$D = -2.84\text{e-}06 A^2 + 6.99\text{e-}03 A + 1.17$
		TG	$D = -2.32\text{e-}06 A^2 + 6.47\text{e-}03 A + 1.15$	$D = -2.06\text{e-}06 A^2 + 6.26\text{e-}03 A + 1.11$
		TGb	$D = -1.45\text{e-}06 A^2 + 4.79\text{e-}03 A + 1.18$	$D = -7.19\text{e-}07 A^2 + 3.93\text{e-}03 A + 1.35$
		TS	$D = -8.47\text{e-}07 A^2 + 4.00\text{e-}03 A + 0.92$	$D = -3.77\text{e-}07 A^2 + 3.20\text{e-}03 A + 1.2$
		TSb	$D = -3.57\text{e-}07 A^2 + 2.46\text{e-}03 A + 0.97$	$D = -1.15\text{e-}07 A^2 + 1.90\text{e-}03 A + 1.09$
	Combined	TCC	$D = -2.12\text{e-}06 A^2 + 6.07\text{e-}03 A + 1.59$	$D = -2.25\text{e-}06 A^2 + 6.01\text{e-}03 A + 1.54$
		TG	$D = -1.93\text{e-}06 A^2 + 5.91\text{e-}03 A + 1.27$	$D = -1.33\text{e-}06 A^2 + 5.45\text{e-}03 A + 1.27$
		TGb	$D = -1.48\text{e-}06 A^2 + 4.80\text{e-}03 A + 1.38$	$D = -7.58\text{e-}07 A^2 + 3.88\text{e-}03 A + 1.59$
		TS	$D = -5.65\text{e-}07 A^2 + 3.53\text{e-}03 A + 1.08$	$D = -3.77\text{e-}07 A^2 + 3.20\text{e-}03 A + 1.2$
		TSb	$D = -4.01\text{e-}07 A^2 + 2.50\text{e-}03 A + 1.21$	$D = -1.68\text{e-}07 A^2 + 1.95\text{e-}03 A + 1.34$
Exposed		TCC	$D = 6.96\text{e-}07 A^2 + 1.73\text{e-}03 A + 3.01$	$D = 3.23\text{e-}06 A^2 + 1.60\text{e-}04 A + 3.17$
		TG	$D = 1.12\text{e-}06 A^2 + 1.32\text{e-}03 A + 2.77$	$D = 4.08\text{e-}06 A^2 + -7.53\text{e-}04 A + 2.98$
		TGb	$D = -1.04\text{e-}07 A^2 + 2.11\text{e-}03 A + 2.64$	$D = 8.11\text{e-}07 A^2 + 1.34\text{e-}03 A + 2.65$
		TS	$D = -5.03\text{e-}07 A^2 + 3.32\text{e-}03 A + 1.17$	$D = -4.62\text{e-}07 A^2 + 3.27\text{e-}03 A + 1.17$
		TSb	$D = -4.27\text{e-}07 A^2 + 2.53\text{e-}03 A + 1.29$	$D = -1.98\text{e-}07 A^2 + 2.01\text{e-}03 A + 1.41$

Figure 7-50: Marked-up span equation table with relevant equations (From Table 7-13)

Rearranging using the quadratic formula, the maximum area for the TCC system can be found using Equation 7-1 and setting $D = 3$ feet. Note that web-based quadratic formula calculators are available to simplify manual calculation procedures. [313]

$$A = \frac{-1.6 \times 10^{-4} \pm \sqrt{(1.6 \times 10^{-4})^2 - (4 \times 3.23 \times 10^{-6} \times (3.17 - D))}}{2 \times 3.23 \times 10^{-6}} \quad (7-1)$$

The solution consists of two complex roots, so there is no real area that can provide a maximum 3-foot depth for the TCC system. Using the lowest possible bay area under consideration, $A = 150 \text{ ft}^2$, Equation 7-2 can be found to determine the corresponding depth for that area.

$$D = 3.23 \times 10^{-6} \times A^2 + (1.6 \times 10^{-4}) \times A + 3.17 \quad (7-2)$$

In this case, $D = 3.27$ feet, which is greater than the desired 3-foot max. Similarly using the quadratic formula, the maximum area for the TG system can be found using Equation 7-3, and again setting $D = 3$:

$$A = \frac{7.53 \times 10^{-4} \pm \sqrt{(-7.53 \times 10^{-4})^2 - (4 \times 4.08 \times 10^{-6} * (2.98 - D))}}{2 * 4.08 \times 10^{-6}} \quad (7-3)$$

In this case, $A = 208 \text{ ft}^2$, which meets the desired minimum bay area of 150 ft^2 . The corresponding minimum depth that corresponds with the minimum 150 ft^2 bay size under consideration can be found using Equation 7-4:

$$D = 4.08 \times 10^{-6} * A^2 + (-7.53 \times 10^{-4}) * A + 2.98 \quad (7-4)$$

In this case, $D = 2.96 \text{ ft}$. The maximum area for the TS system can be found using Equation 7-5, and again setting $D = 3$:

$$A = \frac{7.53 \times 10^{-4} \pm \sqrt{(-7.53 \times 10^{-4})^2 - (4 \times 4.08 \times 10^{-6} * (2.98 - D))}}{2 * 4.08 \times 10^{-6}} \quad (7-5)$$

In this case, $A = 612 \text{ ft}^2$, which meets the desired minimum bay area of 150 ft^2 . Note that the maximum bay size under consideration is 500 ft^2 . The corresponding minimum depth that corresponds with the minimum 150 ft^2 bay size under consideration can be found using Equation 7-6:

$$D = -4.62 \times 10^{-7} * A^2 + 3.27 \times 10^{-3} * A + 1.17 \quad (7-6)$$

In this case, $D = 1.67 \text{ ft}$ (0.51 m), which is well below the 3-foot maximum for the project. While these equations and estimates are average values with opportunities for refinement in later stages of design, for now the TCC system will be eliminated from consideration as both the TG and TS system present feasible options for meeting the project goals. The remaining options include:

- The TG system with a maximum area of 208 ft^2 (19 m^2) and a minimum depth just under 3 feet (0.9 m) if a 150 ft^2 (14 m^2) bay size is selected.
- The TS system with a maximum area of 500 ft^2 (46 m^2) and a minimum depth of 1.67 feet (0.5 m) if a 150 ft^2 (14 m^2) bay size is selected.

The TS system can span farther by taking advantage of the steel framing capabilities; however, assume that a small to medium bay is still preferred due to the CLT spanning capabilities. For the purposes of this example, assume a 200 ft^2 bay for both systems to maximize bay area while

keeping the area for each considered system the same for simpler comparisons. Initial system mass and EC estimates are made using Figure 7-51 with the 200 ft² (18.6 m²) bay area and system information. Based on this bay area and the economical spans noted in Table 7-13, the TG system with a span range of 10-20 feet (3-6.1 m) has a possible bay aspect ratio range of 0.5 to 2, and the TS system with a span range of 18-26 feet (5.5-7.9 m) has a possible bay aspect ratio range of 1.6 to 3.4. The tables have in Figure 7-51 are for a maximum bay aspect ratio of 2.0.

Based on Figure 7-51, for the TG system, a bay aspect ratio of 1.5 offers the most carbon storage and lowest mass while remaining below the 3-foot depth maximum. For the TS system, interpolating between 1.5 and 2.0 for a bay aspect ratio of 1.75 offers a balanced set of metrics with some carbon storage and a system mass similar to that of the TG system. Depth is similar for all aspect ratios and is well below the 3-foot maximum.

Having used these design guidance figures, Table 7-14 provides a summary of design information for the two options coming out of this example. These options may be carried to be refined in later stages of design or further studied using the charts and tables in this chapter. This example concludes with the two design options in Table 7-14; however, more or fewer design options can be carried into later design stages for refinement as appropriate.

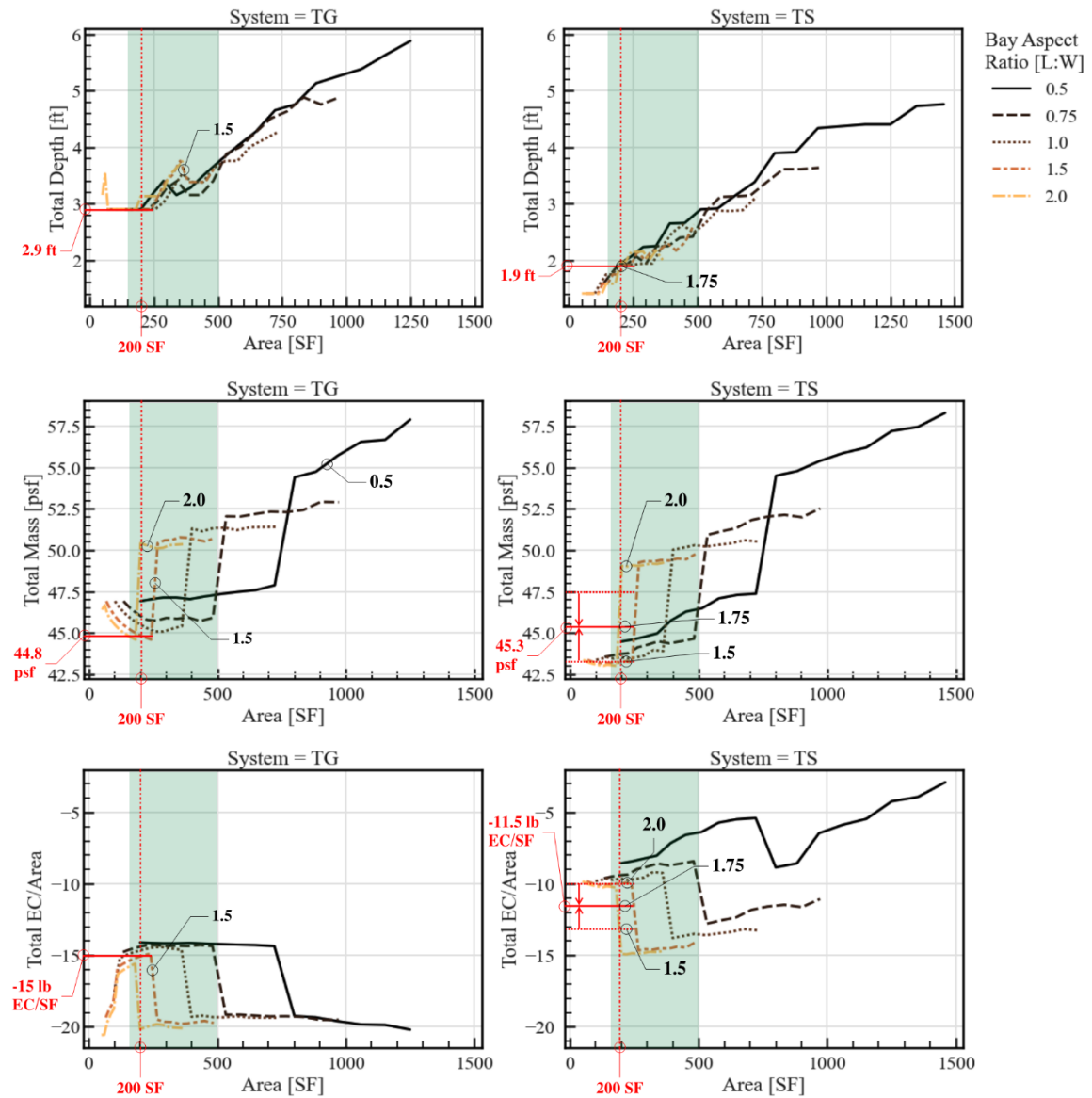


Figure 7-51: Marked-up Mass and EC estimate tables to select bay aspect area (From Figure 7-36 through Figure 7-38)

Table 7-14: Design options based on early design decision making in the design example and adding estimated values for the acoustic raised wooded sleepers assembly (RSA)

Design Data	Timber-framed (TG)	Steel-framed (TS)
<i>Depth*</i>	TG system (2.9') + Raised sleeper assembly (RSA) (2.7'') = 3.1' ** (0.94 m)	TS system (1.9') + RSA (2.7'') = 2.3' (0.70 m)
<i>Mass*</i>	TG system (44.8 psf) + RSA (15 psf) = 59.8 psf (292 kg/m²)	TS system (45.3 psf) + RSA (15 psf) = 60.3 psf (294 kg/m²)
<i>EC*</i>	TG system (-15 lbs CO ₂ e/ft ²) + RSA (2.2 lbs CO ₂ e/ft ²) = -12.8 lbs CO₂ e/ft² (-62.5 CO₂ e/m²)	TS system (-11.5 lbs CO ₂ e/ft ²) + RSA (2.2 lbs CO ₂ e/ft ²) = -9.2 lbs CO₂ e/ft² (-44.9 CO₂ e/m²)
<i>STC (min STC-60)</i>	Bare CLT Floor (STC-44) + Raised Sleeper Assembly (STC-23) = STC-67	
<i>IIC (min IIC-60)</i>	Bare CLT Floor (IIC-30) + Raised Sleeper Assembly (IIC-33) = IIC-63	
<i>Bay Area and Aspect Ratio</i>	200 ft ² , 1.5 AR (18.6 m ²)	200 ft ² , 1.75 AR (18.6 m ²)
<i>Bay Width and Length</i>	11.5' x 17.5' (3.5 m x 5.3 m)	10.5' x 19' (3.2 m x 5.8 m)

* RSA values for these performance metrics are for the “raised wooden sleepers with no topping” category because the topping is already included in the main systems model.

** Although the addition of the acoustic assembly pushes this system depth over the 3-foot max, this depth is close enough to provide opportunity for design refinement in later stages of design.

7.1.10.2 Design Example B

For this example, design goals are described below and summarized in Figure 7-52.

- 6-story Type IV-C office building
- Project located in the North Region of the U.S.
- Target a 20-30' (6.1-9.1 m) bay span with a maximum total system depth of 4' (1.2 m) as set by the architecture of the project (possible bay area range: 300-750 ft² (28-70 m²))
- Coordinate mechanical equipment to run between girders or infill beams; however design for as few infill beams as possible to improve coordination, cost, and schedule.
- Reduce EC and provide noncombustible protection.
- Provide code minimum acoustic insulation (concrete topping and basic acoustic mat.)

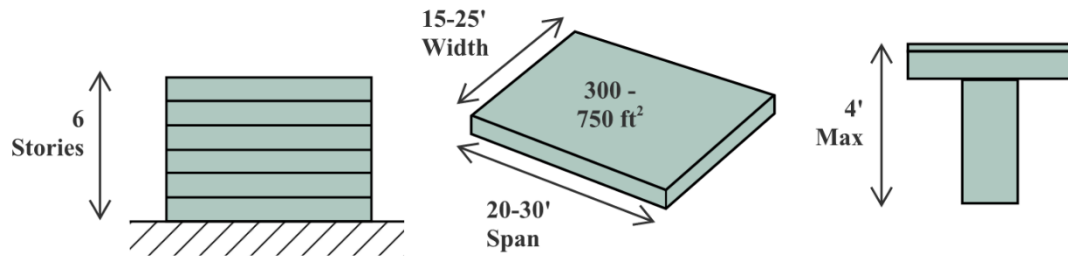


Figure 7-52: Hypothetical design example dimensional criteria (1 ft = 0.305 m)

Because the project is located in the Northern region of the U.S., it was initially assumed that the wood will also be sourced from the north. Per Figure 7-53, approximately 0% SST is conservatively assumed based on the certified wood sourcing data.

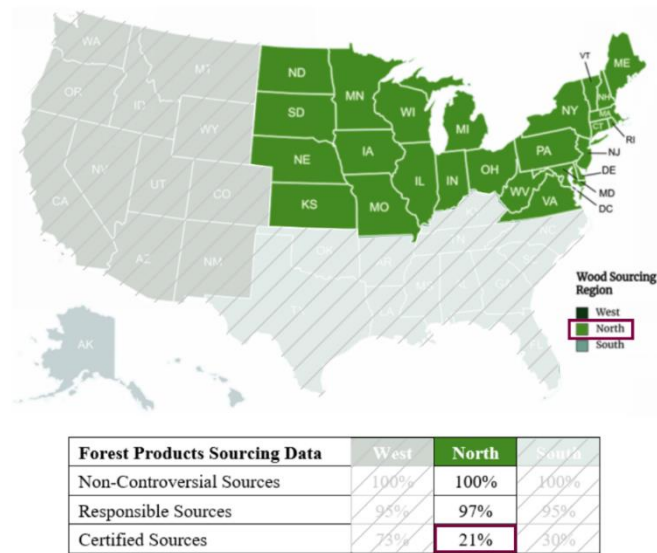


Figure 7-53: Marked up wood sourcing map and table for hypothetical example located in the West region of the U.S. (From Figure 7-41)

For MEP coordination needs, assume that a maximum of one infill beam should be used, such that the CLT span is effectively halved. Based on the possible bay area range and the protected fire design option, Figure 7-54 is marked up for the remaining options. Because the values in this figure are mean values, those designs which are close to and below 4 feet (1.2 m) are selected for additional consideration. Based on Figure 7-54, the TGb, TS, and TSb systems could work well with any size in the bay area range for the design example, while the TCC and TG systems could work well at smaller bay areas below 500 and 600 ft² (46 and 56 m²), respectively. In the interest

of targeting a larger bay size, only the TGb, TS, and TSb systems will be considered. The TS system is limited to a maximum span of approximately 27 feet (8.2 m).

Protected Fire Design Strategy															
Area Range (SF)	TCC			TG			TGb			TS			TSb		
	Depth	Mass	EC	Depth	Mass	EC	Depth	Mass	EC	Depth	Mass	EC	Depth	Mass	EC
0-50	2.4	57.0	6.2	2.1	44.8	-6.8	1.6	47.8	-4.4	1.7	44.8	-3.0	1.1	43.8	6.4
50-100	1.9	54.5	-4.5	1.8	42.7	-5.6	1.6	52.1	-5.0	1.3	42.7	-1.9	1.2	42.4	5.7
100-150	1.7	51.3	-1.2	1.7	39.8	-5.6	1.8	44.3	-2.2	1.2	39.7	0.7	1.1	36.2	7.7
150-200	1.7	51.1	-0.8	1.6	36.6	-5.7	1.8	48.2	-2.2	1.1	38.4	2.0	1.5	42.1	8.9
200-250	3.0	61.3	9.9	2.6	48.0	-9.4	2.1	44.8	-2.0	1.9	47.9	-8.5	1.6	42.4	6.0
250-300	3.3	62.1	18.1	2.9	49.8	-18.0	2.4	44.4	-2.2	2.0	48.9	5.4	1.7	42.4	6.3
300-400	3.4	63.2	-11.0	3.3	50.2	-10.6	2.8	45.5	-2.3	2.2	49.9	-6.0	1.8	43.4	6.7
400-500	4.0	65.4	-12.5	3.7	52.3	-12.0	3.1	47.5	-2.6	2.5	52.0	-6.9	2.0	44.4	7.3
500-600	4.2	65.4	-12.3	3.9	51.5	-10.5	3.5	49.1	-3.3	2.8	51.3	-4.3	2.2	45.2	7.9
600-750	4.7	68.8	-14.8	4.4	54.5	-12.8	3.8	50.6	-4.1	3.2	54.2	-6.2	2.4	46.1	8.7
750-1000	8.1	71.5	-16.4	4.9	58.0	-14.5	4.1	50.2	-5.4	3.8	57.5	-5.7	2.8	46.8	9.4

Figure 7-54: Marked-up fire design plot. Red-line strikethroughs are for design categories which are too deep. Dark red boxes outline ranges of interest for each system under consideration. (From Figure 7-22)

Units: Depth [feet], Mass [lbs / ft²], EC [lbs CO₂ eq./ft²]

Note that Figure 7-54 shows EC data for 75% SST, while 0% SST is assumed here. Although the focus of this design chapter was on 75% SST, an additional plot is provided here to offer an EC comparison between systems. Figure 7-55 presents EC data for the systems of interest for 0% SST. The TGb system generally has the lowest direct assembly EC, but is also likely deeper than the other systems at similar spans. At this time, all three systems are still under consideration.

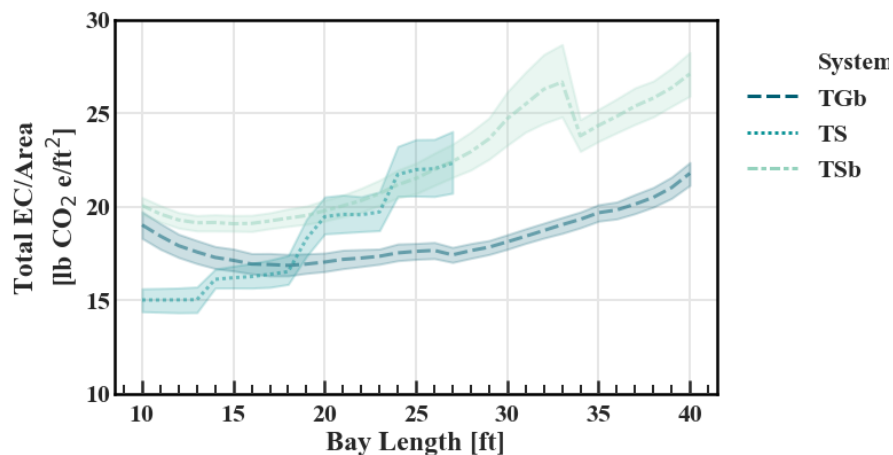


Figure 7-55: EC versus bay length for the considered systems and 0% SST. Trend lines represent mean values, while the shaded area around each trend line represents the 95% CI.

Based on the discussion so far, the following systems will be further evaluated and compared for a protected fire design strategy:

- A TS system with a bay area of 500-600 ft² (46-56 m²).
- A TSb system with a bay area of 500-750 ft² (46-70 m²) and a single infill beam.
- A TGb system with a bay area of 500-750 ft² (46-70 m²) and a single infill beam.

Next, the equations for depth can be used to estimate the maximum bay area that can be designed given the 4-ft (1.2 m) depth limit imposed on the project. Per the equations in Figure 7-56, the maximum areas for each considered system can be found. An economical span is preferred, so those equations will be used, keeping in mind that the final selected span needs to be within the economical span range.

		System	Full Span Length Range*	Economical Span Length Range*
Fire Design Approach	Protected	TCC	$D = -2.82\text{e-}06 A^2 + 7.13\text{e-}03 A + 1.25$	$D = -2.84\text{e-}06 A^2 + 6.99\text{e-}03 A + 1.17$
		TG	$D = -2.32\text{e-}06 A^2 + 6.47\text{e-}03 A + 1.15$	$D = -2.06\text{e-}06 A^2 + 6.26\text{e-}03 A + 1.11$
		TGb	$D = -1.45\text{e-}06 A^2 + 4.79\text{e-}03 A + 1.18$	$D = -7.19\text{e-}07 A^2 + 3.93\text{e-}03 A + 1.35$
		TS	$D = -8.47\text{e-}07 A^2 + 4.00\text{e-}03 A + 0.92$	$D = -3.77\text{e-}07 A^2 + 3.20\text{e-}03 A + 1.2$
		TSb	$D = -3.57\text{e-}07 A^2 + 2.46\text{e-}03 A + 0.97$	$D = -1.15\text{e-}07 A^2 + 1.90\text{e-}03 A + 1.09$
	Combined	TCC	$D = -2.12\text{e-}06 A^2 + 6.07\text{e-}03 A + 1.59$	$D = -2.25\text{e-}06 A^2 + 6.01\text{e-}03 A + 1.54$
		TG	$D = -1.93\text{e-}06 A^2 + 5.91\text{e-}03 A + 1.27$	$D = -1.33\text{e-}06 A^2 + 5.45\text{e-}03 A + 1.27$
		TGb	$D = -1.48\text{e-}06 A^2 + 4.80\text{e-}03 A + 1.38$	$D = -7.58\text{e-}07 A^2 + 3.88\text{e-}03 A + 1.59$
		TS	$D = -5.65\text{e-}07 A^2 + 3.53\text{e-}03 A + 1.08$	$D = -3.77\text{e-}07 A^2 + 3.20\text{e-}03 A + 1.2$
		TSb	$D = -4.01\text{e-}07 A^2 + 2.50\text{e-}03 A + 1.21$	$D = -1.68\text{e-}07 A^2 + 1.95\text{e-}03 A + 1.34$
	Exposed	TCC	$D = 6.96\text{e-}07 A^2 + 1.73\text{e-}03 A + 3.01$	$D = 3.23\text{e-}06 A^2 + 1.60\text{e-}04 A + 3.17$
		TG	$D = 1.12\text{e-}06 A^2 + 1.32\text{e-}03 A + 2.77$	$D = 4.08\text{e-}06 A^2 + 7.53\text{e-}04 A + 2.98$
		TGb	$D = -1.04\text{e-}07 A^2 + 2.11\text{e-}03 A + 2.64$	$D = 8.11\text{e-}07 A^2 + 1.34\text{e-}03 A + 2.65$
		TS	$D = -5.03\text{e-}07 A^2 + 3.32\text{e-}03 A + 1.17$	$D = -4.62\text{e-}07 A^2 + 3.27\text{e-}03 A + 1.17$
		TSb	$D = -4.27\text{e-}07 A^2 + 2.53\text{e-}03 A + 1.29$	$D = -1.98\text{e-}07 A^2 + 2.01\text{e-}03 A + 1.41$

Figure 7-56: Marked-up span equation table with relevant equations (From Table 7-13)

Rearranging using the quadratic formula, the maximum area for the TGb system can be found using Equation 7-7 and setting D = 4 feet. Note that web-based quadratic formula calculators are available to simplify manual calculation procedures. [313]

$$A = \frac{-3.93x10^{-3} \pm \sqrt{(3.93x10^{-3})^2 - (4*(-7.19x10^{-7})*(1.35-D))}}{2*(-7.19x10^{-7})} \quad (7-7)$$

The solution consists of two values, one of which is too large for the design space, the other is 787 ft², which meets the range of interest. Using A = 750 ft², Equation 7-8 can be used to determine the corresponding depth for that area.

$$D = (-7.19x10^{-7}) * A^2 + (3.93x10^{-3}) * A + 1.35 \quad (7-8)$$

In this case, D = 3.9 feet, which falls below the desired 4-foot max. Similarly using the quadratic formula, the maximum area for the TS system can be found using Equation 7-9, and again setting D = 4:

$$A = \frac{-3.20x10^{-3} \pm \sqrt{(3.20x10^{-3})^2 - (4*(-3.77x10^{-7})*(1.2-D))}}{2*(-3.77x10^{-7})} \quad (7-9)$$

In this case, A = 990 ft², which falls above the maximum bay area of 750 ft². The corresponding minimum depth that corresponds with the 600 ft² bay size under consideration for the TS system can be found using Equation 7-10:

$$D = -3.77x10^{-7} * A^2 + (3.2x10^{-3}) * A + 1.2 \quad (7-10)$$

In this case, D = 3.0 ft for the TS system. The maximum area for the TSb system can be found using Equation 7-11, and again setting D = 4:

$$A = \frac{-1.90x10^{-3} \pm \sqrt{(1.90x10^{-3})^2 - (4*(-1.15x10^{-7})*(1.09-D))}}{2*(-1.15x10^{-7})} \quad (7-11)$$

In this case, A = 1708 ft², which meets the desired maximum bay area of 750 ft². The corresponding minimum depth that corresponds with the 750 ft² bay size under consideration can be found using Equation 6:

$$D = -1.15x10^{-7} * A^2 + (1.90x10^{-3}) * A + 1.09 \quad (7-12)$$

In this case, D = 2.5 ft for the TSb system, which is well below the 4-foot maximum for the project. Because all systems met the depth restriction, EC will be compared for each to further

narrow down the options to two systems. Figure 7-57 presents EC data for the TGb, TS, and TSb systems, and is highlighted with the regions of bay areas under consideration for each system.

Based on these comparisons, the TGb and TS systems have the lowest EC. Because the TS system offers relatively low-depth options, the TSb system will no longer be considered.

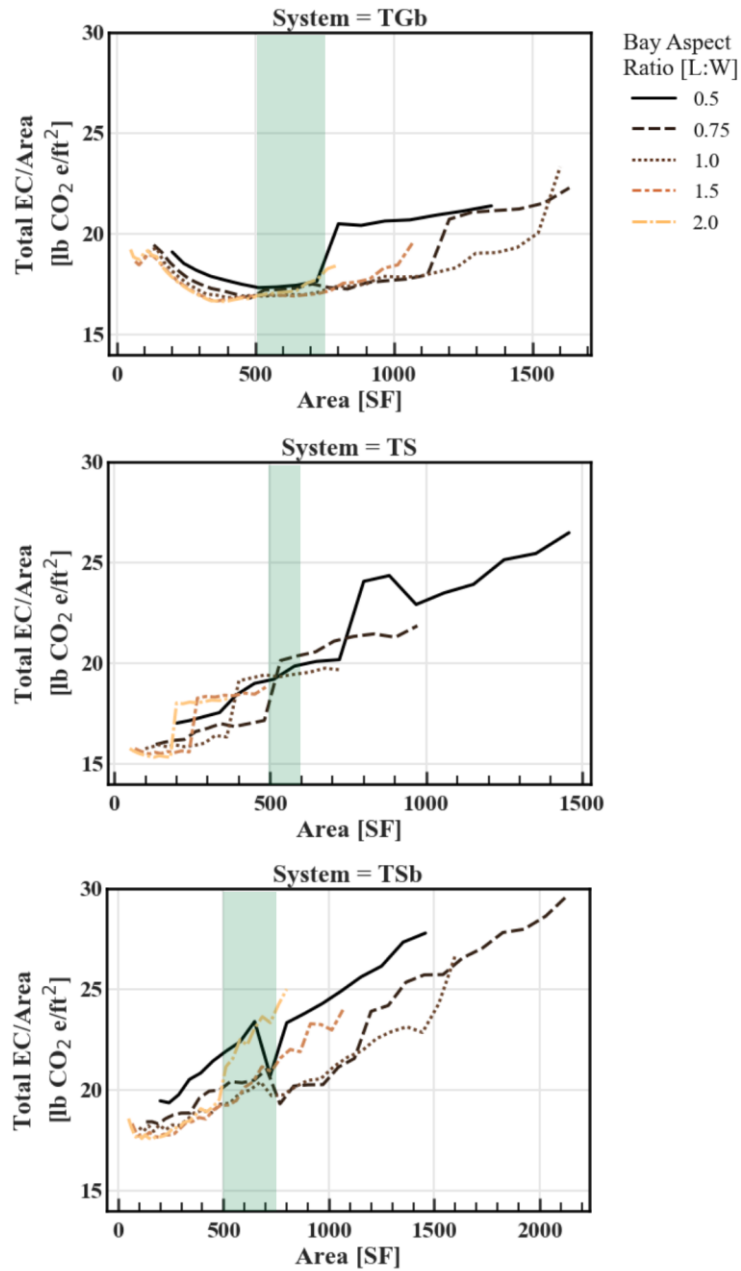


Figure 7-57: EC comparison between systems. Green shaded region highlights bay areas meeting design goals.

As previously stated, a larger bay area is preferred in this design example, however, larger bay areas results in greater depth, which can affect EC elsewhere in a full building design. To compare the TSb and TS and roughly similar depths, the TGb system will be studied further for a 500 ft² bay area, while the TS system will be studied for the max bay area of 600 ft² within its design range as previously noted. System depth, mass, and EC estimates can be made for both scenarios per Figure 7-58. In this marked up figure, both systems exhibit similar values for each performance objective with a slight tradeoff between EC, depth, and bay area, such that the TGb system has a lower EC but also a greater depth requiring a smaller bay area as compared to the TS system. Based on refining the performance objectives for each system, the bay aspect ratio of 0.75 and 1.0 is selected for the TGb and TS systems, respectively.

Having used these design guidance figures, Table 7-15 provides a summary of design information for the two options coming out of this example. Similar as in Design Example A, these two systems may be further refined during later design stages, or additional iterative early design decision making steps can be made. Future work based on this chapter will provide a guide with full tables and an accompanying web-based tool to help compare the data for different designs more easily. This can be an iterative process in reality, using a mix of the various figures and plots within this chapter to inform decision-making. This example concludes with the two design options in Table 7-15; however, more or fewer design options can be carried into later design stages for refinement as appropriate.

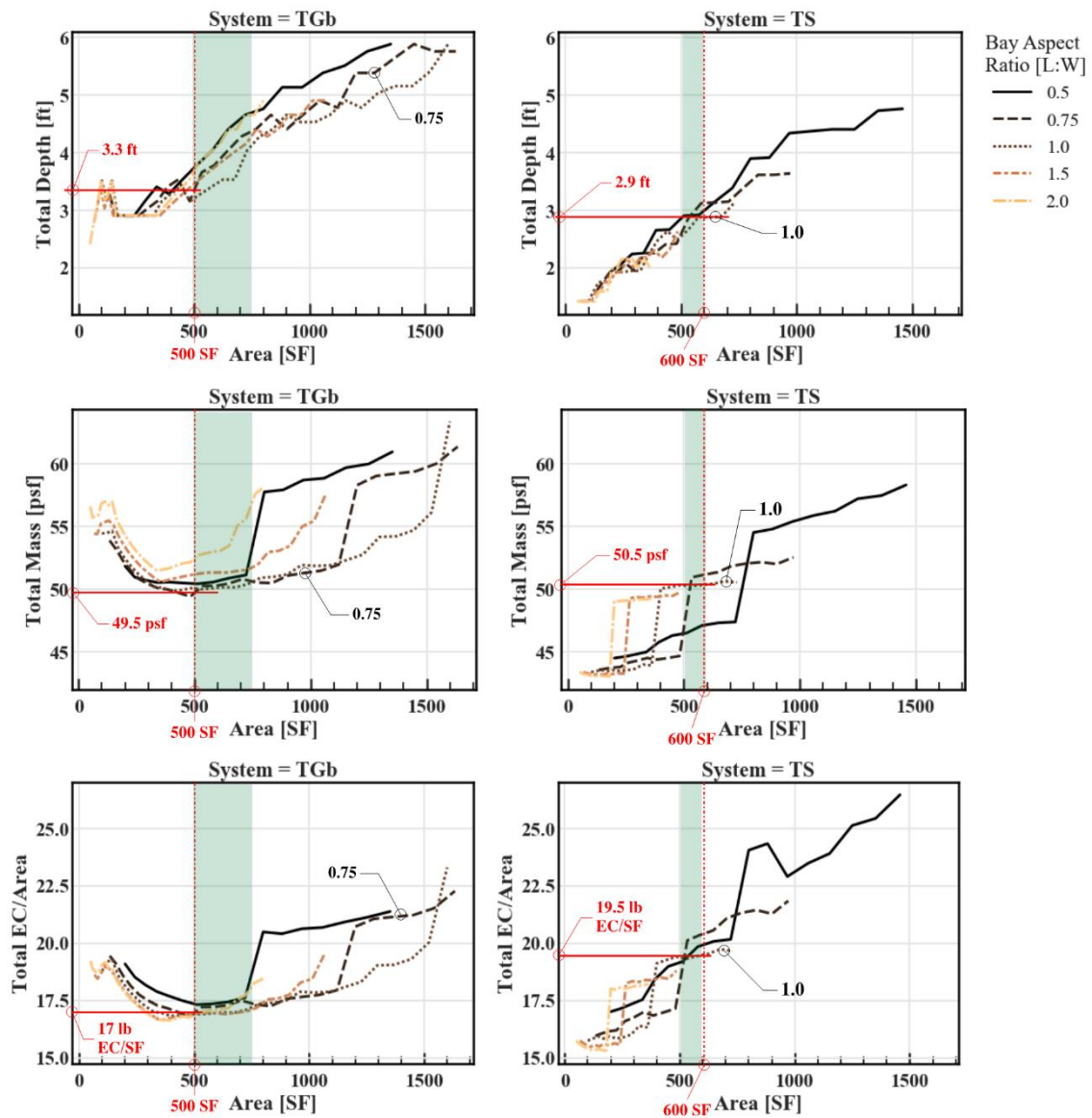


Figure 7-58: Marked-up Mass and EC estimate tables to select bay aspect area (From Figure 7-36 through Figure 7-38)

Table 7-15: Design options based on early design decision making in the design example

Design Data	Timber-framed with 1 infill (TGb)	Steel-framed (TS)
<i>Depth</i>	3.3' (1.0 m)	2.9 ft (0.9 m)
<i>Mass</i>	49.5 psf (242 kg/m ²)	50.5 psf (246 kg/m ²)
<i>EC</i>	17.0 lbs CO ₂ e/ft ² (83.0 CO ₂ e/m ²)	19.5 lbs CO ₂ e/ft ² (95.2 CO ₂ e/m ²)
<i>Bay Area and Aspect Ratio</i>	500 ft ² , 1.5 AR (46.5 m ²)	600 ft ² , 1.0 AR (55.7 m ²)
<i>Bay Width and Length</i>	18' x 27' (5.5 m x 8.2 m)	25' x 25' (7.6 m x 7.6 m)

7.1.11 Conclusions

The sections in this chapter presented plots and guidance for the early-design decision-making process for mass timber floor systems. Some key takeaways are as follows:

- If reducing EC and mass is a main priority:
 - Consider sourcing the most sustainable timber available.
 - Consider designing for deconstruction and reuse at the end of the building life to maintain carbon storage within the building elements.
 - Avoid designs which are overly deep.
 - Avoid a steel hybrid system with infill beams.
 - Design for systems with infill beams should consider limiting the design to a single infill beam where possible.
- If reducing depth is a main priority:
 - Select a steel-hybrid system to take advantage of steel's greater spanning capabilities.
 - Select a bay aspect ratio of 1.0 or greater so the steel girders are spanning the short direction.
 - Design for small bay sizes less than 20 feet (6.1 m).
- When designing for fire:
 - Plan to select a minimum 5-ply panel for the combined fire design configuration for a 2-hr FRR with 40 minutes of char and 80 minutes of noncombustible protection.

- Plan to select a minimum 7-ply panel for the exposed fire design configuration for a 2-hr FRR with 2 hours of char.
- When designing for improved acoustic insulation beyond code:
 - Consider under-ceiling treatment for the greatest improvements to STC and IIC for protected designs.
 - Consider raised wooden sleepers for moderate improvements to STC and IIC for designs with aesthetically exposed ceilings.

Future work related to this chapter is the further development of the chapter content and findings into an publicly-available web-based interactive design tool and an accompanying design guide. This work is intended to fulfill the proposed deliverables for the AIA Upjohn research initiative grant. The tool and guide will include additional baseline comparisons to steel floor systems.

7.1.12 Data Availability Statement

The full data set generated by all floor systems models for and discussed in this chapter is available by request from the corresponding author. The data set includes initial element sizing, material takeoffs, and estimates for EC, depth, and mass for the modeled systems. EC is based on the material EC factors in this chapter; however, a designer may use their own material EC assumptions in combination with the material takeoffs to estimate EC.

7.1.13 Acknowledgements

This research is supported in part by the American Institute of Architects (AIA) Upjohn Research Initiative grant. AIA did not have any role or input in the planning and implementation of this research; however, the grant work will include milestones to receive industry input and feedback on the guidance presented in this chapter prior to developing this further into a design guide.

Chapter 8

Conclusion and Future Work

To answer the research questions described in Chapter 1, a parametric modeling approach was applied to 5 mass timber and hybrid mass timber systems. Here, parametric models were created for each of the five CLT floor systems: two with Glulam framing, with and without infill beams (TGb and TG), two steel-hybrid floors with W-shape steel framing, with and without infill beams (TSb and TS), and a timber-concrete composite floor (TCC). By varying floor geometry, fire design approaches, and sustainable timber sourcing assumptions, a set of approximately 5,500 designs was generated, which were automatically sized to meet accepted industry code structural requirements using the smallest elements possible. Model output information for each design's member sizing, material takeoffs (mass), and embodied carbon (EC) were generated to look at performance trends. Modeling results were used to develop early design recommendations for industry professionals who are responsible for selecting or eliminating mass timber solutions. An additional study of acoustic assemblies was performed to evaluate the effect of different levels of sound insulation, particularly STC and IIC, on depth, mass, and EC.

As originally discussed, this research had a total of 5 research questions (discussed in Section 1.1). These research questions were answered throughout the chapters of this dissertation, particularly within Chapters 4 through 6. Chapter 4 focuses on impacts to structural design and EC, Chapter 5 focuses on impacts of prescriptive fire design options, and Chapter 6 presents the results of the acoustic assembly evaluation. Further, the main guidance coming out of Chapters 4 through 6 is summarized and distilled into useable industry guidance and recommendations that are documented in Chapter 7.

Key findings and observations for the originally stated research questions are summarized in

Table 8-1 for each main research question.

Table 8-1: Summary of key findings to the research questions

Research Question	Key Findings
<i>What are the <u>trends in EC and structural design objectives</u> for a variety of mass timber and hybrid mass timber floor systems?</i>	• The steel-hybrid systems have a depth range of about 1-3 feet (0.31 to 0.91 m). • The all-timber-framed systems have a depth range of about 2-5 feet (0.61 to 1.5 m). • Below approximately 18-20-foot (5.5-6.1 m) spans, the TG and TS systems are the lightest, ranging from about 40-50 psf (195-244 kg/m²). • Above approximately 18-20-foot (5.5-6.1 m) spans, the TGb and TSb systems are the lightest, ranging from about 48-56 psf (234-273 kg/m²). • With 75% SST, at spans below approximately 15 feet (4.6 m), the TGb system stores the most direct EC, about 10-14 lbs CO₂ eq./ft² (49-68 kg CO₂ eq./m²). • With 75% SST, at spans greater than 15 feet (4.6 m), the TCC and TG systems store the most direct EC, about 15-20 lbs CO₂ eq./ft² (73-98 kg CO₂ eq./m²). • See Chapter 4 for additional information
<i>How do mass timber and hybrid mass timber floor systems compare to <u>baseline steel-reinforced concrete floor systems</u> in relation to EC and structural design objectives?</i>	• All-timber-framed systems are typically 2-3 feet (0.61-0.91 m) deeper than the baseline concrete floors. • Steel-framed systems are typically 1-2 feet (0.31-0.61 m) deeper than the baseline concrete floors. • For floor spans ranging from 10-40 ft (3.1-12.2 m), the CFP floors had mass varying from 80 to 280 psf (390-1370 kg/m²), the CVP floors had mass varying from 100 to 240 psf (490-1170 kg/m²), and the mass timber systems fell within a range of 40 to 75 psf (200-370 kg/m²). • Concrete baseline floors were only competitive for EC when 0% sustainably-sourced timber is assumed and smaller bay spans less than 20 feet (6.1 m) are used. • Between the concrete baseline systems, at spans below 24 feet (7.6 m), the CFP system has the lowest EC, about 18-25 lbs CO₂ eq./ft² (89-122 kg CO₂ eq./m²). • Between the concrete baseline systems, at spans greater than 24 feet (7.3 m), the CVP system has the lowest EC, about 30-55 lbs CO₂ eq./ft² (146-269 kg CO₂ eq./m²). • See Chapter 4 for additional information
<i>How do <u>prescriptive fire design options</u> affect EC and floor system depth for mass timber and hybrid mass timber floor systems?</i>	• For the all-timber-framed systems, exposed designs with a 2-hr fire resistance rating are 6-12 inches (152-305 mm) deeper than protected designs for spans below 20 feet (6.1 m), but become competitive at spans above 20 feet (6.1 m). • The hybrid steel-framed systems can be upwards of 1.5 feet (0.46 m) shallower than their timber-framed counterpart due to the improved spanning capabilities of steel framing as compared to Glulam framing. • Protected hybrid-steel designs are marginally shallower than exposed designs. • See Chapter 5 for additional information.

Research Question	Key Findings
<i>How does designing for improved acoustic insulation beyond code minimum for floor assemblies affect mass timber EC and floor system depth?</i>	• Acoustic assembly categories including “concrete or gypsum topping,” “no concrete or gypsum topping,” and “raised wooden sleepers with no topping” offered the best balance of STC, IIC, depth, mass, and EC. • Assemblies with raised wooden sleepers maximized STC and IIC. • Many assemblies with very high IIC incorporated underside ceiling treatment (i.e. concealed ceilings) • See Chapter 6 for additional information.
<i>What recommendations and guidance should be provided to inform decision making during early design?</i>	• Parametric modeling results can provide estimates for depth, mass, and EC of the various studied floor systems at an early-design-stage level of detail. • Designers should keep holistic design considerations in mind and take an approach that seeks designs with balanced initial performance metrics. • For example, with carbon-storing designs, deeper systems may store more carbon directly in the floor system; however, deeper systems can lead to greater operational carbon and other impacts. • See Chapter 7 for additional information.

This research has therefore contributed to early design guidance for mass timber floors, particularly where EC and structural design goals meet. The research contribution involved answering these questions for a selection of mass timber and hybrid mass timber floor systems, as well as the establishment of design guidance for the industry from the results, as presented in Chapter 7.

8.1 Limitations

Due to the early-design-focused and parametric nature of this study, there are several limitations to this work that presented themselves throughout the process. Most of the limitations were in the form of simplification to manage model complexity and offer a clear and focused analysis of the research questions.

- Connections were not modeled or included in the structural analysis or EC estimates as they are typically assumed to have low impact relative to the rest of the system. Further, simple support conditions were assumed in the structural model.
- The focus was on gravity loads only because of the floor system level of modeling, and therefore lateral is not combined with the analysis. As a result the impact of seismic and wind loads were out of the scope of the research.
- The systems studied were modeled at a single bay scale, so considerations are not made for the impacts of foundations, podium levels, and possible concrete roof systems.
- Only rough estimates are provided for columns based on established rules of thumb for column size and an assumed mid-rise building height.
- The focus is on residential loads and other load cases which are similar in magnitude.
- A single mid-range strength wood species and grade were assumed for all mass timber component structural properties.
- Increases to floor system self-weight due to acoustic assembly mass were not incorporated into the parametric model.
- Fire design is based on prescriptive options only, rather than performance-based design.
- Design for walking-induced vibrations used industry accepted simplified analyses.

Despite these limitations, the models were found (through model verification comparing to real case study projects) to present realistic sizing outcomes, and are therefore considered valid for this dissertation's scope of research. Further, because of the significant contribution of floor systems to overall structural EC, the models and findings presented offer valid guidance into EC impact for mass timber structures.

8.2 Future Work

Future work that will proceed directly out of this dissertation work is the further development of the Chapter 7 content into an interactive web-based tool and a published design guide. This planned work is to fulfill the proposed deliverables for the AIA Upjohn research initiative grant. Additional baseline comparisons to steel floor systems will be included. The

architecture and structural engineering fields would further benefit from additional future work related to the topics in this dissertation, including but not limited to, the following:

- Similar parametric design studies incorporating lateral system design.
- Full-scale building analysis and comparisons for refined design sets that are representative of common mass timber construction.
- Studies into the cost and scheduling of various mass timber structure types and construction methods
- Studies into the effects of structural design on operational carbon to understand increased depth impacts envelope area, building height, operational energy, cost, lateral loads, etc.
- Parametric studies of the contribution of connections to structural sizing and EC estimates.

It is recommended to prioritize lateral system studies because there is relatively scarce data available comparing different lateral system types to each other for EC and other structural design goals. Modeling complexity will continue to present challenges in parametric studies like the ones proposed for future work; however, complexity can be reduced by carefully narrowing the focus and variable selection of such studies to the topics of greatest interest.

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Appendix A

Modeling Process Clarifications

Included in this Appendix are clarifying figures and discussion related to the typical modeling process for this dissertation. This Appendix is intended to mainly supplement Chapter 3, which discusses the general research methodology used throughout the dissertation. As a reminder, the basic process is that most systems are sized in Grasshopper (GH) using custom script components. The exception is the TCC system, for which a set of designs are checked and filtered using a spreadsheet-based model in Excel.

A.1 Grasshopper Modeling

The GH script sizes the structural elements of each design for all considered limit states (flexure, shear, deflections, fire design, walking-induce vibrations.) The floor system included are the all-timber and timber-steel hybrid systems, both with and without infill beams (TG, TS, TGb, and TSb.) Included in this section are screenshots depicting the main modeling process used.

The plugins used for the GH script include DSE and TT Toolbox. Figure A-1 shows the portion of the GH script which includes sliders for the floor system geometry, starting loading assumptions, and other design parameters. Sliders are controlled later in the model by a separate Design Space Exploration (DSE) component. Figure A-2 shows generally how the script imports a database of structural shapes for references in future steps. The ReadXL component from the TT Toolbox plugin is used to read a separate .csv file with section properties. The relevant properties that are used in the model were baked into data components to reduce processing time when the model runs. Any section properties file can be substituted by importing in the same manner.

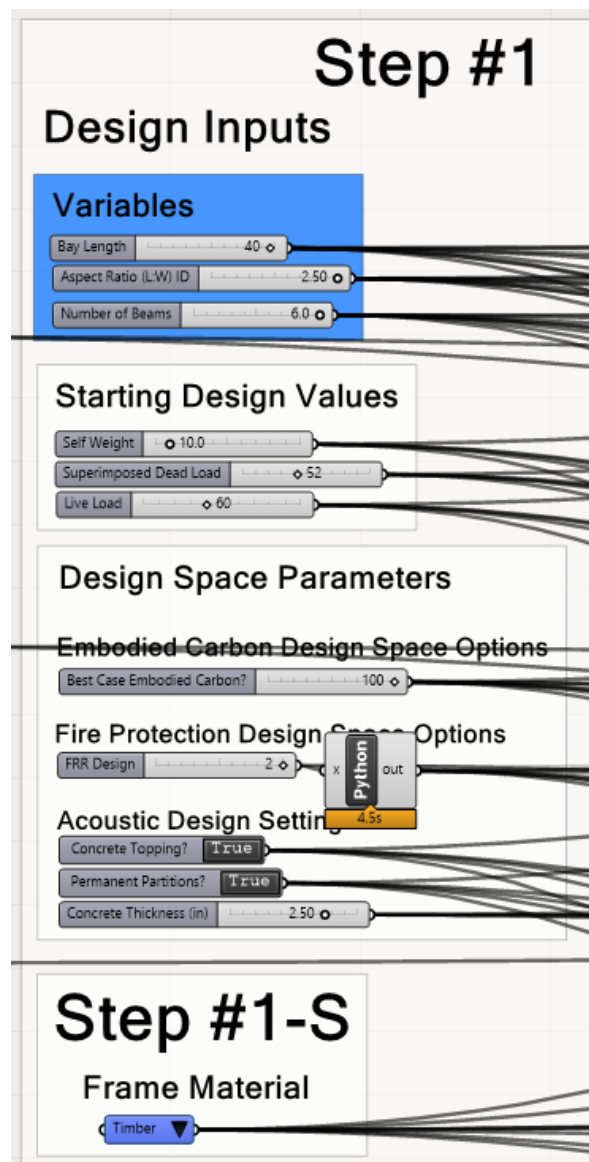


Figure A-1: GH Model variable sliders used to set different the floor system geometry and starting assumptions for each design within the design space.

Figure A-3 depicts a representation of a custom structural element sizing component, for which the editing dialogue has been opened. A component is included for each main element type, including the CLT floor panel, Glulam girder, Glulam beam, steel girder, and steel beam. Properties from the sizing components are sent to other components for data export when the model runs. Figure A-4 depicts the portion of the model which generates a design map, or the set of designs which fill the design space. This is where specific variable values can be edited.

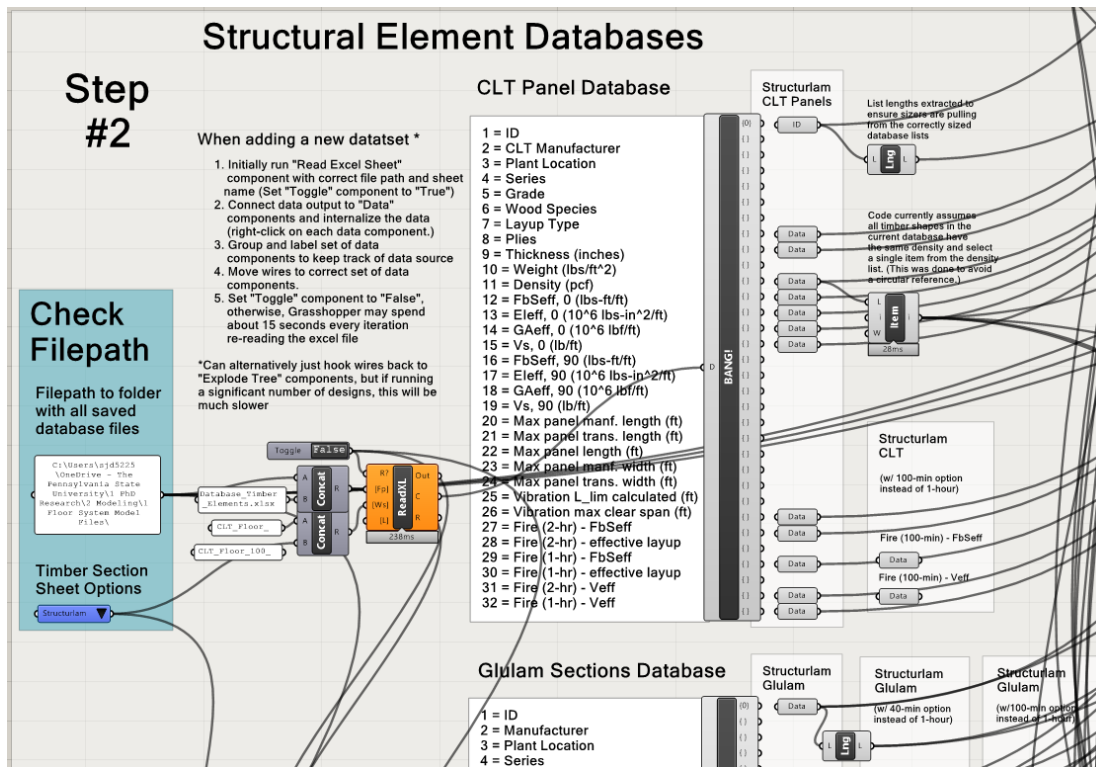


Figure A-2: Representative portion of GH script showing how structural element properties are imported.

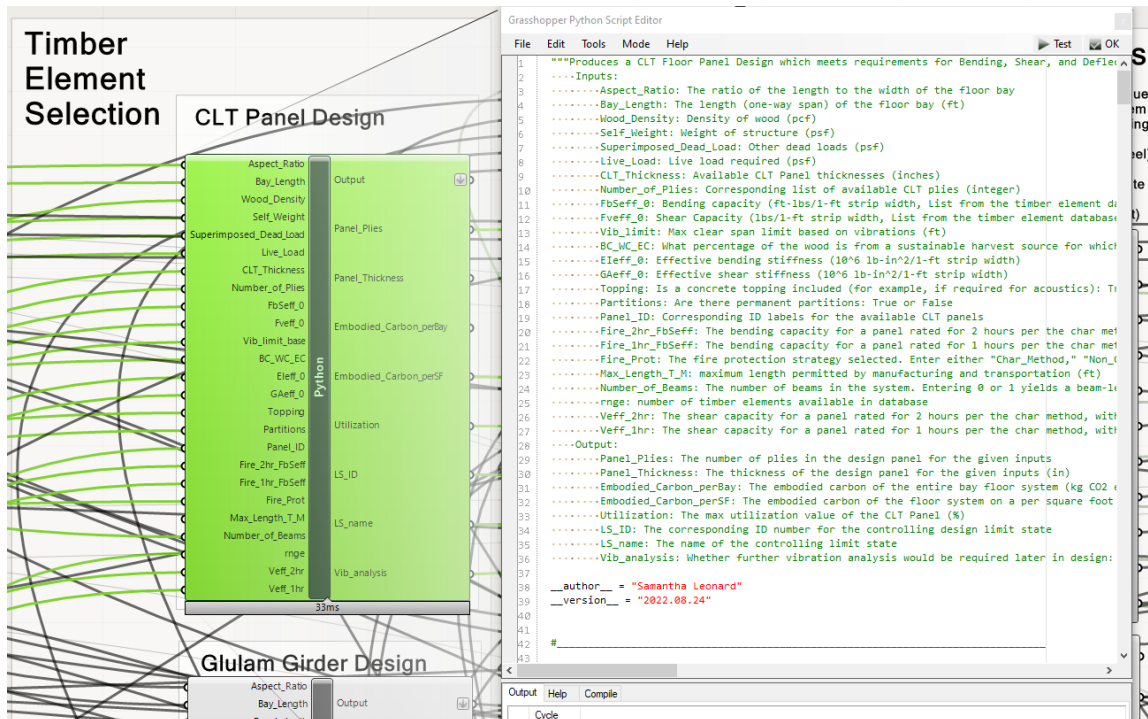


Figure A-3: Representative portion of GH script showing custom Python component and related scripting box for structural element sizing.

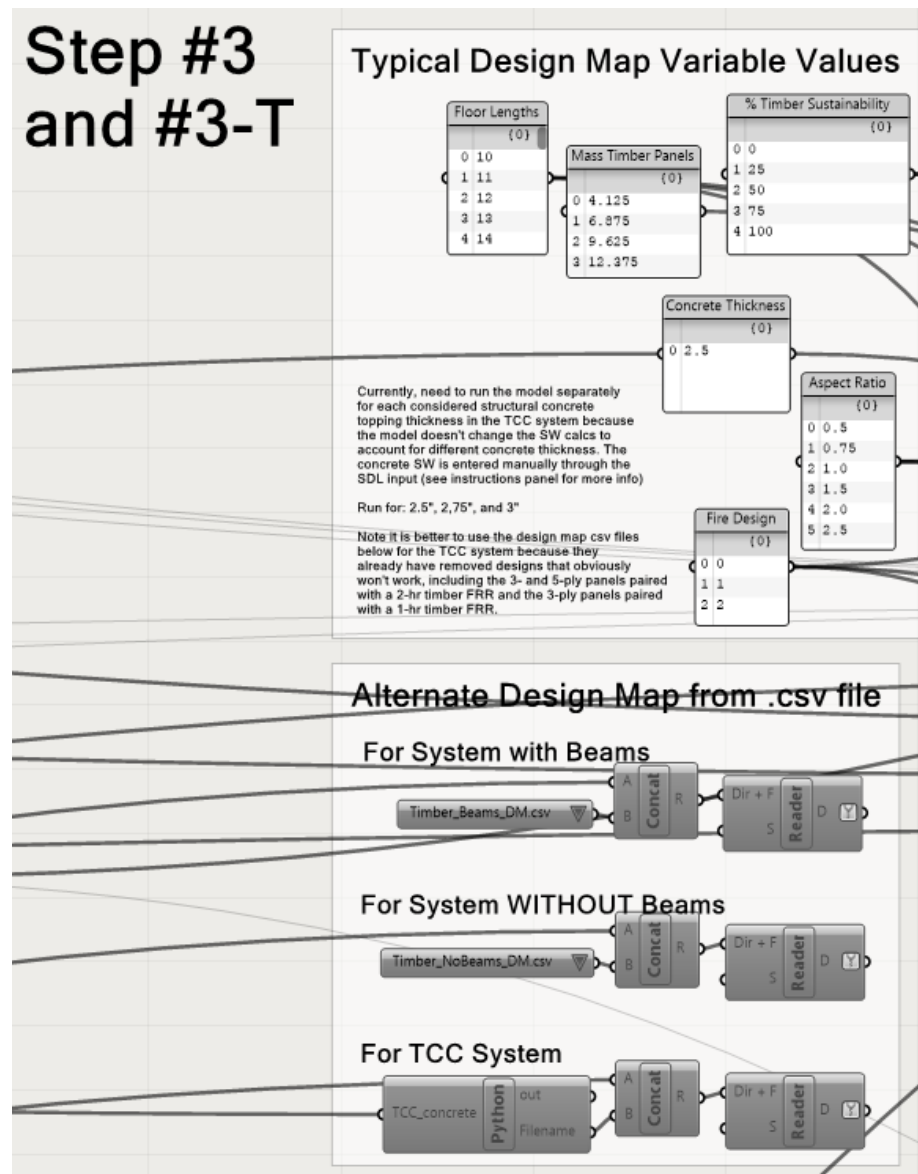


Figure A-4: Portion of GH script showing Design Map generation. The script may alternatively import a design map from a .csv file, but this option is not currently used (grayed out components).

Finally, Figure A-5 represents how the design map information is used to run the Capture component from the DSE plug-in, which controls the variable sliders and exports the resulting data for each design in the design space. Other components through the script improve the model performance and data export, but are not included in this set of representative screen shots.

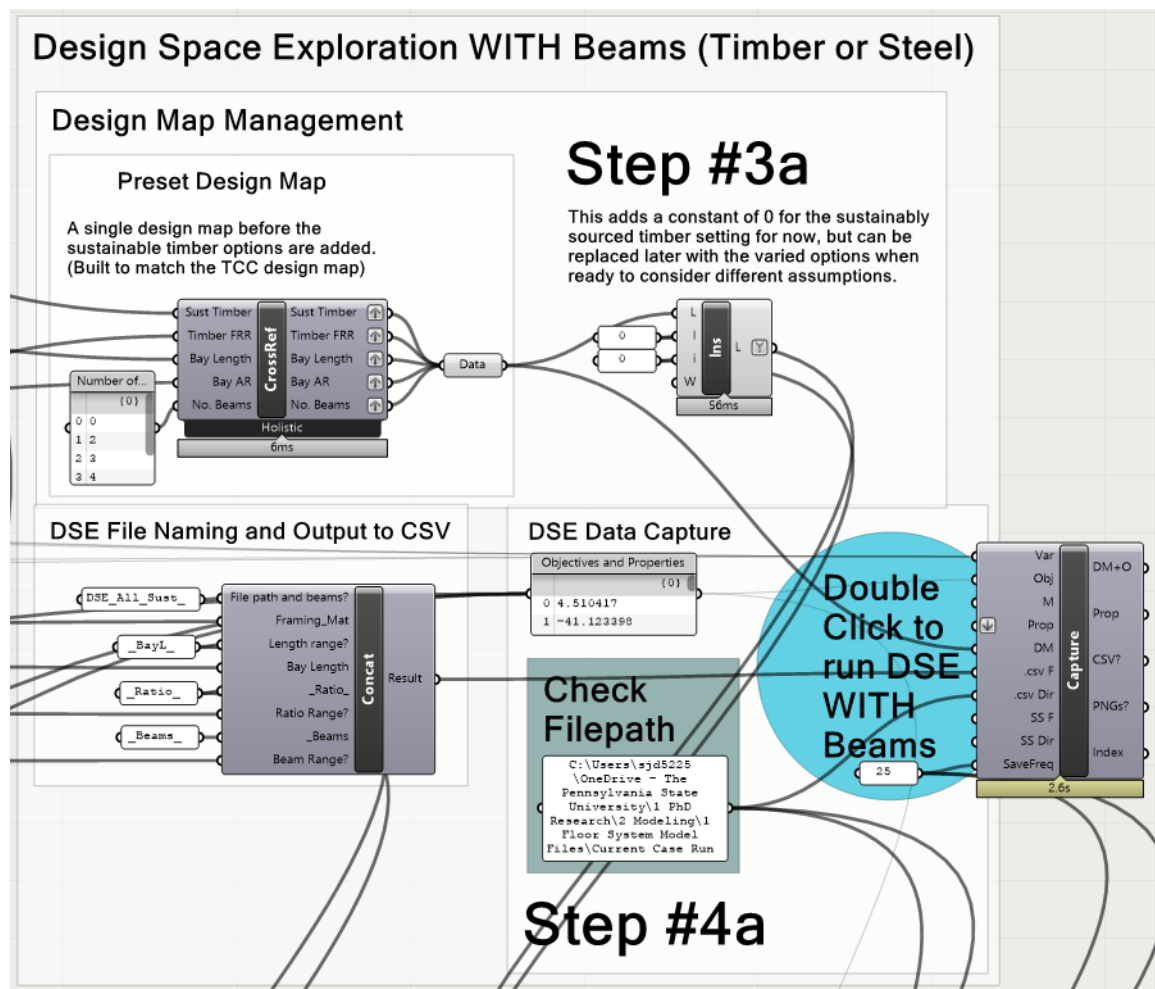


Figure A-5: Representative portion of GH which uses the Capture component from the DSE plug-in to run the model for the designs in the Design Map and output the data to an excel file for post-processing.

A.2 Spreadsheet-based TCC Model

The TCC model is run by generating a design space, or a set of potential completed designs, and then checking each design for the limit states and filtering out both the designs that did not work and those which are deeper with greater EC as compared to a design with the same set of design variables. This section includes representative screenshots to further demonstrate how this model is used. Figure A-6 presents the general instructions and information included in the TCC model.

This spreadsheet is intended to be used per the following steps:	
Step 1: Edit the values in the "Modeling Constants" tab as needed	
Step 2: Copy and paste the design map and objective values generated by Grasshopper into the "DM" tab. (DM = Design Map) Alternatively create and enter your own set of designs, but note that currently the Girder information comes from the GH script	
Step 3: Check that at least as many rows are included in each tab to include the size of the design map	
Step 4: Export the data (number of rows to match size of design map) from the "Export" tab into a separate .csv file for post-processing and data visualization in the Jupyter Notebook (copy-paste)	
Note that data is brought into the spreadsheet in US units and will be extracted in US units. Data is converted to metric for use in the design calculations and then converted back to US units for post processing and comparison to other models used in this research	
Limit State ID Key	Color Code Key
ID	Name
1	Flexure
2	Shear
3	Vibration Control
4	Deflections
5	Fire Design
	Color
	Description
	Input Value
	Output Values
	Value validated with design example
	Value validated in Grasshopper/elsewhere
	Calculated value - do not edit
	Check value is No Good
Key For Tab Names in this Spreadsheet*	
Abbreviation	Full Name/Description
DM	Design map (US Units)
Constants	Constant material and other design values
CLT DB	CLT element database (US Units)
Design (US)	Floor system geometry and properties in US units
Design (SI)	Floor system geometry and properties in SI units
(EI)eff	Calculations of effective bending stiffness
Serviceability	Calculations of serviceability criteria
Ult ST	Ultimate limit state design - short term loading
Ult LT	Ultimate limit state design - long term loading
Ult Fire	Ultimate limit state design - fire design
Checks	Checks against all design criteria
EC	Embodied carbon calculations (US Units)
Results	Final results in table easy-to-read format (US Units)
Export	Final results in easy-to-export format (US Units)
*Values in a tab are in SI units unless otherwise noted	

Figure A-6: Spreadsheet-based model instructions and general information tab

Figure A-7 provides a representation of the design map input tab. Similar to the GH script, this is where floor system geometry and other properties can be included for future use in calculations throughout the spreadsheet. In this case, the spreadsheet only performs the composite TCC floor panel design, and the girder design information is imported from the GH script results, adjusted for additional load from the structural concrete topping as needed.

Figure A-8 depicts how design and material constants are provided in a single tab for reference throughout the other tabs and quick updates. Note that only a portion of the constants tab is shown in this figure for clarity. Figure A-9 similarly shows a portion of the CLT properties tab, which is again treated as constants which can be readily updated in a single tab for reference throughout the spreadsheet model.

Design Map Data Input (US)												
<i>Note: Grasshopper is used to generate a design map (or design space) of values for various floor system designs and spans, which is exported to a .csv file. Copy and paste data from the relevant .csv file generated from Grasshopper. This includes the current model variables and the girder design which is performed in Grasshopper for each configuration</i>												
	Component Property Units	Variables						Design and Results				
		L ft	AR -	h _t in	h _c in	% Sust %	FRR hours	G _w in	G _d in	Δ _g in	G _U	G _{LS_IS}
	Notes	Bay Length	Bay Aspect Ratio	Timber depth	Concrete Depth	% Sust sourced timber	Fire resistance rating on timber	Girder width	Girder depth	Deflection of the girder	Girder Utilization	Girder Limit State ID
DSE Design ID ↓	1	10	1.0	4.125	2.50	0.00	0	5.125	11.750	0.080	0.699	2
	2	11	1.0	4.125	2.50	0.00	0	5.125	11.750	0.128	0.844	2
	3	12	1.0	4.125	2.50	0.00	0	5.125	13.250	0.138	0.891	1
	4	13	1.0	4.125	2.50	0.00	0	5.125	14.750	0.160	0.986	2
	5	14	1.0	4.125	2.50	0.00	0	5.125	17.750	0.141	0.940	2
	6	15	1.0	4.125	2.50	0.00	0	5.125	19.250	0.156	0.996	2
	7	16	1.0	4.125	2.50	0.00	0	5.125	22.250	0.140	0.981	2
	8	17	1.0	4.125	2.50	0.00	0	5.125	25.250	0.130	0.977	2
	9	18	1.0	4.125	2.50	0.00	0	6.750	28.250	0.078	0.814	1
	10	19	1.0	4.125	2.50	0.00	0	6.750	26.750	0.121	0.957	1
	11	20	1.0	4.125	2.50	0.00	0	6.750	29.750	0.114	0.954	1
	12	21	1.0	4.125	2.50	0.00	0	6.750	32.750	0.109	0.956	1
	13	22	1.0	4.125	2.50	0.00	0	6.750	35.750	0.106	0.962	1
	14	23	1.0	4.125	2.50	0.00	0	8.500	31.250	0.166	0.998	2
	15	24	1.0	4.125	2.50	0.00	0	8.500	34.250	0.157	0.993	2
	16	25	1.0	4.125	2.50	0.00	0	8.500	37.250	0.149	0.991	2
	17	26	1.0	4.125	2.50	0.00	0	8.500	40.250	0.144	0.993	2
	18	27	1.0	4.125	2.50	0.00	0	8.500	41.750	0.376	0.941	1

Figure A-7: Representative view of TCC Model design map input tab. For clarity, not all rows are shown.

Design Constants (US)

Timber				Concrete				Connection System			
Property	Value	Units	Notes	Property	Value	Units	Notes	Property	Value	Units	Notes
Density_t	29.3	pcf		phi_c	0.65			K_creep, conn	4		*
K_creep,t	2			f'c	4351.13	psi					
Et_0	1.38E+06	psi		Ec	3.63E+06	psi		*from eq. 4.4 with minimum reinf. Ratio = 0.002			
Et_90	1.20E+06	psi		density_c	149.8271	pcf	NW concrete				
f_t,0	9.45E+02	psi		K_creep,c	2.82						
f_t,90	5.25E+02	psi									

Design density for CLT should be 35

Design Constants (SI)

Timber				Concrete				Connection System			
Property	Value	Units	Notes	Property	Value	Units	Notes	Property	Value	Units	Notes
Density_t	470	kg/m^3		phi_c	0.65			K_creep, conn	4		*
K_creep,t	2			f'c	30	Mpa					
Et	9.50E+03	MPa		Ec	25000	MPa		*from eq. 4.4 with minimum reinf. Ratio = 0.002			
*Density for example = 470				density_c	2400	kg/m^3	NW concrete				
				K_creep,c	2.82						
*Density for example values set to 2400											

Figure A-8: Representative view of TCC model design constants tab. For clarity, not all columns are included here.

CLT Properties Database (US)						
0-hr FRR						
h_t in	M_r,t ft-lbs/ft	T_r,t lb/ft	V_r,t lb/ft	(EA)_t lb/ft	GA_eff,t lb/ft	(EI)_eff,t lb-in ² /ft
4.125	2042	39847.5	1440	6.53E+07	5.00E+05	9.60E+07
6.875	4701	64102.5	1980	1.08E+08	1.10E+06	3.66E+08
9.625	8315	88357.5	2500	1.5E+08	1.60E+06	9.06E+08
12.375	12896	112612.5	3025	1.93E+08	2.10E+06	1.81E+09

Figure A-9: Representative view of TCC model CLT properties tab. For clarity, not all columns are included here.

Figure A-10 presents a portion of the floor system design properties tab, which generates information about the properties of each design based on the design map, constants, and CLT panel properties database tab. Both a US and SI unit-based tab is included, and calculations are performed in ST units. Figure A-11 show one of many calculation tabs which perform the calculations for the various limit states using the properties for each design in the design properties tab.

Floor System Design Properties (US)												
Component Property Units	Floor Geometry											
	L ft	W ft	Strip Width ft	t in	b _t in	h _t in	G _w in	G _d in	M _{r,t} ft-lbs	M _{r,t,f} ft-lbs	T _{r,t} lb	
Notes	Bay Length	Bay Width	Design for strip width of floor	Gap betw conc. & timber	Timber width	Timber depth	Girder width	Girder depth	Flexural resistance of timber	Flexural resistance of timber for fire	Tensile resistance of timber	
Example Value	29.5	29.5	3.3	1.0	38.9	7.2	14.0	22.0	5.8E+05		2.7E+05	
Example Test	29.5	29.5	3.3	1.0	38.9	7.2	14.0	22.0	5.8E+05		2.7E+05	
DSE 1	10	10	3.3	1.0	39.37	4.125	5.125	11.75	6.7E+03	6.7E+03	1.3E+05	
Design 2	11	11	3.3	1.0	39.37	4.125	5.125	11.75	6.7E+03	6.7E+03	1.3E+05	
ID 3	12	12	3.3	1.0	39.37	4.125	5.125	13.25	6.7E+03	6.7E+03	1.3E+05	
	4	13	3.3	1.0	39.37	4.125	5.125	14.75	6.7E+03	6.7E+03	1.3E+05	
	5	14	3.3	1.0	39.37	4.125	5.125	17.75	6.7E+03	6.7E+03	1.3E+05	
	6	15	3.3	1.0	39.37	4.125	5.125	19.25	6.7E+03	6.7E+03	1.3E+05	
	7	16	3.3	1.0	39.37	4.125	5.125	22.25	6.7E+03	6.7E+03	1.3E+05	
	8	17	3.3	1.0	39.37	4.125	5.125	25.25	6.7E+03	6.7E+03	1.3E+05	
	9	18	3.3	1.0	39.37	4.125	6.75	28.25	6.7E+03	6.7E+03	1.3E+05	
	10	19	3.3	1.0	39.37	4.125	6.75	26.75	6.7E+03	6.7E+03	1.3E+05	
	11	20	3.3	1.0	39.37	4.125	6.75	29.75	6.7E+03	6.7E+03	1.3E+05	

Figure A-10: Representative view of TCC Model design properties tab. For clarity, not all rows and columns are shown.

Effective Bending Stiffness															
Category Property Units		Short term and standard term loading													
		s_eff/n	K	γ_c	γ_t	a	h_c,eff	h_c,eff	t_eff	r	(EI)_c	(EA)_c	a_c	a_t	(EI)_eff
		mm	Mpa			mm	mm	mm	mm	mm	Nmm^2	N	mm	mm	Nmm^2
Notes				γ_c = 1 assumes perfect composite action				limited by actual h_c							
DSE Design ID	Example Value	140.0	257.1	1.0	0.55	38.0	95.9	95.9	29.1	169.0	1.84E+12	2.40E+09	48.0	121.1	2.62E+13
	Example Test	140.0	257.1	1.0	0.55	38.0	95.9	95.9	29.1	169.0	1.84E+12	2.40E+09	48.0	121.1	2.62E+13
	1	140.0	257.1	1.0	0.20	7.7	39.6	39.6	48.9	121.1	1.29E+11	9.89E+08	19.8	101.3	2.54E+12
	2	140.0	257.1	1.0	0.24	9.0	42.1	42.1	46.4	119.8	1.55E+11	1.05E+09	21.0	98.8	2.85E+12
	3	140.0	257.1	1.0	0.27	10.2	44.4	44.4	44.1	118.7	1.82E+11	1.11E+09	22.2	96.5	3.16E+12
	4	140.0	257.1	1.0	0.30	11.4	46.5	46.5	42.0	117.6	2.09E+11	1.16E+09	23.2	94.4	3.45E+12
	5	140.0	257.1	1.0	0.33	12.7	48.4	48.4	40.1	116.7	2.36E+11	1.21E+09	24.2	92.5	3.73E+12
	6	140.0	257.1	1.0	0.36	13.9	50.2	50.2	38.3	115.8	2.63E+11	1.25E+09	25.1	90.7	3.99E+12
	7	140.0	257.1	1.0	0.39	15.0	51.7	51.7	36.8	115.0	2.89E+11	1.29E+09	25.9	89.1	4.23E+12
	8	140.0	257.1	1.0	0.42	16.1	53.2	53.2	35.3	114.3	3.14E+11	1.33E+09	26.6	87.7	4.46E+12
	9	140.0	257.1	1.0	0.45	17.2	54.5	54.5	34.0	113.6	3.38E+11	1.36E+09	27.3	86.4	4.67E+12
	10	140.0	257.1	1.0	0.48	18.2	55.7	55.7	32.8	113.0	3.60E+11	1.39E+09	27.9	85.2	4.87E+12
	11	140.0	257.1	1.0	0.50	19.2	56.8	56.8	31.7	112.5	3.82E+11	1.42E+09	28.4	84.1	5.06E+12
	12	140.0	257.1	1.0	0.53	20.1	57.8	57.8	30.7	112.0	4.03E+11	1.45E+09	28.9	83.1	5.23E+12
	13	140.0	257.1	1.0	0.55	21.0	58.8	58.8	29.7	111.5	4.23E+11	1.47E+09	29.4	82.1	5.40E+12
	14	140.0	257.1	1.0	0.57	21.8	59.6	59.6	28.9	111.1	4.41E+11	1.49E+09	29.8	81.3	5.55E+12
	15	140.0	257.1	1.0	0.59	22.6	60.4	60.4	28.1	110.7	4.58E+11	1.51E+09	30.2	80.5	5.69E+12
	16	140.0	257.1	1.0	0.61	23.4	61.1	61.1	27.4	110.3	4.75E+11	1.53E+09	30.5	79.8	5.82E+12
17	140.0	257.1	1.0	0.63	24.1	61.7	61.7	26.8	110.0	4.90E+11	1.54E+09	30.9	79.1	5.94E+12	
18	140.0	257.1	1.0	0.65	24.7	62.3	62.3	26.2	109.7	5.05E+11	1.56E+09	31.2	78.5	6.06E+12	

Figure A-11: Representative view of TCC Model stiffness calculations tab. For clarity, not all rows and columns are shown.

Figure A-12 and Figure A-13 show samples from the design checks and embodied carbon calculation tabs. These tabs offer a more concise location to place all final design checks based on the relevant properties and calculated values from each tab, as well as to take the resulting sizing info to estimate EC. Finally, Figure A-14 shows a small portion of the final tab in which key design properties, variables, and objectives are included in plain formatting for easy export into a separate .csv file. This helps with using the data elsewhere for combining the data set with the other systems from the GH model and performing data analysis and visualization in Jupyter Notebook.

Design Checks and Utilization Summary													
Category Property Units		Deflection						Vibration Criterion					
		Δ_L mm	Δ_L ,limit	Δ_{tot}	Δ_{tot} ,limit	Δ check	Δ util.	L m	L_max	f_n Hz	f_nr	L check	Vib util.
Notes						0 = no good 1 = good						0 = no good 1 = good	
DSE Design ID	Example Value	7.8	25.0	50	50.0	1	1.00	9.0	9.0	4.3	4 to 15	1	1.00
	Example Test	7.8	25.0	50	50.0	1	1.00	9.0	9.0	4.3	4 to 15	1	1.00
	1	1.1	8.5	7	16.9	1	0.39	2.7	5.3	11.8	4 to 15	1	0.52
	2	1.4	9.3	8	18.6	1	0.46	3.0	5.5	10.4	4 to 15	1	0.56
	3	1.8	10.2	11	20.3	1	0.53	3.4	5.6	9.3	4 to 15	1	0.60
	4	2.2	11.0	13	22.0	1	0.60	3.7	5.8	8.3	4 to 15	1	0.63
	5	2.8	11.9	16	23.7	1	0.69	4.0	5.9	7.6	4 to 15	1	0.67
	6	3.4	12.7	20	25.4	1	0.78	4.3	6.0	6.9	4 to 15	1	0.71
	7	4.2	13.5	24	27.1	1	0.88	4.6	6.1	6.3	4 to 15	1	0.75
	8	5.1	14.4	28	28.8	1	0.99	4.9	6.2	5.8	4 to 15	1	0.79
	9	6.1	15.2	34	30.5	0	1.11	5.2	6.2	5.3	4 to 15	1	0.83
	10	7.2	16.1	40	32.2	0	1.23	5.5	6.3	4.9	4 to 15	1	0.87
	11	8.5	16.9	46	33.9	0	1.37	5.8	6.4	4.6	4 to 15	1	0.91
	12	10.0	17.8	54	35.6	0	1.52	6.1	6.4	4.2	4 to 15	1	0.95
	13	11.7	18.6	62	37.3	0	1.68	6.4	6.5	3.9	4 to 15	1	0.99
	14	13.6	19.5	72	38.9	0	1.85	6.7	6.5	3.7	4 to 15	0	1.03
	15	15.7	20.3	82	40.6	0	2.03	7.0	6.6	3.4	4 to 15	0	1.07
	16	18.1	21.2	94	42.3	0	2.22	7.3	6.6	3.2	4 to 15	0	1.11
	17	20.7	22.0	107	44.0	0	2.43	7.6	6.7	3.0	4 to 15	0	1.14
	18	23.7	22.9	121	45.7	0	2.65	7.9	6.7	2.8	4 to 15	0	1.18

Figure A-12: Representative view of TCC Model design checks tab. For clarity, not all rows and columns are shown.

Embodied Carbon (US)								
Category Property		EC for each Component per Bay (l						
		CLT Factor	Timber Panel	Glulam Factor	Girder	Concrete Factor	Concrete	Steel Factor
Units								
Notes								
Example Value		0.437	6749.2	0.512	948.9	0.13	5578	1.07
Example Test		0.437	6749.2	0.512	948.9	0.13	5578	1.07
DSE	1	0.437	440.8	0.512	62.8	0.13	406	1.07
Design	2	0.437	533.3	0.512	69.1	0.13	492	1.07
ID	3	0.437	634.7	0.512	85.0	0.13	585	1.07
	4	0.437	744.9	0.512	102.5	0.13	687	1.07
	5	0.437	863.9	0.512	132.9	0.13	796	1.07
	6	0.437	991.7	0.512	154.4	0.13	914	1.07
	7	0.437	1128.3	0.512	190.3	0.13	1040	1.07
	8	0.437	1273.8	0.512	229.5	0.13	1174	1.07
	9	0.437	1428.1	0.512	358.1	0.13	1316	1.07
	10	0.437	1591.1	0.512	357.9	0.13	1467	1.07
	11	0.437	1763.0	0.512	419.0	0.13	1625	1.07
	12	0.437	1943.7	0.512	484.3	0.13	1792	1.07
	13	0.437	2133.3	0.512	553.8	0.13	1966	1.07
	14	0.437	2331.6	0.512	637.4	0.13	2149	1.07
	15	0.437	2538.8	0.512	728.9	0.13	2340	1.07

Figure A-13: Representative view of TCC Model EC calculations tab. For clarity, not all rows and columns are shown.

60	0	0	0	0	0	0	0	0	0	0	0	0
61	0	0	0	0	0	0	0	0	0	0	0	0
62	0	0	0	0	0	0	0	0	0	0	0	0
63	0	0	10	1	1.989583333	18.73658098	0	10	10	1	0	0
64	0	0	11	1	1.989583333	18.63624519	0	11	11	1	0	0
65	0	0	12	1	2.114583333	18.66368447	0	12	12	1	0	0
66	0	0	13	1	2.239583333	18.68617022	0	13	13	1	0	0
67	0	0	14	1	2.489583333	18.80063154	0	14	14	1	0	0
68	0	0	15	1	2.614583333	18.8097204	0	15	15	1	0	0
69	0	0	16	1	2.864583333	18.9009625	0	16	16	1	0	0
70	0	0	17	1	3.114583333	18.98091038	0	17	17	1	0	0
71	0	0	18	1	3.364583333	19.31750917	0	18	18	1	0	0
72	0	0	19	1	3.239583333	19.14081456	0	19	19	1	0	0
73	0	0	20	1	3.489583333	19.22077906	0	20	20	1	0	0
74	0	0	21	1	3.739583333	19.29267469	0	21	21	1	0	0
75	0	0	22	1	3.989583333	19.35760174	0	22	22	1	0	0
76	0	0	0	0	0	0	0	0	0	0	0	0
77	0	0	0	0	0	0	0	0	0	0	0	0
78	0	0	0	0	0	0	0	0	0	0	0	0
79	0	0	0	0	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0	0	0	0	0

Figure A-14: Representative view of TCC Model data export tab. For clarity, not all rows and columns are shown.

A.3 Data Post-processing

Using the structural element sizing data from the model, post-processing was performed in a combination of Jupyter Notebook using Python scripting and Excel spreadsheets. Post-processing included compiling data sets from GH and the TCC model into a single data set, estimating material (mass) takeoffs, calculating embodied carbon, performing data analysis, and generating data visualizations for this dissertation. The plots throughout the dissertation chapters are representative of the types of post-processing analysis and data visualizations performed.

Appendix B

Enlarged Design Plots

Included in this appendix are enlarged plots from Chapter 7's Figures 7-33 through 7-38. The plots included here may either be viewed larger on a screen for ease of use, or can be printed out for use with hand-measuring tools. Each plot includes a header above with the specific design conditions and variable settings for which it applies. Plots for systems with beams are only for 1 infill beam, effectively halving the CLT floor panel span across the bay length. Note that the plot scales in each are sized individually for the plot's data and are not the same in all cases. While only the exposed and protected fire design options are included here, interpolation between the results of these plots may be used to estimate values for the combine approach. EC plots are shown only for 75% SST. In each section plots are included in the following order:

- TCC System:
 - Exposed
 - Protected
- TG System:
 - Exposed
 - Protected
- TGb System:
 - Exposed
 - Protected
- TS System:
 - Exposed
 - Protected
- TSb System:
 - Exposed
 - Protected

B.1 Depth

TCC System - Exposed - 75% SST

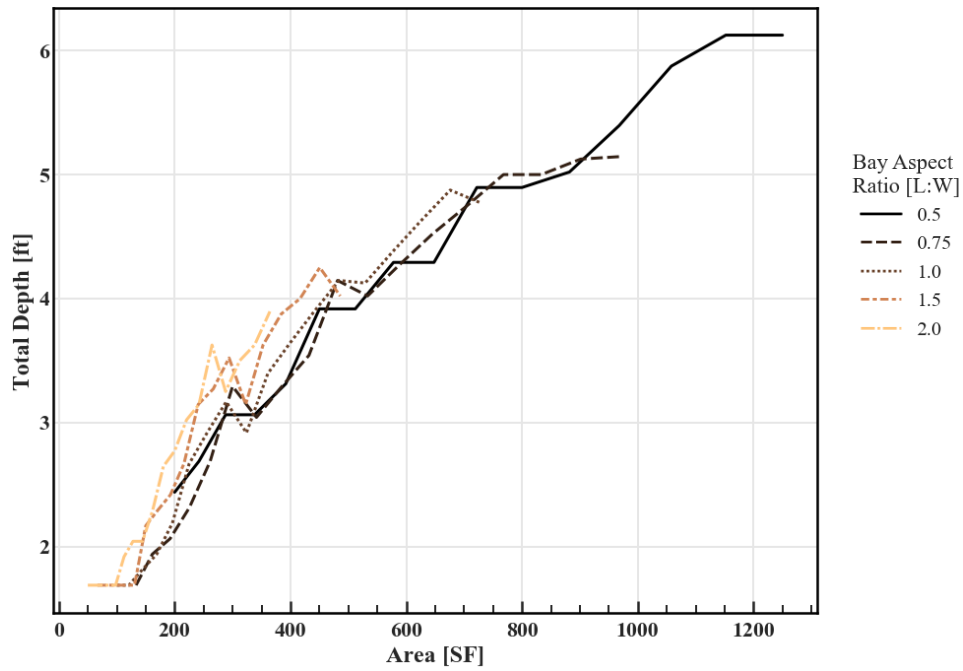


Figure B-1: Enlarged depth plot for Exposed TCC System with 75% SST

TCC System - Protected - 75% SST

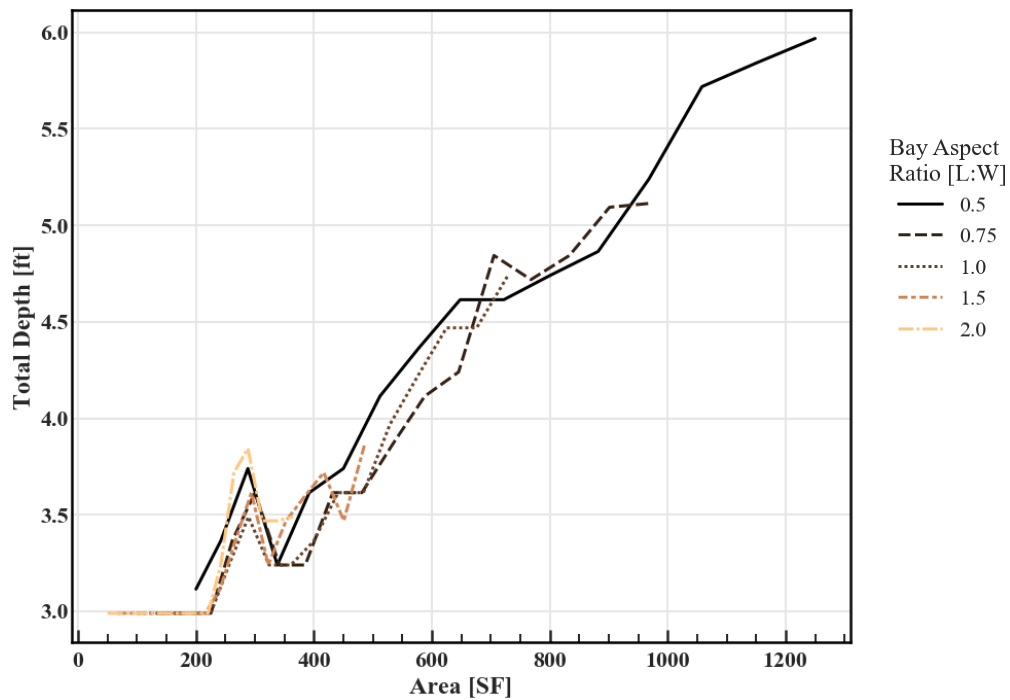


Figure B-2: Enlarged depth plot for Protected TCC System with 75% SST

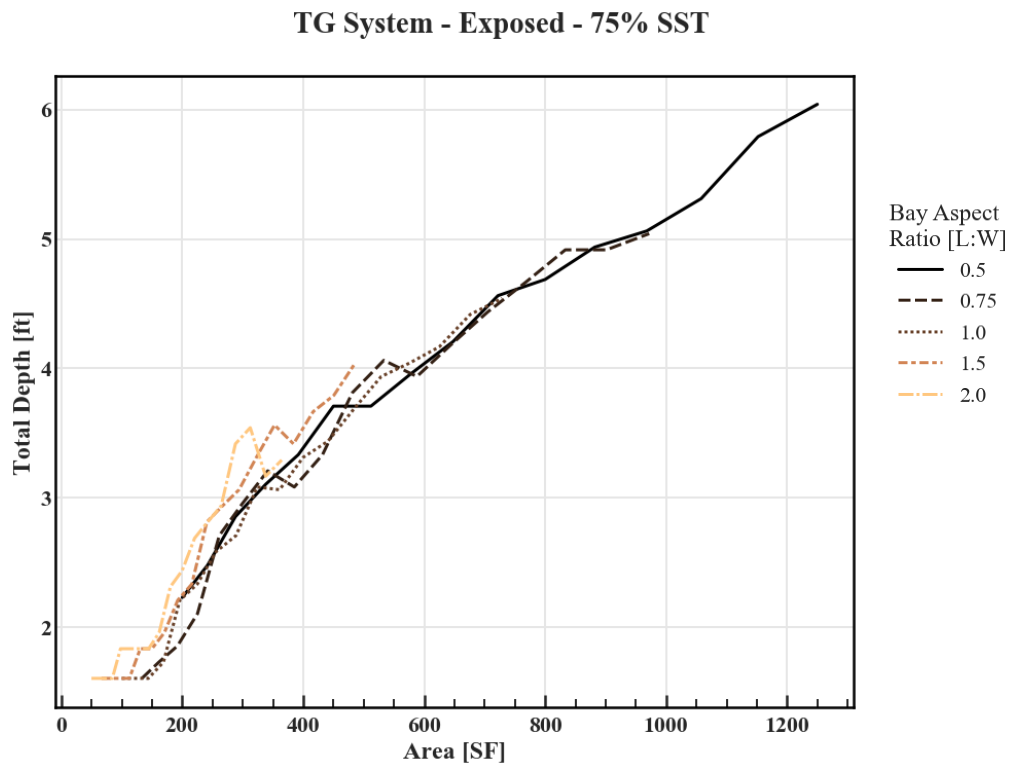


Figure B-3: Enlarged depth plot for Exposed TG System with 75% SST

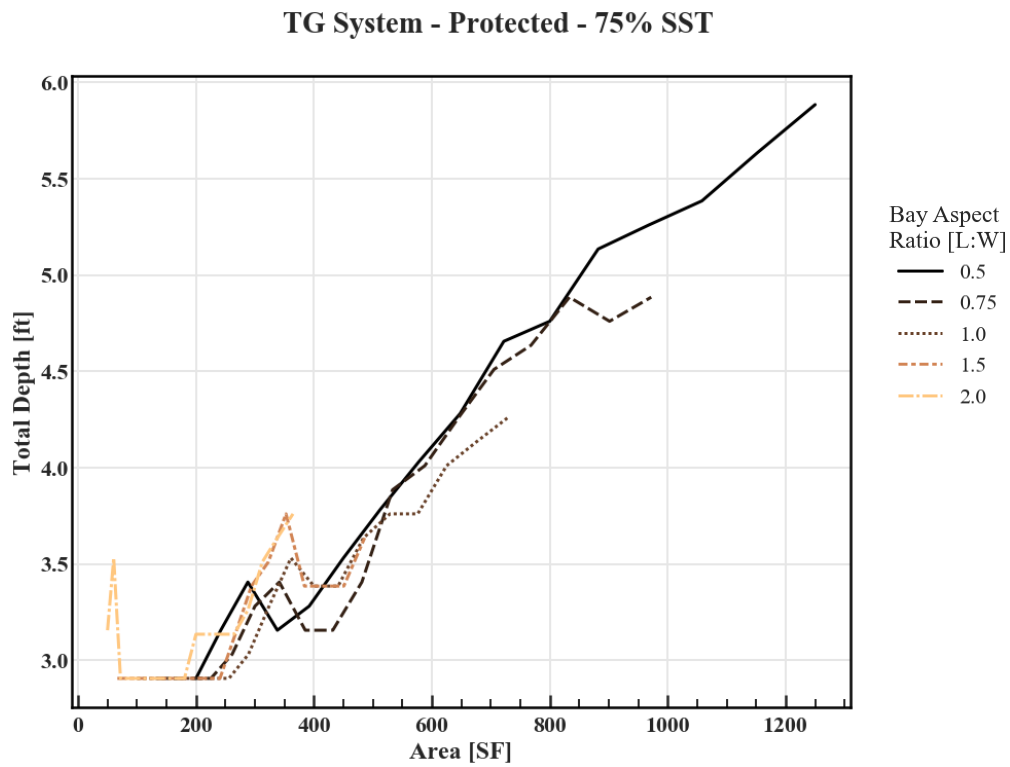


Figure B-4: Enlarged depth plot for Protected TG System with 75% SST

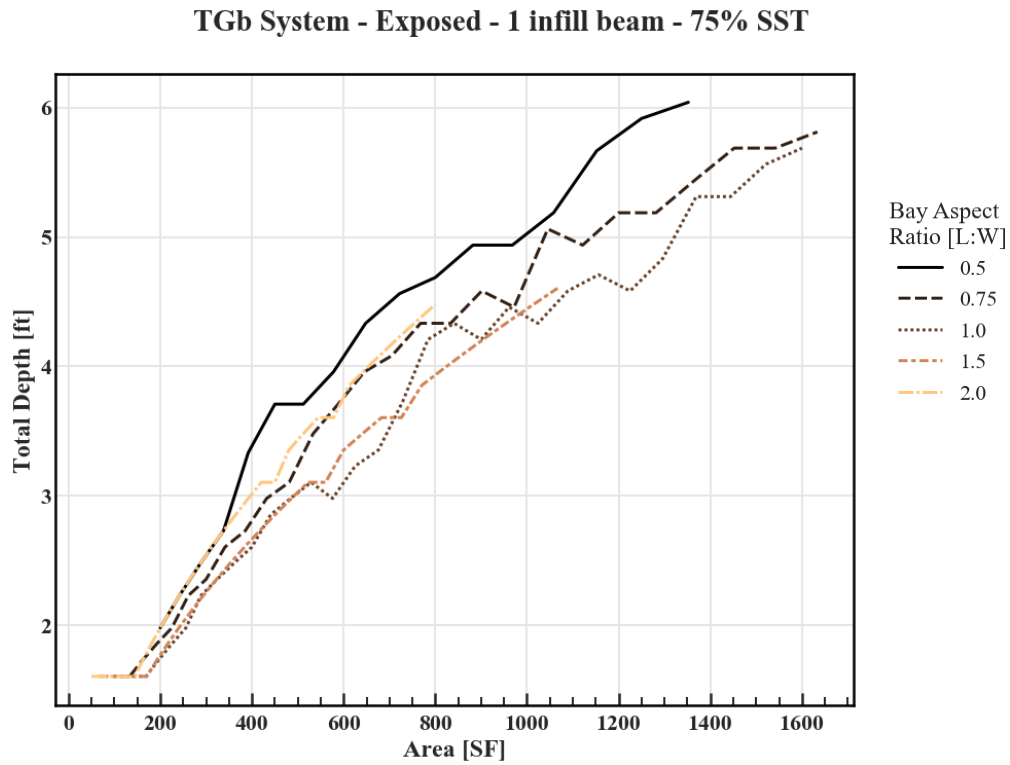


Figure B-5: Enlarged depth plot for Exposed TGb System with 75% SST and 1 infill beam

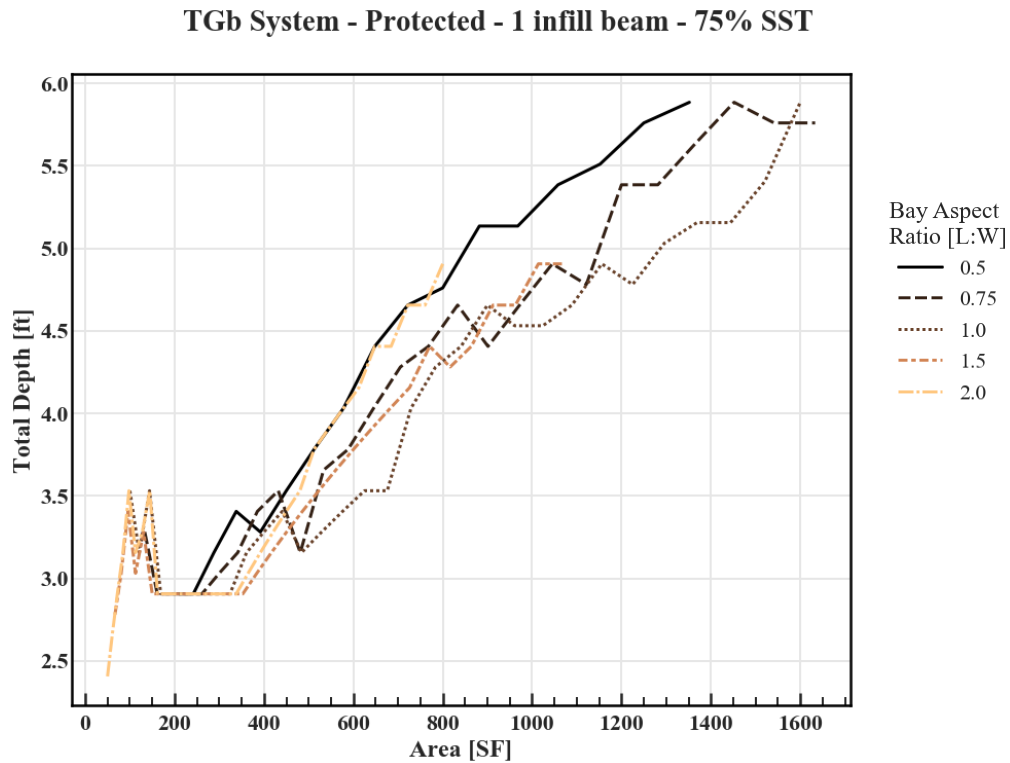


Figure B-6: Enlarged depth plot for Protected TGb System with 75% SST and 1 infill beam

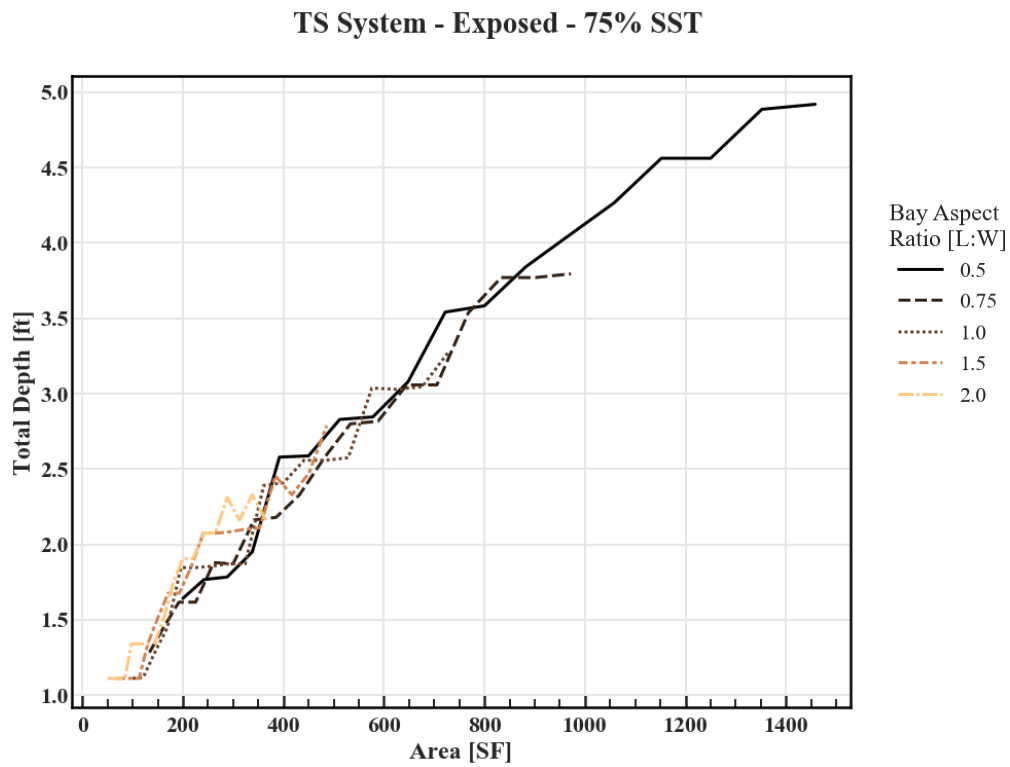


Figure B-7: Enlarged depth plot for Exposed TS System with 75% SST

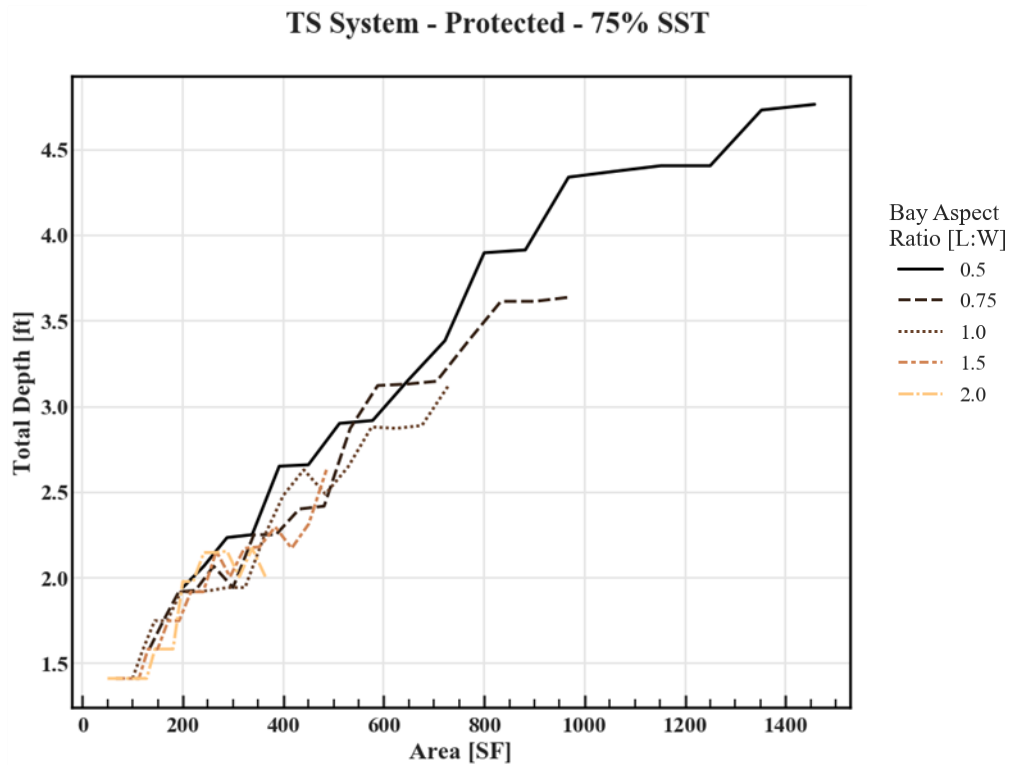


Figure B-8: Enlarged depth plot for Protected TS System with 75% SST

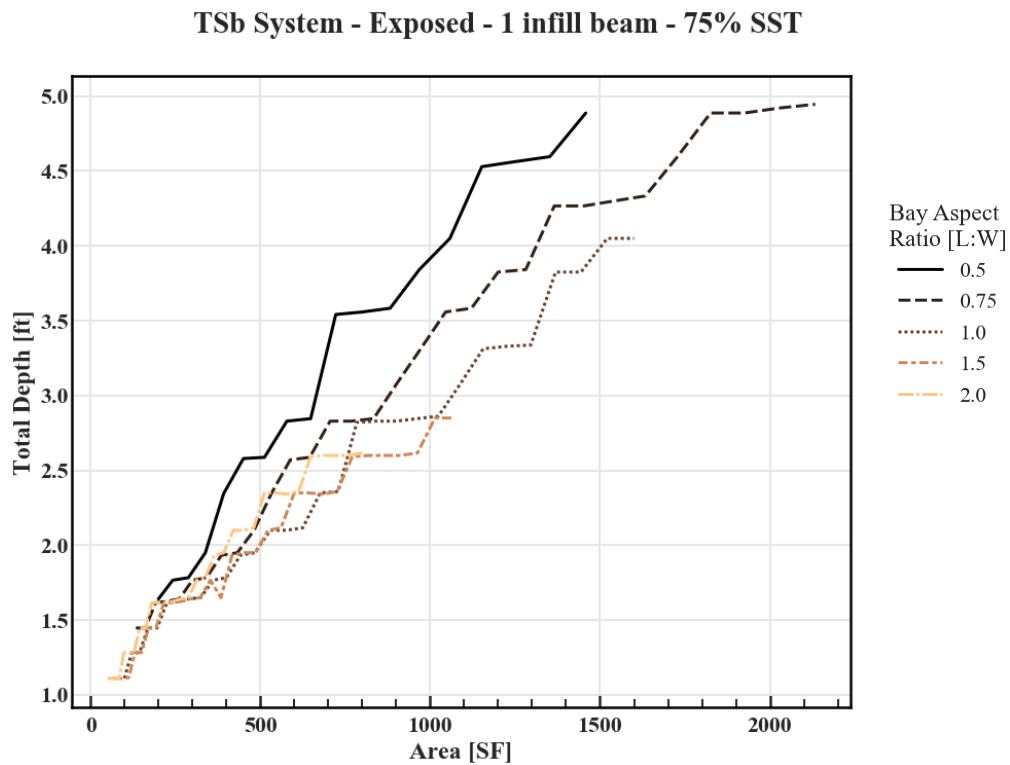


Figure B-9: Enlarged depth plot for Exposed TSb System with 75% SST and 1 infill beam

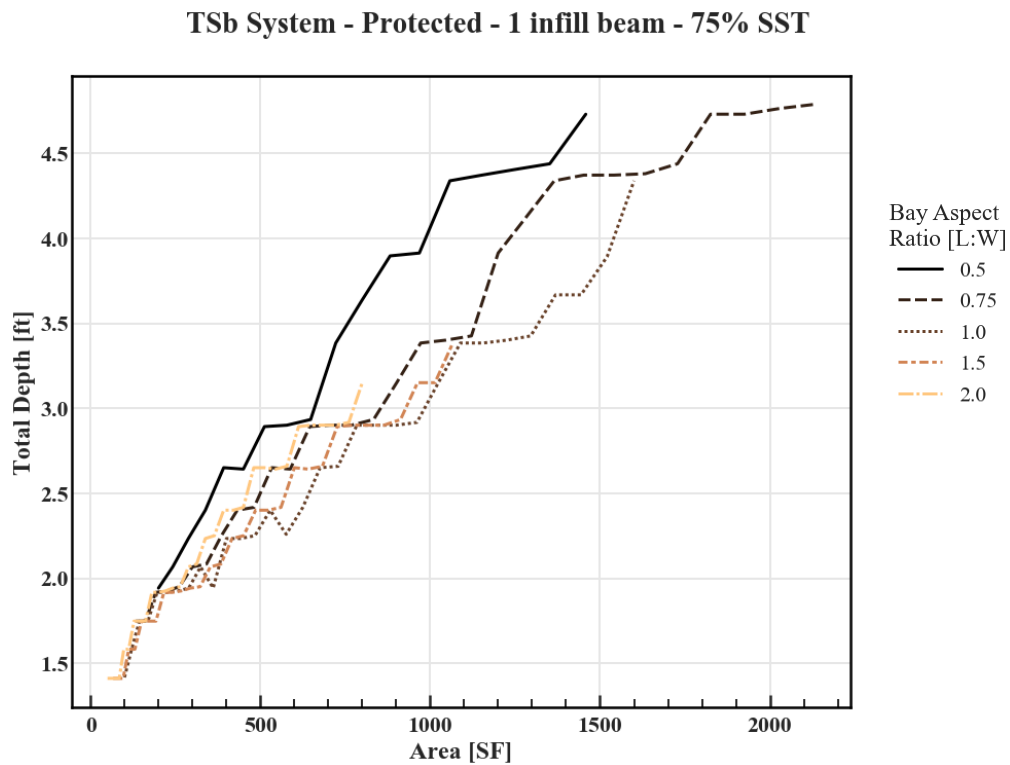


Figure B-10: Enlarged depth plot for Protected TSb System with 75% SST and 1 infill beam

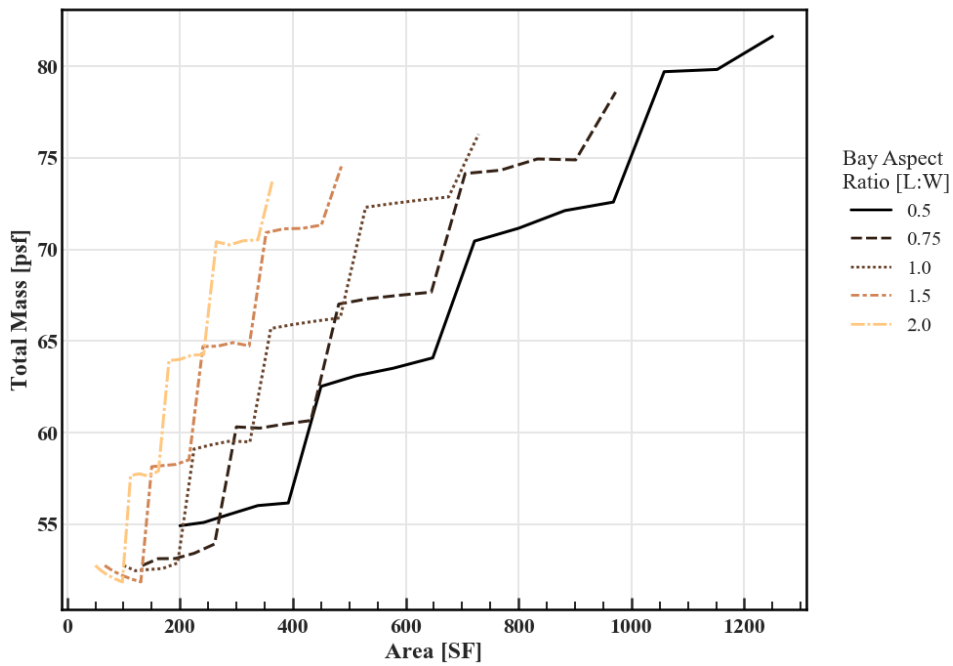
B.2 Mass**TCC System - Exposed - 75% SST**

Figure B-11: Enlarged mass plot for Exposed TCC System with 75% SST

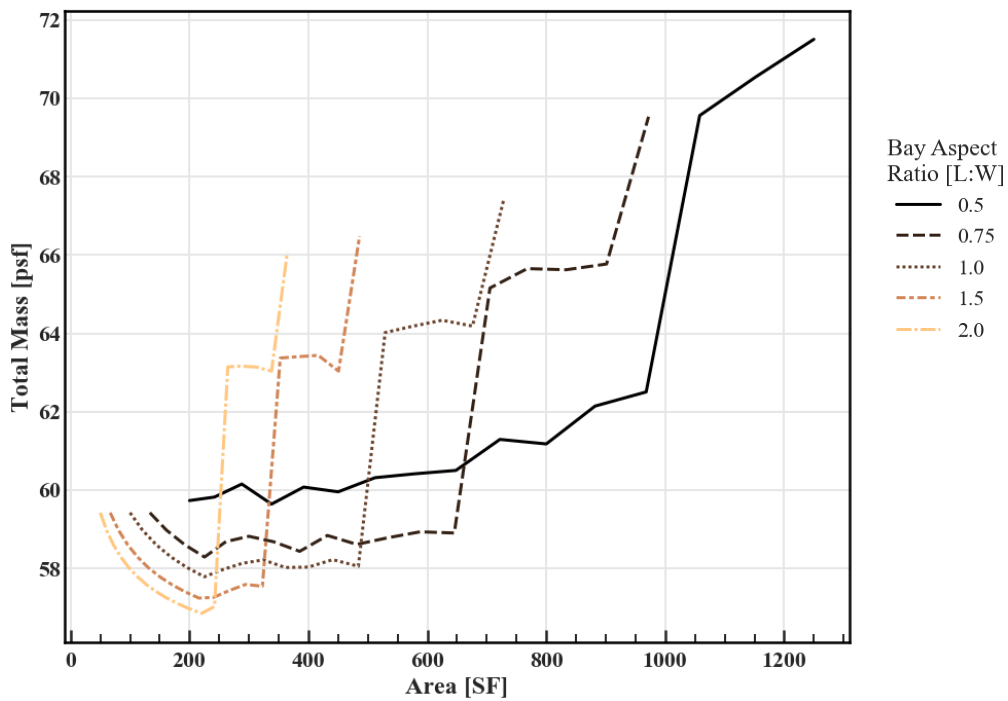
TCC System - Protected - 75% SST

Figure B-12: Enlarged mass plot for Protected TCC System with 75% SST

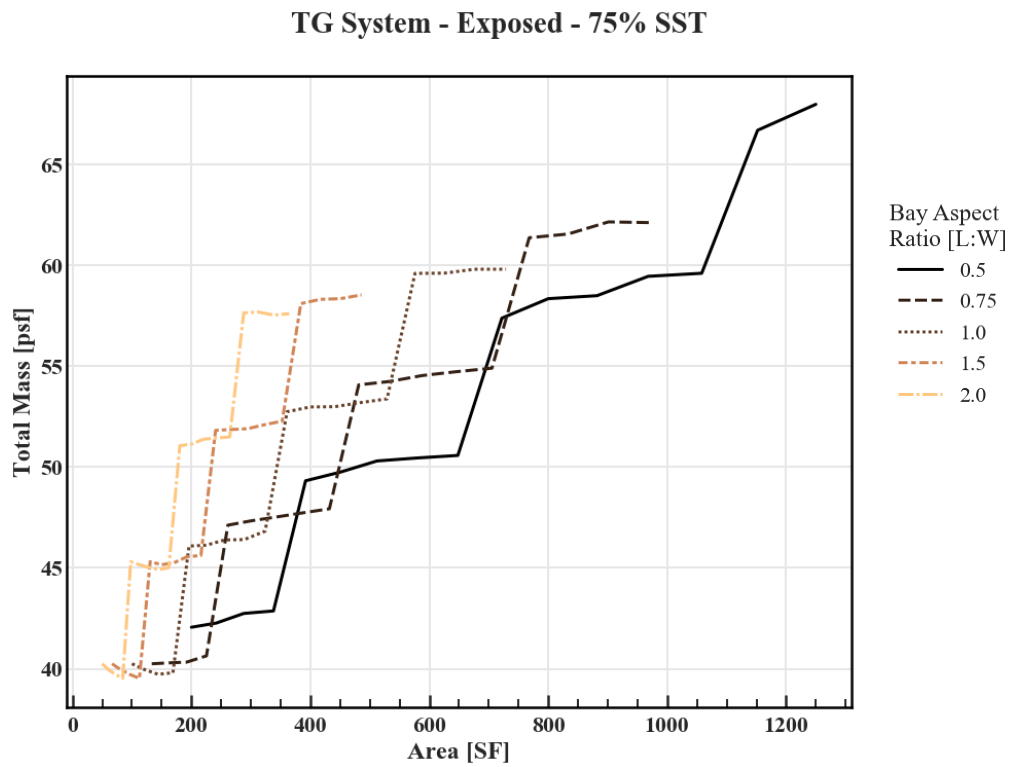


Figure B-13: Enlarged mass plot for Exposed TG System with 75% SST

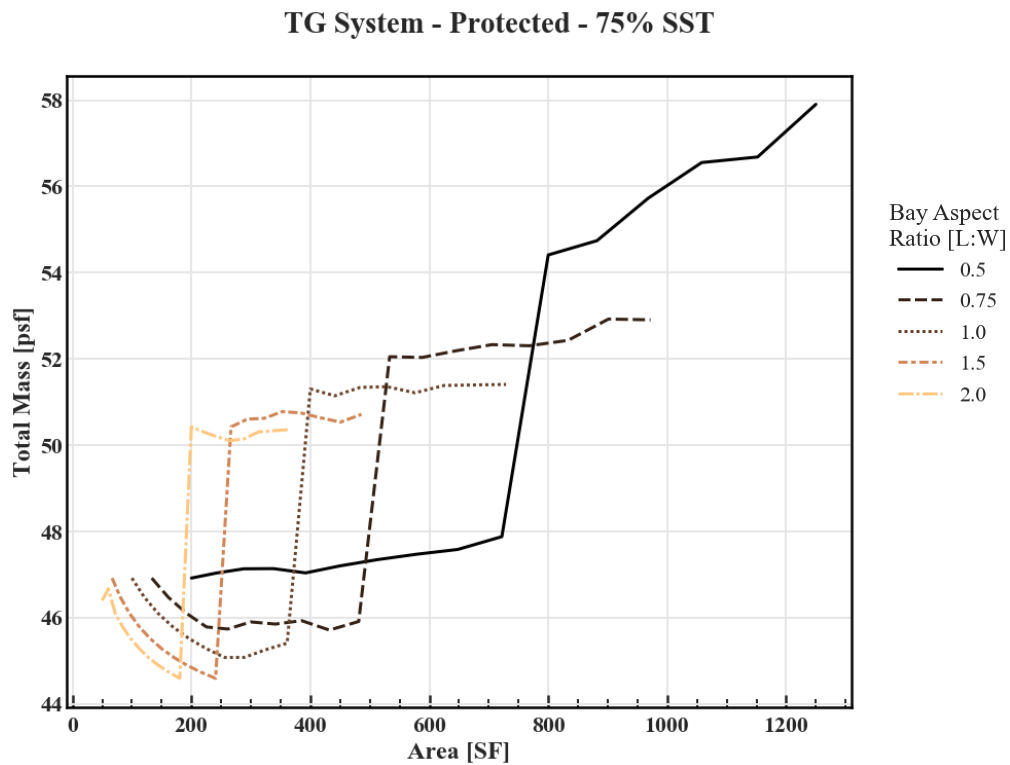


Figure B-14: Enlarged mass plot for Protected TG System with 75% SST

TGb System - Exposed - 1 infill beam - 75% SST

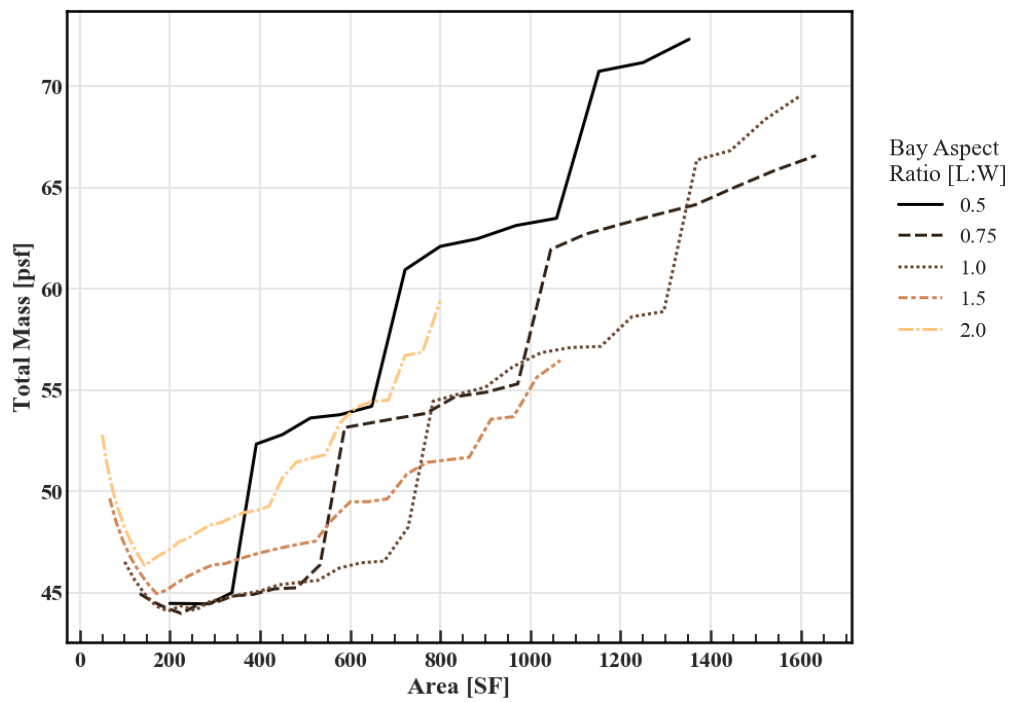


Figure B-15: Enlarged mass plot for Exposed TGb System with 75% SST and 1 infill beam

TGb System - Protected - 1 infill beam - 75% SST

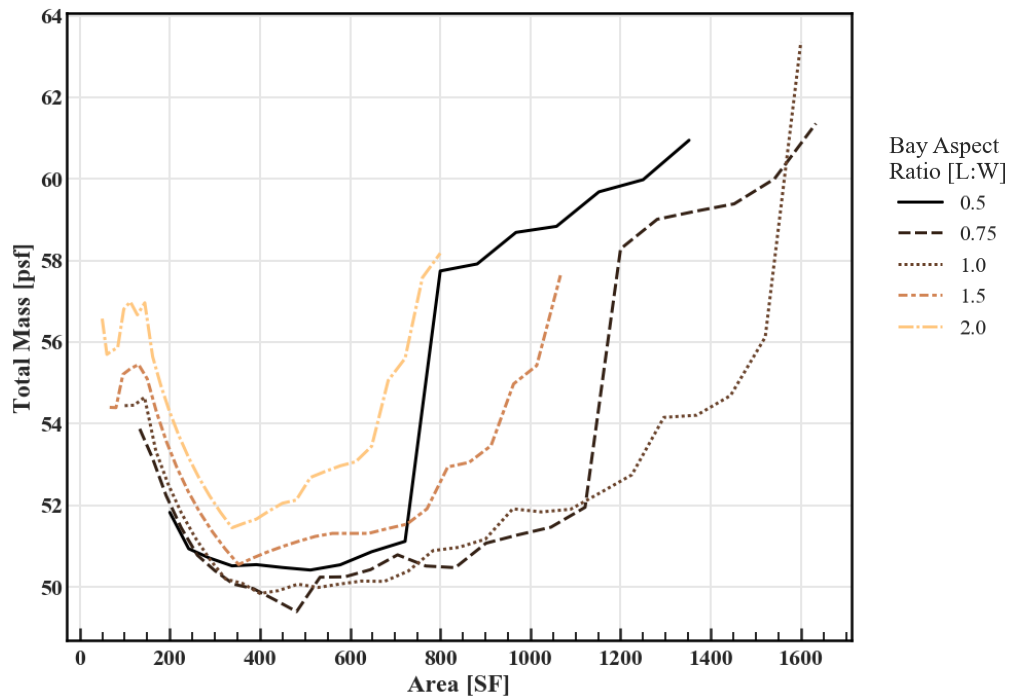


Figure B-16: Enlarged mass plot for Protected TGb System with 75% SST and 1 infill beam

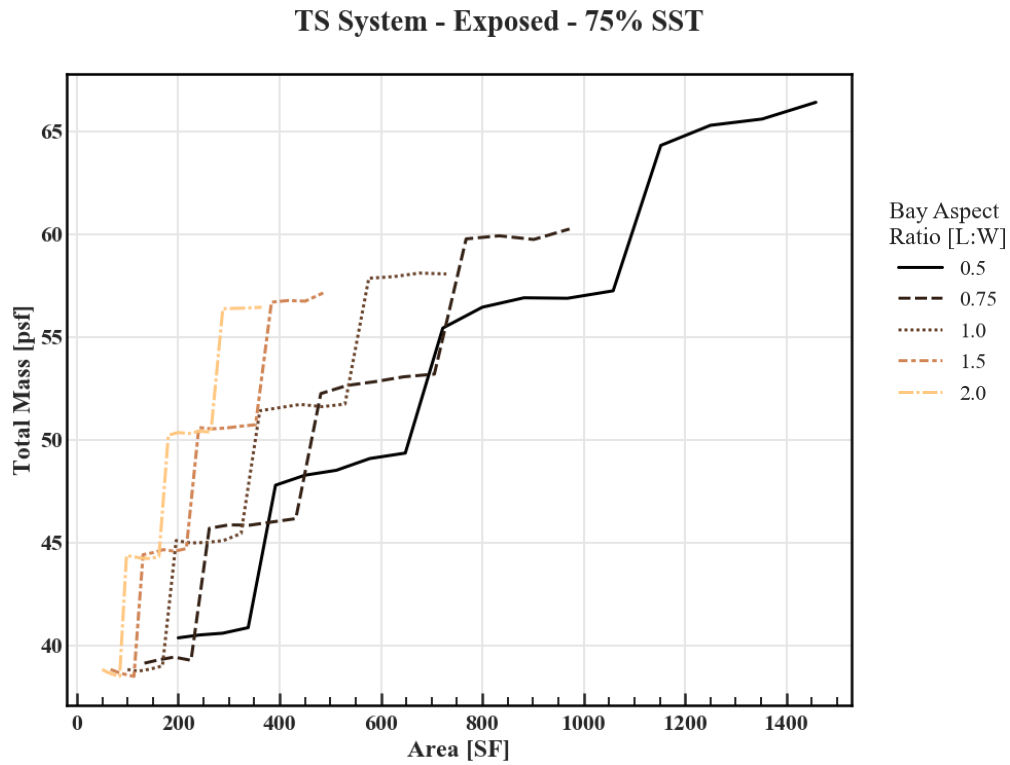


Figure B-17: Enlarged mass plot for Exposed TS System with 75% SST

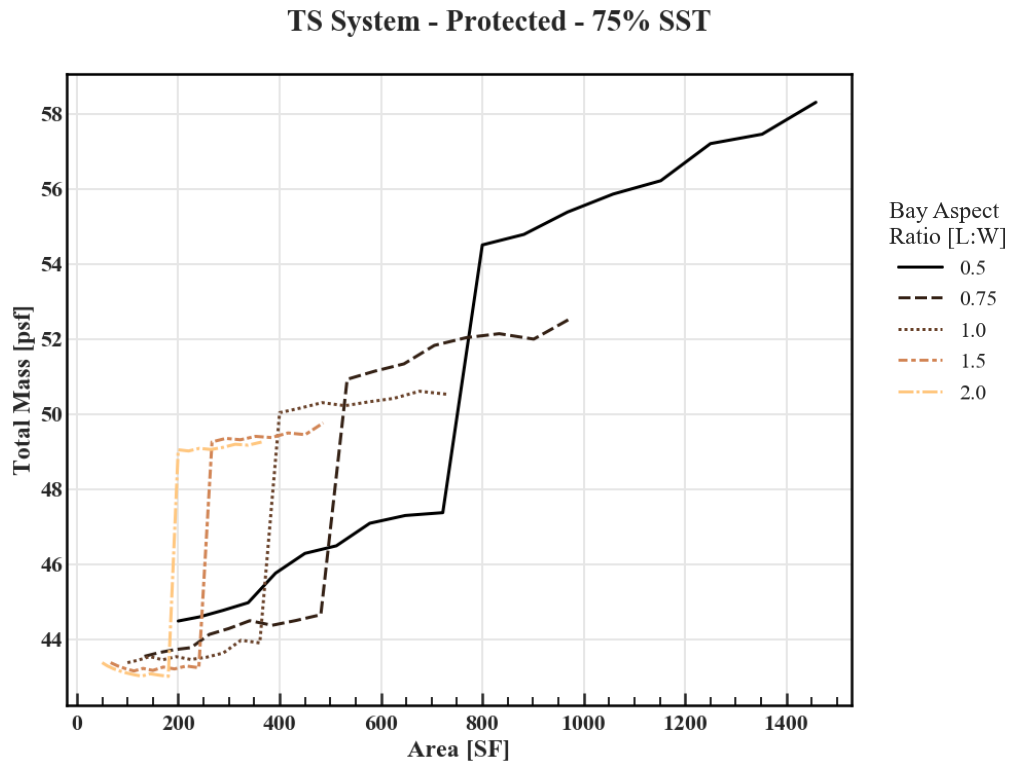


Figure B-18: Enlarged mass plot for Protected TS System with 75% SST

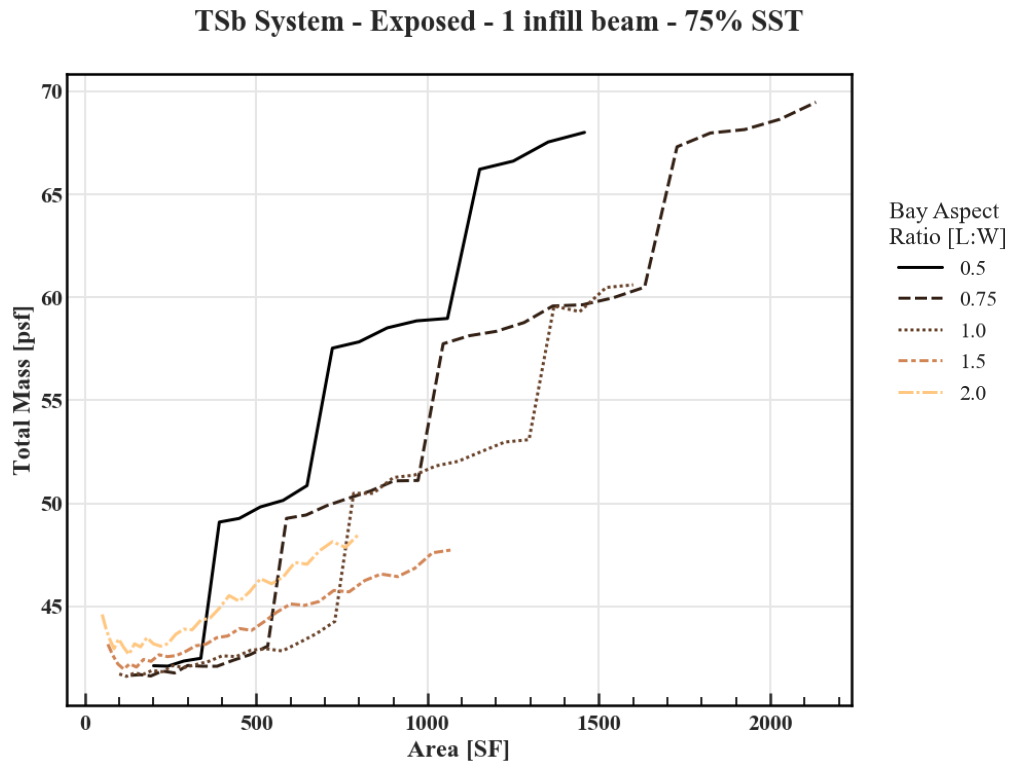


Figure B-19: Enlarged mass plot for Exposed TSb System with 75% SST and 1 infill beam

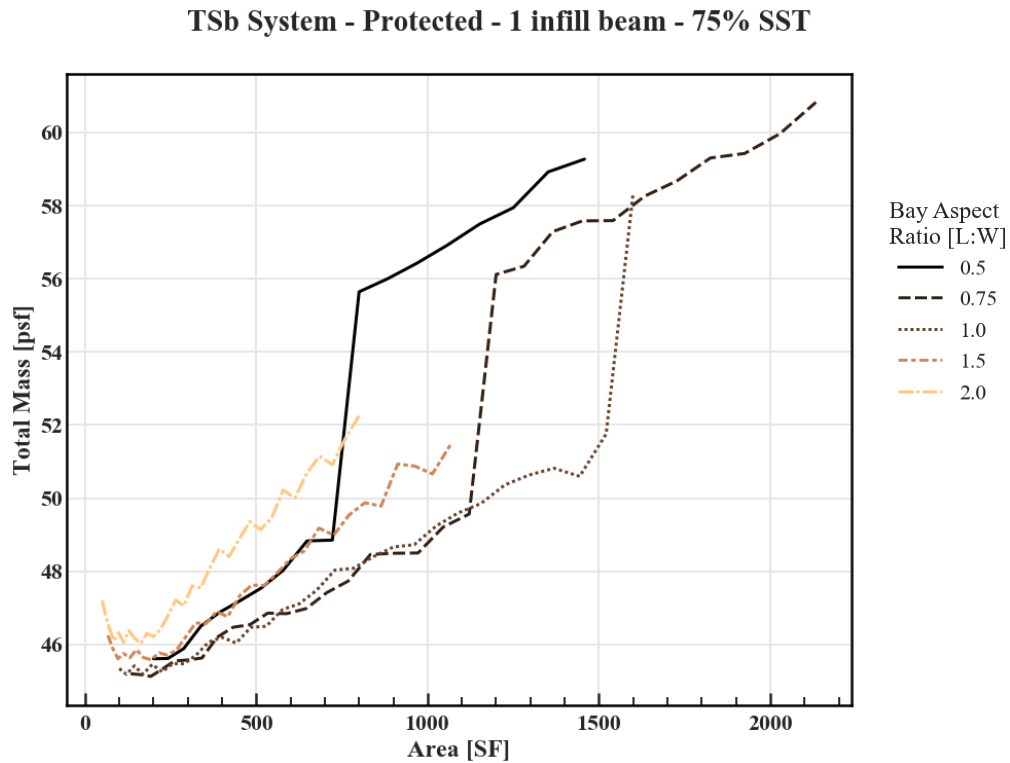


Figure B-20: Enlarged mass plot for Protected TSb System with 75% SST and 1 infill beam

B.3 Embodied Carbon

TCC System - Exposed - 75% SST

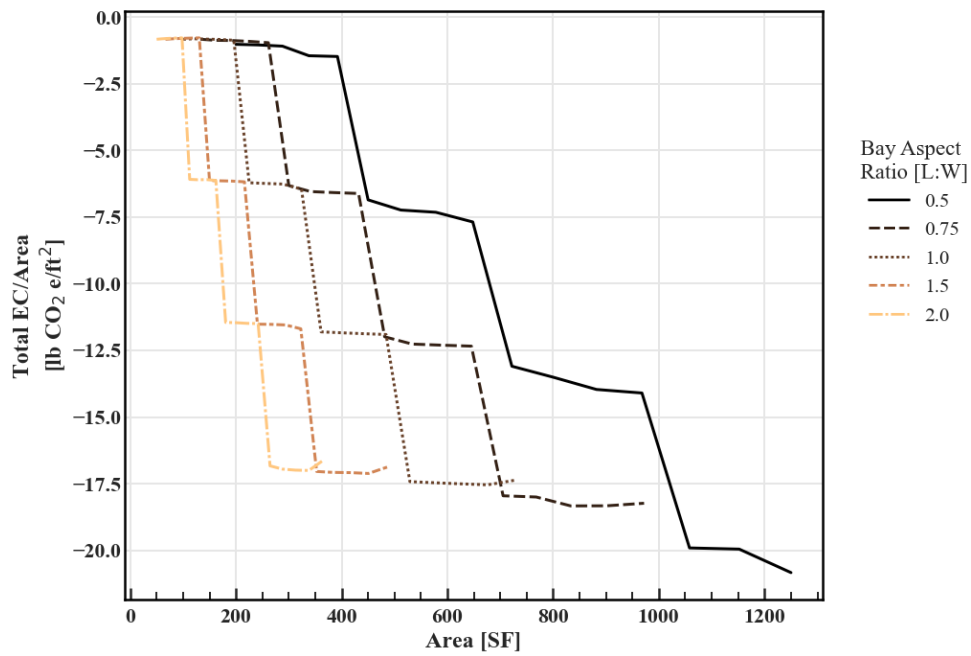


Figure B-21: Enlarged EC plot for Exposed TCC System with 75% SST

TCC System - Protected - 75% SST

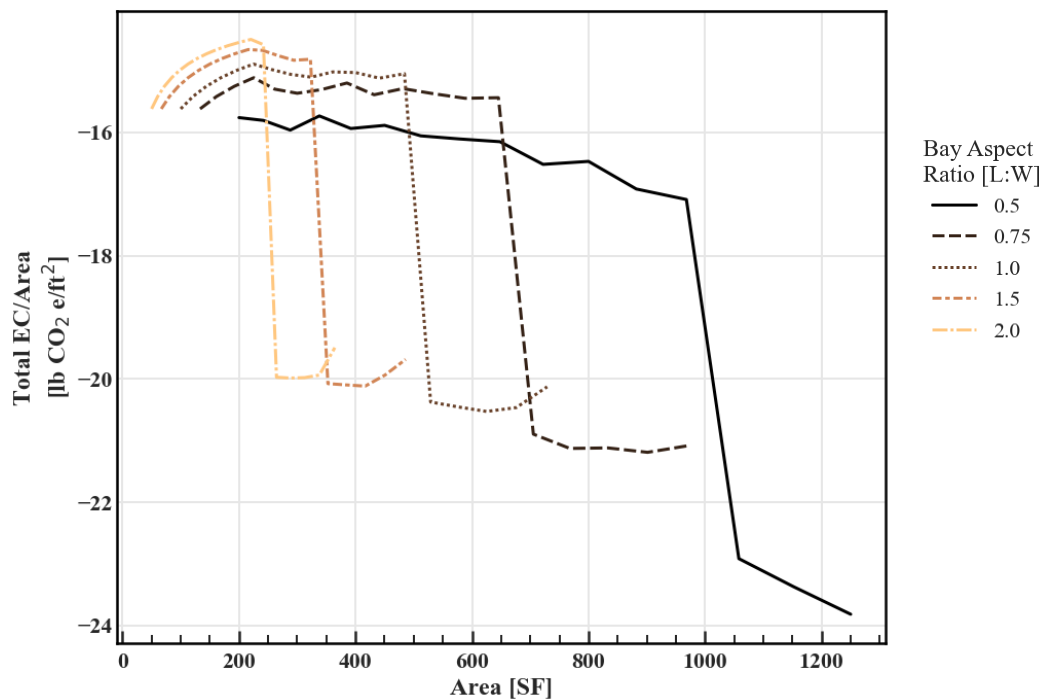


Figure B-22: Enlarged EC plot for Protected TCC System with 75% SST

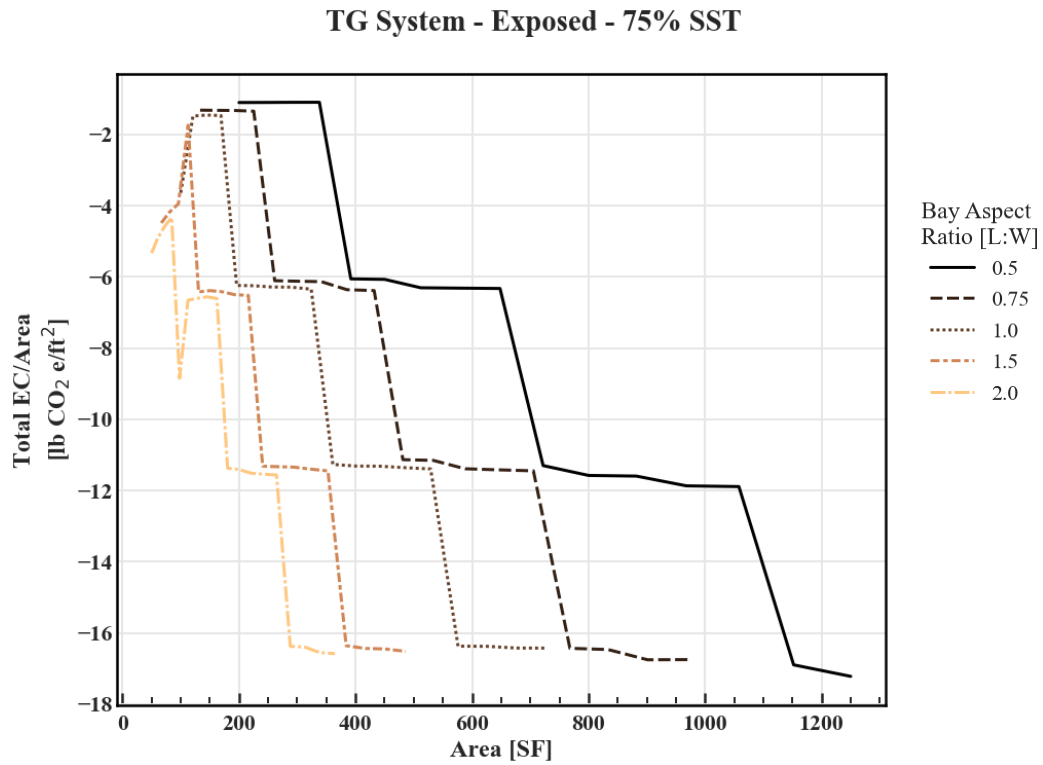


Figure B-23: Enlarged EC plot for Exposed TG System with 75% SST

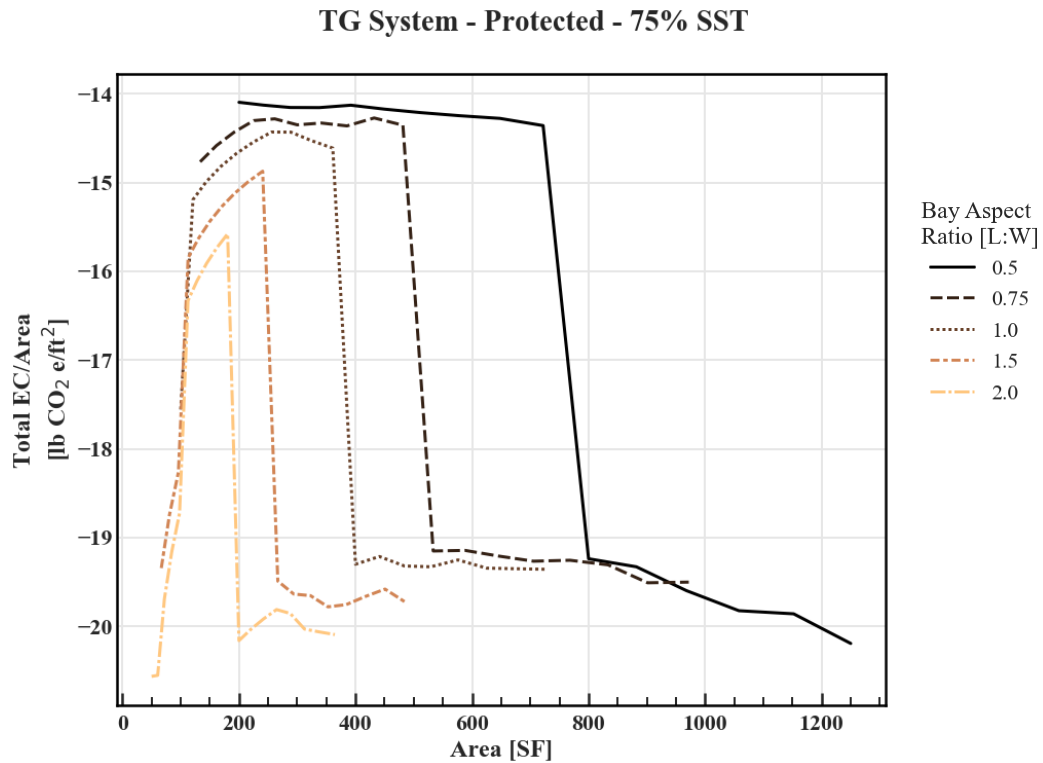


Figure B-24: Enlarged EC plot for Protected TG System with 75% SST

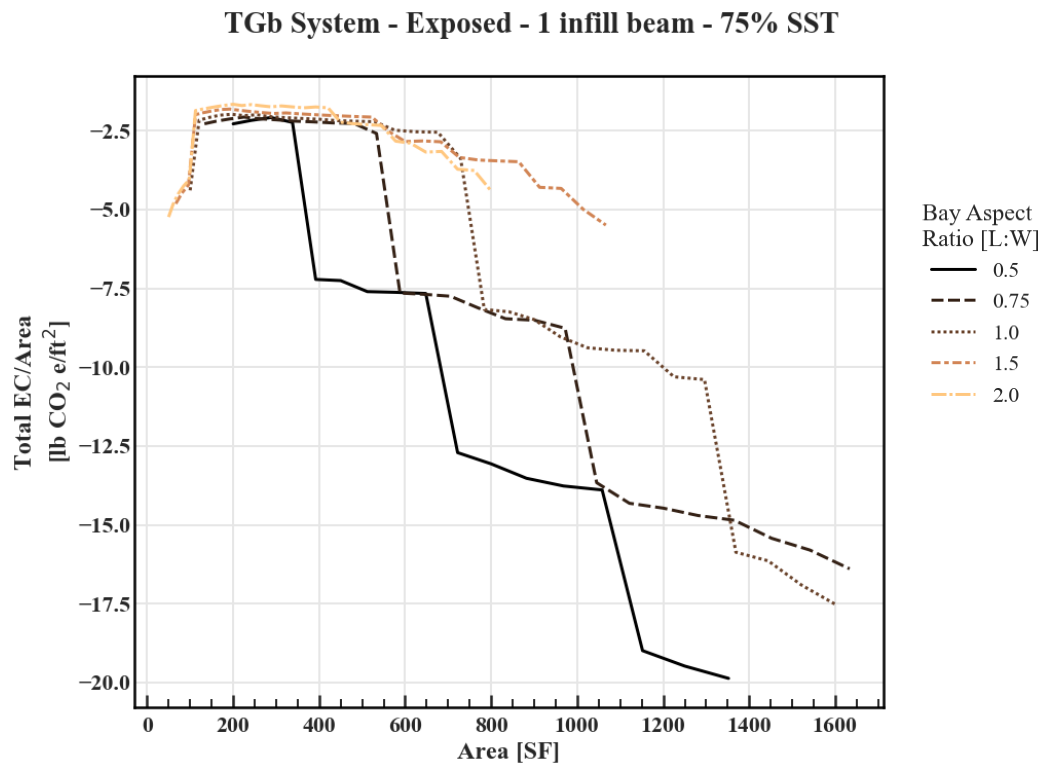


Figure B-25: Enlarged EC plot for Exposed TGb System with 75% SST and 1 infill beam

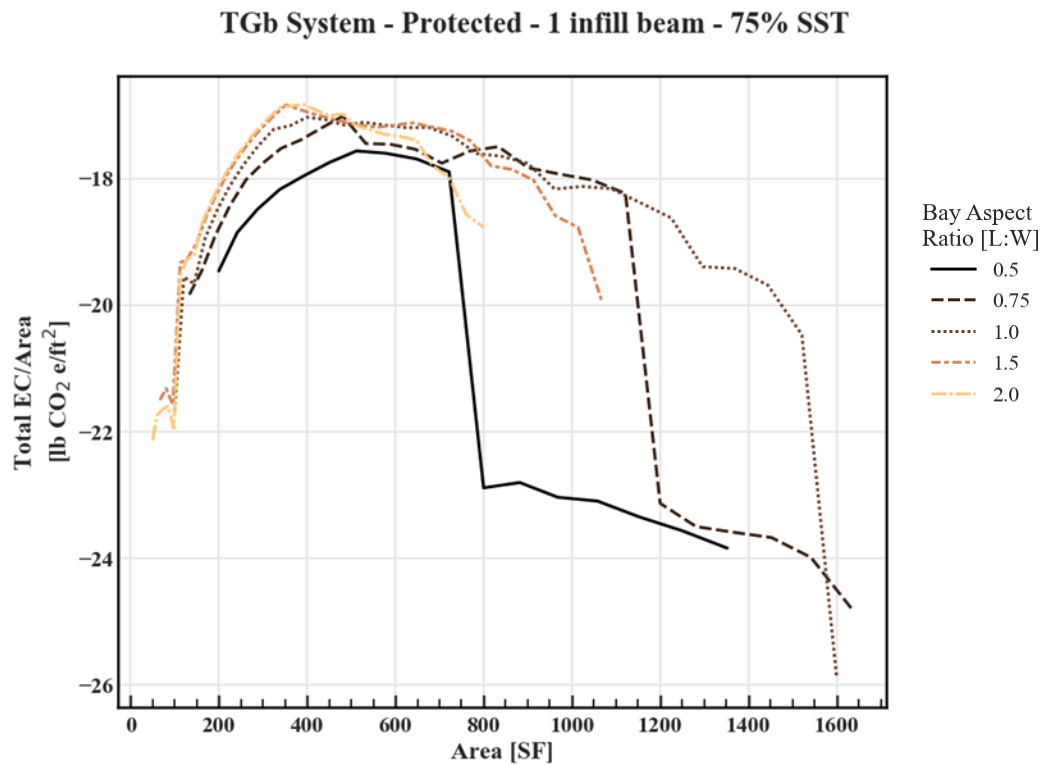


Figure B-26: Enlarged EC plot for Protected TGb System with 75% SST and 1 infill beam

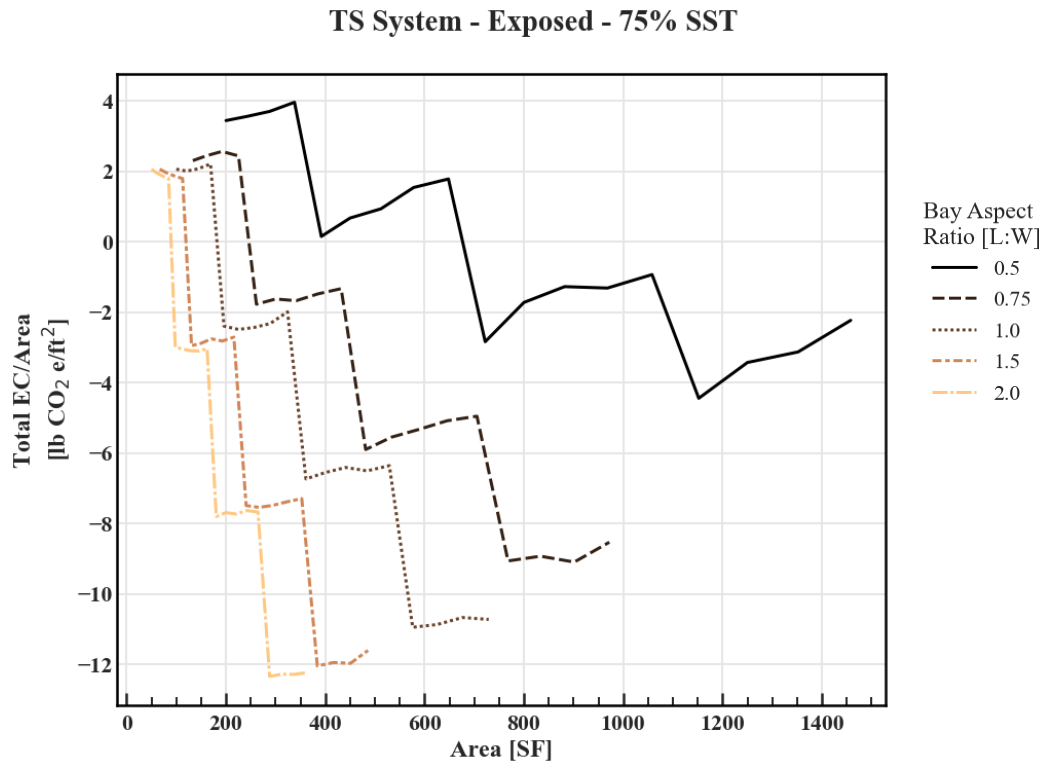


Figure B-27: Enlarged EC plot for Exposed TS System with 75% SST

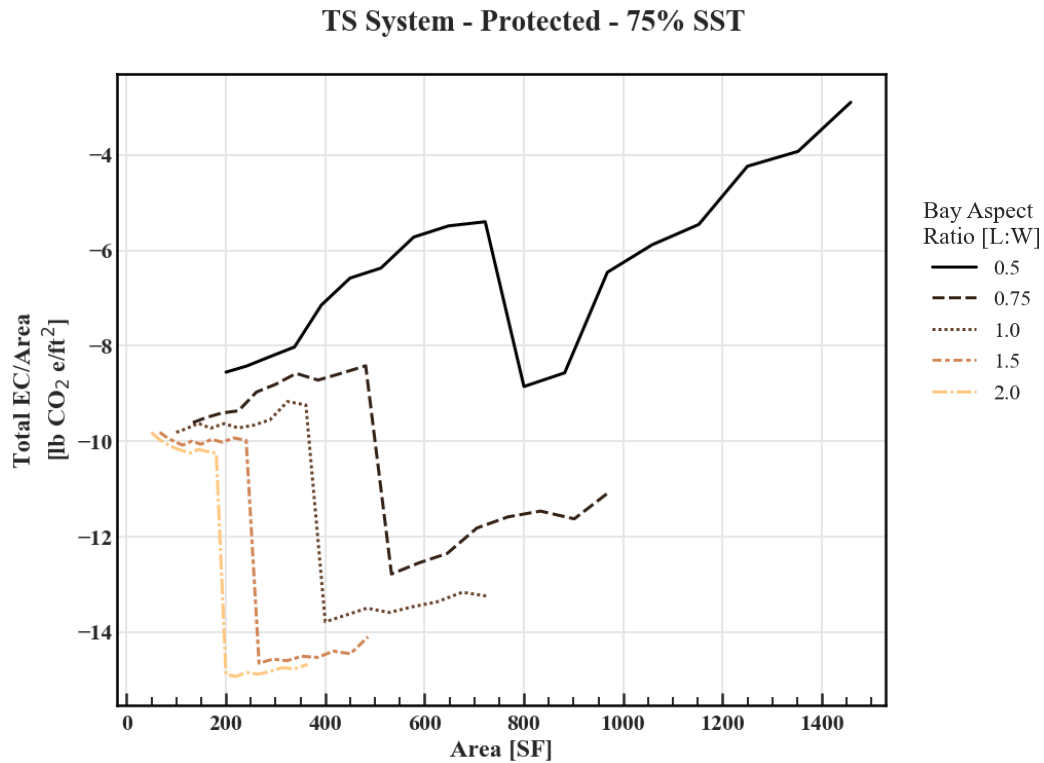


Figure B-28: Enlarged EC plot for Protected TS System with 75% SST

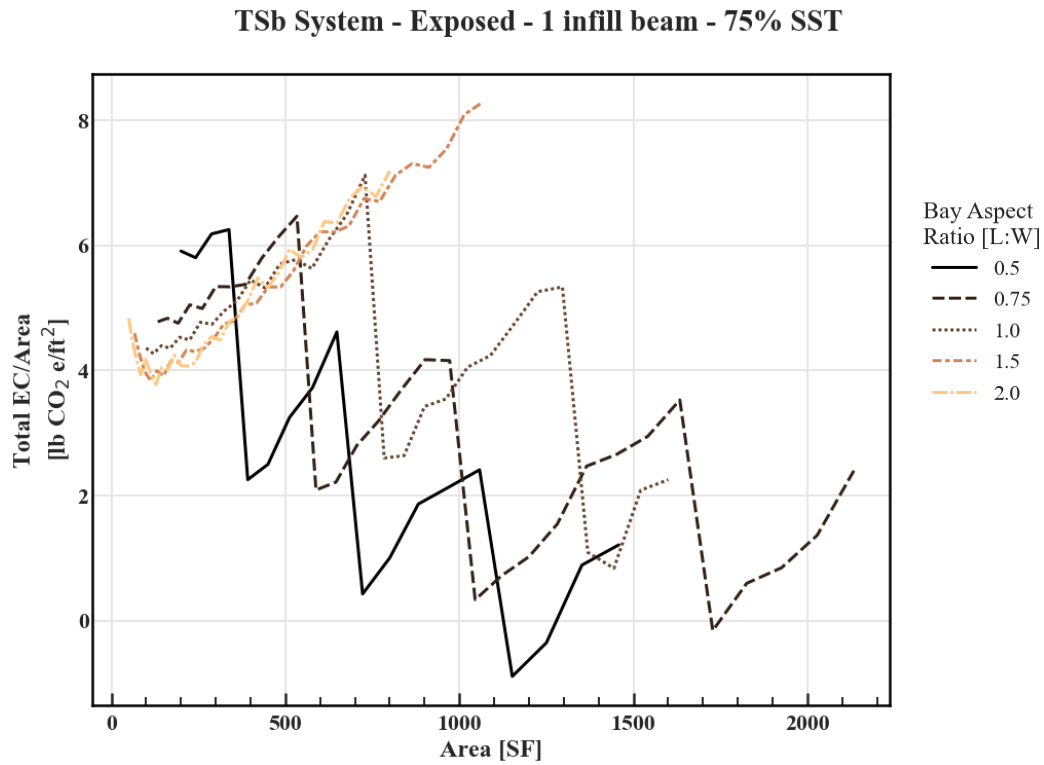


Figure B-29: Enlarged EC plot for Exposed TSb System with 75% SST and 1 infill beam

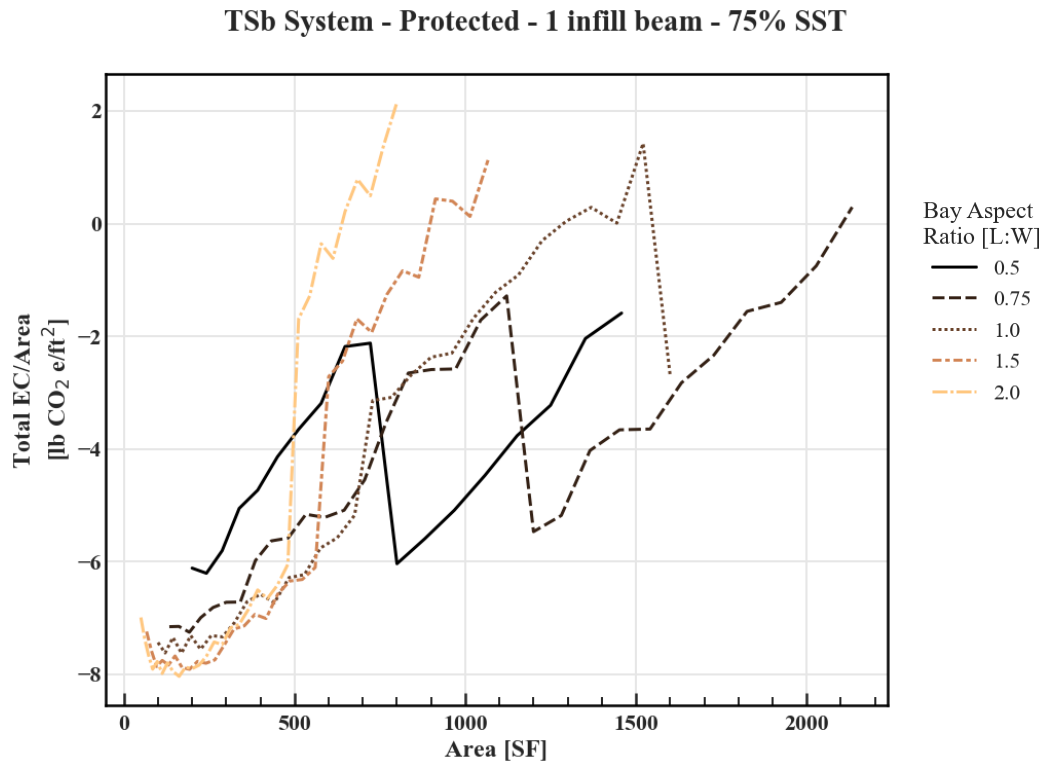


Figure B-30: Enlarged EC plot for Protected TSb System with 75% SST and 1 infill beam

VITA

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Education

- Ph.D. Architectural Engineering, Penn State University 2023
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Research Experience

- Graduate Research Assistant, Penn State University, Department of Architectural Engineering 2019-2023

Teaching Experience

- Research Undergraduate student advising 2021-2023
- Senior Thesis Capstone Project consulting and advising 2020-2022
- Teaching Assistant for the AE 222 Course 2020-2022
- Structural Review for Arch 491 - Timber in the City, 2022

Industry Experience

- RDH Building Science, Remote Consultant (Project Engineer) 2019-Present
- RDH Building Science, Building Science Engineer (Seattle, WA) 2016-2019
- Simpson Gumpertz & Heger; Technical Intern (Washington, DC) 2015
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Publications

- Leonard, S., Solnosky, R., Brown, N.C., Gracie-Griffin, C.Z. (2022). “***Parametric Evaluation of Embodied Carbon within Design for Hybrid Mass Timber Floor Systems,***” PHRC 6th Residential Building Design & Construction Conference, May 2022, University Park, PA
- Leonard, S. and Solnosky, R. (2023). “***Guiding Mass Timber Design and Research: A Parametric Modeling Approach to Understanding Impacts,***” SEI Structures Congress, May 2023, New Orleans, LA.
- Leonard, S., Eddin, M., Prichard, M., Broyles, J., Menard, S., Brown, N.C. (2023). “***Trade-Offs Between Embodied Carbon And Acoustic Insulation For Mass Timber Floor Structures,***” World Conference on Timber Engineering, June 2023, Oslo, Norway.