MECHANIZING RAMMED EARTH:

MAKING NEW EARTH CONSTRUCTION VIABLE IN THE US

A Thesis in
Architecture
by
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Abstract

Rammed earth and stabilized rammed earth, two common forms of earth construction, are readily accessible techniques with long histories of use as building methods in many parts of the world. Despite this global commonplaceness, they are currently considered specialized and/or antiquated forms of construction in the United States (US). While mechanization and industrialization have significantly enhanced other materials and methods commonly used in building construction, modern forms of rammed earth and stabilized rammed earth used in the US still employ traditional labor intensive construction processes, and simple tools. Although contemporary technology has been applied in refining the earth material mix and toward creating better understanding of the material behavior and the ramming tools themselves, it has not been brought to bear on the rammed earth construction process. In response to this technological stasis, this thesis imagines the mechanization of rammed earth construction processes through industrial potentials that range from a hand-cranked gravity ram to automated robotic labor enhancement. Three distinct machines – Monument, Mass, and Needle – were designed and are presented as means to advance earth as an US building material through mechanization/industrialization, with the ultimate goal of re-inserting it into the portfolio of contemporary US building methods. This thesis primarily focuses on rammed earth construction methods, not on public perceptions of rammed earth in the US. The machines are also an exploration of mechanized earth’s new and/or resultant architectural potentials and possibilities.

Note: Henceforth the term “rammed earth” will refer to both rammed earth and stabilized rammed earth unless indicated with (RE) or (SRE) respectively.
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Chapter 1. Introduction

1.0.0 Rammed Earth in the US

Rammed earth in the continental US is largely treated as a niche material/building method – one that has not been fully taken advantage of as a construction material, or for its architectural potential. Internationally, earth-building is an ancient, vernacular construction method and building material that continues to be used and explored in the construction of homes, schools, health clinics and more. Within the US, rammed earth is a relatively young building method that is commonly considered to be archaic and unsuitable for construction in the majority of the US climate zones. Earth construction is also restricted and prejudiced by US building economics, the construction industry, trades, code requirements, economic stratification, and other stereotypes.

The current method of rammed earth construction in the US still employs the traditional manner of building (frame, fill, ram – repeat), introduced in 1806 with the publication of Rural Economy by Stephen W. Johnson\(^1\), and has yet to go through a process of evolving through industrialization, as have many of the building methods/materials in common use. As a material, rammed earth has been and is currently being analyzed for its applicability across the different climate and geographical regions that comprise our built environment. By employing different locally-sourced compositions of earth, combined with the stabilizing effects of rebar and concrete additives, rammed earth has great architectural potential and a wide range of applications. Once compacted, the material essentially acts like a manmade sedimentary rock, with a compressive strength that ranges between 145 psi and 1,015 psi\(^2\). Although the material mix and behavior of rammed earth as a building material has been studied and refined (see the
work of Deb Dulal Tripura\(^3\), P. A. Jaquin\(^4\), David Easton\(^5\), Peter Walker\(^6\), etc.), there has been little focus on evolving the building process.

In an environment of construction technologies development circa 2016, common building materials such as wood, brick, masonry, and concrete – along with their associated tools and processing – are quickly-evolving semi-automated and fully-automated potentials in a post-industrial phase of invention and advancement. Recent work in applying robotics to the building of steel bridges by MX3D\(^7\) and the use of a 3D printer to create walls/houses by Yingchuang New Materials\(^8\) are two of the many indicators of where the construction world is heading. On the other, more-primitive end of the technology spectrum, sit the tools and processes associated with rammed earth construction in the US. While these tools and methods remain “true” to a traditional/authentic manner of rammed earth construction (which does have a DIY value), they cannot meet modern demands for mass building in the US, demands largely governed by efficiency, economy and delivered by ever-evolving technologies. The high level of skilled labor requirements associated with traditional rammed earth building and the high cost of formwork (design, materials and assembly) associated with the traditional approach results in construction expenses that are prohibitively high – despite the economic accessibility of the raw material which is local in the extreme. In addition to facilitating greater accessibility financially, the mechanization of rammed earth construction processes could yield a new perspective into the applicability and aesthetics of rammed earth as a contemporary building material. Introducing elements of the machine into the construction of rammed earth architecture would also allow a critical acceleration of the process of building – an acceleration
that introduces new potentials/improvements in the realms of construction safety, production quality, and an easing of environmental impact.

In this thesis, three distinctly different forms of mechanized rammed earth are represented and explored though the development of three machines – Monument, Mass, and Needle. Each machine was intentionally developed to represent a specific point on a speculative timeline of mechanical/industrial invention and development, with the qualities and resultant architectures of one machine subsequently informing the development and processes explored in the next. These machines were primarily developed to explore how rammed earth could be mechanized, and are not yet market-ready as tools or systems. Their value, at the moment, is conceptual and/or academic. As is the case with all mechanical development, a complete/mature/sophisticated machine design requires multiple iterations, use followed by responsive improvements, and a prolonged period of continuous invention. These three machines are all at their beginnings, and so currently live in the prototype stage. At the time of this writing, two machines, Monument and Mass, have been fabricated at full-scale and were tested in rammed earth construction. The third machine, Needle, has gone though one iteration and moved back into digital representation and design.

1.1.0 Thesis Statement

How can mechanization make rammed earth more accessible, reinvent the architecture of rammed earth, and redefine public expectations associated with the material?
1.2.0 Background

1.2.1 Earth, a Singular Building Material

“Moreover, are there not in Africa and Spain walls made of earth that are called rammed walls, because they are made by packing in a frame enclosed between two boards, on each side, and so are stuffed in rather than built, and do they not last for ages, undamaged by rain, wind and fire, and stronger than any quarry-stone?”

- Pliny the Elder³

There are two potential assessments to be made of earth as a building material; one is through numerical data related to material “performance”, the other governed by what is physically achievable – what can be built with earth. As building material, earth that is rammed is fairly unique in the realm of US construction, as it does not necessarily require transport from a factory/store/mill to the building site; nor does it generate large amounts of waste as a construction progresses. Once rammed, earth inherently has many of the qualities that must be designed (and budgeted) into modern buildings

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as applied (mechanical) systems, e.g., longevity, renewability, thermal performance, fire-resistance, etc., (Figure 1).

In basic terms, rammed earth is essentially a three-step process: dig, mix, and compress. First, earth is dug out of the ground from the B horizon and tested for appropriate ratios of silt, sand and clay (Figure 2). This earth mixture can be modified with additional sand, silt or clay if the native material is not optimally balanced. Once a viable source of earth is located, the earth is excavated, screened and then mixed with minimal amounts of water. Additives, such as cement, dye (liquid or powdered), and other aggregates or other types of earth, are incorporated as specified/desired. This final mixture is then stockpiled on site and is ready for the compression process. In compression, loose earth mix is loaded into constructed formwork and compressed with the expectation that the earth material must be rammed to half of its loose volume in the formwork.

*Figure 2: Soil Horizons and Triangle*
Rammed earth is an onsite construction process. Each wall or construction is unique to its location, and in its creation. Material mixtures and formwork can be easily adapted or fabricated to design specifications. As a construction system with natural, rather than a processed material base, rammed earth’s inherent qualities include moisture and air transmission – the material will “breathe”, unlike a glass façade or a conventionally built US stick wall. The resulting architectural whole is one that will age with, and adapt to, the environment, instead of one that is aged and deteriorated by the environment.

There is an inherently poetic quality to earth as a material. The best way to understand what rammed earth is materially, and how it behaves, is to work with it. An analogy for understanding earth as a building material would be to compare it to the behaviors of ice, stone and concrete. Like ice, earth is a material with characteristics that change depending on its form. Water in a solid state creates forms and spaces that shape the surroundings and provides iconic landmarks – consider the Norwegian fiords and Glacier Bay National Park. As a liquid, water is a surface upon which we can build or “cut” through - consider surf breaks and piers. When pressure and temperature are changed, water becomes a solid that can be used as a construction material – consider ice blocks used to construct igloos. When earth is put under pressure, particles are compacted and the spaces between them become smaller and smaller until the material becomes almost stone-like (e.g., bedrock). As with stone, earth can become a monolithic material. Compacted earth, like stone, is heavy and slow to change with the passage of time. Depending on the content of the earth mix and additives, it can have
varying hardmesses, analogous to the varying compressive strengths exhibited by different types of building stone. Like concrete, earth is a material that can be controlled to respond to a variety of sites and desired forms. The dry, clay-like malleability of the earth mix allows for the construction of building forms that may be curved or linear as determined by the designer/builder. As mass-materials subject to gravity, concrete and earth do not want to become vertical materials. Before they are put into the formwork, both materials follow the path of least resistance, spreading horizontally. Once placed into formwork, both concrete and earth are given a defined form that will resist impacts, wind, water, and loads.

1.2.2 Historical Use of Earth as a Building Material

Historically, as a material, earth has been used in an adobe format in the US. There are several sites of preserved earth building such as the Mesa Verde National Park in Colorado and the Casa Grande Ruins National Monument in Arizona. The Mesa Verde National Park contains 600 cliff dwellings and 4,700 archeological sites dating from 600 CE to 1300 CE.11 Constructed by the ancestral Puebloans many of these structures were built with either the local stone or in a pit-style, where the lower half of the structure is dug down into/carved out of the ground. The Casa Grande Ruins are a collection of structures from 900 CE12 constructed by the Hohokam. Most notable of these ruins is the Casa Grande itself (Figure 3) a four story
structure that has walls approximately four feet thick at the ground level. Adobe techniques have continued to evolve since these early uses and have a strong presence as a building material in the Southwest US.

1.2.3 Earth and Architecture

Previous sections of this document have established that earth has, for the most part, been ignored by North American architects (certainly those with formal training) and builders as a construction material. Although built on and into, earth has been typically considered as the site, rather than as potential architecture. US engineers are aware of earth’s structural properties – what loads can be supported, behavioral characteristics, etc. However, the engineer’s focus is primarily on how earth behaves in resistance to what is built above or into it as a site– not as a building material in and of itself. Compounding the ignorance surrounding earth construction is the fact that a vast majority of contemporary US architects are not aware of earth as a viable building material. They perceive earth as an old material, one associated with poverty. There are also common misperceptions among architects that earth requires specialized knowledge and has a limited application range.

1.3.0 Thesis Language and Definitions

Earth: “Soils laid down in discrete horizons [...] whose compositions vary over time and space.”

– Pat Megonigal

Rammed Earth (RE): An earth construction method in which a mixture of earth, sand, clay, and water is tamped directly into wall formwork. Cement and other additives may be added
to the mix to increase compressive strength and water resistance. There little to no organic matter in the earth that is used.

Stabilized Rammed Earth (SRE): Rammed earth that has had 8-10 percent of cement added to the mixture. It can also have rebar added during the construction process.

Concrete: A liquid mixture of sand, cement, water and gravel/stone that can be poured into formwork.

Adobe: A mixture of water, earth and organic matter such as straw or small sticks that is cured with the heat of the sun.

Formwork: The temporary molds into which the earth mix is poured during rammed earth construction. The formwork must be supported with lateral bracing in order to resist the outward force from tamping.

Skill: 1. Capability of accomplishing something with precision and certainty; practical knowledge in combination with ability; cleverness, expertness.: Also, an ability to perform a function, acquired or learnt with practice. – Oxford English Dictionary

2. An art or science. – Oxford English Dictionary

Tool: ‘Any instrument of manual operation’ (Johnson); a mechanical implement for working upon something, as by cutting, striking, rubbing, or other process, in any manual art or industry; usually, one held in and operated directly by the hand (or fixed in position, as in a lathe), but also including certain simple machines, as the lathe; sometimes extended to simple instruments of other kinds, as in quote n. – Oxford English Dictionary

Machine: 1. An apparatus constructed to perform a task or for some other purpose; also in derived senses.
2. A complex device, consisting of a number of interrelated parts, each having a definite function, together applying, using, or generating mechanical or (later) electrical power to perform a certain kind of work (often specified by a preceding verbal noun). – Oxford English Dictionary

Mechanization: The action or process of mechanizing something. – Oxford English Dictionary

1.4.0 Thesis Breakdown: Questions Investigated

1. Could mechanization/mechanical enhancements to the process of rammed earth construction make rammed earth more viable in the US housing market?

2. What architectural forms/typologies can earth construction take to become more accepted in the US?

3. How will mechanization affect traditional rammed earth building practices and resultant forms?

1.5.0 Rammed Earth in 2016

As a process, method and material, rammed earth is one of the lesser known building systems in the US. Commercially, the processes of rammed earth construction in the US remain rooted in the early 1800s, when it was first widely introduced as a building material to the American public. As a construction method, it has not technologically evolved with other building forms (e.g. wood, brick, glass, concrete, etc.), from a tool-based methodology to a mechanized one. As a material, earth has a low/no price tag, as there are not specific, specialized sources from which the material must be obtained. The high costs associated with rammed earth in the US arise from the costs of labor, formwork, and building approval.
procedures needed for rammed earth construction. When rammed earth is used in the US, it typically takes on architectural forms characteristic of other materials, and it is held to code for concrete, which, as a material and structure does not behave in the same manner as earth. While earth as a material and process in other countries carries a great degree of accessibility and acceptance, in the US it is a highly labor-intensive and expensive process often used as a novelty, or for wealthy clients. Mechanizing the process has the potential to lower the cost, and to optimize the process of rammed earth construction. As a result of mechanization, the architectural forms of earthen structures may change, with new configurations that have the potential to revitalize public expectations of rammed earth. Mechanization has the potential to expand rammed earth beyond the extremes of very low end and very high end housing markets, making earth construction more available to the mainstream building industry and potential home owners.
Chapter 2. Building Earth Walls

2.0.0 US Earth Building Culture

Where and how earth construction is used depends on the building culture in a given location. Depending on geographic location, the process of earth construction can range from communal and ritualized (dance-like) to industrialized. In the US there are two processes of rammed earth construction. On one end of the spectrum is deeply rooted in the DIY industry where the relationships between individuals and the community are key elements of construction. The other end of the spectrum is a highly commercial product where the earth and workers are imported to the site and there is a lack of formalized ritual between community and construction. Most of the communal rituals once associated with building construction have faded away from the US culture or have been stripped out by the high demands of the US construction economics.

Within economically-driven rammed earth construction, the ritual of preparation of the earth, a set order of the construction process and a resultant physically layered map of the building rhythm has not been entirely lost. There is also a greater level of knowledge and skill needed for the process of earth construction, because the builder must analyze the raw ingredients and compose them in a particular manner, so as to create a site-specific, individual result. This is very different from the construction of a glass curtain wall, where the final product can be matched to the specifications that were drawn out before the construction, built remotely from the site and overall building process, and then shipped to the site in units. Certainly, to some degree, specifications are also possible for rammed earth construction, yet there are always the unique elements of site and material that modify original specifications.
The nature of the material, whose tones and textures are dependent on the soils of the region, allows earth to be a reflection of the people and the landscape in which it is made. The builder’s skill brings an originality to rammed earth construction.

2.1.0 Construction and Character of Earth Walls vs. Conventional Walls

“There is an obscure allegorical tale from the 19th century in which an architectural dispute between a trio of diminutive swine and a large, mean wolf shows brick to be preferable to straw or sticks when constructing a protective shelter. My how times have changed. [...] Nearly forgotten - but by no means gone - [rammed earth is] a form of construction as ancient as dirt itself.”

- Dean, Jason

The characteristics and construction of earth walls (mass, length and appearance) are different from conventional walls built in common US housing. A typical residential wall in the US is either stick framing (3.5”) or CMU (8”) – relatively light materials – that, when assembled in a wall, are essentially compositions of one joint multiplied over the surface. Unlike the solid one-unit integrity of a rammed earth wall, one inaccurate joint can compromise the stability of the wall. These wall systems’ internal structures are assembled with factory manufactured units (2 x 4 boards) then clad with factory manufactured materials/systems to the specifications of a drawn wall section. As these walls are an assembly of variably manufactured parts, there are pre-established material proportions that must be modified on site during construction, yielding large amounts of waste.

In contrast, earth is a particulate-based, locally-sourced material assembled onsite in the exact position of a building’s excavation. Consequently, earth construction changes the
conventional rules of wall characteristics and construction. The mass of rammed earth walls, made additively by accumulating particulate materials into a whole, reduces complexity of materials, construction techniques, and also radically limits generation of poorly recyclable, construction waste. Rammed earth construction still retains the aesthetically-desirable complexity of a façade design with the design being controlled by lifts, reveals, formwork and placement of earth. Wall length is not confined by a factory preset material module when working with earth. For example, the Great Wall of WA by Luigi Rosselli Architects, embraces this quality with a 230 meter²² (~754 foot) rammed earth wall that is central to the design. Locally-sourced earth for construction enhances the structure as a unique reflection of place that may not be apparent in a structure made with factory-sourced materials. The aesthetic of place is built into the wall and into the architecture as a whole, with the use of rammed earth.

2.2.0 Coding Rammed Earth

Rammed earth building plans must go through approvals, as is typical of all forms of construction, and this is problematic in the US. In the US, only New Mexico’s Title 14; Chapter 7, part 4 – 2009 New Mexico Earth Building Materials Code, has building code specifically written for rammed earth²³. In all of the other forty-nine states, a rammed earth building must meet the standards set forth in a state’s concrete building codes²⁴. If the intended rammed earth building is to be built in an area without traditions of rammed earth use, the number of compromises (e.g. reinforcing, sealing the walls, and amount of concrete in the earth building mix) that must be implemented for approval increases.

In terms of compressive strength, bending, buckling, shear and torsion, it should be obvious that rammed earth does not structurally behave in the same manner as cast-in-place
concrete. The strength of a rammed earth wall without rebar is dependent on the mixture of earth, the level of compaction, and compaction consistency. Papers published at the University of Bath in England\textsuperscript{25}, by Daniela Ciancio\textsuperscript{26}, and by Bly Windstorm\textsuperscript{27} discuss the behavior of rammed earth. From the data presented in the afore-mentioned authors’ papers, it is clear that judging how an earth wall behaves based on cast-in-place concrete specifications does not present an accurate measure of an earth wall’s strength.

A key element to establishing a base level of standardization of rammed earth is having a regulated, uniform compaction to each lift of earth during construction. Regulated compaction would ensure a compressive strength that, although variable depending on the soil used, would establish a framework for measurement of the strength of the wall. Further testing would yield site-specific a standard to which the rammed earth wall must meet for code. Regulated, uniform compaction during earth construction can only reasonably be achieved using mechanized techniques.

2.3.0 Frozen Method and Practice of Rammed Earth in the US

Unlike other building materials/methods that have gone through a process of industrialization, rammed earth in the US is “frozen” as a tool-based, labor-intensive means of building. Summary of rammed earth publications and events shows that there have been three periods of interest in rammed earth – the 1840s-60s, 1920s-early 40s, and 1970s-90s (Figure 4).

In examination of Figure 4, a comparison of the major events in the history of commercial US rammed earth and changes made in the construction process, it becomes evident that rammed earth has not gone through a period of significant industrialization/mechanization and remains localized in use (Figure 5). Interest in the US has
been confined within the DIY potential of rammed earth as a construction method, cost of materials, and aesthetic properties of the resultant architecture.

Based on recent rammed earth works that have been completed by firms such as DUST, Rick Joy and Rammed Earth Works, it appears that the US is entering into a fourth stage of interest in rammed earth. There has also been interest in the US in an international rammed earth project – The Great Wall of WA by Luigi Rosselli, which was one of the top twenty most popular projects of 2015 on the Arch Daily website (www.archdaily.com). This renewed interest provides an opportunity for industrialization/mechanization of rammed earth construction. The military sector of the US is also interested in earth, specifically earth bag, structures that shield those that occupy outposts and fortifications from bomb, bullet and shrapnel damage.
Figure 4: History of Rammed Earth Use in the US Aligned with Changes to the Process of Construction

- **1806**: Rural Economy
  - Written by Stephen W. Johnson
  - First US publication on earth construction

- **1810**: Industrial Revolution

- **1820**: Basic (primitive) rammed earth tools and methods in practice

- **1849**: Church of the Holy Cross
  - Built by William Anderson
  - South Carolina

- **1856**: The Economic Cottage Builder
  - Written by Charles Dwyer
  - Rammed earth is mentioned

- **1869**: The Manufacturer and Builder
  - Journal in which articles on rammed earth are published

- **1870**
- **1880**
- **1890**
US patent: US001530137 “Pneumatic Tamper” approved
File by Samuel Oldham, 1920 Pennsylvania
a portable, one operator, pneumatic tamper

Note: use of rammed earth during the Great Depression leaves lasting impression as a “last resort” building material of the poor/destitute

“Farmers Bulletin No. 1500 - Rammed Earth Walls for Buildings”
Published by USDA as an alternative low cost building method for homes

Gardendale Homestead
Architect/engineer Thomas Hibben
Government funded
Alabama
seven homes and one barn built

Revised “Farmers Bulletin No. 1500 - Rammed Earth Walls for Buildings”
Published by USDA

Cooperative Homesteads
Architect Frank Lloyd Wright
Michigan
drawn but never built

“Soil Cement”
Published by UN
the invention and promotion of SRE

Architecture for the Poor
Written by Hassan Fathy
(Figure 4 continued)

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1978</td>
<td>Rammed Earth Works&lt;br&gt;Founded by David Easton&lt;br&gt;California&lt;br&gt;first modern rammed earth construction firm in the US</td>
</tr>
<tr>
<td>1980</td>
<td>Rammed Earth Solar Homes Inc&lt;br&gt;established&lt;br&gt;Arizona&lt;br&gt;rammed earth builder</td>
</tr>
<tr>
<td>1980s</td>
<td>PISE&lt;br&gt;Developed by David Easton&lt;br&gt;cousin of RE where earth is shot against the formwork</td>
</tr>
<tr>
<td>1990</td>
<td>The Construction Zone, SIREWALL, &amp; Rammed Earth Builders&lt;br&gt;established&lt;br&gt;Arizona, Canada, &amp; California&lt;br&gt;rammed earth builder</td>
</tr>
<tr>
<td>1992</td>
<td>Rick Joy Architects&lt;br&gt;established&lt;br&gt;Arizona&lt;br&gt;rammed earth architect</td>
</tr>
<tr>
<td>1993</td>
<td>Mechanization of earth mixing process&lt;br&gt;Increased control of earth mix quality</td>
</tr>
<tr>
<td>1996</td>
<td>Wendell Burnette Architects&lt;br&gt;established&lt;br&gt;Arizona&lt;br&gt;rammed earth architect</td>
</tr>
<tr>
<td>2000</td>
<td>DUST&lt;br&gt;established&lt;br&gt;Arizona&lt;br&gt;rammed earth architect and builder</td>
</tr>
<tr>
<td>2007</td>
<td>1 of 7 Gardendale houses put on Jefferson County Historical Register</td>
</tr>
<tr>
<td>2010</td>
<td>International Year of Soils&lt;br&gt;Perth, Australia&lt;br&gt;first international conference on rammed earth construction</td>
</tr>
<tr>
<td>2014</td>
<td></td>
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<tr>
<td>2015</td>
<td></td>
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<tr>
<td>2020</td>
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</table>
Figure 5: Areas of Rammed Earth Use in the US
Chapter 3. Program of a Rammed Earth Machine

Out of the many actions that machines can perform, the four that are most important to a rammed earth machine are:

1. the ability to adapt to site and circumstance
2. the ability to sculpt the earth
3. the ability to move throughout the site and along the foundation
4. the ability to compact earth (Figure 6)

This chapter addresses these four actions from the perspectives of scale, accessibility and transportation, compaction, and formwork requirements.

3.0.0 Increasing Scale

The current scale and methods of rammed earth building and dissemination of knowledge are not suitable for contemporary US building methodologies. As of 2016, rammed earth buildings require a large group of experienced builders to construct the walls, and all of the tools used in rammed earth construction, i.e., formwork and tampers (Figure 7), are scaled to the construction worker. The only machines in use on site are those used for moving and mixing earth. These machines are not specific to earth construction, rather, they are machines borrowed from the larger construction industry.

The labor involved in rammed earth construction is calorie intensive, very demanding on the body, and requires a certain degree of experience with rammed earth construction to ensure the proper amount of compaction. If the building being constructed requires a custom wall, there needs to be an experienced carpenter on the construction crew who can design and fabricate the necessary formwork. The ramming process involves a significant amount of risk
associated with working in the formwork with the tampers, and the increase in wall height as construction of the wall nears completion. Using a basic tamper, a builder’s shoulders, back, and arms are used to repeatedly lift and slam the tools down on the loose earth mixture into the formwork. When standing within the formwork, feet must be kept clear of the tamper’s path. Using a pneumatic tamper (one where the impact of the tamper is powered by pressurized air) produces a different kind of physical strain on the builder, in that the vibration from repeated impact travels through the worker’s hands, up the arms, and down through the shoulders to the lower back. The physical effect is similar to the use of a jackhammer, and hearing protection must be worn. Furthermore, the pneumatic tamper can only be used in intervals, as the air compressors needs to refill periodically. When looked at from the perspective of assembling a building crew, the cost of experienced workers and the physical strain on them harkens back to the 1920s where experienced, cheap labor was available, a condition not present in today’s industry. If rammed earth is to step into the current and future US construction industry along with other earth technologies, it needs machinery specific to rammed earth walls, as similar to those developed for compressed earth block (CEB) technology in the Mega Block and the Watershed Block, both innovations in US earth CEB technology though mechanization.

Instruction for those interested in rammed earth construction is not found in pamphlet format as it was in the 1800s. Instead, the information is communicated through workshops by rammed earth construction firms, such as those offered by Sirewall and Quentin Branch. While these workshops do provide a solid knowledge base, they also have kept rammed earth firmly locked within its traditional construction methods. The information about rammed earth
is spread, but not to the degree or in the form necessary to meet needs in the US (Figure 5).

Rammed earth exists within a gray zone where it is neither a pure DIY form of building, due to the cost of materials and machinery, nor does it fit within the industrial rubric of large-scale technologies that enhance building processes.

Clearly, the monetary and physical costs of the labor and packaging of information need to be re-scaled for the US building industry. Mechanization is a pathway to address both cost reduction and information dissemination by using machinery rather than muscle, and by standardizing rammed earth construction processes.

3.1.0 Accessibility and Transportation

The degree of adaptability of a rammed earth machine to design requirements is difficult to hard-wire into the machine, as the machine is not one that can be factory-based but must be an on-site unit that is adaptable to different wall conditions. Rammed earth does not have a unit base, like CEB construction, where the brick is able to be manufactured offsite, shipped, then laid down to form a structure. It is a mass wall assembled on the foundation, on site. A rammed earth machine must avoid being locked within the factory environment. A factory-bound rammed earth machine would require the transport of ponderous wall sections to site. The Herzog & de Meuron’s Kräuterzentrum did fabricate rammed earth panels in a factory setting, which had the disadvantage of high transportation costs, pollution associated with transport, and loss of structural integrity found in on-site built rammed earth walls. It is essential that a rammed earth machine operates on site and produces a structurally sound wall with variations needed for door/window openings, wall thickness, and height.
The constructability/de-constructability of the machine itself is another key element. An effective rammed earth machine should consist of components that can be transported in a pickup or medium-sized trailer to and from site. The small components also mean that the scale of the machine will not lose relationship to the builder and become too large to use. The machine must change its scale so that, when in pieces, it is scaled to the individual, but when assembled, it is scaled to the architecture it will be constructing. Once assembled, the components of the machine need to be easily understood, manipulated, and interchangeable by the builders so it can be adapted to project specific designs/elements.

3.2.0 Compaction

In looking at other machines that compact (Figure 6), there are two main means of mechanized compaction. The first is in the application of a mechanical force on a target. Each blow incrementally moves the targeted material downward such as a pneumatic tamper or pile driver. The second way is by a weighted force that is applied across the surface of the target material – similar to a steam roller. Traditionally, rammed earth compaction employs the former – repeated downward applications of force. As this form of force is intrinsic to the method of rammed earth building, I considered it first in the process of designing a machine to ram earth. A uniform, controllable force – likely a weight of considerable mass or a mass equal or greater to compaction requirements in psi – applied repeatedly on the targeted material without straining the builder was the initial objective. Mechanizing compaction in this manner would lessen or remove the physical effects of compaction on the human body during construction of earth walls, as well as remove the worker from the formwork where the danger of injury is high. The mechanized ramming action needs to be repeated for long periods of time.
without constant recalibration or concern related to malfunction (in other words repetition and consistency without error – a standard of mechanization). Additionally, the compaction method must work with reinforcing in the wall. The likelihood of rammed earth walls requiring rebar within the wall to comply with current and/or future rammed earth construction codes is very high, and rammed earth machines must anticipate working around pre-placed rebar, or installing it as walls are constructed.

3.3.0 Formwork

The form and finish of a rammed earth wall is governed by the formwork that is used, thus, the interchangeability and integrity of the formwork is the final element of a program for a rammed earth machine. The formwork must be designed to consider variability of the wall, movement during construction, stress of impact compaction during construction, as well as force of the lateral push of the earth equally, instead of favoring one quality over the other as is typical in traditional formwork designs (Figure 7).

The finish of the wall is dependent on the surface of the formwork that the earth is pressed against during compaction. Architectural reveals, patterns, texture, etc, of the wall are highly customizable and easily fabricated with a CNC router or (a simple design) by hand (Figures 8 & 9). Interchangeability of the formwork without disassembly of the ramming element or overall structure of the machine, will allow the construction to continue without large interruptions or delays. In typical rammed earth construction, large and expensive formwork that extends from the foundation to the top of the wall is built out of either steel or wood. The formwork is filled with loose earth mix that is then compacted to fifty-percent of its loose volume, typically in six to eight-inch-high layers that run the length of the formwork. In
mechanizing rammed earth, the formwork could be integral to the machine, working in-synch with the compacting mechanism. In this scenario, the formwork must move latterly and vertically with the construction of the wall, thus avoiding the extensive formwork construction typical to current rammed earth construction. Movable formwork should also be proportional to the building so that reveals/patterns are scaled to the wall and to the builder so that she/he can manipulate it with ease. Lastly, the formwork must be of solid construction as the amount of outward force generated by the earth as it is compacted into a wall is capable of breaking formwork that is either not strong enough or does not have enough exterior bracing.
Figure 6: Compaction Machine Qualities

ADAPT
The flywheel is adaptable to many types of machines and uses due to its universal functionality.

SCULPT
Earth Master agricultural equipment shapes the surface of earth.

MOVE
Curb machines continuously move while leaving behind a structured form.

COMPACT
Pile drivers have a consistent strong downward compaction along a controlled path.

Sources read left to right, top to bottom: Flywheel, Earth Master, Curb Machine, Pile Driver, Caterpillar Design, CAT Tamping Wheel Tip, Locomotive, CAT Excavator, CAT Loader, Concrete Climbing Formwork, Big Lizzie 1915, Rolling Compactor, Mono Wheel, Garbage Truck, 1856 Dreadnought/Pedrial Wheel, Asphalt Roller.
Figure 7: Tools for Rammed Earth Construction

Source: Earth Construction: A comprehensive Guide
Figure 8: Aerie 31

Figure 9: Tucson Mountain Retreat

Source top to bottom: The Construction Zone$^{34}$, DUST$^{35}$
Chapter 4. Rammed Earth Machine Design

The design program of a rammed earth machine outlined above must be supplemented with the larger concerns over introducing a machine/robot into the building industry. In Thomas Bock’s writings on construction robotics and automation, he outlines reasons for change related to the competitive nature and negative perceptions of the construction industry. The following qualifications govern a change-over from a hand-made and human worker centered industry into one of mechanization:

1. lack of qualified workers,
2. facilitation in working,
3. quality enhancement,
4. labor protection,
5. environmental protection and
6. productivity improvements.

My intent, as an architect, is to deal with new potentials/improvements in the realms of safe-use, production quality/cost, easing environmental impact, and eliminating arduous labor. These objectives were met with varying degrees of success in each of the three rammed earth machines described in this chapter.
4.1.0 Monument

Figure 10: Monument
Within my speculative timeline of mechanization, *Monument* falls into a period between the 1800s to early 1990s. *Monument* is composed of two steel frames and a central ram that applies a vertical compaction to the earth. *Monument* is intended to be operated by a team of three builders who work together to keep the formwork filled of the loose earth mix, operate the ram, and move *Monument* throughout the site/on the foundation. The mechanized ramming process still requires an understanding of how rammed earth gains strength, and of how openings are made in traditional rammed earth walls.

The machine is scaled to fit within a pickup truck bed (78.9” long and 50.6” wide$^{54}$) and complies with allowable overhang regulations for road hauling (a general rule of thumb is 4’ overhang in the back and 4” from the side before it must be tagged). The size of *Monument* means that moving to and from building sites does not require the pre-planning that a large delivery truck requires for compliance with variable Department of Transportation and city regulations. Due to the scale of *Monument*, the team of builders must all be present for on-site assembly. In terms of skill level needed for basic operation, *Monument* lies between traditional and pneumatic tampers (Figure 11).

*Figure 11: Monument in Relation to Existing Skills and Technology*
4.1.1 Assembly

Figure 12: Assembly of Monument
Figure 13: Monument Pieces

- Beam
- X-Bracing
- Frame
- Formwork
- Formwork guilds
- Winch
- Ram
- Inverted T Foundation
Once an inverted T foundation is cast to geographically specific dimensions (to keep the water away from the base of the wall) the assembly of Monument has four steps (Figure 12-1 through 12-4). First two steel frames are lifted onto the foundation, positioned vertically to the base of the foundation, rolled parallel to each other and temporarily secured in place. Second, the top ram beam, which has a cable and pulley system for the ram built into the unit, is centered on top of the frames and bolted in place. This beam joins the two vertical steel frames, securing the spacing between frames. The temporary bracing can then be removed. The ram cable, which is mounted on a winch secured at the base of one of the frames, is pulled down and secured within reach of a builder standing at grade. Third, x-bracing on both sides of the ram is bolted into place. This bracing adds structural stability to the top of the ram and is a secondary means of keeping the correct spacing between the two vertical steel frames. Lastly, the cable on the ram beam is clipped to the ram, and the ram is ratcheted to the top of the rebar. The ram is then threaded onto four pieces of rebar which have been cast into the foundation using a template (Figure 12-5), and the winch is locked, securing the ram out of the builders immediate working space. It is at this point that different formwork can be secured in the guides that run vertically on the insides of the steel frames. Once the formwork is secured, Monument is ready for use. The earth mixture is poured into the formwork that rides within the rebar (Figure 12-6), and then distributed so that there is an even surface of a four-inch “lift” of loose earth on the foundation. Once the loose mix is distributed, the winch switch is released and the ram falls guided by the rebar (Figure 12-7 and 12-8). The rebar acts in the same manner as guide rails on the sides of
an elevator car, keeping the ram aligned until it impacts the earth below. The impact of the gravity driven ram, has enough force behind it to compact one lift (approximately four-inches) of earth to 50% of its loose volume. As the height of the wall increases so, too, does the number of times the ram must be dropped. The force behind the ram, because it is driven by gravity, drops proportionally with the height of the wall. Once the formwork is filled with compacted earth, it is released and moved up along the guides and secured for the next series of lifts (Figure 14). When the formwork reaches the top of the frames, *Monument* is moved over to begin sequential construction on the neighboring section of wall.
Figure 14: Formwork Movement in Frames

- Beam
- Frame
- Ram
- Formwork
- Winch
- X-Bracing
- Inverted T Foundation

The image illustrates the movement of formwork in frames, showing the various components involved in the construction process.
4.1.2 Fabrication and Use

*Figure 15: Frames*
Figure 16: Ram Internal Frame

Figure 17: Clad Internal Frame

Figure 18: Ram set on Rebar in Formwork
Figure 19: Bracing at top of Monument

Figure 20: Pulley system
Figure 21: Formwork A (Ornamental)
Figure 22: Formwork B (Plain)
Figure 23: Compaction during Ramming

Figure 24: Compaction around Rebar
Figure 25: Compaction against Formwork A Pattern

Figure 26: Damage caused by Ramming
Monument was largely fabricated with reclaimed materials and components. The steel, reclaimed from old Penn State theater sets, was cut, cleaned and welded to form the two vertical frames (Figure 15) and the inner frame of the ram (Figure 16). The formwork, wheels, and ram cladding were all fabricated to fit the frames and existing foundation. Formwork A (Figure 21) has an insert of a CNC routed pattern. There are two sliders bolted on either side of the main panel with a strip of steel plate along the seam on the exterior side of the formwork. When the formwork needs to be shifted, these are unbolted and the formwork pulled away, leaving a clear imprint of the pattern. Formwork B (Figure 22) is a smooth formwork with a central hinge that allows the formwork to be folded away from the wall and out of the rails when the steel brace on the exterior formwork is unbolted. The ram used is a second iteration, a smaller ram with an interior steel frame clad in waxed plywood. These modifications to the ram enable easy transport and the ability to withstand the stresses of being dropped and lifted repeatedly. Monument was fabricated and assembled on the ground instead of the foundation, and once complete, was tilted up to its final orientation and lifted onto the foundation.

The ram used on Monument was operated with a manual boat winch. One rotation of cranking the ram up and dropping it took approximately one minute. While this process did compact the earth, several areas need to be redesigned. The ram was left hollow and did not have enough weight to compact the earth sufficiently with a single fall as the wall grew in height. Operation of the ram by means of a manual winch was not ideal for monitoring the progress of the ramming process nor was it physically
comfortable. In future iterations the manual winch should be switched out with a fully automated winch. Thirdly, the ram did not impact across the entire extent of the formwork boundaries nor adequately around the rebar (Figure 23 and 24). While the rough finish is not a problem against formwork B, the pattern in formwork A left a poor imprint and an undesirable result in the rammed earth wall (Figure 27, 28).
Figure 27: Results Formwork A
Figure 28: Results Formwork B
4.1.3 Resultant Architecture

The architecture manufactured by *Monument* is a collection of walls that do not touch. Much like a barcode, these walls can differ in width and length but never touch. The ridged nature of the frames means that *Monument* cannot turn sharp corner or create curves as the frame would need to occupy the same space as previously rammed wall. The rammed earth walls are individual elements that must be joined and/or intersected by another material/building system. Any opening would be created with volume distributing boxes and framed in the same manner currently employed in existing rammed earth techniques.
4.1.4 Future Development

The second version of Monument operates in a similar manner to the first, however, the form of the ram shape, supporting frames, and winch are redesigned. The new ram shape (Figure 32) is designed to align with either prefabricated or site-built endcaps/joints, and the rebar runs though the ram rather than along the sides. Running the rebar thought the ram allows the compression of earth to be complete around the rebar while maintaining the alignment with the formwork below. The new ram will also be fabricated from one-inch steel plate, increasing the weight, precision of ram shape, and durability. The increased weight of the ram would lessen the number of compactions needed per lift as the wall grows in height. The new frame design (Figure 31) is not so over-structured and has a different shape in plan view. Changing the shape from rectangular to a 30°-60°-90° triangle was done so that Monument could make walls that radiate from other walls. The acute 30° angle of the frame fits into tighter spaces. Different endcaps and joints (Figure 34) are the nodes into which the rammed earth wall locks and from which it originates. These nodes also provide a vertical path for utilities. Thirdly, the manual winch is exchanged for an automated, remote-controlled winch. In addition to reducing physical effort, the operation of the ram could be controlled away from the base of the ram and allow the operator to visually gauge the ramming process of Monument.
Figure 31: Monument V2

Elevation

Section

Plan
Figure 32: Arrow Ram
Figure 33: Monument V2 operation side
Figure 34: Monument V2 Nodes
Figure 35: Monument V2 Intersection with Node
Figure 36: Monument V2 Radial Node Architecture
4.2.0 Mass

Figure 37: Mass
Mass (Figure 37) is a machine design inspired by the 1900s to early 2000s era of mechanization. Mass, in basic terms, is a large wheel with formwork that rolls along a foundation. The intent of Mass is to move along the wall in a continuous manner while allowing the user to operate the machine at ground level. Mass compresses the earth in the same manner as a steam roller, where the force is applied through a continuous rolling element. Consequently, Mass’ slow continuous force creates smaller “lifts” of compaction than is typical of traditional rammed earth walls (one-inch to two-inch). Two builders are the minimum number of people needed to operate Mass for a small scale construction. The manner in which Mass functions necessitates that their skill level be slightly above what is needed to use a pneumatic tamper to ram earth (Figure 39).

Figure 38: Mass - Wheel only

Figure 39: Mass in Relation to Existing Skills and Technology
4.2.1 Assembly

*Figure 40: Assembly of Mass*
Mass has a seven step process of assembly, eight if the wheel element is not premade. Assuming that the wheel is prefabricated, either off or on site, the first step (Figure 40-1) is to roll the wheel up a ramp onto the foundation and rotate it so that it is aligned with the foundation. Once the wheel has been chocked to prevent it from rolling, a hopper (Figure 40-2) is positioned in front of the wheel. The hopper has two arms that extend to the central axle of the wheel. This hopper provides a consistent thin layer of loose earth in front of the wheel during construction, constantly supplying material so that the ramming/rolling is a continuous process. Two large smooth formwork pieces in the shape of a wheel (Figure 40-3) are placed on either side of the wheel. The axle is run through the center of the formwork, hopper and wheel and pinned on both sides of the wheel (Figure 40-4). The axle extends beyond the formwork to the interior side of the wall to allow for attachment into a guide and power source. In Figure 40, steps five though eight show the wheel attached into a vertical guide that is secured to a golf cart that will power the wheel during the construction process. There are two other low-tech options (Figure 41) where the power source can be two builders, or a beast of burden such as a mule. Both of these options have different constraints in

*Figure 41: Mass Alternatives*
terms of wall height, speed of construction and level top surface of the wall than that of a mechanical power source. Once the wall reaches the desired height, the wheel, hopper and formwork must be rolled off the wall onto a ramp and down to the ground.

Unlike Monument where the wall is made of vertical sections, Mass rolls out one lift for the total horizontal length of the wall before creating the next.

4.2.2 Fabrication and Use

The built version of Mass is an eight-hundred-and-eighty pound, twelve-inch-thick, three-foot diameter wheel. The weight of the wheel is essential to compression as it is one pass of the wheel, instead of multiple impacts, that is used to compact the earth 50%. This wheel was cast flat in formwork made of two-inch thick foam that was CNCed then stacked in a box built to keep the foam tightly pressed together. Once the formwork was assembled, the wheel was cast flat with an in-place central steel axle of quarter-inch walled steel pipe. The concrete wheel was allowed to cure, then stripped of the formwork. A lever, blocking and about 6 people were needed to tilt the wheel upright. Another piece of quarter inch steel pipe with an inch interior opening was lathed down to fit into the axle pipe that was cast into the wheel. The wheel is easily rolled (Figure 51) but cannot make sharp turns without coming to a full stop and being pushed on one side. The side formwork (Figure 50) built for Mass increased the diameter of the assembled machine to 5-feet. To test the compressive force of Mass, a simple straight eight-foot length of formwork was built. (Figure 52) The formwork was built to withstand the outward push of the soil and give the wheel enough length to turn.
Mass was used in a simple wall section test where the wheel was rolled back and forth linearly. Once rolled onto the formwork, a one-inch layer of earth mix was laid down and evenly distributed along the length of the formwork. When rolled, Mass compressed the loose earth to fifty percent of its height in one pass. Little earth stuck to the surface of the wheel and the imprint of the foam on the wheel was transferred to the now compacted earth. Another layer of earth was put down, overlapping the bare area where Mass rested during the first lift and Mass was rolled once more with the same results. As these steps were repeated the layers of compressed earth grew in height, but Mass became harder to roll as a hill developed in the middle of the formwork. This was caused by an uneven distribution of the loose earth mixture which was concentrated in the middle of the test wall and not the two ends where Mass rested alternatively between each pass. The thin layers and rough corners indicate that a volume distribution box cannot be used to create openings with Mass. Openings would need to be cut out subsequent to wall construction.

A surprising element of Mass was that the process of ramming was completely silent. A regular hand tamper or a pneumatic tamper make noise. Monument operates with a constant rhythm of the chittering of the winch and rattle of ram falling down the rebar. The silence of Mass is uncharacteristic of all contemporary construction methods and would be ideal for areas with noise restrictions such as wildlife preserves as well as more pleasant for the builders.
Figure 42: Axle

Figure 43: Mass Formwork
Figure 44: Compression on Foam Joint

Figure 45: Midpoint on Casting Mass
Figure 46: Casting Mass

Figure 47: Formwork being Removed
Figure 48: Wheel before Tilt

Figure 49: Texture on Wheel Compaction Surface from Formwork
Figure 50: Mass Side Formwork
Figure 51: Mass Rolling

Figure 52: Mass in Formwork
Figure S3: Mass First Layer of Earth
Figure S4: Mass Fourth Layer of Earth
Figure 55: Imprint of Mass on Earth

Figure 56: End Condition of Wall
Figure 57: View at Ramming Layer
Figure 58: Ramming Surface after use
4.2.3 Resultant Architecture

*Mass* creates curvilinear/circular solid forms that require the architecture to be finished with a blade or chiseled. The difficulty of turns and ends when using *Mass* indicates that the machine would work best under a condition where it would not need to stop or reverse direction while in use. The ideal built form for *Mass* is one with a circular plan. Such rammed earth forms have precedent in the *Fujian Tulou* homes of China\(^5\). To make a large circular form, the axis of *Mass* would need to be anchored with a chain to a pole placed at the center of the architecture. The chain would be the guide keeping *Mass* along the correct path as the wall increases in height. With the change in scale from a small program (e.g. residential) to a large one (e.g. apartment), the number of *Masses* on site could be increased which would speed up the progress of construction.

The nature of the construction method of *Mass*, where thin layers of earth are rammed, requires that the architecture must be “finished” through cutting and carving the rammed earth walls. While ramming, steel lintels can be put down within the earth and rammed into place. When the ramming process is finished, the builders would need to return to where the steel lintels were rammed into place and cut out the desired wall openings. After the cut has been made, the compacted earth can be knocked out.
leaving the raw openings. The steel lintels already rammed into place will support the load of the earth above and the openings can be framed.

Figure 60: Mass with lintel and future cut area:

4.2.4 Future Development

The second iteration of Mass compacts in the same manner as the first but the design of the wheel and formwork have been redesigned. The wheel central to Mass is changed to a hollow, one-inch walled steel, three-foot diameter wheel with a second wall inset six inches. Within the double wall an electric motor would operate to propel the wheel forward, ridding the need for an external power source, and maintaining the silent quality of the first iteration of Mass (Figure 61-1). The movement would be similar to that of the Mono Wheel (Figure 6). The inner most core of the wheel would
contain paddles radiating from the axle (Figure 61-2) that would mix the earth as it is fed into the wheel via external means. As the wheel rolls, it would compress the earth in front of it but at the same time lay down a layer of loose earth behind itself in preparation for the next lift (Figure 61-3). The earth would move out of the wheel on the two sides and be leveled with a heavy steel pipe rolling behind the wheel (Figure 61-4). The formwork on either side is decreased to four feet so there is only a 6” overlay on the lifts below. The new wheel within Mass would lighten the weight of the wheel and make it more a unit that would travel from site to site rather than object that would be left on site and recreated at each new site.

*Figure 61: Mass V2*
Figure 62: Mass V2

Elevation

Section

Plan
4.3.0 Needle

Within my speculative timeline of mechanization, *Needle* falls into the late 2000s, at the soonest, and looks toward future eras of mechanization. Although *Needle* is the most complicated of the three machines to operate (Figure 63), it requires the least number of builders. *Needle* requires one operator who is versed in the operation of the robot. Two versions of *Needle* are possible. The first is with the use of an industrial robot, specifically the ABB robot at the Stuckeman Family Building and the second is a demolition robot manufactured by Husqvarna. Robots within architecture and construction are developing concepts in the US, though they have been under development in Japan since the 70s\(^{56}\), and within factory settings. Herzog and De Meuron’s *Kräuterzentrum*\(^ {57}\) rammed earth wall panels were constructed in a factory setting, shipped to the site and lifted into place with a crane. This process is not one that takes advantage of the strengths of rammed earth as a local, mass wall constructed in place. Both versions of *Needle* are intended for onsite construction that brings the strengths of robotics – lack of harm and fatigue to the human body – to onsite rammed earth construction. The basic intention for each version is to use a plate attachment to hold a pneumatic tamper that is then bolted to the head of the robot.

*Figure 63: Needle in Relation to Existing Skills and Technology*
Figure 64: Assembly of Needle

Source: image 61-3 Ingersoll-Rand

4.3.1 Use of Needle, Version One
The ABB robot in Needle version one is intended for a factory setting. The robot remains fixed either at a single point or on a track and is fed a prewritten code that gives specific reference points and paths from which the robot does not deviate. The prescribed nature of the coding when brought out to site would demand an equal level of precision in the casting of the foundation and placement of rebar. If there is too much variance a new code will need to be written. Once on site, the robot would need a fixed housing unit from which to operate, which would be difficult to transport to and from the site. Units such as those used by Gramazio Kohler⁵⁹ and SAM by Construction Robotics⁶⁰, use an external housing to mount the robot and provide a frame of reference.

While these systems do bring the robot out of the factory, the housing units make them difficult to move through the small spaces, such as doorways, typical to the built environment. These robots also have limitations in the loads and vibrations they can safely tolerate.

In designing for the ABB robot at the Stuckeman Family Building a code was developed in Grasshopper software (Figure 64-1) that was then run through Robot Studio software and finally to the robot itself (Figure 64-2 & 3). The code that was produced made a

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*Figure 65: Needle Code*

*Figure 66: Needle Foundation and Formwork*
stich like pattern that wove the pneumatic tamper through the rebar (Figure 65). The site for the robot to operate on is a section of concrete foundation that was cast on wheels (Figure 66) so it could be brought to the robot. The formwork was specially designed to fold back on itself to allow for movement of the robot and ram within. As the wall would increase in height, the formwork would fold up and be secured. Like Monument, the formwork of Needle has one side with a pattern to test the ramming processes’ ability to hold an imprint in the earth. Once in place, an Ingersoll Rand 341A2M tamper was to be connected to the robot and used to ram a wall section. This was never built as it was determined that the vibrations of the tamper, despite additional vibration damping material within the attachment, would be too extreme for the robot.

Figure 67: Coded Movement of ABB Robot Needle V1

4.3.2 Use of Needle, Version Two

Needle, version two, uses a demolition robot as its base. Demolition robots, such as those manufactured by Husqvarna, specifically the DXR 310 (Figure 68), are sized for the built environment, and have the maneuverability and capacity to work with heavy loads in on-site conditions.
Designed to operate in real time through a simple interface, this robot is able to respond to changes in site circumstances and inconsistencies in rebar placement quickly. The Husqvarna demolition robot is constructed with two treads and four outriggers that are designed to consider the threshold sizes typical of the built environment. The demolition robot is thirty-one inches wide when the outriggers are retracted. The treads are rugged enough that the robot can “walk” itself out to a site through rough ground if it cannot be delivered right next to the building site. The robot is also able to move around sharp turns and rotate the arm a full 360 degrees. The builder will follow behind the robot with the remote control. (Figure 69) The control panel has two joysticks that control the movement and telescopic arm. One of the attachments for the Husqvarna robot is a 463-pound breaker (similar to a jackhammer) which makes the 34.88 pound Ingersoll Rand pneumatic tamper well within the workload range.

Figure 68: DXR 310  

Figure 69: Remote Control  

Source: left and above Husqvarna61
Figure 70: DXR 310 in use

Source: Husqvarna

Figure 71: Movement through Doorway

Source: Husqvarna
Figure 72: Needle V2

tamper secured in clamp that is bolted to baseplate
to air compressor 29-35 cfm

Source: Needle Base Photos- Husqvarna\textsuperscript{52} for robot base and Ingersoll-Rand\textsuperscript{58}
Figure 73: Use of Needle V2
4.3.3 Design Results

*Needle*, due to its small size and mobility, is not as dependent on the foundation as *Monument* and *Mass* are. The manner in which *Needle* moves means that it can manipulate earth in a variety of small spaces that are typical of residential construction. The power and mobility of the arm of the robot become an extension of the operator without adding large amounts of stress to the process. This results in a highly specific wall design. Current robotic construction of earth structures such as those put forth by *WASP* have only been done at a small scale, where the robot can operate above the structure. When this is scaled for real-world operation, there is too much false work and support necessary for the robot to actually work at a building site. A robot that is scaled to the worker retains the relation to site, architecture and builder, the whole of the architecture behaves much in the same way of traditional rammed earth architecture.
4.4.0 Monument, Mass and Needle Architecture

Figure 74: Monument, Mass and Needle Architecture in Plan
Although *Monument, Mass and Needle* all use the same base mixture of rammed earth, the resultant forms, openings, surfaces and wall textures all differ, resulting in rammed earth architectures that, although they maintain wall thickness, are departures from traditional rammed earth architecture.

*Table 1: Monument Mass and Needle Architecture*

<table>
<thead>
<tr>
<th><strong>FORM</strong></th>
<th><strong>OPENINGS</strong></th>
<th><strong>SURFACE</strong></th>
<th><strong>TEXTURE</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TRADITIONAL</strong></td>
<td>Typically, a small to medium rectangular form.</td>
<td>Rectangular opening made with a volume distributing box.</td>
<td>A regular pattern of holes (2’-4’ spacing typical) or strong horizontal and vertical (4’-8’ spacing typical) reveals caused by the type of formwork used.</td>
</tr>
<tr>
<td>*<em>MONUMENT</em></td>
<td>A new radial form caused by the endcaps and nodes necessary for the operation of <em>Monument</em>.</td>
<td>Same as traditional.</td>
<td>Strong vertical reveals governed by the size of the arrow ram (2’-3’).</td>
</tr>
<tr>
<td>*<em>MASS</em></td>
<td>A revitalization of circular forms.</td>
<td>Steal lintels are placed in the wall during ramming and then the opening is carved out from the finished wall.</td>
<td>As the machine does not operate within fixed formwork there are no reveals. The wall has the appearance of a solid mass.</td>
</tr>
<tr>
<td>*<em>NEEDLE</em></td>
<td>Small to very large rectangular forms.</td>
<td>Same as traditional.</td>
<td>The wall will have two sides. Where the machine operates there will be strong horizontal reveals caused by the stacking of the formwork. On the other side, where the formwork is not stacked, but goes from floor to ceiling the vertical reveals will be more evident.</td>
</tr>
</tbody>
</table>

*based on the second versions of the machines
4.5.0 Conclusions

*Monument, Mass* and *Needle* were designed to be a means of ramming earth, a way of easing the construction process and of transmitting design intent. How the three machines function in their capacity to ram earth and ease the construction process are measured against the program of rammed earth machines set forth earlier (accessibility, transportability, compaction, and formwork) and machine intent (new potentials/improvements in the realms of safe-use, production quality, and easing environmental impact) (Table 1). Of these categories, none of the three machines fulfill all qualities to an optimum degree, and there is a need for redesign and rebuilding.

A measure of *Monument’s*, *Mass’s* and *Needle’s* success, however, is their capacity to transmit a design intent. The design intent of a machine is the same capacity found in a drawing or built architecture to propose a manner of building and a way of living. Such elements refabricate the world in which we live and add a new layer to the field of architecture. *Monument, Mass* and *Needle* are ways of storing, presenting, and transmitting new information on methods of rammed earth construction and the resulting form to the construction and architectural industries. Each machine is an alternative to building rammed earth in the traditional manner, alternatives that would begin to move rammed earth out of the niche of a specialized construction form and into the realm of a contemporary US building methods.
As the central wheel of Mass is solid concrete, lifting it in and out of a truck or rolling up and down a steep trailer ramp would be very difficult and potentially break the wheel or injure those attempting to move it. It would be best then just to move the formwork for the wheel and recast it onsite. The second version of Mass is likely to be easier to transport however there still needs to be an external machine to lift it off the wall when construction is completed.

Needle uses the same formwork that is currently used – either custom built wood or repurposed concrete formwork.

The impact of all these machines brings an old technology that forward that is local, low cost, and does not generate large amounts of waste or pollution during fabrication/assembly of the wall.
4.5.1 Nature of Change

“the human grade of intelligence is such that when presented with a choice between two alternatives, we invent a third, or we answer a question with a question. The !Kung bushmen have a term for those who excel at this: they are called t’xudi kaus, ‘masters of cleverness’ (Yellen 1977:47)” – Donald Preziosi

In architecture, where the new idea is always proposed as the best, newest, most ideal, *Monument, Mass* and *Needle* are alternatives to the modern wall section, of combining old and new technologies into a novel new one. In a profession/industry that is so full of products, technologies, and forms seeking to create the ideal architecture for site, performance, program, environment and client, looking backwards to a simple material and staying within today’s economic and cultural setting presents a third design approach. Bringing rammed earth forward as a third design approach necessitates adaptations to current social, cultural and economic realities while looking forward to reforming public attitude toward the material itself.

*Monument, Mass* and *Needle* address, to varying degrees, the four essential complications that currently exist with rammed earth construction in the US (outlined in Chapter 2: Building Earth Walls) accessibility to knowledge, cost of material/labor/physical, lack of change, and lack of code/consistency. These three machines work to speed up the process of ramming earth, they can be replicated, and with the abundance of the raw material, reopen the door to rammed earth construction on a national scale.
<table>
<thead>
<tr>
<th></th>
<th>Accessibility to Product and Knowledge</th>
<th>Cost of Material Labor and Physical Toil</th>
<th>Lack of Change</th>
<th>Lack of Code and Consistency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monument</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Needle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Monument, Mass and Needle vs US Conditions

- Good
- Excellent
Chapter 5. Final Thoughts

"Every day in some form or another, I touch earth. I don’t mean I walk on it, everybody does that. I mean the earth that you pick up and touch, it’s all different, you know. Some of it's granular and coarse, and some of it's silky and soft. It comes in all these different colors, it can be gold, red, brown, grey. It has an aroma. You can build things with it, you can grow things in it. It's remarkable stuff, and it's everywhere. If I were blind, I would still feel the earth."

5.1.0 Monument, Mass, and Needle

Each machine is a collapsible mobile reality, containing the means of creating architecture that is inspired by place, and they can be reformed to design needs. The use of these machines removes the builder from within the wall and brings them out to the larger site context, where the construction of the wall becomes the totality of an architecture, one of natural elegance and comfort, instead of the work of the individual lift.

I began these studies with three specific questions in mind:

1. Could mechanization/mechanical enhancements to the process of rammed earth construction make rammed earth more viable in the US housing market?

2. What architectural forms/typologies can earth construction take to become more accepted in the US?

3. How will mechanization affect traditional rammed earth building practices and resultant forms?
With regards to the first question, the answer is a resounding YES, and I hope to continue my work with rammed earth machines to address this need for rammed earth mechanization. Mechanization/mechanical enhancements to the process of rammed earth construction can definitely make rammed earth more viable in the US housing market. Each machine creates different forms appropriate to different rammed earth applications. The second version of Monument most closely aligns with the scale/style of buildings built and lot size typical to US single family homes. Mass and Needle would be applicable to the housing market if an alternative design form were being used or if the building site is especially remote and minimal impacts (such as sound pollution, construction of wide roads, etc.) on the environment were desired.

Earth as a material is so different and versatile in its particle nature that asking what architectural forms/typologies can earth construction take to become more accepted in the US does not have a straightforward answer. Standard features such as doors, windows, façades, etc., can readily be incorporated into rammed earth structures. However, the nature of the material requires a thicker wall profile, a properly designed base and appropriate overhead completion. Both the base and overhead completion are relatively minor aspects that fit readily into the standard construction paradigm. However, architects, builders and users need to understand wall thickness requirements and inherent benefits.

Obviously, irrespective of the environmental and performance benefits, a poorly constructed simple rectangular form will not be received favorably as the finished structure will not be aesthetically pleasing or structurally sound. With current labor-based construction methods, the quality of rammed earth walls is highly variable. Use of Monument, Mass or
*Needle* would remove some of the uncertainty in the appearance and stability of the finished wall. Ideally, *Monument, Mass or Needle* are used by an individual with a high degree of craft, knowledge of earth, and vision to build a form unique to the site/client/design, resulting in architecture that showcases the material and architectural form.

Lastly, how mechanization affects traditional rammed earth building practices and resultant forms is really quite liberating. The speed and changes to the rammed earth process that are inherent in *Monument, Mass and Needle* is akin to giving rammed earth a new “social mobility” within architecture that does not currently exist. *Monument’s* node and line architecture is new to rammed earth. *Mass’s* large (circumference and height) circular forms, while not new to rammed earth architecture, are a re-imaging of the process of building that does not necessitate the construction of specialized formwork or heavy labor. The forms created by *Mass* are scalable to site and circumstance; and, unlike any other rammed earth building process, it is completely silent. Silence means a significant reduction in noise at building sites, a condition that is the antithesis of the creation of architecture - a very violent and thunderous process.

*Needle*, the most futuristic of the three, is ahead of where the US construction industry is currently. Although used in factory settings and demolition processes, robotics have yet to be used as full scale construction elements. Due to the flexibility, strength, mobility and size of *Needle*, a complex, quite tall, linear plan-based rammed earth structures can be safely and quickly built.
5.2.0 Mechanized Rammed Earth

Rammed earth, despite its desirable performance and aesthetic qualities, has remained in the shadows of the US architectural field. Given our climate and energy needs, rammed earth cannot continue to be overlooked, as it naturally possesses many of the qualities that are designed into contemporary wall systems at a great expense of materials and energy. Current views of earth as a “dirty” material that requires a special type of builder and occupant to appreciate rammed earth architecture are inconsistent with the true nature of the material. Rammed earth is fluid enough to address multiple ideas of “Beauty”. Rammed earth is free and local. Rammed earth architecture breathes slowly with the passage of time, adapting to seasons and environment.

The mechanization of rammed earth as seen in *Monument, Mass, and Needle* are the first steps toward pushing rammed earth though a period of industrialization of the construction process while still retaining the site-specificity that is inherent to the material. Although in their current prototype existence there is a level of impracticality with each machine, the essence of projecting a new way of living within earth walls is at the root of *Monument, Mass and Needle*. Although removed from direct contact with the assembly of the wall, there is still the tactile connection and control of the resultant wall and architecture. The current timing for mechanization of rammed earth is ideal as, although public perception of earth as a material of last resort is still widely held, the return to less industrialized/purer styles of living is a large movement in US culture. Returning to the simplicity inherent to rammed earth and away from highly industrialized materials, through processes of mechanization is not an ironic twist sneaking an industrial process in placed of traditional methods, but is an update
to rammed earth that anticipates demands of current and future social, cultural and economic conditions in the US.
Appendix A: Context of Work

Figure 75: Context for Mechanizing Rammed Earth in the US
Appendix B: Development Sketches
- hold upper -
  - rigidity of the beam -
  - hold together -
    - through bolts

- need help to frame work -
  - need something a don that
  - keeps idea green
  - put threaded stud and through -

- put normal in every -

- cut joint
  - 1/8 - 2 in. depth

- root fire
The words: "necessary to fine structure that means either the real problem. - to..."
By waiting
Where we areO

RE line

What I can as absolutely go

cheaper RE

Test locally
It might be temporary + building

RE

Proven RE

RE nothing - feeling skill where and what
Say the direction in the machine so
It is possible for
people who do not know

Signed on 20th Nov.

most do not promote what work but people expect you
be here a stop has to look & over all
Most hole for rebar
Making them slots more that
the rebar can contain
These are not needed to
"nail" as joint project

just slide the
end down the
rebar slot and

End
We need the holes for
rebar on this as
otherwise the wall could
rebar not show

8
6.5
[Handwritten text and diagrams related to engineering or technical details.]

146
For Troubleshooting:
- New feed at building of blades turned on
- 3 pulses from each sensor
- Sketch shows the new figure
  - Model
  - Small sample
  - Big sample = magic then?
  - OB elements
  - foul air floods
  - Framework for small samples

No need to be O otherwise there is trouble = problem
A method to calculate display knowledge for women in the background

- Display space
- Catalog space
- Sections
- Stands
- Living room
- Kitchen
- Bathrooms

End weight.
Longer,
Development,
solid,
bureaucratic.
5th connection

corner - usual - cast #4 (hand ground or factory input)

- All angles obtuse - if made will break on curve

60° radial reamer

- at 60° min
References


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http://people.bath.ac.uk/abspw/rammedearth/review.pdf.


http://people.bath.ac.uk/abspw/rammedearth/review.pdf.


32 Brownell, Blaine. "Herzog & De Meuron Shapes A Processing Plant with Rammed Earth."


35 "Rammed Earth Tucson Mountain Retreat Is Intimately Connected with the Sonoran Desert."

http://mi.eng.cam.ac.uk/IALego/steam.html.

http://www.earthmastertillage.com/product/dyna-drive


http://en.tslzzg.com/products_detail/&productId=f805fa08-5c64-4536-a4f9-47b2a27bb713&comp_stats=comp-FrontProducts_list01-1308185610280.html.


http://www.intechopen.com/books/robotics_and_automation_in_construction/construction_automation_and_robotics.


http://gramaziokohler.arch.ethz.ch/web/e/forschung/186.html.
"Construction Robotics - Advancing Construction | Home of the Semi-Automated Mason."


https://www.youtube.com/watch?v=guW-D6l4Ak.


