LIMIT DESIGN OF REINFORCED MASONRY WALLS FOR EARTHQUAKE-RESISTANT CONSTRUCTION

A Thesis in
Architectural Engineering

by

Reynaldo E. Sánchez Bravo

© 2012 Reynaldo E. Sánchez Bravo

Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science

August 2012
The thesis of Reynaldo E. Sanchez Bravo was reviewed and approved* by the following:

Andres Lepage  
Assistant Professor of Architectural Engineering  
Thesis Advisor

Ali M. Memari  
Professor of Architectural Engineering

Gordon Warn  
Assistant Professor of Civil Engineering

Chimay J. Anumba  
Professor or Architectural Engineering  
Head of the Department of Architectural Engineering

*Signatures are on file in The Graduate School
ABSTRACT

A Limit Design methodology is presented for the design of Special Reinforced Masonry Shear Walls subjected to in-plane seismic forces. The method is presented following the framework of the Masonry Building code by the Masonry Standards Joint Committee (MSJC). It incorporates concepts from displacement-based design that are applied to the controlling yield mechanism of a wall configuration subjected to lateral seismic loading.

Four case studies are evaluated. The first three represent typical construction of low-and mid-rise reinforced masonry structures. These cases involve situations where design decisions are not favorably addressed by the current MSJC code.

The structures are analyzed and designed using the Allowable Stress Design and Strength Design provisions of the MSJC code and the proposed Limit Design alternative. For this purpose, different reinforcement options are evaluated. The design outcomes are compared for different design methods to help expose the limitations of current design provisions in the MSJC code and to showcase the advantages of the proposed Limit Design methodology.

The fourth case study, involves small-scale shake table test structures. The measured peak base shears and displacement maxima for the test structures are compared with those calculated with the proposed Limit Design code provisions.

Two modeling techniques for practical nonlinear static analysis are presented to support the usage of the Limit Design method. The proposed modeling techniques when applied to the case studies led to a satisfactory identification of the controlling mechanism and associated base shear strength.
TABLE OF CONTENTS

LIST OF TABLES......................................................................................................................................................... vii
LIST OF FIGURES........................................................................................................................................................... ix
ACKNOWLEDGMENTS...................................................................................................................................................... xviii

CHAPTER 1 INTRODUCTION.................................................................................................................................................. 1
  1.1 Statement of the Problem........................................................................................................................................... 1
  1.2 Objectives and Scope............................................................................................................................................... 1
  1.3 Organization.......................................................................................................................................................... 2

CHAPTER 2 LIMIT DESIGN METHOD.................................................................................................................................. 4
  2.1 Framework........................................................................................................................................................... 4
  2.2 Code Provisions.................................................................................................................................................... 5
  2.3 Design Steps........................................................................................................................................................ 5
  2.4 Limitations........................................................................................................................................................... 7

CHAPTER 3 CASE STUDY A: SINGLE-STORY WALL WITH OPENINGS........................................................................... 8
  3.1 Description........................................................................................................................................................... 8
  3.2 Linear-Elastic Analysis......................................................................................................................................... 9
  3.3 Allowable Stress Design...................................................................................................................................... 10
  3.4 Strength Design.................................................................................................................................................. 11
  3.5 Limit Design........................................................................................................................................................ 13
  3.6 Nonlinear Static Analysis.................................................................................................................................... 15

CHAPTER 4 CASE STUDY B: MULTI-STORY WALL WITH LARGE OPENING AT BASE.................................................. 16
  4.1 Description.......................................................................................................................................................... 16
  4.2 Linear-Elastic Analysis......................................................................................................................................... 17
  4.3 Allowable Stress Design...................................................................................................................................... 18
  4.4 Strength Design.................................................................................................................................................. 19
  4.5 Limit Design........................................................................................................................................................ 21
  4.6 Nonlinear Static Analysis.................................................................................................................................... 22
LIST OF TABLES

Table 2.1 Limit Design Code........................................................................................................... 201
Table 2.2 Commentary to Limit Design Code.................................................................................. 202
Table 3.1 Reinforcement Options.................................................................................................... 203
Table 3.2 Member Forces due to Dead, Live, and Earthquake Loads.......................................... 204
Table 3.3 Lateral Stiffness for Different Mesh Sizes ...................................................................... 205
Table 3.4 Controlling Provisions and Seismic Base Shear per Design Method............................ 206
Table 3.5 Base Shear Strength for Nonlinear Static Analyses....................................................... 207
Table 3.6 Base Shear Strength and Displacement Capacity........................................................... 207
Table 3.7 Selected Nonlinear Static Analysis Observations............................................................ 208
Table 4.1 Reinforcement Options................................................................................................... 209
Table 4.2 Member Forces due to Dead, Live, and Earthquake Loads.......................................... 210
Table 4.3 Controlling Provisions and Seismic Base Shear per Design Method............................ 211
Table 4.4 Base Shear Strength for Nonlinear Static Analyses....................................................... 212
Table 4.5 Base Shear Strength and Displacement Capacity........................................................... 212
Table 4.6 Selected Nonlinear Static Analysis Observations............................................................ 213
Table 5.1 Reinforcement Options................................................................................................... 214
Table 5.2 Member Forces due to Dead, Live, and Earthquake Loads.......................................... 215
Table 5.3 Controlling Provisions and Seismic Base Shear per Design Method............................ 216
Table 5.4 Base Shear Strength for Nonlinear Static Analyses....................................................... 217
Table 5.5 Base Shear Strength and Displacement Capacity........................................................... 217
Table 5.6 Selected Nonlinear Static Analysis Observations............................................................ 218
Table 6.1 Reinforcement Schedules................................................................................................. 219
Table 6.2 Material Properties.......................................................................................................... 219
Table 6.3 Measured First-Mode Frequency of Vibration................................................................. 219
Table 6.4 Measured Base Shear Strength......................................................................................... 219
Table 6.5 Calculated Base Shear Strength, Structures RM1 and RM2......................................... 220
Table 6.6 Calculated Base Shear Strength, Structure RM3............................................................ 220
Table 6.7  Base Shear Strength for Nonlinear Static Analyses........................................ 220
Table 6.8  Nonlinear Static Analysis Observations....................................................... 221
Table A.1  Experimental Data..................................................................................... 222
LIST OF FIGURES

Figure 3.1  Single-Story Wall with Openings................................................................. 225
Figure 3.2  Lateral Stiffness for Different Mesh Sizes, after Linear-Elastic Analysis........ 225
Figure 3.3  Controlling Yield Mechanism.................................................................. 226
Figure 3.4  Base Shear per Design Method................................................................. 226
Figure 3.5  Base Shear Strength for Nonlinear Static Analyses.................................. 227
Figure 3.6  Wall Shear vs. Roof Displacement for Nonlinear Layer Model,
Reinforcement Option 1, Eastward Loading............................................................. 228
Figure 3.7  Wall Shear vs. Roof Displacement for Nonlinear Layer Model,
Reinforcement Option 1, Westward Loading............................................................ 228
Figure 3.8  Wall Shear vs. Roof Displacement for Nonlinear Link Model,
Reinforcement Option 1, Eastward Loading............................................................. 229
Figure 3.9  Wall Shear vs. Roof Displacement for Nonlinear Link Model,
Reinforcement Option 1, Westward Loading............................................................ 229
Figure 3.10 Wall Shear vs. Roof Displacement for Nonlinear Layer Model,
Reinforcement Option 2, Eastward Loading............................................................. 230
Figure 3.11 Wall Shear vs. Roof Displacement for Nonlinear Layer Model,
Reinforcement Option 2, Westward Loading............................................................ 230
Figure 3.12 Wall Shear vs. Roof Displacement for Nonlinear Link Model,
Reinforcement Option 2, Eastward Loading............................................................. 231
Figure 3.13 Wall Shear vs. Roof Displacement for Nonlinear Link Model,
Reinforcement Option 2, Westward Loading............................................................ 231
Figure 3.14 Wall Shear vs. Roof Displacement for Nonlinear Layer Model,
Reinforcement Option 3, Eastward Loading............................................................. 232
Figure 3.15 Wall Shear vs. Roof Displacement for Nonlinear Layer Model,
Reinforcement Option 3, Westward Loading............................................................ 232
Figure 3.16 Wall Shear vs. Roof Displacement for Nonlinear Link Model,
Reinforcement Option 3, Eastward Loading............................................................. 233
Figure 3.17 Wall Shear vs. Roof Displacement for Nonlinear Link Model,
Reinforcement Option 3, Westward Loading............................................. 233

Figure 3.18 Wall Shear vs. Roof Displacement for Nonlinear Layer Model,
Reinforcement Option 4, Eastward Loading............................................. 234

Figure 3.19 Wall Shear vs. Roof Displacement for Nonlinear Layer Model,
Reinforcement Option 4, Westward Loading............................................. 234

Figure 3.20 Wall Shear vs. Roof Displacement for Nonlinear Link Model,
Reinforcement Option 4, Eastward Loading............................................. 235

Figure 3.21 Wall Shear vs. Roof Displacement for Nonlinear Link Model,
Reinforcement Option 4, Westward Loading............................................. 235

Figure 3.22 Wall Shear vs. Roof Displacement for Nonlinear Layer Model,
Reinforcement Option 5, Eastward Loading............................................. 236

Figure 3.23 Wall Shear vs. Roof Displacement for Nonlinear Layer Model,
Reinforcement Option 5, Westward Loading............................................. 236

Figure 3.24 Wall Shear vs. Roof Displacement for Nonlinear Link Model,
Reinforcement Option 5, Eastward Loading............................................. 237

Figure 3.25 Wall Shear vs. Roof Displacement for Nonlinear Link Model,
Reinforcement Option 5, Westward Loading............................................. 237

Figure 3.26 Wall Shear vs. Roof Displacement for Nonlinear Layer Model,
Reinforcement Option 6, Eastward Loading............................................. 238

Figure 3.27 Wall Shear vs. Roof Displacement for Nonlinear Layer Model,
Reinforcement Option 6, Westward Loading............................................. 238

Figure 3.28 Wall Shear vs. Roof Displacement for Nonlinear Link Model,
Reinforcement Option 6, Eastward Loading............................................. 239

Figure 3.29 Wall Shear vs. Roof Displacement for Nonlinear Link Model,
Reinforcement Option 6, Westward Loading............................................. 239

Figure 3.30 Wall Shear vs. Roof Displacement for Nonlinear Layer Model,
Reinforcement Option 7, Eastward Loading............................................. 240
Figure 3.45  Wall Shear vs. Roof Displacement for Nonlinear Link Model,
Reinforcement Option 10, Westward Loading................................. 247
Figure 3.46  Wall Shear vs. Roof Displacement for Refined Nonlinear Layer
Model, Reinforcement Option 1, Eastward Loading.............................. 248
Figure 3.47  Wall Shear vs. Roof Displacement for Refined Nonlinear Layer
Model, Reinforcement Option 1, Westward Loading............................ 248
Figure 3.48  Wall Shear vs. Roof Displacement for Refined Nonlinear Layer
Model, Reinforcement Option 10, Eastward Loading............................ 249
Figure 3.49  Wall Shear vs. Roof Displacement for Refined Nonlinear Layer
Model, Reinforcement Option 10, Westward Loading........................... 249
Figure 4.1  Multi-Story Wall with Large Opening at Base............................... 250
Figure 4.2  Linear-Elastic Model with 8 in. by 8 in. Mesh.............................. 250
Figure 4.3  Controlling Yield Mechanism.................................................. 251
Figure 4.4  Base Shear per Design Method.................................................. 251
Figure 4.5  Base Shear Strength for Nonlinear Static Analyses......................... 252
Figure 4.6  Wall Shear vs. Roof Displacement for Nonlinear Layer Model,
Reinforcement Option 1................................................................. 253
Figure 4.7  Wall Shear vs. Roof Displacement for Nonlinear Link Model,
Reinforcement Option 1................................................................. 253
Figure 4.8  Wall Shear vs. Roof Displacement for Nonlinear Layer Model,
Reinforcement Option 2................................................................. 254
Figure 4.9  Wall Shear vs. Roof Displacement for Nonlinear Link Model,
Reinforcement Option 2................................................................. 254
Figure 4.10 Wall Shear vs. Roof Displacement for Nonlinear Layer Model,
Reinforcement Option 3................................................................. 255
Figure 4.11 Wall Shear vs. Roof Displacement for Nonlinear Link Model,
Reinforcement Option 3................................................................. 255
Figure 4.12 Wall Shear vs. Roof Displacement for Nonlinear Layer Model,
Reinforcement Option 4................................................................. 256
Figure 4.13 Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 4………………………………………………………………………………………………………………… 256

Figure 4.14 Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 5………………………………………………………………………………………………………………… 257

Figure 4.15 Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 5………………………………………………………………………………………………………………… 257

Figure 4.16 Wall Shear vs. Roof Displacement for Refined Nonlinear Layer Model, Reinforcement Option 1………………………………………………………………………………………………………………… 258

Figure 4.17 Wall Shear vs. Roof Displacement for Refined Nonlinear Layer Model, Reinforcement Option 5………………………………………………………………………………………………………………… 258

Figure 5.1 Multi-Story Coupled Shear Walls……………………………………………………………………………………………………………………………………………………………………………………………………… 259

Figure 5.2 Linear-Elastic Model with 8 in. by 8 in. Mesh……………………………………………………………………………………………………………………………………………………………………………………………………… 259

Figure 5.3 Controlling Yield Mechanism…………………………………………………………………………………………………………………………………………………………………………………………………………………………… 260

Figure 5.4 Base Shear per Design Method…………………………………………………………………………………………………………………………………………………………………………………………………………………………… 260

Figure 5.5 Base Shear Strength for Nonlinear Static Analyses……………………………………………………………………………………………………………………………………………………………………………………………………… 261

Figure 5.6 Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 1………………………………………………………………………………………………………………… 262

Figure 5.7 Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 1………………………………………………………………………………………………………………… 262

Figure 5.8 Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 2………………………………………………………………………………………………………………… 263

Figure 5.9 Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 2………………………………………………………………………………………………………………… 263

Figure 5.10 Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 3………………………………………………………………………………………………………………… 264

Figure 5.11 Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 3………………………………………………………………………………………………………………… 264

Figure 5.12 Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 4………………………………………………………………………………………………………………… 265
Figure 5.13  Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 4................................................................. 265
Figure 5.14  Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 5................................................................. 266
Figure 5.15  Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 5................................................................. 266
Figure 5.16  Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 6................................................................. 267
Figure 5.17  Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 6................................................................. 267
Figure 5.18  Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 7................................................................. 268
Figure 5.19  Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 7................................................................. 268
Figure 5.20  Wall Shear vs. Roof Displacement for Refined Nonlinear Layer Model, Reinforcement Option 1................................................................. 269
Figure 5.21  Wall Shear vs. Roof Displacement for Refined Nonlinear Layer Model, Reinforcement Option 7................................................................. 269
Figure 5.22  Beam Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 1................................................................. 270
Figure 5.23  Beam Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 1................................................................. 270
Figure 5.24  Beam Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 2................................................................. 271
Figure 5.25  Beam Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 2................................................................. 271
Figure 5.26  Beam Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 3................................................................. 272
Figure 5.27  Beam Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 3.......................... 272
Figure 5.28  Beam Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 4.......................... 273
Figure 5.29  Beam Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 4.......................... 273
Figure 5.30  Beam Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 5.......................... 274
Figure 5.31  Beam Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 5.......................... 274
Figure 5.32  Beam Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 6.......................... 275
Figure 5.33  Beam Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 6.......................... 275
Figure 5.34  Beam Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 7.......................... 276
Figure 5.35  Beam Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 7.......................... 276
Figure 5.36  Beam Shear vs. Roof Displacement for Refined Nonlinear Layer Model, Reinforcement Option 1.......................... 277
Figure 5.37  Beam Shear vs. Roof Displacement for Refined Nonlinear Link Model, Reinforcement Option 7.......................... 277
Figure 6.1  Structural Configurations and Direction of Lateral Force (after Paulson and Abrams, 1990).......................... 278
Figure 6.2  Configuration of Structures RM1 and RM2.......................... 278
Figure 6.3  Configuration of Structure RM3.......................... 279
Figure 6.4  Typical Construction of Test Structures (after Paulson and Abrams, 1990).......................... 279
Figure 6.5  Configuration and Layout of Reinforcement for Structures RM1 and RM2

Figure 6.6  Configuration and Layout of Reinforcement for Structure RM3

Figure 6.7  Measured Base Shear and Roof Displacement Histories for Structure RM1, Run 4 (after Paulson and Abrams, 1990)

Figure 6.8  Measured Base Shear and Roof Displacement Histories for Structure RM3, Run 6 (after Paulson and Abrams, 1990)

Figure 6.9  RM1 Final Crack Pattern (after Paulson and Abrams, 1990)

Figure 6.10  RM2 Final Crack Pattern (after Paulson and Abrams, 1990)

Figure 6.11  RM3 Final Crack Pattern (after Paulson and Abrams, 1990)

Figure 6.12  Controlling Yield Mechanism for Structures RM1 and RM2

Figure 6.13  Controlling Yield Mechanism for Structure RM3

Figure 6.14  Nonlinear Layer Model, Structure RM1 View from Southwest

Figure 6.15  Nonlinear Layer Model, Structure RM3 View from Southwest

Figure 6.16  Nonlinear Layer Model, Structure RM3 View from Southeast

Figure 6.17  Wall Shear vs. Roof Displacement for Nonlinear Layer Model of Structures RM1 and RM2, Eastward Loading

Figure 6.18  Wall Shear vs. Roof Displacement for Nonlinear Layer Model of Structure RM3, Eastward Loading

Figure 6.19  Wall Shear vs. Roof Displacement for Nonlinear Layer Model of Structure RM3, Westward Loading

Figure 6.20  Measured and Calculated Base Shear vs. Roof Displacement for Structure RM1

Figure 6.21  Measured and Calculated Base Shear vs. Roof Displacement for Structure RM2

Figure 6.22  Measured and Calculated Base Shear vs. Roof Displacement for Structure RM3

Figure A.1  Definition of Displacement Capacity for Experimental Data

Figure A.2  Key for Experimental Data Shown in Figure A.3 to Figure A.6
Figure A.3  Drift Capacity of Specimens Failing in Shear (Effects of Shear Force)........... 290
Figure A.4  Drift Capacity of Specimens Failing in Shear (Effects of Axial Force)......... 290
Figure A.5  Drift Capacity of Specimens Failing in Flexure (Effects of Shear Force)...... 291
Figure A.6  Drift Capacity of Specimens Failing in Flexure (Effects of Axial Force)......... 291
Figure A.7  Displacement Capacity of Flexure-Controlled Walls................................. 292
Figure A.8  Measured vs. Calculated Deformation Capacity, All Data.......................... 292
Figure B.1  Linear-Elastic Model with 8 in. by 8 in. Mesh, Case Study A....................... 293
Figure B.2  Nonlinear Layer Model, Case Study A.................................................. 293
Figure B.3  Masonry Model Axial Direction............................................................ 294
Figure B.4  Reinforcement Steel Model, Axial Direction............................................. 294
Figure B.5  Representative Shear Model, Walls A and C (Case Study A, Reinforcement Option 1) ................................................................. 295
Figure B.6  Nonlinear Link Model, Case Study A...................................................... 295
Figure B.7  Nonlinear Link Definition, Axial Direction, Interior Links in Walls A and C (Case Study A, Reinforcement Option 1)................................................. 296
Figure B.8  Nonlinear Link Definition, Shear Direction, Interior Links in Walls A and C (Case Study A, Reinforcement Option 1)................................................. 296
Figure B.9  Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Eastward Loading (Case Study A, Reinforcement Option 1)........................................ 297
Figure B.10 Wall Shear vs. Roof Displacement for Nonlinear Link Model, Eastward Loading (Case Study A, Reinforcement Option 1)...................................... 297
ACKNOWLEDGMENTS

This study was made possible by financial support from The NCMA Education and Research Foundation and the Department of Architectural Engineering and College of Engineering of The Pennsylvania State University.

The writer is grateful to his advisor, Dr. Andres Lepage, for the assistance and guidance provided throughout this project. Special recognition is given to Steve Dill from KPFF Consulting Engineers and Jason Thompson from The National Concrete Masonry Association (NCMA) for their valuable discussions and suggestions.

Gratitude is due to Professors Ali M. Memari and Gordon Warn for their contributions as members of the thesis committee.

Special thanks to my parents Andreina and Reynaldo for supporting me in every step of my graduate studies at Penn State.
CHAPTER 1
INTRODUCTION

1.1 Statement of the Problem

Several design methods are available in the Masonry Standards Joint Committee (MSJC) building code for earthquake-resistant masonry shear walls using either Allowable Stress Design (ASD) or Strength Design (SD). These methods are well suited for cantilever walls but are often difficult to apply in cases of perforated walls (i.e., walls with windows and other openings).

Current design procedures in the MSJC code generally focus on the response of wall segments without careful consideration of the global system behavior that may severely affect local component demands. Under many circumstances, ASD and SD lead to impractical solutions or deficient designs incapable of meeting the desired seismic performance.

The Limit Design method is presented as an alternative for the seismic design of reinforced masonry walls. The method uses the framework of the current MSJC code and combines linear-elastic analysis with concepts from limit analysis and displacement-based design to determine the in-plane base shear strength and deformation capacities that may be safely assigned to a masonry wall.

1.2 Objectives and Scope

Three main objectives drive the present study. The first objective is to develop a Limit Design methodology that leads to structural designs that are more economical and achieve superior seismic performance than the current available methods in the MSJC code. The second objective is to develop trial designs using ASD, SD, and LD and compare their outcomes. The third objective is to develop a modeling approach for practical nonlinear static analysis of
reinforced masonry wall structures that would support the use of LD, especially to help identify the controlling yield mechanism.

Limit Design is intended for the design of Special Reinforced Masonry Shear Walls as defined in ASCE/SEI 7-10 (2010) and MSJC (2011).

1.3 Organization

Chapter 2 introduces the Limit Design (LD) method for reinforced masonry walls in earthquake-resistant construction. The chapter describes the framework that underlies the method and presents code and commentary language to support its inclusion in modern building codes. Essential design steps and method limitations are also presented. The deformation capacities incorporated in the LD code provisions were derived using experimental data presented in Appendix A.

Chapter 3 presents the design outcome of a single-story wall with openings. The wall is designed for 10 reinforcement options using ASD, SD, and LD. Also included in this Chapter are results from nonlinear static analyses based on the Nonlinear Layer and Nonlinear Link models developed as part of this study. The nonlinear models are described in Appendix B while representative design calculations are presented in Appendix C.

Chapter 4 presents the design outcome of a multi-story wall with a large opening at its base. The wall is designed for five reinforcement options using ASD, SD, and LD. Results of nonlinear static analyses are also presented based on the nonlinear models described in Appendix B. Representative design calculations are presented in Appendix C.

Chapter 5 presents the design outcome of a multi-story coupled-wall configuration. The walls are designed for seven reinforcement options using ASD, SD, and LD. The chapter includes
results from nonlinear static analyses based on the models described in Appendix B. Representative design calculations are presented in Appendix C.

In Chapter 6, the Limit Design concepts are applied to three small-scale masonry test structures and the outcome is compared with the measured test data. Results of nonlinear static analyses are also presented based on the nonlinear models described in Appendix B and compared with the experimental data.

Chapter 7 closes with concluding remarks.
CHAPTER 2
LIMIT DESIGN METHOD

This chapter introduces the Limit Design method for reinforced masonry walls in earthquake-resistant construction. The chapter describes the framework underlying the method; code and commentary to facilitate the adoption of Limit Design in modern building codes; essential design steps; and method limitations.

2.1 Framework

Several design methods are available in the building code requirements by the Masonry Standards Joint Committee (MSJC, 2011) for special reinforced masonry shear walls. Either the Allowable Stress Design or Strength Design methods are well suited for cantilever rectangular walls controlled by flexural yielding but are often difficult to apply in cases of irregular configurations with wall segments controlled by shear.

Current design procedures generally focus on the response of wall segments without careful consideration of the global system behavior that may severely affect local component demands and potentially lead to either impractical solutions or deficient designs incapable of meeting the desired performance.

Limit Design was developed to provide an alternative to the maximum tension reinforcement and special boundary element provisions of the MSJC code provided that the designer confirms the deformation capacity of the masonry wall segments. Simply put, the provisions were intended to identify the expected yielding regions of the structure and to detail them appropriately –in exchange for some relief from flexural reinforcement requirements through a plastic distribution of loads. The desired result is to produce structural designs that are more economical and achieve superior performance by directing the designer to focus on
the portions of the structure subjected to high deformation demands during a strong seismic event.

2.2 Code Provisions

Codified provisions to support the proposed Limit Design method are presented in Table 2.1. Commentary to the code is presented in Table 2.2. The underpinnings for the method stem from activities in committee TS5 of the Building Seismic Safety Council (BSSC), and from the Ductility Task Group formed under the Executive Subcommittee of MSJC, for the purpose, in part, of exploring the implementation of Limit Design in the MSJC code (Lepage et al., 2011).

The proposed Limit Design code uses the framework of the current MSJC code (MSJC, 2011) and combines linear-elastic analysis with concepts from limit analysis and displacement-based design to determine the in-plane strength and deformation capacities that may be safely assigned to a masonry wall configuration. The codified deformation capacities are supported by experimental data of masonry walls subjected to cyclic loading (see Appendix A).

2.3 Design Steps

The approach the designer is expected to follow is largely similar to the current seismic design approach, on purpose. An objective when developing the Limit Design method (Lepage et al., 2011) was to make no changes to the requirements of the loading provisions of ASCE/SEI 7-10 (2010) and as few changes to the design provisions of the MSJC code as possible. The proposed Limit Design code provisions (Tables 2.1 and 2.2) direct the designer to:

1. Perform a conventional seismic analysis
   - Conduct a linear-elastic analysis based on current seismic provisions in ASCE/SEI 7
   - Use reduced section properties to account for the effects of cracked sections
   - Determine maximum seismic forces and displacements at the line of resistance of interest
2. Select a reinforcement layout
   - Define a tentative reinforcement layout for the masonry wall configuration
   - Satisfy minimum reinforcement requirements

3. Determine the controlling yield mechanism
   - Identify the potential plastic hinge regions
   - Assign plastic hinge strengths based on nominal flexural strength \((M_n)\) and/or shear strength \((V_n)\)
   - Determine the limiting mechanism (assume story forces are proportional to those determined in step 1)

4. Check for shear-controlled wall segments and adjust plastic hinge strengths
   - If \(V_n \geq 2V_{Mn}\) then wall segment is not shear controlled
   - If \(V_n < 2V_{Mn}\) then wall segment is shear controlled
     \([V_{Mn} \text{ is the shear associated with } M_n]\)
     For shear-controlled wall segments:
     Adjust the plastic hinge strength, \(M_p\), using
     \[
     \begin{align*}
     \text{If } V_n &\geq 2V_{Mn} \text{ then } M_p = V_n \\
     \text{else } M_p &= M_n \left(\frac{V_n}{2V_{Mn}}\right) \quad \text{[shear-controlled condition]}
     \end{align*}
     \]

5. Check mechanism strength
   - Determine the limiting base shear strength, \(V_{lim}\), for the controlling yield mechanism (step 3) using adjusted plastic hinge strengths
   - Check \(\phi V_{lim} \geq V_{ub}\) \((\phi = 0.8)\)
     \([V_{ub} \text{ is the base shear demand at the line of resistance being designed}]\)

6. Check deformation capacities
   - Deformation capacity, \(\delta_{cap}\), of a wall segment is defined using
     \[
     \delta_{cap} = 0.5 \ell_w h_w e_{mu} / c \quad \text{[See notation in MSJC (2011)]}
     \]
     For shear-controlled wall segments, \(\delta_{cap} = h_w / 400\), except that \(h_w / 200\) applies where conditions of § X.3.2 (Table 2.1) are satisfied
   - Deformation demands are determined by imposing the calculated design roof displacement to the controlling yield mechanism
2.4 Limitations

The main limitation of the Limit Design code provisions is that it applies only to Special Reinforced Masonry Shear Walls (SRMSW). The MSJC code (MSJC, 2011) defines SRMSW as walls meeting special detailing and design requirements aimed at providing the highest level of ductility for masonry walls. Accordingly, ASCE/SEI 7-10 (2010) assigns the highest $R$ value associated with masonry structures to SRMSW. ASCE 7 requires SRMSW where masonry wall systems are used in buildings assigned to the highest Seismic Design Categories (D, E, and F).

Combined axial loads due to gravity and seismic effects are limited to compressive forces not exceeding $0.3 f'_m A_g$. This limitation is intended to promote designs where yielding of the reinforcement occurs before crushing of the masonry.

An additional limitation is to require that for a wall segment where yielding is expected, its nominal shear strength $V_n$ shall exceed the shear associated with the development of its nominal flexural strength, i.e. $V_n \geq V_{Mn}$. This limitation is intended to promote the development of the controlling yield mechanism (step 3 in Section 2.3).
A single-story perforated wall is designed as a special reinforced masonry shear wall using three methods: Allowable Stress Design (ASD), Strength Design (SD), and Limit Design (LD). The ASD and SD methods follow the MSJC code (2011) while LD follows Chapter 2 of this thesis. This case study considers a total of 10 reinforcement options. For each of the reinforcement options, the maximum seismic forces that can be resisted are determined for the three design methods and the controlling design provisions are identified. Design forces and displacements are obtained from linear-elastic analysis. The controlling yield mechanism and base shear strength of the wall configuration, for all 10 reinforcement options, are determined using the nonlinear static analysis procedure described in Appendix B.

3.1 Description

The structure of case study A is classified as a special reinforced masonry shear wall per ASCE/SEI 7-10 (2010) and in compliance with the detailing and reinforcement requirements of MSJC (2011). Details of the structure are presented in Figure 3.1 with descriptions of materials, loads, and seismic design parameters.

Case study A represents a typical masonry wall arrangement for a small commercial building. Three vertical wall segments are defined by the presence of two openings. The walls are labeled A, B, and C (from left to right) with lengths of 4, 2, and 4 ft, respectively. The overall length of the wall configuration is 24 ft with a total height of 18 ft. The roof diaphragm is attached at an elevation of 16 ft from ground level. The clear height of wall A is 10 ft while that of walls B and C is 8 ft. The structure is assumed fixed at the base.

Table 3.1 describes the 10 reinforcement options considered in case study A. The description is limited to flexural and shear reinforcements of the three walls (A, B, and C).
defined by the openings. Additional information required for designing the walls is included in Figure 3.1.

3.2 Linear-Elastic Analysis

For the structure of case study A, a two-dimensional (2D) linear-elastic model is developed using program SAP2000 (CSI, 2011b), refer to Figure B.1 in Appendix B. The linear elastic model is presented as a reference model to obtain design forces (Table 3.2) and displacements needed for the application of the various design methods (ASD, SD, and LD) presented below in Sections 3.3 to 3.5. It is assumed that the 2D models used in this study incorporate the interaction with other lines of resistance and torsional effects, as required in ASCE/SEI 7-10 (2010).

The following general assumptions and simplifications were involved in developing the 2D linear-elastic model of case study A:

- The structure, loads, and response are defined in one vertical plane.
- Structural response accounts for the effects of shear, axial, and flexural deformations.
- The wall segments are modeled using area elements with an 8-in. square mesh. This mesh size allows a direct representation of the modular dimensions of the standard concrete masonry unit (two-core 8×8×16-in. block).
- To consider the effects of cracked sections, stiffness properties are based on 50% of gross section properties.
- The foundation of the structure is rigid. The wall configuration is fixed at the ground level.
- All nodes at floor and roof levels are constrained by rigid diaphragms.
- Dead, live, and seismic loads are assigned at diaphragm levels. The gravity loads are distributed tributary to the area involving each node at a given diaphragm level.
- \(P-\Delta\) effects are neglected.
The effects of meshing the area elements in the linear-elastic model were evaluated for mesh sizes varying from 1 to 12 in. The wall stiffnesses reported in Table 3.3 and Figure 3.2, correspond to the ratio of the total applied lateral force to the calculated roof displacement. The stiffness of the model with an 8-in. square mesh does not differ by more than 3% from the model with a 1-in. square mesh, indicating that adopting an 8-in. square mesh is sufficiently accurate.

### 3.3 Allowable Stress Design

Spreadsheet formulations were developed incorporating the Allowable Stress Design (ASD) provisions of the MSJC (2011) code, see Section C.1 in Appendix C of this thesis. The spreadsheet checks the provisions related to combined axial, flexure, and shear forces that apply to the design of special reinforced masonry shear walls, including those related to maximum ratio of flexural tensile reinforcement, $\rho_{max}$.

For a given reinforcement option, Table 3.4 reports the maximum lateral seismic forces that may be applied to the wall configuration without failing the ASD code requirements. The reported seismic base shears are associated with $1.0E$ but ASD provisions were checked using $E/1.4$. It is important to clarify that the data in Table 3.4 neglect the contribution of the minimum prescribed reinforcement of MSJC 2011 Section 1.18 for special reinforced masonry shear walls. In addition, the horizontal wall segments above the openings are reinforced with minimum (prescribed) reinforcement and were assumed not to control the design outcome.

With a clear height of 8 ft and a length of 4 ft, wall C is stiffer than walls A and B; therefore, wall C takes a higher fraction of the base shear and dominates the response of the wall configuration. Reinforcement options in Table 3.4 are presented in order of increased amount of reinforcement (from options R1 to R10). The maximum base shear that can be resisted by the wall configuration when reinforced with option R1 is controlled by the flexural strength at the base of wall C even though none of the walls include shear reinforcement.
Reinforcement options R2, R3, R4, and R5 correspond to a gradual increase of the vertical reinforcement in walls A and C, but higher amounts of vertical reinforcement did not change the design base shear that may be tolerated by the wall configuration using ASD code provisions. Design was controlled by the shear strength at the bottom of wall C.

Reinforcement options R6, R7, and R8 consider the addition of horizontal shear reinforcement in walls A and C while maintaining the same vertical reinforcement as in options R2, R3, and R4, respectively. The additional horizontal shear reinforcement changed the controlling action in wall C from shear in options R2 to R4 to flexure in options R6 to R8.

Reinforcement option R9, with the same vertical reinforcement as option R5, considers the addition of horizontal shear reinforcement in walls A and C. For this condition, the flexural strength at bottom of wall B was the controlling action. In reinforcement option R10, the increase in vertical reinforcement of wall B shifted the controlling action to flexure at the bottom of wall C.

The application of ASD code provisions of MSJC (2011) to the 10 reinforcement options of case study A, shows that flexural strength or shear strength of the wall segments controlled the maximum design seismic base shear. In all cases, the controlling load case was $0.9D – E/1.4$. Provisions of $\rho_{\text{max}}$ in MSJC 2011 Section 2.3.4.4 did not control the seismic base shear for any of the reinforcement options considered.

### 3.4 Strength Design

Spreadsheet formulations were developed incorporating the Strength Design (SD) provisions of the MSJC (2011) code, see Section C.2 in Appendix C of this thesis. The spreadsheet checks the provisions related to combined axial, flexure, and shear forces that apply to the design of special reinforced masonry shear walls, including those related to special
boundary element requirements and maximum ratio of flexural tensile reinforcement, $\rho_{\text{max}}$. For case study A, the check for the need of special boundary elements are based on the rapid screening of MSJC 2011 Section 3.3.6.5.1 and the boundary stress check of Section 3.3.6.5.4. Section 3.3.6.5.3 does not apply because none of the walls (A, B, or C) are in single curvature bending. If special boundary elements are required and the provisions of $\rho_{\text{max}}$ (Section 3.3.3.5) are not satisfied, then the wall is considered noncompliant with SD.

For a given reinforcement option, Table 3.4 reports the maximum lateral seismic forces that may be applied to the wall configuration without failing the SD code requirements. It is important to clarify that the data in Table 3.4 neglect the contribution of the minimum prescribed reinforcement of MSJC 2011 Section 1.18 for special reinforced masonry shear walls. Additionally, the horizontal wall segments above the openings are reinforced with minimum (prescribed) reinforcement and were assumed not to control the design outcome.

Reinforcement options R1, R2, and R3 correspond to a gradual increase of the vertical reinforcement in walls A and C. The maximum design base shears (Table 3.4) were controlled by the flexural strength at the base of wall C even though none of the walls include shear reinforcement. Reinforcement options R4 and R5, also without shear reinforcement, were controlled by the shear strength of wall C and led to a seismic base shear lower than that for option R3. The shear demand in SD is tied to the flexural strength of the wall following Section 1.18.3.2.6.1.1 of MSJC (2011), which controls in options R4 and R5.

Reinforcement options R6, R7, and R8 consider the addition of horizontal shear reinforcement in walls A and C while maintaining the same vertical reinforcement as in options R2, R3, and R4, respectively. Due to the addition of horizontal reinforcement shear was not the controlling action. Flexural strength of wall C controlled the seismic base shear.

Reinforcement option R9, with the same vertical reinforcement as option R5, considers the addition of horizontal shear reinforcement in walls A and C. For this condition, the flexural
strength at bottom of wall B was the controlling action. In reinforcement option R10, the increase in vertical reinforcement of wall B shifted the controlling action to shear at the bottom of wall C.

The application of SD code provisions of MSJC (2011) to the 10 reinforcement options of case study A, shows that flexural strength or shear strength of the wall segments controlled the maximum design seismic base shear. In all cases, the controlling load case was $0.9D - E$. Checks related to $\rho_{max}$ (MSJC 2011 Section 3.3.3.5) or the special boundary element provisions (MSJC 2011 Sections 3.3.6.5.1 and 3.3.6.5.2) did not control the seismic base shear for any of the reinforcement options.

### 3.5 Limit Design

The seismic base shear capacities for case study A were also determined following the Limit Design (LD) code provisions presented in Chapter 2. Spreadsheet formulations were developed to check the provisions related to combined axial, flexure, and shear forces that apply to the design of special reinforced masonry shear walls. For this purpose, LD refers to the provisions that support SD in the MSJC (2011) code. Representative set of calculations are included in Section C.3 (Appendix C of this thesis). The spreadsheet determines: the plastic hinge strength at potential hinge locations; the strength of the assumed mechanism; and the deformation capacity of the yielding wall segments. Both the hinge strengths and deformation capacities are adjusted for the case of shear-controlled walls. A wall segment is defined shear controlled when the shear demand exceeds half of its nominal shear strength, refer to Section X.1 item (d) in Table 2.1.

For a given reinforcement option, Table 3.4 reports the maximum lateral seismic forces that may be applied to the wall configuration without failing the LD code requirements. It is important to clarify that the data in Table 3.4 neglect the contribution of the minimum prescribed reinforcement of MSJC 2011 Section 1.18 for special reinforced masonry shear walls.
Additionally, the horizontal wall segments above the openings are reinforced with minimum (prescribed) reinforcement and were assumed to remain elastic and therefore did not control the design outcome of case study A. For all reinforcement options, the yield mechanism in Figure 3.3 was used to determine the mechanism strength.

Reinforcement options R1, R2, R3, R4, and R5 correspond to a gradual increase of the vertical reinforcement in walls A and C without horizontal shear reinforcement. The maximum design base shears for LD are shown in Table 3.4. The most lightly reinforced option, R1, was controlled by the mechanism strength. Options R2 to R5 were controlled by the reduced deformation capacity assigned to shear-controlled wall C.

Reinforcement options R6 and R7 consider the addition of horizontal shear reinforcement in walls A and C while maintaining the same vertical reinforcement as in options R2 and R3, respectively. Due to the addition of horizontal reinforcement shear was not the controlling action. The mechanism strength controlled the seismic base shear.

Reinforcement options R8 and R9, with the same vertical reinforcement as options R4 and R5, considers the addition of horizontal shear reinforcement in walls A and C. For these conditions, wall C was shear controlled and the seismic base shear was controlled by the displacement limit. In reinforcement option R10, the increase in vertical reinforcement of wall B did not change the shear-controlled condition of wall C.

The application of LD code provisions of MSJC (2011) to the 10 reinforcement options of case study A, shows that the reduced deformation capacity of shear-controlled wall segments or the mechanism strength controlled the maximum design seismic base shear. The mechanism strength controlled the seismic base shear in cases where none of the walls were shear controlled.
Figure 3.4 shows a summary of the seismic base shear per design method that can be resisted by the wall configuration of case study A.

### 3.6 Nonlinear Static Analysis

Nonlinear analyses were performed with program SAP2000 (CSI, 2011b) for the wall structure of case study A using the modeling approach described in Appendix B for both the Nonlinear Layer model and Nonlinear Link model. In addition, a refined Nonlinear Layer model was developed only for reinforcement options R1 and R10. The refined model used a reduced mesh of 4 in. by 4 in., extended the nonlinear area elements throughout the clear length and joints of the wall segments (i.e., all area elements included nonlinear layer definitions), and included the tensile strength of the masonry (with a zero post-peak residual stress). A summary of the calculated base shear strength for the different models is shown in Table 3.5 and Table 3.6, see also Figure 3.5. The base shear strength for the Layer and Link models is determined (arbitrarily) from the shear vs. roof displacement curves (Figures 3.6 to 3.49) using the last point on the curve where the slope exceeds 5% of the initial slope (at the origin). Table 3.7 gives brief observations on selected nonlinear analysis results.

The summary of calculated base shear strengths presented in Figure 3.5 indicates that the base shear strength calculated using provisions of Limit Design (Table 2.1) has ample safety margin when compared with the calculated base shear strength using the Nonlinear Layer and Nonlinear Link models.
CHAPTER 4
CASE STUDY B: MULTI-STORY WALL WITH LARGE OPENING AT BASE

A five-story wall with a large first-story opening is designed as a special reinforced masonry shear wall using three methods: Allowable Stress Design (ASD), Strength Design (SD), and Limit Design (LD). The ASD and SD methods follow the MSJC code (2011) while LD follows Chapter 2 of this thesis. This case study considers a total of five reinforcement options. For each of the reinforcement options, the maximum seismic forces that can be resisted are determined for the three design methods and the controlling design provisions are identified. Design forces and displacements are obtained from linear-elastic analysis. The controlling yield mechanism and base shear strength of the wall configuration, for all five reinforcement options, are determined using the nonlinear static analysis procedure described in Appendix B.

4.1 Description

The structure of case study B is classified as a special reinforced masonry shear wall per ASCE/SEI 7-10 (2010) and in compliance with the detailing and reinforcement requirements of MSJC (2011). Details of the structure are presented in Figure 4.1 with descriptions of materials, loads, and seismic design parameters. Seismic story forces are assumed proportional to story elevations.

Case study B is a five-story wall structure. Two vertical wall segments are defined by the presence of a single large opening in the first story. The walls are labeled A and B (from left to right), each 8-ft long. The clear height of the vertical wall segments is 10 ft in the first story. The overall length of the wall configuration is 40 ft with a total height of 54 ft. The roof diaphragm is attached at an elevation of 52 ft from ground level. The structure is assumed fixed at the base.
Table 4.1 describes the five reinforcement options considered in case study B. The description is limited to flexural and shear reinforcements of the two walls (A and B) defined by the opening. Additional information required for designing the walls is included in Figure 4.1.

4.2 Linear-Elastic Analysis

For the structure of case study B, a two-dimensional (2D) linear-elastic model is developed using program SAP2000 (CSI, 2011b), see Figure 4.2. The linear elastic model is presented as a reference model to obtain design forces (Table 4.2) and displacements needed for the application of the various design methods (ASD, SD, and LD) presented below in Sections 4.3 to 4.5. It is assumed that the 2D models used in this study incorporate the interaction with other lines of resistance and torsional effects, as required in ASCE/SEI 7-10 (2010).

The following general assumptions and simplifications were involved in developing the 2D linear-elastic model of case study B:

- The structure, loads, and response are defined in one vertical plane.
- Structural response accounts for the effects of shear, axial, and flexural deformations.
- The wall segments are modeled using area elements with an 8-in. square mesh. This mesh size allows a direct representation of the modular dimensions of the standard concrete masonry unit (two-core 8×8×16-in. block).
- To consider the effects of cracked sections, stiffness properties are based on 50% of gross section properties.
- The foundation of the structure is rigid. The wall configuration is fixed at the ground level.
- All nodes at floor and roof levels are constrained by rigid diaphragms.
- Dead, live, and seismic loads are assigned at diaphragm levels. The gravity loads are distributed tributary to the area involving each node at a given diaphragm level.
- $P$-$\Delta$ effects are neglected.
The effects of meshing the area elements were evaluated in Chapter 3 for case study A, refer to Table 3.3 and Figure 3.2. Typically, the stiffness of the model with an 8-in. square mesh does not differ by more than 3% from the model with a 1-in. square mesh, indicating that adopting an 8-in. square mesh is sufficiently accurate.

### 4.3 Allowable Stress Design

Spreadsheet formulations, similar to those presented in Appendix C of this thesis, were developed incorporating the Allowable Stress Design (ASD) provisions of the MSJC (2011) code. The spreadsheet checks the provisions related to combined axial, flexure, and shear forces that apply to the design of special reinforced masonry shear walls, including those related to maximum ratio of flexural tensile reinforcement, $\rho_{max}$.

For a given reinforcement option, Table 4.3 reports the maximum lateral seismic forces that may be applied to the wall configuration without failing the ASD code requirements. Two design scenarios are evaluated depending on how the structure is conceptualized, as a single wall (cantilever action) or as two walls. The reported seismic base shears are associated with $1.0E$ but ASD provisions were checked using $E/1.4$. It is important to clarify that the data in Table 4.3 neglect the contribution of the minimum prescribed reinforcement of MSJC 2011 Section 1.18 for special reinforced masonry shear walls. In addition, the wall segment above the opening is reinforced with minimum (prescribed) reinforcement and was assumed not to control the design outcome.

Reinforcement options in Table 4.3 are presented in order of increased amount of reinforcement (from options R1 to R5). For all reinforcement options, the maximum base shear that can be resisted by the wall configuration is controlled by the ASD code provisions related to wall shear strength. Note that the additional vertical reinforcement in option R2 did not provide additional base shear capacity in relation to option R1. The seismic base shears assigned to the structure, conceptualized as a single cantilever wall, were higher than when
conceptualized as two walls. When conceptualized as a cantilever wall, the effects of axial forces (due to seismic overturning) on wall shear strength were neglected.

Reinforcement options R3 to R5 consider the use of a fixed amount of horizontal shear reinforcement while increasing the vertical reinforcement. Because the controlling action was shear, the increase in vertical reinforcement did not increase the seismic base shear. The wall configuration conceptualized as a single cantilever wall led to higher design base shear than when conceptualized as two walls.

The application of ASD code provisions of MSJC (2011) to the five reinforcement options of case study B, shows that shear strength of the wall segments controlled the maximum design seismic base shear. In all cases, the controlling load case was $0.9D – E/1.4$.

4.4 Strength Design

Spreadsheet formulations, similar to those presented in Appendix C of this thesis, were developed incorporating the Strength Design (SD) provisions of the MSJC (2011) code. The spreadsheet checks the provisions related to combined axial, flexure, and shear forces that apply to the design of special reinforced masonry shear walls, including those related to special boundary element requirements and maximum ratio of flexural tensile reinforcement, $\rho_{\text{max}}$. For case study B, the check for the need of special boundary elements are based on the rapid screening of MSJC 2011 Section 3.3.6.5.1, the neutral axis depth of Section 3.3.6.5.3, and the boundary stress check of Section 3.3.6.5.4. Section 3.3.6.5.3 is applied to the case of the wall structure conceptualized as a single cantilever wall, whereas Section 3.3.6.5.4 is applied to the case of the wall structure conceptualized as two walls. If special boundary elements are required and the provisions of $\rho_{\text{max}}$ (Section 3.3.3.5) are not satisfied, then the wall is considered noncompliant with SD.
For a given reinforcement option, Table 4.3 reports the maximum lateral seismic forces that may be applied to the wall configuration without failing the SD code requirements. It is important to clarify that the data in Table 4.3 neglect the contribution of the minimum prescribed reinforcement of MSJC 2011 Section 1.18 for special reinforced masonry shear walls. Additionally, the wall segment above the opening is reinforced with minimum (prescribed) reinforcement and was assumed not to control the design outcome.

Reinforcement options in Table 4.3 are presented in order of increased amount of reinforcement (from options R1 to R5). For all reinforcement options, the maximum base shear that can be resisted by the wall configuration is controlled by the SD code provisions related to wall shear strength. Note that the additional vertical reinforcement in option R2 did not provide additional base shear capacity in relation to option R1. For these reinforcement options (R1 and R2), the seismic base shears assigned to the structure, conceptualized as a single cantilever wall, was higher than when conceptualized as two walls. When conceptualized as a cantilever wall, the effects of axial forces (due to seismic overturning) on wall shear strength were neglected.

Reinforcement options R3 to R5 consider the use of a fixed amount of horizontal shear reinforcement while increasing the vertical reinforcement. Because the controlling action was shear, the increase in vertical reinforcement did not increase the seismic base shear. For these reinforcement options (R3 to R5), the wall configuration conceptualized as a single cantilever wall led to slightly lower seismic base shear than when conceptualized as two walls, mainly due to the cap on maximum shear stress which is a function of $M/Vd$, refer to MSJC 2011 Section 3.3.4.1.2 items (a) through (d).

The application of SD code provisions of MSJC (2011) to the five reinforcement options of case study B, shows that shear strength of the wall segments controlled the maximum design seismic base shear. In all cases, the controlling load case was $0.9D – E$. 
The seismic base shear capacities for case study B were also determined following the Limit Design (LD) code provisions presented in Chapter 2. Spreadsheet formulations were developed, similar to those presented in Appendix C (Section C.3), to check the provisions related to combined axial, flexure, and shear forces that apply to the design of special reinforced masonry shear walls. For this purpose, LD refers to the provisions that support SD in the MSJC (2011) code. The spreadsheet determines: the plastic hinge strength at potential hinge locations; the strength of the assumed mechanism; and the deformation capacity of the yielding wall segments. Both the hinge strengths and deformation capacities are adjusted for the case of shear-controlled walls. A wall segment is defined shear controlled when the shear demand exceeds half of its nominal shear strength, refer to Section X.1 item (d) in Table 2.1.

For a given reinforcement option, Table 4.3 reports the maximum lateral seismic forces that may be applied to the wall configuration without failing the LD code requirements. It is important to clarify that the data in Table 4.3 neglect the contribution of the minimum prescribed reinforcement of MSJC 2011 Section 1.18 for special reinforced masonry shear walls. Additionally, the wall segment above the opening is reinforced with minimum (prescribed) reinforcement and was assumed to remain elastic and therefore did not control the design outcome of case study B. For all reinforcement options, the yield mechanism in Figure 4.3 was used to determine the mechanism strength.

Reinforcement options in Table 4.3 are presented in order of increased amount of reinforcement (from options R1 to R5). The controlling mechanism is associated with the wall acting as a single cantilever wall, and therefore LD is not applied for the case of the wall structure conceptualized as two walls (which would lead to a first story mechanism).

The most lightly reinforced option, R1, was controlled by the mechanism strength. Option R2 led to a shear demand (associated with global base hinging) greater than the shear
Nonlinear analyses were performed with program SAP2000 (CSI, 2011b) for the wall structure of case study B using the modeling approach described in Appendix B for both the Nonlinear Layer model and Nonlinear Link model. In addition, a refined Nonlinear Layer model was developed only for reinforcement options R1 and R5. The refined model used a reduced mesh of 4 in. by 4 in., extended the nonlinear area elements throughout the clear length and joints of the wall segments (i.e., all area elements included nonlinear layer definitions), and included the tensile strength of the masonry (with a zero post-peak residual stress). A summary of the calculated base shear strength for the different models is shown in Table 4.4 and Table 4.5, see also Figure 4.5. The base shear strength for the Layer and Link models is determined (arbitrarily) from the shear vs. roof displacement curves (Figures 4.6 to 4.17) using the last point on the curve where the slope exceeds 5% of the initial slope (at the origin). Table 4.6 gives brief observations on selected nonlinear analysis results.
The summary of calculated base shear strengths presented in Figure 4.5 indicates that the base shear strength calculated using provisions of Limit Design (Table 2.1) has ample safety margin when compared with the calculated base shear strength using the Nonlinear Layer and Nonlinear Link models.
CHAPTER 5
CASE STUDY C: MULTI-STORY COUPLED SHEAR WALLS

A five-story wall configuration, consisting of a symmetrical arrangement of two walls connected with beams at each story, is designed as a special reinforced masonry shear wall system. Three methods of design are used: Allowable Stress Design (ASD), Strength Design (SD), and Limit Design (LD). The ASD and SD methods follow the MSJC code (2011) while LD follows Chapter 2 of this thesis. This case study considers a total of seven reinforcement options. For each of the reinforcement options, the maximum seismic forces that can be resisted are determined for the three design methods and the controlling design provisions are identified. Design forces and displacements are obtained from linear-elastic analysis. The controlling yield mechanism and base shear strength of the wall configuration, for all seven reinforcement options, are determined using the nonlinear static analysis procedure described in Appendix B.

5.1 Description

The structure of case study C is classified as a special reinforced masonry shear wall per ASCE/SEI 7-10 (2010) and in compliance with the detailing and reinforcement requirements of MSJC (2011). Details of the structure are presented in Figure 5.1 with descriptions of materials, loads, and seismic design parameters. Seismic story forces are assumed proportional to story elevations.

Case study C is a five-story coupled wall structure. Two vertical wall segments are defined by the presence of a single large opening at every story. The walls are labeled A and B (from left to right), each 8-ft long. The clear height of the vertical wall segments is 10 ft in the first story and 8 ft in all other stories. The overall length of the wall configuration is 40 ft with a total height of 54 ft. The roof diaphragm is attached at an elevation of 52 ft from ground level. The structure is assumed fixed at the base.
Table 5.1 describes the seven reinforcement options considered in case study C. The descriptions are limited to flexural and shear reinforcements of the walls and beams defined by the openings. Additional information required for designing the walls is included in Figure 5.1.

5.2 Linear-Elastic Analysis

For the structure of case study C, a two-dimensional (2D) linear-elastic model is developed using program SAP2000 (CSI, 2011b), see Figure 5.2. The linear elastic model is presented as a reference model to obtain design forces (Table 5.2) and displacements needed for the application of the various design methods (ASD, SD, and LD) presented below in Sections 5.3 to 5.5. It is assumed that the 2D models used in this study incorporate the interaction with other lines of resistance and torsional effects, as required in ASCE/SEI 7-10 (2010).

The following general assumptions and simplifications were involved in developing the 2D linear-elastic model of case study C:

- The structure, loads, and response are defined in one vertical plane.
- Structural response accounts for the effects of shear, axial, and flexural deformations.
- The wall segments are modeled using area elements with an 8-in. square mesh. This mesh size allows a direct representation of the modular dimensions of the standard concrete masonry unit (two-core 8×8×16-in. block).
- To consider the effects of cracked sections, stiffness properties are based on 50% of gross section properties.
- The foundation of the structure is rigid. The wall configuration is fixed at the ground level.
- All nodes at floor and roof levels are constrained by rigid diaphragms.
- Dead, live, and seismic loads are assigned at diaphragm levels. The gravity loads are distributed tributary to the area involving each node at a given diaphragm level.
- $P$-$\Delta$ effects are neglected.
The effects of meshing the area elements were evaluated in Chapter 3 for case study A, refer to Table 3.3 and Figure 3.2. Typically, the stiffness of the model with an 8-in. square mesh does not differ by more than 3% from the model with a 1-in. square mesh, indicating that adopting an 8-in. square mesh is sufficiently accurate.

5.3 Allowable Stress Design

Spreadsheet formulations, similar to those presented in Appendix C of this thesis, were developed incorporating the Allowable Stress Design (ASD) provisions of the MSJC (2011) code. The spreadsheet checks the provisions related to combined axial, flexure, and shear forces that apply to the design of special reinforced masonry shear walls, including those related to maximum ratio of flexural tensile reinforcement, $\rho_{\text{max}}$.

For a given reinforcement option, Table 5.3 reports the maximum lateral seismic forces that may be applied to the wall configuration without failing the ASD code requirements. The reported seismic base shears are associated with $1.0E$ but ASD provisions were checked using $E/1.4$. It is important to clarify that the data in Table 5.3 neglect the contribution of the minimum prescribed reinforcement of MSJC 2011 Section 1.18 for special reinforced masonry shear walls.

Reinforcement options in Table 5.3 are presented in order of increased amount of reinforcement (from options R1 to R7). Reinforcement options R1 and R2 only differ in the amount of flexural reinforcement in the coupling beams. Both options do not include horizontal shear reinforcement in the supporting walls but the strength of the structure was controlled by the flexural strength of the coupling beams.

Reinforcement options R3, R4, and R5 only differ in the amount of flexural reinforcement in the supporting walls. Shear reinforcement is provided in both the walls and
the beams. The strength of the structure continued to be controlled by the flexural strength of the coupling beams.

Reinforcement options R6 and R7 only differ in the amount of flexural reinforcement in the coupling beams. These options have the beams more heavily reinforced than the previous options changing the controlling action to shear strength of the coupling beams.

The application of ASD code provisions of MSJC (2011) to the seven reinforcement options of case study C, shows that flexural strength or shear strength of the coupling beams controlled the maximum design seismic base shear. The governing load case was $1.0D + 1.0L + E/1.4$.

5.4 Strength Design

Spreadsheet formulations, similar to those presented in Appendix C of this thesis, were developed incorporating the Strength Design (SD) provisions of the MSJC (2011) code. The spreadsheet checks the provisions related to combined axial, flexure, and shear forces that apply to the design of special reinforced masonry shear walls, including those related to special boundary element requirements and maximum ratio of flexural tensile reinforcement, $\rho_{\text{max}}$. For case study C, the check for the need of special boundary elements are based on the rapid screening of MSJC 2011 Section 3.3.6.5.1 and the boundary stress check of Section 3.3.6.5.4. Section 3.3.6.5.3 does not apply because none of the wall segments are in single curvature bending. If special boundary elements are required and the provisions of $\rho_{\text{max}}$ (Section 3.3.3.5) are not satisfied, then the wall is considered noncompliant with SD.

For a given reinforcement option, Table 5.3 reports the maximum lateral seismic forces that may be applied to the wall configuration without failing the SD code requirements. It is important to clarify that the data in Table 5.3 neglect the contribution of the minimum prescribed reinforcement of MSJC 2011 Section 1.18 for special reinforced masonry shear walls.
Reinforcement options in Table 5.3 are presented in order of increased amount of reinforcement (from options R1 to R7). Reinforcement options R1 and R2 only differ in the amount of flexural reinforcement in the coupling beams. Both options do not include horizontal shear reinforcement in the supporting walls but the strength of the structure was controlled by the flexural strength of the coupling beams.

Reinforcement options R3, R4, and R5 only differ in the amount of flexural reinforcement in the supporting walls. Shear reinforcement is provided in both the walls and the beams. The strength of the structure in option R3 continued to be controlled by the flexural strength of the coupling beams; however, options R4 and R5 were controlled by the supporting walls: $\rho_{\text{max}}$ provisions (MSJC 2011 Section 3.3.3.5) controlled option R4 while the special boundary element provisions (MSJC 2011 Section 3.3.6.5.4) controlled option R5.

Reinforcement options R6 and R7 only differ in the amount of flexural reinforcement in the coupling beams. These options have the beams more heavily reinforced than the previous options. The special boundary element requirements in the supporting walls (MSJC 2011 Section 3.3.6.5.4) controlled the design.

The application of SD code provisions of MSJC (2011) to the seven reinforcement options of case study C, shows that the flexural strength of coupling beams or the requirements for special boundary elements in the supporting walls controlled the maximum design seismic base shear. In all cases, the governing load case was $1.2D + 0.5L + E$.

5.5 Limit Design

The seismic base shear capacities for case study C were also determined following the Limit Design (LD) code provisions presented in Chapter 2. Spreadsheet formulations were developed, similar to those presented in Appendix C (Section C.3), to check the provisions
related to combined axial, flexure, and shear forces that apply to the design of special reinforced masonry shear walls. For this purpose, LD refers to the provisions that support SD in the MSJC (2011) code. The spreadsheet determines: the plastic hinge strength at potential hinge locations; the strength of the assumed mechanism; and the deformation capacity of the yielding wall segments. Both the hinge strengths and deformation capacities are adjusted for the case of shear-controlled walls. A wall segment is defined shear controlled when the shear demand exceeds half of its nominal shear strength, refer to Section X.1 item (d) in Table 2.1.

For a given reinforcement option, Table 5.3 reports the maximum lateral seismic forces that may be applied to the wall configuration without failing the LD code requirements. It is important to clarify that the data in Table 5.3 neglect the contribution of the minimum prescribed reinforcement of MSJC 2011 Section 1.18 for special reinforced masonry shear walls. Reinforcement options in Table 5.3 are presented in order of increased amount of reinforcement (from options R1 to R7). For all reinforcement options, the yield mechanism in Figure 5.3 was used to determine the mechanism strength.

Reinforcement options R1 to R5 were all controlled by the deformation capacity at the base of the first-story walls. For these reinforcement options, all wall segments led to flexure-controlled conditions. Increasing the amount of vertical reinforcement (from option R1 to R5) at the base of the structure did not increase the capacity of the structure (the neutral axis depth arrests the deformation capacity).

Options R6 and R7 led to shear-controlled beams with reduced deformation capacities. The maximum seismic base shear that can be assigned to options R6 and R7 were lower than options R1 to R5.

The application of LD code provisions of MSJC (2011) to the seven reinforcement options of case study C, shows that the calculated deformation capacities of the wall segments
controlled the maximum design seismic base shear, even for reinforcement options that did not trigger shear-controlled conditions.

Figure 5.4 shows a summary of the seismic base shear per design method that can be resisted by the wall configuration of case study C.

5.6 Nonlinear Static Analysis

Nonlinear analyses were performed with program SAP2000 (CSI, 2011b) for the wall structure of case study C using the modeling approach described in Appendix B for both the Nonlinear Layer model and Nonlinear Link model. In addition, a refined Nonlinear Layer model was developed only for reinforcement options R1 and R7. The refined model used a reduced mesh of 4 in. by 4 in., extended the nonlinear area elements throughout the clear length and joints of the wall segments (i.e., all area elements included nonlinear layer definitions), and included the tensile strength of the masonry (with a zero post-peak residual stress). A summary of the calculated base shear strength for the different models is shown in Table 5.4 and Table 5.5, see also Figure 5.5. The base shear strength for the Layer and Link models is determined (arbitrarily) from the shear vs. roof displacement curves (Figures 5.6 to 5.21) using the last point on the curve where the slope exceeds 5% of the initial slope (at the origin). Beam shear vs. Roof displacement curves are presented in Figure 5.22 to 5.37. Table 5.6 gives brief observations on selected nonlinear analysis results.

The summary of calculated base shear strengths presented in Figure 5.5 indicates that the base shear strength calculated using provisions of Limit Design (Table 2.1) has ample safety margin when compared with the calculated base shear strength using the Nonlinear Layer and Nonlinear Link models.
CHAPTER 6
CASE STUDY D: SMALL-SCALE TEST STRUCTURES

The outcome of Limit Design in the previous three chapters was conveniently expressed in terms of the seismic base shear that can be safely assigned to the masonry structures studied. In this chapter, the Limit Design methodology is applied to three small-scale test structures and its outcome is compared with the measured test data.

The experiments on structures RM1, RM2, and RM3 by Paulson and Abrams (1990) were performed to study the dynamic and static response characteristics of reinforced masonry building structures. Structures RM1 and RM3 were subjected to simulated ground motions and structure RM2 (a replica of RM1) was subjected to static lateral loading.

This chapter aims to provide a basic experimental validation of the Limit Design methodology. The calculated limiting base shear, $V_{\text{lim}}$, for each of the test structures, is compared with the measured response.

In addition, Nonlinear Layer and Nonlinear Link models (described in Appendix B) were developed for each of the test structures to determine their plastic base shear strength, $V_p$. The results from these models were also compared with the experimental data.

6.1 Description

Three small-scale masonry structures (RM1, RM2, and RM3) were tested by Paulson and Abrams (1990). Two of the structures, RM1 and RM3, were subjected to unidirectional base motions on The University of Illinois Earthquake Simulator (Sozen et al., 1969). Structure RM2 was subjected to lateral forces applied with computer-controlled hydraulic actuators targeting the same roof displacement histories (at static rates) that were recorded for structure RM1.
during simulated earthquake motions. The focus of the study by Paulson and Abrams was on the response of the structures in the nonlinear range.

The test structures were built at one-quarter scale with different configurations as shown in Figures 6.1, 6.2, and 6.3. Each test structure consisted of two perforated flanged walls in parallel. The walls were coupled by reinforced concrete floor slabs. Structures RM1 and RM2 had the same masonry wall configuration with a symmetrical pattern of window openings. The masonry wall configuration of structure RM3 had an asymmetrical pattern of window and door openings.

The typical construction of the specimens used 2×2×4-in. (nominal dimensions) hollow concrete blocks, fully grouted, with uniformly distributed vertical and horizontal reinforcement, see Figure 6.4. Horizontal and vertical reinforcement consisted of No. 11-gage steel wire (diameter = 0.121 in.). Reinforcement schedules are shown in Table 6.1 and material properties are summarized in Table 6.2. The average compressive strength of masonry, $f_m'$, from three-unit prisms was 1,215 psi for RM1 and RM2, and 1228 psi for RM3. Direct tension tests on wire coupons resulted in a mean yield strength, $f_y$, of 47 ksi and a mean tensile strength, $f_u$, of 61 ksi.

Structures RM1 and RM2 were constructed identically. The vertical reinforcement ratio was 0.15%. The horizontal reinforcement was spaced at every 6 in. on center for a horizontal reinforcement ratio of 0.10%. The wall configuration and steel reinforcement layout for these structures are shown in Figure 6.5.

Structure RM3 had narrower flanges than those of structures RM1 and RM2. All wall segments had vertical reinforcement ratios of 0.15%. Horizontal reinforcement ratios were 0.30% for walls A and B (short walls) and 0.15% for wall C. The structural configuration and steel reinforcement layout for this structure are shown in Figure 6.6. Further details of structural properties and test setups for structures RM1, RM2, and RM3, are provided in the report by Paulson and Abrams (1990).
6.2 Linear-Elastic Analysis

For structures RM1, RM2, and RM3, a three-dimensional computer model was developed using program SAP2000 (CSI, 2011b). This model is also used as the base model for the nonlinear static analysis of the test structures presented in Section 6.8.

The following general assumptions and simplifications were involved in developing the linear-elastic model of the test structures considered:

- The structure, loads, and response are defined in the vertical planes that define the wall webs (one XZ plane) and flanges (two YZ planes). The translational degree of freedom in the Y direction is inactive. Lateral loads representing seismic effects are applied in the X direction.
- Structural response accounts for the effects of shear, axial, and flexural deformations.
- The wall segments are modeled using area elements with a typical 2-in. square mesh. This mesh size allows a direct representation of the modular dimensions of the concrete masonry units (two-core 2×2×4-in. block). The web-flange intersections are defined using 1×2-in. area sections, and the intersection of wall segments with floor slabs are modeled with 1.5×2-in. area sections or 1.5×1-in. area sections.
- Stiffness properties are based on measured material properties.
- The foundation of the structure is rigid. The wall configuration is fixed at the ground level.
- Nodes at floor and roof levels are constrained by rigid diaphragms.
- Dead, live, and seismic loads are assigned at diaphragm levels. The gravity loads are distributed tributary to the area involving each node at a given diaphragm level.
- $P$-$\Delta$ effects are neglected.

The effects of meshing the area elements were evaluated in Chapter 3 for case study A, refer to Table 3.3 and Figure 3.2. The stiffness of the model for case study A with an 8-in.
square mesh did not differ by more than 3% from the model with a 1-in. square mesh, suggesting that a 2-in square mesh for the one-quarter scale test structures is sufficiently accurate.

6.3 Dynamic Properties

Small-amplitude free vibration tests were conducted by Paulson and Abrams (1990) to evaluate the natural frequency and damping of structures RM1 and RM3. Table 6.3 contains the measured and calculated first-mode frequencies of vibration. The calculated values correspond to the linear-elastic model described in Section 6.2. In general, the measured response (before any earthquake simulation) indicates that the models based on gross-section properties are stiffer than the actual test structures.

6.4 Observed Dynamic Response

The goal of the experiments by Paulson and Abrams (1990) was to excite the test structures similarly to the shaking of actual structures in real earthquakes. The input motion used for the earthquake simulations was based on the north-south accelerations measured at El Centro in 1940 during the Imperial Valley Earthquake. The time duration of the input motion was compressed by a factor of 2.5 which was approximately the ratio of the natural periods of vibration of a hypothetical full-scale three-story reinforced masonry wall structure and that for the reduced-scale structures.

Test runs included repetitions of free vibration test, to determine low-amplitude natural frequencies, followed by earthquake simulation. The sequence was repeated with the amplitude of the input base motion increased in successive runs. During test runs, displacements and accelerations were measured at all three levels.
Base shear and roof displacement histories during the last runs for structures RM1 and RM3 are shown in Figures 6.7 and 6.8. The figures show that the most prominent sequence of large amplitude response occurred in the first 3 seconds of shaking. The maximum measured base shear for structures RM1 and RM2 occurred around the 1 second mark. A summary of the maximum measured base shear for the test structures is presented in Table 6.4.

6.5 Observed Static Response

Structure RM2 was subjected to the recorded displacement history for structure RM1 during earthquake simulations. Paulson and Abrams (1990) developed a computerized loading system for the static tests. The loading protocol involved sending displacement command signals to the third-level actuator, from which the third-level force was measured and used as the basis for forces to be applied at the two lower levels such that an inverted triangular force distribution would result.

The loading rate applied to structure RM2 was considered static because the duration of each test run was approximately six to eight hours. In contrast, the duration of each dynamic test run applied to structures RM1 and RM3 was approximately 20 seconds with a loading rate in the range of 10 to 20 inches per second.

A summary of the maximum measured base shear for the test structures is presented in Table 6.4. The statically loaded structure RM2 achieved a peak base shear of nearly 2/3 of that reached by the dynamically loaded structure RM1. It is likely that the difference in strength was due to the rate of loading.

6.6 Observed Damage

The final damage pattern for one side of structures RM1, RM2, and RM3 are shown in Figures 6.9, 6.10, and 6.11, respectively. The crack pattern of structure RM1 shows significant
diagonal cracking, especially in the exterior walls. The orientation of the diagonal cracks corresponds to conditions of combined shear and axial compression. Paulson and Abrams (1990) observed that flexural cracking along a joint at the top of the first-story walls may have permitted sliding along this joint. As a consequence, much of the story shear was resisted by the one exterior wall which was in axial compression.

A comparison of crack patterns of twin structures RM1 and RM2 after the last run shows that the extent of damage for RM2 (statically loaded) was more severe than for RM1 (dynamically loaded), see Figures 6.9 and 6.10. Structure RM1 was initially both stronger and stiffer than structure RM2, and with successive cycles, RM1 suffered less deterioration in strength and stiffness. Observed damage in structure RM1 was much less than in structure RM2 despite the fact that RM1 resisted larger forces.

In structure RM3, hinging of the two short walls was prevalent during the last two earthquake simulations (Run 5 and Run 6) which led to crushing of the masonry in localized areas at the top and bottom of these walls. The final crack pattern of structure RM3 (Figure 6.11) shows that the slender exterior wall sustained diagonal cracking during the last simulation, an indication that the available strength of the two short walls had been severely reduced.

6.7 Limit Design

Limiting base shear strengths were determined for the test structures using the Limit Design methodology based on Chapter 2. The controlling mechanisms used in the calculations are shown in Figures 6.12 and 6.13. The resulting base shear strengths are shown in Tables 6.5 and 6.6 assuming a strength reduction factor of one, $\phi = 1$. Determining the controlling yield mechanism required the consideration of two sets of plastic hinge strengths to account for the different capacities of the L-shaped walls depending on the direction of loading (eastward vs. westward).
The calculated mechanism strength, $V_{lim}$, was based on flexural strengths of plastic hinges corresponding to unfactored axial loads due to the actual weight of the test structures (reported by Paulson and Abrams, 1990). All of the test structures resulted with shear-controlled wall segments. The reduced displacement capacities of shear-controlled walls led to the adjusted mechanism strength, $V'_{lim}$. Note the severe reduction in base shear strength after triggering a shear-controlled condition.

### 6.8 Nonlinear Static Analysis

Nonlinear static analyses were conducted for the test structures using the nonlinear modeling approach described in Appendix B. The analyses are based on the use of the Nonlinear Layer model, see section B.4.4 in Appendix B. To simplify the geometry of the computer models, the structures were defined using 2-in. thick walls with a modulus of elasticity adjusted by the ratio of 1.9 to 2.0.

The computer models are displayed in Figures 6.14, 6.15, and 6.16. A summary of the calculated base shear strength for the Nonlinear Layer models of the test structures is presented in Table 6.7. The base shear strength from these Nonlinear Layer models is determined using the shear vs. roof displacement curves, see Figures 6.17, 6.18, and 6.19. The point identified in each of these figures corresponds to where the slope of the curve reduces to 5% of the initial slope. Table 6.8 gives brief observations on selected nonlinear analysis results. The output from the nonlinear analyses confirmed the development of the limiting mechanisms (Figure 6.12 and 6.13) used in Section 6.7.

The summary of calculated and measured base shear strengths is presented in Figures 6.20, 6.21, and 6.22. These figures show that the values of $V_p$ are in reasonable agreement with the values of $V_{lim}$ (within 10% of each other). The measured maximum base shear during the earthquake simulation tests exceeded both $V_p$ and $V_{lim}$.
CHAPTER 7
CONCLUSIONS

The Limit Design method presented in this study uses the framework of the current Masonry Standards Joint Committee (MSJC) building code and combines linear-elastic analysis with concepts from limit analysis and displacement-based design to determine the in-plane base shear strength and deformation capacities that may be safely assigned to a masonry wall configuration. The method relies on deformation capacities derived from experimental data of masonry walls subjected to cyclic loading (Appendix A).

Four case studies (A through D) were analyzed using the Limit Design methodology. The case studies represent masonry wall configurations where the Limit Design method addressed several design issues typically ignored in conventional seismic design of reinforced masonry walls. The results of the analyses helped expose several limitations of current design provisions.

For the perforated wall configurations studied, the Limit Design approach led to more rational and economical solutions. Compared with conventional design methods, Limit Design generally led to higher base shear capacities with lower reinforcement levels for wall configurations that are both redundant and capable of meeting displacement demands defined by the applicable building code.

Design outcomes from the case studies indicated that the ultimate capacity of perforated walls, proportioned using Limit Design, were frequently controlled by deformation capacity. With the reduced displacement capacity that Limit Design assigns to shear-controlled wall segments, designers are directed to minimize flexural reinforcement and maximize shear strength.

To support the application of Limit Design, two simplified models were developed: the Nonlinear Layer model and the Nonlinear Link model. These models are suited for practical
nonlinear static analysis of masonry shear walls. Step-by-step instructions to implement these models using program SAP2000 (CSI, 2011b) are presented in Appendix B. When applied to the case studies A through C, results from these models were in reasonable agreement to those obtained from the analysis output of more refined analytical models.

The Nonlinear Layer and Link models were also applied to small-scale masonry test structures (case study D). These masonry structures included perforated walls with flanges. Calculated base shear strength obtained from the simplified models (Nonlinear Layer and Link models) were lower than the maximum base shear measured during earthquake simulations. The mechanism strength identified using Limit Design code provisions led to safe values when compared with the measured response and with the output from the Nonlinear Layer and Links models.

In this study, the proposed Limit Design method has been presented as an alternative for the design of special reinforced masonry shear walls. The design approach is relatively simple and does not trigger the use of complicated methods of analysis nor depends on elaborate redefinitions of the design displacement and/or of the required strength of the seismic force-resisting system.
APPENDIX A

DEFORMATION CAPACITY OF REINFORCED MASONRY WALLS

Experimental data are presented for reinforced masonry walls subjected to reversed cyclic lateral loading. Displacement capacities are obtained from 25 wall specimens. The measured data are used to evaluate a proposed simplified model for calculating the in-plane lateral deformation capacity of masonry walls.

A.1 Description of Experimental Data

Experimental data by three different groups of researchers (Shing et al., 1989; Voon and Ingham, 2006; and Shedid et al. 2008) are available with the following common attributes: reinforced masonry shear walls; full-scale specimens; fully-grouted concrete masonry units; horizontal shear reinforcement hooked at wall boundaries; overall wall height-to-length ratio of 1 or more; subjected to reversed cyclic lateral loading; and failure modes in flexure and/or shear. A brief description of these experiments follows.

Shing et al., 1989:

A series of 16 full-scale concrete masonry wall specimens was tested under reversed cyclic loading. All specimens had a height-to-length ratio (\(h_w/l_w\)) of 1 and were constructed using 6×8×16-in. (nominal dimensions) hollow concrete blocks, fully grouted, with uniformly distributed vertical and horizontal reinforcement. The compressive strength of masonry prisms ranged between 2500 and 3300 psi. The reinforcing bars were either Grade 40 or Grade 60, with yield strengths between 56 and 72 ksi.

The research program by Shing et al. examined the influence of the applied axial compressive stress and the amount of vertical and horizontal reinforcement. As summarized in Table A.1, the specimens tested by Shing et al. had vertical steel ratios of 0.38%, 0.54%, and
0.74%, and horizontal steel ratios of 0.14% and 0.24%. Excluded from Table A.1 are specimens 6, 8, and 11 because they experienced mixed failure modes that included sliding.

Shing et al. observed that increasing the axial load can change the behavior from a mixed flexural/shear mode to a brittle shear mode and therefore axial stress has a more significant influence on the flexural strength than on the shear strength. They also observed that the occurrence of the first major diagonal crack does not depend on the amount of reinforcement present but that increasing the amount of vertical and horizontal reinforcement can substantially improve the postcracking performance of a shear dominated specimen.

Voon and Ingham, 2006:

A total of 10 full-scale concrete masonry wall specimens were tested under reversed cyclic loading. All specimens were constructed using 6×8×16-in. (nominal dimensions) hollow concrete blocks, of which 8 specimens were fully grouted and two partially grouted (excluded here). The height-to-length ratios were $h_w/l_w = 1$ for walls 1 through 8, $h_w/l_w = 2$ for wall 9, and $h_w/l_w = 0.6$ for wall 10. The compressive strength of the masonry prisms varied between 2500 psi to 3500 psi. Reinforcing bars were Grade 40 with yield strengths between 46 and 47 ksi.

The study by Voon and Ingham investigated the effects of shear reinforcement, axial compression load, type of grouting, and wall aspect ratio on the shear strength of masonry walls. As summarized in Table A.1, the fully-grouted specimens had horizontal steel reinforcement ratios between 0.01% and 0.14%. Excluded from Table A.1 are specimen 3 which experienced a sliding failure, specimens 5 and 6 which were partially grouted, and specimen 10 which had an aspect ratio ($h_w/l_w$) of 0.6.

The test results confirmed that masonry shear strength increases with the magnitude of applied axial compressive stress and the amount of shear reinforcement. The tests also showed that the shear strength decreases inversely in relation to an increase in wall aspect ratio ($h_w/l_w$).
They observed that the postcracking performance of shear dominated walls was substantially improved with the use of uniformly distributed horizontal reinforcement.

Shedid et al, 2008:

Six full-scale concrete masonry wall specimens were subjected to reversed cyclic loading. All specimens had a height-to-length ratio \((h/w/l)\) of 2 and were constructed using 8×8×16-in. (nominal dimensions) hollow concrete blocks, fully grouted, with uniformly distributed vertical and horizontal reinforcement. The reported value of compressive strength of masonry prisms was 2500 psi. Reinforcing bars used as vertical reinforcement had a yield strength of 73 ksi for walls 1 through 5, and 90 ksi for wall 6. Yield strength of the horizontal reinforcement was 71 ksi.

The aim of the study by Shedid et al. was to investigate the effects of the amount and distribution of vertical reinforcement and of the applied axial compressive stress on the flexural behavior of masonry walls. All walls were designed to exhibit ductile flexural failure by providing sufficient horizontal reinforcement to safeguard against shear failure. As summarized in Table A.1, the walls tested by Shedid et al. had vertical steel ratios of 0.29% to 1.31%, and horizontal steel ratios of 0.08% to 0.26%.

The test results showed that the displacement at first yield of the vertical reinforcement tended to increase with increased axial compressive stress and with increased amount of vertical reinforcement. The displacement ductility decreased with increased vertical reinforcement ratios and was nearly insensitive to the level of axial compression.

Shedid et al. observed that the behavior of the walls was characterized by concentration of rotation over the lower part of the wall and rigid body deformation for the upper part of the wall. The extent of yielding reached a height, above the foundation, approximately equal to half.
the wall length. These observations form the basis of the proposed simplified model presented in Section A.2.

The data in Table A.1 are organized as a function of two types of failure: shear or flexure. Walls reported as failing in mixed flexure/shear mode are shown in Table A.1 under a flexure type of failure. Walls reported as having a sliding type of failure were excluded from Table A.1.

For both types of wall failure modes considered, the measured deformation capacities are reported in Table A.1 for the definition illustrated in Figure A.1. The data in Table A.1 are grouped as shown in Figure A.2 and the deformation capacity is presented in terms of drift ratio, $\delta_{u,exp}/h_w$, in Figure A.3 to Figure A.6. The drift ratio is plotted against the shear or axial stress. The figures do not clearly identify a strong correlation between drift ratio capacities and shear or axial stress ratios.

A.2 Simplified Model for Calculating the Deformation Capacity of Reinforced Masonry Walls

A.2.1 Flexure-Controlled Walls

The deformation capacity of flexure-controlled wall segments may be estimated using the plastic hinge model presented by Park and Paulay (1975). A simplified version of the plastic hinge model is presented in Figure A.7. The model assumes that under the action of combined gravity and lateral loads a cantilever wall yields in flexure at the base. The flexural deformation is modeled by elastic curvature along the wall height, $h_w$, and inelastic curvature concentrated in a plastic hinge length, $l_p$, at the base. A simple and safe estimate of the deformation capacity, $\delta_{cap}$, may be calculated using only the ultimate curvature, $\phi_u$, over the plastic hinge length (Figure A.7):

$$\delta_{cap} = \phi_u \cdot l_p \cdot h_w = \frac{\varepsilon_{mu}}{c} \cdot l_p \cdot h_w$$

(A.1)
where,
\[ \varepsilon_{mu} = \text{limiting compressive strain of masonry, 0.0025 for concrete masonry and 0.0035 for clay masonry;} \]
\[ c = \text{depth of neutral axis associated with the limiting compressive strain and the applied axial loads;} \]
\[ l_p = \text{length of plastic hinge, typically assumed equal to 0.5} \ h_w; \]
\[ h_w = \text{clear height of wall segment} \]

A.2.2 Shear-Controlled Walls

Shear-controlled wall segments are here defined as having a shear demand exceeding one-half of its nominal shear strength. The deformation capacity of shear-controlled walls is limited to \( h_w/200 \) or \( h_w/400 \) depending on the amount and detailing of reinforcement. These limits were derived from pilot studies using data presented in Section A.1. Comparison of measured and calculated deformation capacities are presented in Section A.3.

The limit of \( h_w/200 \), or drift ratio of 0.5%, applies to walls satisfying the following conditions:

(a) Transverse and longitudinal reinforcement ratios are not less than 0.001;
(b) Spacing of transverse and longitudinal reinforcement does not exceed the smallest of 24 in., \( l_w/2 \), and \( h_w/2 \);
(c) Reinforcement ending at a free edge of masonry terminates in a standard hook.

It is important to note that the deformation capacity assigned to shear-controlled walls in ASCE/SEI 41-06 (2006) is 0.6% and 0.75% for performance levels of Life Safety and Collapse Prevention, respectively. These limits are higher than the limits proposed in this appendix.
A.3 Comparison of Measured and Calculated Deformation Capacities

Using the simplified model presented in Section A.2, the deformation capacities were calculated for the wall specimens tested by Shing et al. (1989), Voon and Ingham (2006), and Shedid et al. (2008), as presented in Table A.1. The measured vs. calculated deformation capacities, expressed in terms of drift ratios, are shown in Figure A.8. In all cases, the deformation capacity was lower than the measured value, an indication that the proposed method for estimating deformation capacities of masonry walls, with $h_w/l_w \geq 1$, is safe.
APPENDIX B
PRACTICAL NONLINEAR STATIC ANALYSIS OF MASONRY WALLS

Analytical models are presented for performing practical nonlinear static analysis of masonry shear walls proportioned and detailed to resist strong ground motions. Two simplified modeling techniques were implemented to support the development and usage of the Limit Design code provisions, see Tables 2.1 and 2.2. Although Limit Design code provisions were written to allow limit analysis based on hand calculations using principles of virtual work, the computer models proposed here directly take into account the effects of varying axial load caused by an increase in lateral forces.

Program SAP2000 (CSI, 2011b) is used to implement two modeling techniques. The models are based on the predominant use of linear-elastic area elements combined with limited number of elements having nonlinear force-displacement relationships. The Limit Design code assumes plastic hinge regions occur at the interface between wall segments. The first model, the Nonlinear Layer model, modifies the area elements at the potential plastic hinge regions with special layer definitions that account for material nonlinearity. The second model, the Nonlinear Link model, substitutes the area elements at the potential plastic hinge regions with nonlinear links. The use of links is attractive because similar types of elements are readily available in standard structural analysis software other than program SAP2000. Both modeling techniques are effective in identifying the yielding wall segments and in determining the base-shear strength of a perforated wall configuration.

To perform a nonlinear static analysis of a masonry shear wall configuration using either nonlinear layers or nonlinear links, the user must first develop a linear-elastic model. The linear-elastic model is used as a reference model to obtain the design roof displacement and to determine the axial forces due to the factored loads that are consistent with the design load combination producing the design roof displacement. These axial forces are used to calculate
the deformation capacity of each wall segment based on simple rules (see Table 2.1, Section X.3).

The proposed analytical models are here described through their application to case study A (presented in Chapter 3) consisting of a one-story concrete masonry wall with two openings (see Figure 3.1). The openings lead to a structure comprised of three wall piers coupled by deep horizontal wall segments. The perforated wall is assumed to have a rigid diaphragm at the roof level, located at 2’-0” from the top of the wall. The definition of material properties for modeling nonlinear response are characterized by the nominal material strengths given in Figure 3.1.

To develop the nonlinear model, the area elements located at the interface of wall segments are replaced with either layered area elements (case of the Nonlinear Layer model) or nonlinear links (case of the Nonlinear Link model). For the wall configuration of case study A (Figure 3.1), the computer model for evaluating its linear-elastic response is shown in Figure B.1. The linear-elastic model uses area elements with an 8-in. square mesh. This level of discretization is sufficiently accurate considering that for a unit load applied at the roof level the resulting roof displacement is within 3% of the displacement calculated using a 1-in. square mesh. The 8-in. square mesh also allows a direct representation of the modular dimensions of the standard concrete masonry unit.

To facilitate the understanding and implementation of the proposed modeling techniques, this Appendix includes the steps involved in creating the Nonlinear Layer model (Section B.4) and the Nonlinear Link model (Section B.5) with program SAP2000 (CSI, 2011b). It is important to emphasize that these models are not suitable for use in nonlinear dynamic analysis, additional special definitions would be needed to properly account for the cyclic behavior involving masonry cracking or reinforcement yielding.
B.1 Nonlinear Layer Model

The layered shell element, available in version 15 of program SAP2000 (CSI, 2011b), is a special type of area element that may be defined with multiple layers in the thickness direction. Each layer may represent independent materials with user-defined nonlinear stress-strain relationships. A detailed description of the advanced features of the layered shell element is presented by CSI (2011a).

The proposed model is based on the use of nonlinear area elements to represent the region at the interface of wall segments where yielding is likely to occur, see Figure B.2. The area elements outside the assumed yielding regions are modeled with linear-elastic area elements using full gross-section properties. For a planar wall configuration the area elements may be defined as membrane elements with layers assigned to materials with nonlinear behavior. Layers of masonry and steel reinforcement are combined to represent reinforced masonry sections. For unreinforced masonry sections, only masonry layers are used.

Material stress-strain relationships are defined to represent axial and shear behavior of the wall segments. The in-plane flexural behavior of the walls is controlled by the axial response characteristics of the materials assigned to the layers. Independent materials are defined to represent the axial response of masonry and steel reinforcement. Masonry in compression is assumed to have a bilinear stress-strain curve and is neglected in tension as shown in Figure B.3. Reinforcing steel is characterized by a bilinear and symmetrical stress-strain curve as shown in Figure B.4. The peak stress of masonry is taken as 0.8 times the specified compressive strength of masonry, $f'_m$, and the peak stress of the reinforcing steel is based on the specified yield strength, $f_y$. Material property definitions neglect the strain hardening effects of steel and the expected overstrengths of steel and masonry.

The shear response is also modeled using a bilinear and symmetrical stress-strain curve, see Figure B.5. The initial line segment of the stress-strain curve is defined by the shear
modulus, taken as $E_m/2.4$. The peak values in Figure B.5 correspond to two times the calculated shear strength divided by the cross-sectional area of the wall, refer to CSI (2011a). Because the shear strength of masonry walls depends on the ratio $M_u/(V_u d_v)$ and on the axial load $P_u$, different material definitions are required for the various wall segments involved. For this purpose, the values of $M_u$, $V_u$, and $P_u$ are obtained from the linear-response model used as a basis to create the nonlinear model. The nonlinear stress-strain idealization used for shear is meant to represent the combined effects of masonry and shear reinforcement. This modeling approach is not intended to simulate realistic shear behavior but to help identify the wall segments that reach their code-based shear strength before their flexural strength.

The thickness of the layer representing masonry in compression or shear is the actual wall thickness. The thickness of the layer representing the flexural and axial reinforcing steel is defined by the steel area divided by the discretized length of area element represented. The definition of a layer also requires assigning a material angle. For instance, an area element with nonlinear layers in Figure B.2 representing the reinforced masonry of walls A, B, or C, should incorporate a layer of masonry with nonlinear capabilities in the local 2-2 direction (or vertical direction) while linear-response is assigned to the local 1-1 direction (or horizontal direction). The material representing the flexural and axial reinforcement incorporates a layer of steel with nonlinear capabilities in the local 2-2 direction. The nonlinear material to represent masonry in shear is assigned only to the local 1-2 direction. For more details, see CSI (2011a).

Once the properties of the nonlinear layers have been assigned, a gravity load case is defined as a pre-load condition to determine the starting points on the stress-strain curves of each nonlinear layer before proceeding with the nonlinear static analyses for lateral loads.

### B.2 Nonlinear Link Model

The nonlinear link element is a special type of line element that allows the modeling of material nonlinearity by means of user-defined force-deformation relationships. The area elements
representing the interface of wall segments, where yielding is likely to occur, are replaced with nonlinear links, see Figure B.6. The area elements outside the assumed yielding regions are modeled with linear-elastic area elements using full gross-section properties.

The force-deformation relationships assigned to the nonlinear links, to represent both axial and shear behavior, are defined as Multilinear Plastic. The longitudinal direction of the link defines the axial behavior while the in-plane transverse direction defines the shear behavior. The force vs. deformation data depend on the tributary area of wall represented by each of the nonlinear links. The axial response characteristics of the nonlinear links directly control the flexural behavior of the wall. A detailed description of the advanced features of the Link element is presented by CSI (2011a).

For the nonlinear link to simulate axial response in compression, the force-deformation curves need to account for the contributions of both masonry and reinforcement. To simulate axial response in tension, the contribution of masonry is neglected. Typical force-deformation curves are represented as bilinear on both the tension and compression quadrants, see Figure B.7. The initial stiffness in compression is based on the rigidity of masonry and the length of the nonlinear link. Analogously, the initial stiffness in tension is based on the rigidity of the steel reinforcement and the length of the nonlinear link. Peak forces are obtained after assigning \(0.8 f'_m\) to the masonry in compression and \(f_y\) to the reinforcing steel in tension and compression. The post-yield stiffness, in tension and compression, is taken as zero. For links representing unreinforced masonry, the tension quadrant is defined using a horizontal line with an effectively zero force.

To simulate the response in shear, the force-deformation relationships assigned to the nonlinear links are defined as bilinear and symmetrical. The first line is defined by the stiffness based on gross-section properties and the second line is horizontal (constant force) representing the nominal shear strength of the wall segment, see Figure B.8. The links representing shear response are defined so that the shear carried by the link generates a
secondary moment only at one end of the link. To properly account for the effects of this moment, a flexurally-rigid line element is added to fully engage the wall cross section, see Figure B.6. Careful attention is given to the orientation of the link local axes to deal with the secondary moment.

Once the properties of the nonlinear links have been assigned, a gravity load case is defined as a pre-load condition to determine the starting points on the force-deformation curves of each nonlinear link before proceeding with the nonlinear static analyses for lateral loads.

**B.3 Nonlinear Analysis Results**

The nonlinear models of the structure representing case study A (Figures B.2 and B.6) are each analyzed for two lateral load cases, eastward and westward loading. Global shear (base shear) and local shear (pier shear) are monitored against the roof displacement, see Figures B.9 and B.10. Each nonlinear static analysis has three main objectives: (1) identify where yielding occurs; (2) identify the type of nonlinear action (flexure or shear) that limits the force contribution of the yielding elements; and (3) determine the plastic base-shear strength.

The simplified models considered only two types of nonlinear actions: flexure and shear. To identify the wall segments responding nonlinearly, the user needs to monitor the forces in the regions where nonlinear elements were assigned and check if the limiting strength of the nonlinear layers or links was reached.

The plastic base-shear strength, $V_p$, of the wall configuration may be determined using the base shear vs. roof displacement curves that result from the nonlinear static analyses (Figures B.9 and B.10). On each figure, an open circle is used to identify the last point on the curve where the slope exceeds 5% of the slope that refers to the initial stiffness. The initial stiffness was obtained from linear-elastic response using gross-section properties. The plastic
base-shear strength so defined corresponds to the instance at which the structure has nearly developed a yield mechanism.
B.4 Nonlinear Layer Model for Selected Case Studies

B.4.1 Case Study A

Step 1. Define Geometry

File/New Model
New Model Initialization
Initialize Model from Defaults with Units:
kip, in, F
Select Template: Grid Only

Cartesian
Coordinate System Name: GLOBAL

<table>
<thead>
<tr>
<th>Number of Grid Lines</th>
<th>Grid First Spacing Grid Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>X direction:</td>
<td>6</td>
</tr>
<tr>
<td>Y direction:</td>
<td>1</td>
</tr>
<tr>
<td>Z direction:</td>
<td>8</td>
</tr>
</tbody>
</table>

OK

(Click on top tab of right window, close 3-D View)
(Select the XZ view in the top toolbar)

Right click/Edit Grid Data
Modify/Show System
(To modify grid lines using actual coordinates)

Units: Kip, ft, F

<table>
<thead>
<tr>
<th>X Grid Data: Grid ID</th>
<th>Ordinate</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0 ft</td>
</tr>
<tr>
<td>A2</td>
<td>4 ft</td>
</tr>
<tr>
<td>B1</td>
<td>14 ft</td>
</tr>
<tr>
<td>B2</td>
<td>16 ft</td>
</tr>
<tr>
<td>C1</td>
<td>20 ft</td>
</tr>
<tr>
<td>C2</td>
<td>24 ft</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Z Grid Data: Grid ID</th>
<th>Ordinate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z1</td>
<td>0 ft</td>
</tr>
<tr>
<td>Z2</td>
<td>8 ft</td>
</tr>
<tr>
<td>Z3</td>
<td>10 ft</td>
</tr>
</tbody>
</table>

View/Restore Full View
File/Save As
File name: R1-A-LAY
Save

Step 2. Define Material Properties

Define/Materials
Check Show Advanced Properties
Click to: Add New Material
Material Name: M1500
Options
Material Type: Other
Directional Symmetry Type: Isotropic

Modify/Show Material Properties
Modulus of Elasticity: 1350 ksi
Poisson’s Ratio: 0.2
Coeff. of Thermal Expansion: 5.5E-06
Shear Modulus: Auto (562.5 ksi)
Weight and Mass
Weight per Unit Volume: 0.1259 (kip/ft$^3$)
Mass per Unit Volume: 0

Advanced Material Property Data
Nonlinear Material Data
Hysteresis Type: Kinematic
Drucker-Prager Parameters
Friction Angle: 0
Dilatational Angle: 0
User Stress-Strain Curve Data
Number of Points in Stress-Strain Curve: 5

<table>
<thead>
<tr>
<th>Strain</th>
<th>Stress, ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>-8.890E-03</td>
<td>-1.200E+00</td>
</tr>
<tr>
<td>-8.890E-04</td>
<td>-1.200E+00</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

(Check stress is in the right units)
OK/OK/OK/OK
Define/Materials
Check Show Advanced Properties
Click to: Add New Material
Material Name: M1500v-A
Options
Material Type: Other
Directional Symmetry Type: Isotropic

Modify/Show Material Properties
Modulus of Elasticity: 1125 ksi
Poisson’s Ratio: 0
Coeff. of Thermal Expansion: 5.5E-06
Shear Modulus: Auto (562.5 ksi)
Weight and Mass
Weight per Unit Volume: 0
Mass per Unit Volume: 0

Advanced Material Property Data
Hysteresis Type: Kinematic
Drucker-Prager Parameters
Friction Angle: 0
Dilatational Angle: 0
User Stress-Strain Curve Data
Number of Points in Stress-Strain Curve: 5

<table>
<thead>
<tr>
<th>Strain</th>
<th>Stress, ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.610E-03</td>
<td>-1.810E-01</td>
</tr>
<tr>
<td>-1.610E-04</td>
<td>-1.810E-01</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.610E-04</td>
<td>1.810E-01</td>
</tr>
<tr>
<td>1.610E-03</td>
<td>1.810E-01</td>
</tr>
</tbody>
</table>

(Check stress is in the right units)

OK/OK/OK/OK

Define/Materials
Check Show Advanced Properties
Click to: Add New Material
Material Name: M1500v-Coupling
Options
Material Type: Other
Directional Symmetry Type: Isotropic

Modify/Show Material Properties
Modulus of Elasticity: 1125 ksi
Poisson’s Ratio: 0
Coeff. of Thermal Expansion: 5.5E-06
Shear Modulus: Auto (562.5 ksi)
Weight and Mass
Weight per Unit Volume: 0
Mass per Unit Volume: 0

Advanced Material Property Data
Nonlinear Material Data
Hysteresis Type: Kinematic
Drucker-Prager Parameters
Friction Angle: 0
Dilatational Angle: 0
User Stress-Strain Curve Data
Number of Points in Stress-Strain Curve: 5

OK/OK/OK/OK

Define/Materials
Check Show Advanced Properties
Click to: Add New Material
Material Name: M1500v-B
Options
Material Type: Other
Directional Symmetry Type: Isotropic

Modify/Show Material Properties
Modulus of Elasticity: 1125 ksi
Poisson’s Ratio: 0
Coeff. of Thermal Expansion: 5.5E-06
Shear Modulus: Auto (562.5 ksi)
Weight and Mass
Weight per Unit Volume: 0
Mass per Unit Volume: 0

Advanced Material Property Data
Hysteresis Type: Kinematic
Drucker-Prager Parameters
Friction Angle: 0
Dilatational Angle: 0
User Stress-Strain Curve Data
Number of Points in Stress-Strain Curve: 5

<table>
<thead>
<tr>
<th>Strain</th>
<th>Stress, ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.640E-03</td>
<td>-1.850E-01</td>
</tr>
<tr>
<td>-1.640E-04</td>
<td>-1.850E-01</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.640E-04</td>
<td>1.850E-01</td>
</tr>
<tr>
<td>1.640E-03</td>
<td>1.850E-01</td>
</tr>
</tbody>
</table>

(Check stress is in the right units)

OK/OK/OK/OK
Advanced Material Property Data
Nonlinear Material Data
Hysteresis Type: Kinematic
Drucker-Prager Parameters
Friction Angle: 0
Dilatational Angle: 0
User Stress-Strain Curve Data
Number of Points in Stress-Strain Curve: 5

<table>
<thead>
<tr>
<th>Strain</th>
<th>Stress, ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.75E-03</td>
<td>-3.10E-01</td>
</tr>
<tr>
<td>-2.75E-04</td>
<td>-3.10E-01</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2.75E-04</td>
<td>3.10E-01</td>
</tr>
<tr>
<td>2.75E-03</td>
<td>3.10E-01</td>
</tr>
</tbody>
</table>

(Check stress is in the right units)
OK/OK/OK/OK

Define/Materials
Check Show Advanced Properties
Click to: Add New Material
Material Name: R60
Options
Material Type: Steel
Directional Symmetry Type: Uniaxial

Modify/Show Material Properties
Modulus of Elasticity: 29000 ksi
Poisson’s Ratio: 0.3
Coeff. of Thermal Expansion: 6.5E−06
Shear Modulus: Auto (11153.846 ksi)
Weight and Mass
Weight per Unit Volume: 0
Mass per Unit Volume: 0

Units: kip, in, F
Other Properties for Steel Materials
Minimum Yield Stress, Fy: 60
Minimum Tensile Stress, Fu: 60
Effective Yield Stress, Fye: 60
Effective Tensile Stress, Fue: 60

Advanced Material Property Data
Nonlinear Material Data
Hysteretic Type: Kinematic
Stress-Strain Curve Definition Options: User Defined
User Stress-Strain Curve Data
Number of Points in Stress-Strain Curve: 5

<table>
<thead>
<tr>
<th>Strain</th>
<th>Stress, ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.07E-02</td>
<td>-6.00E+00</td>
</tr>
<tr>
<td>2.07E-03</td>
<td>-6.00E+00</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2.07E-03</td>
<td>6.00E+00</td>
</tr>
<tr>
<td>2.07E-02</td>
<td>6.00E+00</td>
</tr>
</tbody>
</table>

( Check stress is in the right units)
OK/OK/OK/OK

File/Save

Step 3. Define Area Sections
Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section
Section Name: M8-LIN
Type: Membrane
Material
Material Name: M1500
Material Angle: 0
Thickness
Membrane: 7.625
Bending: 7.625
OK/OK

Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section
Section Name: M8-U22-A
Type: Shell-Layered/Nonlinear
Modify/Show Layer Definition
Layer Definition Data
Layer Name: M22N
Distance: 0
Thickness: 7.625  
Type: Membrane  
Num. Int. Points: 1  
Material: M1500  
Material Angle: 0  
Material Component Behavior  
\[
\begin{array}{ccc}
S11 & S22 & S12 \\
\text{Linear} & \text{Nonlinear} & \text{Inactive} \\
\end{array}
\]
Modify

Layer Name: M12N  
Distance: 0  
Thickness: 7.625  
Type: Membrane  
Num. Int. Points: 1  
Material: M1500v-B  
Material Angle: 0  
Material Component Behavior  
\[
\begin{array}{ccc}
S11 & S22 & S12 \\
\text{Inactive} & \text{Inactive} & \text{Nonlinear} \\
\end{array}
\]
Add  
OK/OK/OK

Define/Section Properties/Area Sections  
Select Section Type to Add: Shell  
Click to: Add New Section

Section Name: M8-U11-Coupling  
Type: Shell-Layered/Nonlinear  
Modify/Show Layer Definition

Layer Definition Data  
Layer Name: M11N  
Distance: 0  
Thickness: 7.625  
Type: Membrane  
Num. Int. Points: 1  
Material: M1500v-B  
Material Angle: 0  
Material Component Behavior  
\[
\begin{array}{ccc}
S11 & S22 & S12 \\
\text{Inactive} & \text{Inactive} & \text{Nonlinear} \\
\end{array}
\]
Add  
OK/OK/OK

Layer Name: M12N  
Distance: 0  
Thickness: 7.625  
Type: Membrane  
Num. Int. Points: 1  
Material: M1500v-Coupling  
Material Angle: 0  
Material Component Behavior  
\[
\begin{array}{ccc}
S11 & S22 & S12 \\
\text{Inactive} & \text{Inactive} & \text{Nonlinear} \\
\end{array}
\]
Add  
OK/OK/OK
Add
OK/OK/OK

Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section

Section Name: M8-R22-A
Type: Shell-Layered/Nonlinear
Modify/Show Layer Definition

Layer Definition Data
Layer Name: M22N
Distance: 0
Thickness: 7.625
Type: Membrane
Num. Int. Points: 1
Material: M1500
Material Angle: 0
Material Component Behavior
S11  S22  S12
Linear  Nonlinear  Inactive
Modify

Layer Name: M12N
Distance: 0
Thickness: 7.625
Type: Membrane
Num. Int. Points: 1
Material: M1500v-A
Material Angle: 0
Material Component Behavior
S11  S22  S12
Inactive  Inactive  Nonlinear
Add

Layer Name: R22N
Distance: 0
Thickness: 0.03875
Type: Membrane
Num. Int. Points: 1
Material: R60
Material Angle: 90
Material Component Behavior
S11  S22  S12
Nonlinear  Inactive  Inactive
Add

Section Name: M8-R22-B
Type: Shell-Layered/Nonlinear
Modify/Show Layer Definition

Layer Definition Data
Layer Name: M22N
Distance: 0
Thickness: 7.625
Type: Membrane
Num. Int. Points: 1
Material: M1500
Material Angle: 0
Material Component Behavior
S11  S22  S12
Linear  Nonlinear  Inactive
Modify

Layer Name: M12N
Distance: 0
Thickness: 7.625
Type: Membrane
Num. Int. Points: 1
Material: M1500v-B
Material Angle: 0
Material Component Behavior
S11  S22  S12
Inactive  Inactive  Nonlinear
Add

Layer Name: R22N
Distance: 0
 Thickness: 0.03875
Type: Membrane
Num. Int. Points: 1
Material: R60
Material Angle: 90
Material Component Behavior
S11  S22  S12
Nonlinear  Inactive  Inactive
Add
OK/OK/OK

Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section

Section Name: M8-R11-Coupling
Type: Shell-Layered/Nonlinear
Modify/Show Layer Definition

Layer Definition Data
Layer Name: M11N
Distance: 0
Thickness: 7.625
Type: Membrane
Num. Int. Points: 1
Material: M1500
Material Angle: 0
Material Component Behavior
S11  S22  S12
Nonlinear  Linear  Inactive
Modify

Layer Name: M12N
Distance: 0
Thickness: 7.625
Type: Membrane
Num. Int. Points: 1
Material: M1500v-Coupling
Material Angle: 0
Material Component Behavior
S11  S22  S12
Inactive  Inactive  Nonlinear
Add

Layer Name: R11N
Distance: 0
Thickness: 0.025
Type: Membrane
Num. Int. Points: 1
Material: R60
Material Angle: 0
Material Component Behavior

S11  S22  S12
Nonlinear  Inactive  Inactive
Add
OK/OK/OK

File/Save

Step 4. Draw Area Elements
(Draw walls A, B, and C)
Draw/Draw Rectangular Area
Click on bottom left of Wall A (at A1/Z1) and drag to top right of Wall A (at A2/Z3)
Draw/Draw Rectangular Area
Click on bottom left of Wall B (at B1/Z1) and drag mouse to top right of Wall B (at B2/Z2)
Draw/Draw Rectangular Area
Click on bottom left of Wall C (at C1/Z1) and drag mouse to top right of Wall C (at C2/Z2)

(Draw coupling wall segments)
Draw/Draw Rectangular Area
Click on top left of Wall A (at A1/Z3) and drag mouse to top of wall at Grid B1 (at B1/Z4)

Draw/Draw Rectangular Area
Click on top left of Wall B (at B1/Z2) and drag mouse to top of wall at Grid C2 (at C2/Z4)

Select checkmark icon (Set Display Options) on top toolbar
On Joints, uncheck: Invisible
On Joints, check: Labels
On Areas, check: Labels
OK

On side toolbar select all
Edit/Change Labels
Item Type: Element Labels – Area
Auto Relabel Control (use default values)
Edit/Auto Relabel/All in List
Item Type: Element Labels – Joint
Auto Relabel Control (use default values)
Edit/Auto Relabel/All in List
OK

Select checkmark icon (Set Display Options) on top toolbar
On Joints, uncheck: Labels
On Areas, uncheck: Labels
OK

Select bottom joints, verify 6 Points are selected
Assign/Joint/Restraints/
Check boxes for all degrees of freedom (or on Fast Restraints, select fixed-end condition)
OK

On side toolbar select all
Verify 5 Areas and 20 Edges are selected
Edit/Edit Areas/Divide Areas
Divide Area into Objects of This Maximum Size
Along Edge from Point 1 to 2: 8 in.
Along Edge from Point 1 to 3: 8 in.
At bottom, on Restraints and Constraints for Added Points, select
Add on Edge when restraints/constraints exist at adjacent corner points
OK

On side toolbar select all, verify there are 766 Points, 675 Areas, and 2700 Edges
On side toolbar select clr

File/Save

Step 5. Assign Area Elements

Select all area sections
Assign/Area/Sections
Sections: M8-LIN
OK

(Assign nonlinear area elements to the potential hinge regions)
Select the corner area elements at base of Walls A and C (2 elements per wall)
Select the corner area elements at top of clear height of Walls A and C (2 elements per wall)
Verify 8 Areas and 32 Edges are selected
Assign/Area/Sections
Sections: M8-R22-A
OK

Select the area elements in between Area Sections M8-R22A (4 top and 4 bot per wall)
Verify 16 Areas and 64 Edges are selected
Assign/Area/Sections
Sections: M8-U22-A
OK

Select the corner area elements at base of Wall B (2 elements)
Select the corner area elements at top of clear height of Wall B (2 elements)
Verify 4 Areas and 16 Edges are selected
Assign/Area/Sections
Sections: M8-R22-B
OK

Select the area elements in between Area Sections M8-R22-B (1 top and 1 bot)
Verify 2 Areas and 8 Edges are selected
Assign/Area/Sections
Sections: M8-U22-B
OK

Select the area element to the right and above A2/Z3
Select the area element to the right and below A2/Z4
Select the area element to the left and above B1/Z3
Select the area element to the left and below B1/Z4
Select the area element to the right and above B2/Z2
Select the area element to the right and below B2/Z4
Select the area element to the left and above C1/Z2
Select the area element to the left and below C1/Z4
Verify 8 Areas and 32 Edges are selected
Assign/Area/Sections
Sections: M8-R11-Coupling
OK

Select area elements along Grids A2, B1, to define as nonlinear unreinforced
Verify 46 Areas and 184 Edges are selected
Assign/Area/Sections
Sections: M8-U11-Coupling
OK

Step 6. Assign Constraints
Select all joints at Z=192 in
Verify 37 Points are selected
Assign/Joint/Constraints
Choose Constraint Type to Add: Diaphragm
Click to: Add New Constraint
Constraint Name: DIAPH1
Coordinate System: GLOBAL
Constraint Axis: Z Axis
OK/OK

File/Save

Step 7. Define Load Patterns and Load Cases
Define/Load Patterns
Load Pattern Name: LIVE
Type: LIVE
Self-Weight Multiplier: 0
Click to: Add New Load Pattern
OK

Define/Load Patterns
Load Pattern Name: SEISMIC
Type: Other
Self-Weight Multiplier: 0
Click to: Add New Load Pattern
OK

Define/Load Cases
Click to: Add New Load Case
Load Case Name: E
Load Case Type: Static
Analysis Type: Linear
Stiffness to Use: Zero Initial Conditions - Unstressed State
Loads Applied
Load Type = Load Pattern
Load Name = SEISMIC
Scale Factor = 1
Add
OK/OK

Define/Load Patterns
Load Pattern Name: SEISMIC
Type: Other
Self-Weight Multiplier: 0
Click to: Add New Load Pattern
OK

Define/Load Cases
Click to: Add New Load Case
Load Case Name: PRE-LOAD
Load Case Type: Static
Analysis Type: Nonlinear
Initial Conditions
Zero Initial Conditions - Start from Unstressed State
Geometric Nonlinearity Parameters: None
Loads Applied
Load Type = Load Pattern
Load Name = DEAD
Scale Factor = 0.7
Add
Other Parameters
Load Application: Full Load (Default)
Results Saved: Final State Only (Default)
Nonlinear Parameters: Default
OK/OK

(Define Nonlinear Static Analysis - Eastward Loading)
Define/Load Cases
Click to: Add New Load Case
Load Case Name: NSA+
Load Case Type: Static
Analysis Type: Nonlinear
Initial Conditions
Continue from State at End of Nonlinear Case: PRE-LOAD
Geometric Nonlinearity Parameters: None
Loads Applied
Load Type = Load Pattern
Load Name = SEISMIC
Scale Factor = 1
Add
Other Parameters
Load Application: Modify/Show
Load Application Control: Displacement Control
Control Displacement: Use Monitored Displacement
Load to a Monitored Displacement Magnitude of: 1.0 in.
Monitored Displacement DOF: U1 At Joint: 495
OK
Results Saved: Modify/Show
Results Saved: Multiple States For Each Stage
Minimum Number of Saved States: 50
Maximum Number of Saved States: 100
Select Save Positive Displacement Increments Only
OK
Nonlinear Parameters: Default
OK/OK

(Define Nonlinear Static Analysis - Westward Loading)
Define/Load Cases
Click to: Add New Load Case
Load Case Name: NSA-
Load Case Type: Static
Analysis Type: Nonlinear
Initial Conditions
Continue from State at End of Nonlinear Case: PRE-LOAD
Geometric Nonlinearity Parameters: None
Loads Applied
Load Type = Load Pattern
Load Name = SEISMIC
Scale Factor = -1
Add
Other Parameters
Load Application: Modify/Show
Load Application Control: Displacement Control
Control Displacement: Use Monitored Displacement
Load to a Monitored Displacement Magnitude of: 1.0 in.
Monitored Displacement DOF: U1 At Joint: 495
OK
Results Saved: Modify/Show
Results Saved: Multiple States For Each Stage
Minimum Number of Saved States: 50
Maximum Number of Saved States: 100
Select Save Positive Displacement Increments Only
OK
Nonlinear Parameters: Default
OK/OK

File/Save

Step 8. Assign Loads
Select all joints at roof level (2’-0” from the top of wall) except edge joints
Verify 35 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: DEAD
Units: kip, in, F
Loads
Force Global Z: -0.10 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Click PS on the left side toolbar
Verify 35 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: LIVE
Units: kip, in, F
Loads
Force Global Z: -0.15 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the edge joints at Grid Lines A1 and C2 at the roof level (Z=192 in.)
Verify 2 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: DEAD
Units: kip, in, F
Loads
Force Global Z: -0.05 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the roof level (at X=144 in. Z=192 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in, F
Loads
Force Global X: 100 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

File/Save

Step 9. Analyze

Analyze/Set Analysis Options
FAST DOFs: Plane Frame - XZ Plane
OK

Analyze/Set Load Cases to Run
Highlight PRE-LOAD, NSA+, NSA-
Click to: Run/Do Not Run Case
Verify the Nonlinear Static are marked as
Do Not Run
Run Now

(On the top toolbar select the Show Deformed Shape icon)
Deformed Shape
Case/Combo
Case/Combo Name: SEISMIC
OK

Verify the displacement U1 at the roof diaphragm level is 0.139 in.

Step 10. Program Output

Display
Show Forces/Stresses
Joints
Case/Combo Name: E
OK
Verify units are kip, in, F

Draw Section Cut (cut Wall A at Base)
Section Cutting Line
Start Point: X=-1, Y=0, Z=1
End Point: X=49, Y=0, Z=1
Click on Refresh button
Integrated Forces:
Left Side/Save Cut
Close

Draw Section Cut (cut Wall B at Base)
Section Cutting Line
Start Point: X=167, Y=0, Z=1
End Point: X=193, Y=0, Z=1
Click on Refresh button
Integrated Forces:
Left Side/Save Cut
Close

Draw Section Cut (cut Wall C at Base)
Section Cutting Line
Start Point: X=239, Y=0, Z=1
End Point: X=289, Y=0, Z=1
Click on Refresh button
Integrated Forces:
Left Side/Save Cut
Close

Display/Show Plot Function
Define Plot Functions
Choose Function Type to Add: Add Base Functions
Click to: Add Plot Function
Base Functions: Base Shear X
OK/OK

Define Plot Functions
Choose Function Type to Add: Add Joint Disps/Forces
Click to: Add Plot Function
Joint ID: 495
Vector Type: Displ
Component: UX

OK/OK

Define Plot Functions
Choose Function Type to Add: Add Section Cut Forces
Click to: Add Plot Function
Section Cut: SCUT1
Component: F1
OK/OK

Define Plot Functions
Choose Function Type to Add: Add Section Cut Forces
Click to: Add Plot Function
Section Cut: SCUT2
Component: F1
OK/OK

Define Plot Functions
Choose Function Type to Add: Add Section Cut Forces
Click to: Add Plot Function
Section Cut: SCUT3
Component: F1
OK/OK

Choose Plot Functions
List of Functions: Highlight Base Shear X, SCUT1, SCUT2, and SCUT3
Click the Add button
Verify Base Shear X, SCUT1, SCUT2, and SCUT3 show under Vertical Functions
Horizontal Plot Function: Joint495

Load Case (Multi-Stepped Cases); NSA+
Click Display
File/Print Tables to File
File name: NSA+
Save
OK

Load Case (Multi-Stepped Cases); NSA-
Click Display
File/Print Tables to File
File name: NSA-
Save
OK

File/Save
Done
B.4.2 Case Study B

Step 1. Define Geometry

File/New Model
New Model Initialization
Initialize Model from Defaults with Units: kip, in, F
Select Template: Grid Only

Cartesian
Coordinate System Name: GLOBAL

<table>
<thead>
<tr>
<th>Number of Grid Lines</th>
<th>Grid Spacing</th>
<th>First Grid Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>X direction: 4</td>
<td>48</td>
<td>0</td>
</tr>
<tr>
<td>Y direction: 1</td>
<td>48</td>
<td>0</td>
</tr>
<tr>
<td>Z direction: 8</td>
<td>48</td>
<td>0</td>
</tr>
</tbody>
</table>

OK

(Click on top tab of right window, close 3-D View)
(Select the XZ view in the top toolbar)

Right click/Edit Grid Data
Modify/Show System
(To modify grid lines using actual coordinates)

Units: Kip, ft, F

X Grid Data: Grid ID | Ordinate
A1                  | 0 ft
A2                  | 8 ft
B1                  | 32 ft
B2                  | 40 ft

Z Grid Data: Grid ID | Ordinate | Strain | Stress, ksi
Z1                  | 0 ft     | -8.89E-03 | -1.200E+00
Z2                  | 10 ft    | -8.89E-04 | -1.200E+00
Z3                  | 12 ft    | 0         | 0
Z4                  | 22 ft    | 8.89E-04  | 1.200E-03
Z5                  | 32 ft    | 8.89E-03  | 1.200E-03
Z6                  | 42 ft    |           | (Check stress is in the right units)
Z7                  | 52 ft    |           | OK/OK/OK/OK
Z8                  | 54 ft    |           |
Define/Materials
Check Show Advanced Properties
Click to: Add New Material
Material Name: M1500v-A
Options
Material Type: Other
Directional Symmetry Type: Isotropic

Modify/Show Material Properties
Modulus of Elasticity: 1125 ksi
Poisson’s Ratio: 0
Coeff. of Thermal Expansion: 5.5E-06
Shear Modulus: Auto (562.5 ksi)
Weight and Mass
Weight per Unit Volume: 0
Mass per Unit Volume: 0

Advanced Material Property Data
Nonlinear Material Data
Hysteresis Type: Kinematic
Drucker-Prager Parameters
Friction Angle: 0
Dilatational Angle: 0
User Stress-Strain Curve Data
Number of Points in Stress-Strain Curve: 5

OK/OK/OK/OK

Define/Materials
Check Show Advanced Properties
Click to: Add New Material
Material Name: M1500v-Coupling
Options
Material Type: Other
Directional Symmetry Type: Isotropic

Modify/Show Material Properties
Modulus of Elasticity: 1125 ksi
Poisson’s Ratio: 0
Coeff. of Thermal Expansion: 5.5E-06
Shear Modulus: Auto (562.5 ksi)
Weight and Mass
Weight per Unit Volume: 0
Mass per Unit Volume: 0

Advanced Material Property Data
Nonlinear Material Data
Hysteresis Type: Kinematic
Drucker-Prager Parameters
Friction Angle: 0
Dilatational Angle: 0
User Stress-Strain Curve Data
Number of Points in Stress-Strain Curve: 5

Strain Stress, ksi
-2.760E-03 -3.100E-01
-2.760E-04 -3.100E-01
0 0
2.760E-04 3.100E-01
2.760E-03 3.100E-01

OK/OK/OK/OK

Define/Materials
Check Show Advanced Properties
Click to: Add New Material
Material Name: R60
Options
Material Type: Steel
Directional Symmetry Type: Uniaxial

Modify/Show Material Properties
Modulus of Elasticity: 29000 ksi
Poisson’s Ratio: 0.3
Coeff. of Thermal Expansion: 6.5E-06
Shear Modulus: Auto (11153.846 ksi)
Weight and Mass
Weight per Unit Volume: 0
Mass per Unit Volume: 0
Units: kip, in, F

Other Properties for Steel Materials
Minimum Yield Stress, Fy: 60
Minimum Tensile Stress, Fu: 60
Effective Yield Stress, Fye: 60
Effective Tensile Stress, Fue: 60

Advanced Material Property Data
Nonlinear Material Data
Hysteresis Type: Kinematic
Stress-Strain Curve Definition Options: User Defined
User Stress-Strain Curve Data
Number of Points in Stress-Strain Curve: 5

<table>
<thead>
<tr>
<th>Strain</th>
<th>Stress, ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.070E-02</td>
<td>-6.000E+01</td>
</tr>
<tr>
<td>-2.070E-03</td>
<td>-6.000E+01</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2.070E-03</td>
<td>6.000E+01</td>
</tr>
<tr>
<td>2.070E-02</td>
<td>6.000E+01</td>
</tr>
</tbody>
</table>

(Check stress is in the right units)
OK/OK/OK/OK

File/Save

Step 3. Define Area Sections

Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section

Section Name: M8-LIN
Type: Membrane
Material
Material Name: M1500
Material Angle: 0
Thickness
Membrane: 7.625
Bending: 7.625
OK/OK

Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section

Section Name: M8-U22-A
Type: Shell-Layered/Nonlinear
Modify/Show Layer Definition

Layer Definition Data
Layer Name: M22N
Distance: 0
Thickness: 7.625
Type: Membrane
Num. Int. Points: 1
Material: M1500
Material Angle: 0
Material Component Behavior
S11 S22 S12
Linear Nonlinear Inactive
Modify

Layer Name: M12N
Distance: 0
Thickness: 7.625
Type: Membrane
Num. Int. Points: 1
Material: M1500v-A
Material Angle: 0
Material Component Behavior
S11 S22 S12
Inactive Inactive Nonlinear
Add

OK/OK/OK

Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section

Section Name: M8-U11-Coupling
Type: Shell-Layered/Nonlinear
Modify/Show Layer Definition

Layer Definition Data
Layer Name: M11N
Distance: 0
Thickness: 7.625
Type: Membrane
Num. Int. Points: 1
Material: M1500
Material Angle: 0
Material Component Behavior
S11    S22    S12
Nonlinear    Linear    Inactive
Modify

Layer Name: M12N
Distance: 0
Thickness: 7.625
Type: Membrane
Num. Int. Points: 1
Material: M1500v-Coupling
Material Angle: 0
Material Component Behavior
S11    S22    S12
Inactive    Inactive    Nonlinear
Add
OK/OK/OK

Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section

Section Name: M8-R22-A
Type: Shell-Layered/Nonlinear
Modify/Show Layer Definition

Layer Definition Data
Layer Name: M22N
Distance: 0
Thickness: 7.625
Type: Membrane
Num. Int. Points: 1
Material: M1500
Material Angle: 0
Material Component Behavior
S11    S22    S12
Linear    Nonlinear    Inactive
Modify

Layer Name: M12N
Distance: 0
Thickness: 7.625
Distance: 0
Thickness: 7.625
Type: Membrane
Num. Int. Points: 1
Material: M1500v-Coupling
Material Angle: 0
Material Component Behavior
S11 S22 S12
Inactive Inactive Nonlinear
Add

Layer Name: R11N
Distance: 0
Thickness: 0.025
Type: Membrane
Num. Int. Points: 1
Material: R60
Material Angle: 0
Material Component Behavior
S11 S22 S12
Nonlinear Inactive Inactive
Add
OK/OK/OK

File/Save

Step 4. Draw Area Elements

(Draw walls A, and B)
Draw/Draw Rectangular Area
Click on bottom left of Wall A (at A1/Z1)
and drag to top right of Wall A (at A2/Z2)
Draw/Draw Rectangular Area
Click on bottom left of Wall B (at B1/Z1) and
drag mouse to top right of Wall B (at B2/Z2)

(Draw coupling wall segments)
Draw/Draw Rectangular Area
Click on top left of Wall A (at A1/Z2) and
drag mouse to top of wall at Grid B1 (at B2/Z8)

Select checkmark icon (Set Display Options)
on top toolbar

On Joints, uncheck: Invisible
On Joints, check: Labels
On Areas, check: Labels
OK

On side toolbar select all
Edit/Change Labels
Item Type: Element Labels – Area
Auto Relabel Control (use default values)
Edit/Auto Relabel/All in List
Item Type: Element Labels – Joint
Auto Relabel Control (use default values)
Edit/Auto Relabel/All in List
OK

Select checkmark icon (Set Display Options)
on top toolbar
On Joints, uncheck: Labels
On Areas, uncheck: Labels
OK

Select bottom joints, verify 4 Points are
selected
Assign/Joint/Restraints/
Check boxes for all degrees of freedom (or
on Fast Restraints, select fixed-end
condition)
OK

On side toolbar select all
Verify 3 areas and 12 edges are selected
Edit/Edit Areas.Divide Areas
Divide Area into Objects of This Maximum
Size
Along Edge from Point 1 to 2: 8 in.
Along Edge from Point 1 to 3: 8 in.
At bottom, on Restraints and Constraints
for Added Points, select
Add on Edge when restraints/constraints
exist at adjacent corner points
OK

Select checkmark icon (Set Display Options)
on top toolbar

On side toolbar select all, verify there are
4477 Points, 4320 Areas, 17280 Edges
On side toolbar select clr

File/Save

Step 5. Assign Area Elements

Select all area sections
Assign/Area/Sections
Sections: M8-LIN
OK

(Assign nonlinear area elements to the potential hinge regions)
Select the corner area elements at base of Walls A and B (2 elements per wall)
Select the sixth area element from left to right at the same elevation of the previous
Select the corner area elements at top of clear height of Walls A and B (2 elements per wall)
Select the sixth area element from left to right at the same elevation of the previous
Verify 12 Areas and 48 Edges are selected
Assign/Area/Sections
Sections: M8-R22-A
OK

Select the area sections in between Area Sections M8-R22A (9 top and 9 bot per wall)
Verify 36 Areas and 144 Edges are selected
Assign/Area/Sections
Sections: M8-U22-A
OK

Select the area section to the right and above A2/Z2
Select the area section to the right and below A2/Z7
Select the area section to the left and above B1/Z2
Select the area section to the left and below B1/Z7
Verify 4 Areas and 16 Edges are selected
Assign/Area/Sections

Sections: M8-R11-Coupling
OK

Select area sections along Grids A2, B1, to define as nonlinear unreinforced
Verify 128 Areas and 512 Edges are selected
Assign/Area/Sections
Sections: M8-U11-Coupling
File/Save

Step 6. Assign Constraints

Select joints at Z=624 in.
Verify 61 Points are selected
Assign/Joint/Constraints
Choose Constraint Type to Add: Diaphragm
Click to: Add New Constraint
Constraint Name: DIAPH5
Coordinate System: GLOBAL
Constraint Axis: Z Axis
OK/OK

Select joints at Story 4 elevation (Z=504 in.)
Verify 61 Points are selected
Assign/Joint/Constraints
Choose Constraint Type to Add: Diaphragm
Click to: Add New Constraint
Constraint Name: DIAPH4
Coordinate System: GLOBAL
Constraint Axis: Z Axis
OK/OK

Select joints at Story 3 elevation (Z=384 in.)
Verify 61 Points are selected
Assign/Joint/Constraints
Choose Constraint Type to Add: Diaphragm
Click to: Add New Constraint
Constraint Name: DIAPH3
Coordinate System: GLOBAL
Constraint Axis: Z Axis
OK/OK

Select joints at Story 2 elevation (Z=264 in.)
Verify 61 Points are selected
Assign/Joint/Constraints
Choose Constraint Type to Add: Diaphragm
Click to: Add New Constraint
Constraint Name: DIAPH2
Coordinate System: GLOBAL
Constraint Axis: Z Axis
OK/OK

Select joints at Story 1 elevation (Z=144 in.)
Verify 61 Points are selected
Assign/Joint/Constraints
Choose Constraint Type to Add: Diaphragm
Click to: Add New Constraint
Constraint Name: DIAPH1
Coordinate System: GLOBAL
Constraint Axis: Z Axis
OK/OK

File/Save

Step 7. Define Load Patterns and Load Cases

Define/Load Patterns
Load Pattern Name: LIVE
Type: LIVE
Self-Weight Multiplier: 0
Click to: Add New Load Pattern
OK

Define/Load Patterns
Load Pattern Name: SEISMIC
Type: Other
Self-Weight Multiplier: 0
Click to: Add New Load Pattern
OK

Define/Load Cases
Click to: Add New Load Case
Load Case Name: E
Load Case Type: Static
Analysis Type: Linear
Stiffness to Use: Zero Initial Conditions – Unstressed State
Loads Applied
Load Type = Load Pattern
Load Name = SEISMIC
Scale Factor = 1
Add
OK/OK

Define/Load Cases
Click to: Add New Load Case
Load Case Name: PRE-LOAD
Load Case Type: Static
Analysis Type: Nonlinear
Initial Conditions
Zero Initial Conditions – Start from Unstressed State
Geometric Nonlinearity Parameters: None
Loads Applied
Load Type = Load Pattern
Load Name = DEAD
Scale Factor = 0.7
Add
Other Parameters
Load Application: Full Load (Default)
Results Saved: Final State Only (Default)
Nonlinear Parameters: Default
OK/OK

(Define Nonlinear Static Analysis - Eastward Loading)
Define/Load Cases
Click to: Add New Load Case
Load Case Name: NSA+
Load Case Type: Static
Analysis Type: Nonlinear
Initial Conditions
Continue from State at End of Nonlinear Case: PRE-LOAD
Geometric Nonlinearity Parameters: None
Loads Applied
Load Type = Load Pattern
Load Name = SEISMIC
Scale Factor = 1
Add
Other Parameters
Select all joints at roof level (2’-0” from the top of wall) and at floor levels except edge joints
Verify 295 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: DEAD
Units: kip, in. F
Loads
Force Global Z: -0.5333 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Click PS on the left side toolbar
Verify 295 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: LIVE
Units: kip, in. F
Loads
Force Global Z: -0.2666 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK
Select the edge joints at Grid Lines A1 and B2 at each Story
Verify 10 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: DEAD
Units: kip, in. F
Loads
Force Global Z: -0.2666 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Click PS on the left side toolbar
Verify 10 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: LIVE
Units: kip, in. F
Loads
Force Global Z: -0.1333 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the roof level (at X=240 in. Z=624 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in. F
Loads
Force Global X: 53.35 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the roof level (at X=240 in. Z=504 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in. F
 Loads
Force Global X: 42.68 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the roof level (at X=240 in. Z=384 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in. F
Loads
Force Global X: 32.00 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the roof level (at X=240 in. Z=264 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in. F
Loads
Force Global X: 21.34 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the roof level (at X=240 in. Z=144 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in. F
 Loads
Force Global X: 10.67 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

File/Save
Step 9. Analyze
Analyze/Set Analysis Options
FAST DOFs: Plane Frame - XZ Plane
OK

Analyze/Set Load Cases to Run
Highlight PRE-LOAD, NSA+, NSA-
Click to: Run/Do Not Run Case
Verify the Nonlinear Static are marked as
Do Not Run
Run Now

(On the top toolbar select the Show
Deformed Shape icon)
Deformed Shape
Case/Combo
Case/Combo Name: SEISMIC
OK

Verify the displacement U1 at the roof
diaphragm level is 0.193 in.

Analyze/Set Load Cases to Run
Highlight PRE-LOAD, NSA+, NSA-
Click to: Run/Do Not Run Case
Verify the Nonlinear Static are marked as
Run
Run Now

Step 10. Program Output
Display
Show Forces/Stresses
Joints
Case/Combo Name: E
OK
Verify units are kip, in, F

Draw Section Cut (cut wall A at Base)
Section Cutting Line
Start Point: X=-1, Y=0, Z=1
End Point: X=97, Y=0, Z=1
Click on Refresh Button
Integrated Forces:
Left Side/Save Cut
Close

Define Plot Functions
Choose Function Type to Add: Add Base
Disps/Forces
Click to: Add Plot Function
Joint ID: 2478
Vector Type: Displ
Component: UX
OK/OK

Define Plot Functions
Choose Function Type to Add: Add Joint
Disps/Forces
Click to: Add Plot Function
Joint ID: 2478
Vector Type: Displ
Component: UX
OK/OK

Define Plot Functions
Choose Function Type to Add: Add
Section Cut Forces
Click to: Add Plot Function
Section Cut: SCUT1
Component: F1
OK/OK

Define Plot Functions
Choose Function Type to Add: Add
Section Cut Forces
Click to: Add Plot Function
Section Cut: SCUT2
Component: F1
OK/OK
Choose Plot Functions
List of Functions: Highlight Base Shear X, SCUT1 and SCUT2
Click the Add button
Verify Base Shear X, SCUT1, and SCUT2 show under Vertical Functions
Horizontal Plot Function: Joint2478

Load Case (Multi-Stepped Cases); NSA+
Click Display
File/Print Tables to File
File name: NSA+
Save
OK

Load Case (Multi-Stepped Cases); NSA-
Click Display
File/Print Tables to File
File name: NSA-
Save
OK

File/Save
Done
### B.4.3 Case Study C

#### Step 1. Define Geometry

- **File/New Model**
- **New Model Initialization**
- **Initialize Model from Defaults with Units:** kip, in, F
- **Select Template:** Grid Only
- **Cartesian**
  - **Coordinate System Name:** GLOBAL
  - **Number of Grid Lines:** X direction: 4, Y direction: 1, Z direction: 16
  - **Spacing:** Grid Line Spacing: 48, 48, 48
  - **OK**

  (Click on top tab of right window, close 3-D View)

  (Select the XZ view in the top toolbar)

- **Right click/Edit Grid Data**
- **Modify/Show Grid System**

  (To modify grid lines using actual coordinates)

- **Units:** Kip, ft, F

  - **X Grid Data:** Grid ID | Ordinate
    - A1 | 0 ft
    - A2 | 8 ft
    - B1 | 32 ft
    - B2 | 40 ft

  - **Z Grid Data:** Grid ID | Ordinate
    - Z1 | 0 ft
    - Z2 | 10 ft
    - Z3 | 12 ft
    - Z4 | 14 ft
    - Z5 | 20 ft
    - Z6 | 22 ft
    - Z7 | 24 ft
    - Z8 | 30 ft
    - Z9 | 32 ft
    - Z10 | 34 ft
    - Z11 | 40 ft
    - Z12 | 42 ft
    - Z13 | 44 ft
    - Z14 | 50 ft
    - Z15 | 52 ft
    - Z16 | 54 ft

- **OK/OK**

- **View/Restore Full View**
- **File/Save As**

  **File name:** R1-C-LAY

- **Save**

#### Step 2. Define Material Properties

- **Define/Materials**
- **Check Show Advanced Properties**
- **Click to:** Add New Material

  - **Material Name:** M1500
    - **Options**
    - **Material Type:** Other
    - **Directional Symmetry Type:** Isotropic

  - **Modulus of Elasticity:** 1350 ksi
  - **Poisson’s Ratio:** 0.2
  - **Coeff. of Thermal Expansion:** 5.5E-06
  - **Shear Modulus:** Auto (562.5 ksi)
  - **Weight and Mass**
    - **Weight per Unit Volume:** 0.1259 (kip/ft$^3$)
    - **Mass per Unit Volume:** 0

  - **Advanced Material Property Data**

- **Nonlinear Material Data**
  - **Hysteresis Type:** Kinematic
  - **Drucker-Prager Parameters**
    - **Friction Angle:** 0
    - **Dilatational Angle:** 0

  - **User Stress-Strain Curve Data**
    - **Number of Points in Stress-Strain Curve:** 5

- **Strain Stress, ksi**
Check stress is in the right units
OK/OK/OK

OK/OK/OK/OK

OK/OK/OK/OK

OK/OK/OK/OK

OK/OK/OK/OK

OK/OK/OK/OK
Poisson’s Ratio: 0.3
Coeff. of Thermal Expansion: 6.5E−06
Shear Modulus: Auto (11153.846 ksi)
Weight and Mass
Weight per Unit Volume: 0
Mass per Unit Volume: 0

Units: kip, in, F
Other Properties for Steel Materials
Minimum Yield Stress, Fy: 60
Minimum Tensile Stress, Fu: 60
Effective Yield Stress, Fye: 60
Effective Tensile Stress, Fue: 60

Advanced Material Property Data
Nonlinear Material Data
Hysteresis Type: Kinematic
Stress-Strain Curve Definition Options: User Defined
User Stress-Strain Curve Data
Number of Points in Stress-Strain Curve: 5

<table>
<thead>
<tr>
<th>Strain</th>
<th>Stress, ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.070E-02</td>
<td>-6.000E+01</td>
</tr>
<tr>
<td>-2.070E-03</td>
<td>-6.000E+01</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2.070E-03</td>
<td>6.000E+01</td>
</tr>
<tr>
<td>2.070E-02</td>
<td>6.000E+01</td>
</tr>
</tbody>
</table>

(Check stress is in the right units)
OK/OK/OK/OK

File/Save

Step 3. Define Area Sections

Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section

Section Name: M8-LIN
Type: Membrane
Material
Material Name: M1500
Material Angle: 0

Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section

Section Name: M8-U22-A
Type: Shell-Layered/Nonlinear
Modify/Show Layer Definition

Layer Definition Data
Layer Name: M22N
Distance: 0
Thickness: 7.625
Type: Membrane
Num. Int. Points: 1
Material: M1500
Material Angle: 0
Material Component Behavior
S11 S22 S12
Linear Nonlinear Inactive
Modify

Layer Name: M12N
Distance: 0
Thickness: 7.625
Type: Membrane
Num. Int. Points: 1
Material: M1500v-A
Material Angle: 0
Material Component Behavior
S11 S22 S12
Inactive Inactive Nonlinear
Add
OK/OK/OK

Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section

Section Name: M8-U11-Coupling
Layer Name: M11N
Distance: 0
Thickness: 7.625
Type: Membrane
Num. Int. Points: 1
Material: M1500
Material Angle: 0
Material Component Behavior
S11  S22  S12
Nonlinear  Linear  Inactive
Modify

Layer Name: M12N
Distance: 0
Thickness: 7.625
Type: Membrane
Num. Int. Points: 1
Material: M1500v-A
Material Angle: 0
Material Component Behavior
S11  S22  S12
Inactive  Inactive  Nonlinear
Add

Layer Name: R22N
Distance: 0
Thickness: 0.03875
Type: Membrane
Num. Int. Points: 1
Material: R60
Material Angle: 90
Material Component Behavior
S11  S22  S12
Nonlinear  Inactive  Inactive
Add

Layer Name: M22N
Distance: 0
Thickness: 7.625
Type: Membrane
Num. Int. Points: 1
Material: M1500
Num. Int. Points: 1
Material: M1500
Material Angle: 0
Material Component Behavior
S11   S22   S12
Nonlinear  Linear  Inactive
Modify

Layer Name: M12N
Distance: 0
Thickness: 7.625
Type: Membrane
Num. Int. Points: 1
Material: M1500v-Coupling
Material Angle: 0
Material Component Behavior
S11   S22   S12
Inactive  Inactive  Nonlinear
Add

Layer Name: R11N
Distance: 0
Thickness: 0.0775
Type: Membrane
Num. Int. Points: 1
Material: R60
Material Angle: 0
Material Component Behavior
S11   S22   S12
Nonlinear  Inactive  Inactive
Add
OK/OK/OK

File/Save

Step 4. Draw Area Elements

(Draw walls A, and B)

Draw/Draw Rectangular Area
Click on bottom left of Wall A (at A1/Z1) and
drag mouse to top right of Wall A (at A2/Z16)

(Draw coupling wall segments)

Draw/Draw Rectangular Area
Click on top right of Wall A (at A2/Z2) and
drag mouse to top of Wall B (at B1/Z4)

Draw/Draw Rectangular Area
Click on top right of Wall A (at A2/Z5) and
drag mouse to top of Wall B (at B1/Z7)

Draw/Draw Rectangular Area
Click on top right of Wall A (at A2/Z8) and
drag mouse to top of Wall B (at B1/Z10)

Draw/Draw Rectangular Area
Click on top right of Wall A (at A2/Z11) and
drag mouse to top of Wall B (at B1/Z13)

Draw/Draw Rectangular Area
Click on top right of Wall A (at A2/Z14) and
drag mouse to top of Wall B (at B1/Z16)

Select checkmark icon (Set Display Options)
on top toolbar
On Joints, uncheck: Invisible
On Joints, check: Labels
On Areas, check: Labels
OK

On side toolbar select all
Edit/Change Labels
Item Type: Element Labels – Area
Auto Relabel Control (use default values)
Edit/Auto Relabel/All in List
Item Type: Element Labels – Joint
Auto Relabel Control (use default values)
Edit/Auto Relabel/All in List
OK

Select checkmark icon (Set Display Options)
on top toolbar
On Joints, uncheck: Labels
On Areas, uncheck: Labels
OK

Select bottom joints, verify 4 Points are selected
Assign/Joint/Restraints/
Check boxes for all degrees of freedom (or on Fast Restraints, select fixed-end condition)
OK

On side toolbar select all
Verify 7 areas and 28 edges are selected
Edit/Edit Areas/Divide Areas
Divide Area into Objects of This Maximum Size
Along Edge from Point 1 to 2: 8 in.
Along Edge from Point 1 to 3: 8 in.
At bottom, on Restraints and Constraints for Added Points, select
Add on Edge when restraints/constraints exist at adjacent corner points
OK

On side toolbar select all, verify there are 3357 Points, 3024 Areas, 12096 Edges
On side toolbar select clr

File/Save

Step 5. Assign Area Elements

Select all area sections
Assign/Area/Sections
Sections: M8-LIN
OK

(Assign nonlinear area elements to the potential hinge regions)
Select the corner area elements at base of Walls A and B (2 elements per wall)
Select the sixth area element from left to right at the same elevation of the previous

Select the corner area elements at top of clear height of Walls A and B (2 elements per wall)
Select the sixth area element from left to right at the same elevation of the previous
Verify 12 Areas and 48 Edges are selected
Assign/Area/Sections
Sections: M8-R22-A
OK

Select the area sections in between Area Sections M8-R22A (9 top and 9 bot per wall)
Verify 36 Areas and 144 Edges are selected
Assign/Area/Sections
Sections: M8-U22-A
OK

Select the area section to the right and above A2/Z2
Select the area section to the right and below A2/Z4
Select the area section to the left and above B1/Z2
Select the area section to the left and below B1/Z4
Select the area section to the right and above A2/Z5
Select the area section to the right and below A2/Z7
Select the area section to the left and above B1/Z5
Select the area section to the left and below B1/Z7
Select the area section to the right and above A2/Z8
Select the area section to the right and below A2/Z10
Select the area section to the left and above B1/Z8
Select the area section to the left and below B1/Z10
Select the area section to the right and above A2/Z11
Select the area section to the right and below A2/Z13
Select the area section to the left and above B1/Z11
Select the area section to the left and below B1/Z13
Select the area section to the right and above A2/Z14
Select the area section to the right and below A2/Z16
Select the area section to the left and above B1/Z14
Select the area section to the left and below B1/Z16
Verify 20 Areas and 80 Edges are selected
Assign/Area/Sections
Sections: M8-R11-Coupling
OK

Select area sections along in between M8-R11-Coupling on Grids A2, and B1.
Verify 40 Areas and 160 Edges are selected
Assign/Area/Sections
Sections: M8-U11-Coupling
OK

File/Save

Step 6. Assign Constraints

Select joints at Z=624 in.
Verify 61 Points are selected
Assign/Joint/Constraints
Choose Constraint Type to Add: Diaphragm
Click to: Add New Constraint
Constraint Name: DIAPH5
Coordinate System: GLOBAL
Constraint Axis: Z Axis
OK/OK

Select joints at Story 4 elevation (Z=504 in.)
Verify 61 Points are selected
Assign/Joint/Constraints
Choose Constraint Type to Add: Diaphragm
Click to: Add New Constraint
Constraint Name: DIAPH4
Coordinate System: GLOBAL
Constraint Axis: Z Axis
OK/OK

Select joints at Story 3 elevation (Z=384 in.)
Verify 61 Points are selected
Assign/Joint/Constraints
Choose Constraint Type to Add: Diaphragm
Click to: Add New Constraint
Constraint Name: DIAPH3
Coordinate System: GLOBAL
Constraint Axis: Z Axis
OK/OK

Select joints at Story 2 elevation (Z=264 in.)
Verify 61 Points are selected
Assign/Joint/Constraints
Choose Constraint Type to Add: Diaphragm
Click to: Add New Constraint
Constraint Name: DIAPH2
Coordinate System: GLOBAL
Constraint Axis: Z Axis
OK/OK

Select joints at Story 1 elevation (Z=144 in.)
Verify 61 Points are selected
Assign/Joint/Constraints
Choose Constraint Type to Add: Diaphragm
Click to: Add New Constraint
Constraint Name: DIAPH1
Coordinate System: GLOBAL
Constraint Axis: Z Axis
OK/OK

File/Save

Step 7. Define Load Patterns and Load Cases

Define/Load Patterns
Load Pattern Name: LIVE
Type: LIVE
Self-Weight Multiplier: 0
Click to: Add New Load Pattern
OK

Define/Load Patterns
Load Pattern Name: SEISMIC
Type: Other
Self-Weight Multiplier: 0
Click to: Add New Load Pattern
OK

Define/Load Cases
Click to: Add New Load Case
Load Case Name: E
Load Case Type: Static
Analysis Type: Linear
Stiffness to Use: Zero Initial Conditions – Unstressed State
Loads Applied
Load Type = Load Pattern
Load Name = SEISMIC
Scale Factor = 1
Add
OK/OK

Define/Load Cases
Click to: Add New Load Case
Load Case Name: PRE-LOAD
Load Case Type: Static
Analysis Type: Nonlinear
Initial Conditions
Zero Initial Conditions – Start from Unstressed State
Geometric Nonlinearity Parameters: None
Loads Applied
Load Type = Load Pattern
Load Name = SEISMIC
Scale Factor = 1
Add
Other Parameters
Load Application: Modify-Show
Load Application Control: Displacement
Control
Control Displacement: Use Monitored Displacement
Magnitude of: 5.0 in.
At Joint: 3228
OK
Results Saved: Modify-Show
Results Saved: Multiple States
For Each Stage
Minimum Number of Saved States: 250
Maximum Number of Saved States: 500
Select Save Positive Displacement Increments Only
OK
Nonlinear Parameters: Default
OK/OK

(Define Nonlinear Static Analysis - Westward Loading)
Define/Load Cases
Click to: Add New Load Case
Load Case Name: NSA-
Load Case Type: Static
Analysis Type: Nonlinear
Initial Conditions
Continue from State at End of Nonlinear Case: PRE-LOAD
Geometric Nonlinearity Parameters: None
Loads Applied
Load Type = Load Pattern
Load Name = SEISMIC
Scale Factor = 1
Add
Other Parameters
Load Application: Full Load (Default)
Results Saved: Final State Only (Default)
Nonlinear Parameters: Default
OK/OK

(Define Nonlinear Static Analysis - Eastward Loading)
Define/Load Cases
Click to: Add New Load Case
Load Case Name: NSA+
Load Case Type: Static
Analysis Type: Nonlinear
Initial Conditions
Continue from State at End of Nonlinear Case: PRE-LOAD
Geometric Nonlinearity Parameters: None
Loads Applied
Load Type = Load Pattern
Load Name = SEISMIC
Scale Factor = 1
Add
Other Parameters
Load Application: Full Load (Default)
Results Saved: Final State Only (Default)
Nonlinear Parameters: Default
OK/OK
Load Case Type: Static
Analysis Type: Nonlinear
Initial Conditions
Continue from State at End of Nonlinear
Case: PRE-LOAD
Geometric Nonlinearity Parameters: None

Loads Applied
Load Type = Load Pattern
Load Name = SEISMIC
Scale Factor = -1
Add

Other Parameters
Load Application: Modify-Show
Load Application Control: Displacement Control
Control Displacement: Use Monitored Displacement
Load to a Monitored Displacement Magnitude of: 5.0 in.
Monitored Displacement DOF: U1
At Joint: 3228
OK
Results Saved: Modify-Show
Results Saved: Multiple States
For Each Stage
Minimum Number of Saved States: 250
Maximum Number of Saved States: 500
Select Save Positive Displacement Increments Only
OK
Nonlinear Parameters: Default
OK/OK

File/Save

Step 8. Assign Loads

Select all joints at roof level (2'-0" from the top of wall) and at floor levels except edge joints
Verify 295 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: DEAD

Units: kip, in. F
Loads
Force Global Z: −0.2666 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Click PS on the left side toolbar
Verify 295 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: LIVE
Units: kip, in. F
Loads
Force Global Z: −0.2666 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the edge joints at Grid Lines A1 and B2 at each Story
Verify 10 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: DEAD
Units: kip, in. F
Loads
Force Global Z: -0.1333 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Click PS on the left side toolbar
Verify 10 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: LIVE
Units: kip, in. F
Loads
Force Global Z: −0.1333 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the roof level (at X=240 in. Z=624 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in. F
Loads
Force Global X: 53.35 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the roof level (at X=240 in. Z=504 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in. F
Loads
Force Global X: 42.68 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the roof level (at X=240 in. Z=384 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in. F
Loads
Force Global X: 32.00 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the roof level (at X=240 in. Z=264 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in. F
Loads
Force Global X: 21.34 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the roof level (at X=240 in. Z=144 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in. F
Loads
Force Global X: 10.67 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

File/Save

Step 9. Analyze

Analyze/Set Analysis Options
FAST DOFs: Plane Frame - XZ Plane
OK

Analyze/Set Load Cases to Run
Highlight PRE-LOAD, NSA+, NSA-
Click to: Run/Do Not Run Case
Verify the Nonlinear Static are marked as Do Not Run
Run Now

(On the top toolbar select the Show Deformed Shape icon)
Deformed Shape
Case/Combo
Case/Combo Name: SEISMIC
OK

Verify the displacement U1 at the roof diaphragm level is 1.191 in.
Step 10. Program Output

Display
Show Forces/Stresses
Joints
Case/Combo Name: E
OK
Verify units are kip, in, F

Draw Section Cut (cut wall A at Base)
Section Cutting Line
Start Point: X=-1, Y=0, Z=1
End Point: X=97, Y=0, Z=1
Click on Refresh Button
Integrated Forces:
Left Side/Save Cut
Close

Draw Section Cut (cut wall B at Base)
Section Cutting Line
Start Point: X=383, Y=0, Z=1
End Point: X=481, Y=0, Z=1
Click on Refresh Button
Integrated Forces:
Left Side/Save Cut
Close

Display/Show Plot Functions
Define Plot Functions
Choose Function Type to Add: Add Base Functions
Click to: Add Plot Function
Base Functions: Base Shear X
OK/OK

Define Plot Functions
Choose Function Type to Add: Add Joint Disps/Forces
Click to: Add Plot Function
Joint ID: 3228
Vector Type: Displ
Component: UX
OK/OK

Define Plot Functions
Choose Function Type to Add: Add Section Cut Forces
Click to: Add Plot Functions
Section Cut: SCUT1
Component: F1
OK/OK

Define Plot Functions
Choose Function Type to Add: Add Section Cut Forces
Click to: Add Plot Functions
Section Cut: SCUT2
Component: F1
OK/OK

Choose Plot Functions
List of Functions: Highlight Base Shear X, SCUT1 and SCUT2
Click the Add button
Verify Base Shear X, SCUT1, and SCUT2 show under Vertical Functions
Horizontal Plot Function: Joint3228

Load Case (Multi-Stepped Cases); NSA+
Click Display
File/Print Tables to File
File name: NSA+
Save
OK

Load Case (Multi-Stepped Cases); NSA-
Click Display
File/Print Tables to File
File name: NSA-
Save
OK

File/Save
Done
B.4.4 Case Study D

B.4.4.1 Structure RM1

Step 1. Define Geometry

File/New Model
New Model Initialization
Initialize Model from Defaults with Units:
kip, in, F
Select Template: Grid Only
Coordinate System Name: GLOBAL
Cartesian
Number of Grid Lines Spacing Grid Line
X direction: 6 48 0
Y direction: 2 48 0
Z direction: 13 48 0
OK

(Click on top tab of right window, close 3-D View)
(Select the XZ view in the top toolbar)

Cartesian
Coordinate System Name: GLOBAL

X Grid Data: Grid ID Ordinate
A1 1 in
A2 2 in
A3 10 in
B1 20 in
B2 36 in
C1 46 in
C2 55 in

Y Grid Data: Grid ID Ordinate
Y1 1 in
Y2 14 in

Z Grid Data: Grid ID Ordinate
Z1 0 in
Z2 6 in
Z3 22 in
Z4 28 in
Z5 31 in
Z6 37 in
Z7 53 in
Z8 59 in
Z9 62 in
Z10 68 in
Z11 84 in
Z12 90 in
Z13 93 in

OK

Modifier/Show System
(To modify grid lines using actual coordinates)
Units: Kip, in, F

X Grid Data: Grid ID Ordinate
A1 1 in
A2 2 in
A3 10 in
B1 20 in
B2 36 in
C1 46 in
C2 55 in

Y Grid Data: Grid ID Ordinate
Y1 1 in
Y2 14 in

Z Grid Data: Grid ID Ordinate
Z1 0 in
Z2 6 in
Z3 22 in
Z4 28 in
Z5 31 in
Z6 37 in
Z7 53 in
Z8 59 in
Z9 62 in
Z10 68 in
Z11 84 in
Z12 90 in
Z13 93 in

OK

File/Save As
File name: RM1-LAYER
Save

Step 2. Define Material Properties

Right click/Edit Grid Data
Modify/Show System
(To modify grid lines using actual coordinates)
Units: Kip, in, F

X Grid Data: Grid ID Ordinate
A1 1 in
A2 2 in
A3 10 in
B1 20 in
B2 36 in
C1 46 in
C2 55 in

Y Grid Data: Grid ID Ordinate
Y1 1 in
Y2 14 in

Z Grid Data: Grid ID Ordinate
Z1 0 in
Z2 6 in
Z3 22 in
Z4 28 in
Z5 31 in
Z6 37 in
Z7 53 in
Z8 59 in
Z9 62 in
Z10 68 in
Z11 84 in
Z12 90 in
Z13 93 in

OK

Define/Materials
Check Show Advanced Properties
Click to: Add New Material
Material Name: M1215
Options
Material Type: Other
Directional Symmetry Type: Isotropic
Modulus of Elasticity: 684 ksi
Poisson’s Ratio: 0.25
Coeff. of Thermal Expansion: 5.5E-06
Shear Modulus: Auto (273.6 ksi)
Weight and Mass
Weight per Unit Volume: 0
Mass per Unit Volume: 0

Advanced Material Property Data
Nonlinear Material Data
Hysteresis Type: Kinematic
Drucker-Prager Parameters
Friction Angle: 0
Dilatational Angle: 0
User Stress-Strain Curve Data
Number of Points in Stress-Strain Curve: 5

<table>
<thead>
<tr>
<th>Strain</th>
<th>Stress, ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.35E-02</td>
<td>-9.23E-01</td>
</tr>
<tr>
<td>-1.35E-03</td>
<td>-9.23E-01</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.35E-03</td>
<td>9.23E-04</td>
</tr>
<tr>
<td>1.35E-02</td>
<td>9.23E-04</td>
</tr>
</tbody>
</table>

(OK/OK/OK/OK)

Define/Materials
Check Show Advanced Properties
Click to: Add New Material
Material Name: M1215v-A
Options
Material Type: Other
Directional Symmetry Type: Isotropic

OK/OK/OK/OK

Define/Materials
Check Show Advanced Properties
Click to: Add New Material
Material Name: M1215v-B
Options
Material Type: Other
Directional Symmetry Type: Isotropic

 OK/OK/OK/OK
Material Name: M1215v-Coupling
Material Type: Other
Directional Symmetry Type: Isotropic

Modify/Show Material Properties
Modulus of Elasticity: 547 ksi
Poisson’s Ratio: 0
Coefficient of Thermal Expansion: 5.5E-06
Shear Modulus: Auto (273.5 ksi)
Weight and Mass
Weight per Unit Volume: 0
Mass per Unit Volume: 0

Advanced Material Property Data
Nonlinear Material Data
Hysteresis Type: Kinematic
User Stress-Strain Curve Data
Number of Points in Stress-Strain Curve: 5

<table>
<thead>
<tr>
<th>Strain</th>
<th>Stress, ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>-4.84E-03</td>
<td>-2.65E-01</td>
</tr>
<tr>
<td>-4.84E-04</td>
<td>-2.65E-01</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4.84E-04</td>
<td>2.65E-01</td>
</tr>
<tr>
<td>4.84E-03</td>
<td>2.65E-01</td>
</tr>
</tbody>
</table>

(Check stress is in the right units)
OK/OK/OK/OK

Material Name: WIRE
Material Type: Steel
Directional Symmetry Type: Uniaxial

Modify/Show Material Properties
Modulus of Elasticity: 29000 ksi
Poisson’s Ratio: 0.3
Coefficient of Thermal Expansion: 6.5E-06
Shear Modulus: Auto (11153.846 ksi)
Weight and Mass
Weight per Unit Volume: 0
Mass per Unit Volume: 0

Advanced Material Property Data
Nonlinear Material Data
Hysteresis Type: Kinematic
User Stress-Strain Curve Data
Number of Points in Stress-Strain Curve: 5

<table>
<thead>
<tr>
<th>Strain</th>
<th>Stress, ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.62E-02</td>
<td>-4.70E+01</td>
</tr>
<tr>
<td>-1.62E-03</td>
<td>-4.70E+01</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.62E-03</td>
<td>4.70E+01</td>
</tr>
<tr>
<td>1.62E-02</td>
<td>4.70E+01</td>
</tr>
</tbody>
</table>

(Check stress is in the right units)
OK/OK/OK/OK

Material Name: R60
Material Type: Steel
Directional Symmetry Type: Uniaxial

Modify/Show Material Properties
Modulus of Elasticity: 29000 ksi
Poisson’s Ratio: 0.3
Coefficient of Thermal Expansion: 6.5E-06
Shear Modulus: Auto (11153.846 ksi)
Weight and Mass
Weight per Unit Volume: 0
Mass per Unit Volume: 0

Advanced Material Property Data
Nonlinear Material Data
Hysteresis Type: Kinematic
User Stress-Strain Curve Data
Number of Points in Stress-Strain Curve: 5

<table>
<thead>
<tr>
<th>Strain</th>
<th>Stress, ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.62E-02</td>
<td>-4.70E+01</td>
</tr>
<tr>
<td>-1.62E-03</td>
<td>-4.70E+01</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.62E-03</td>
<td>4.70E+01</td>
</tr>
<tr>
<td>1.62E-02</td>
<td>4.70E+01</td>
</tr>
</tbody>
</table>

(Check stress is in the right units)
OK/OK/OK/OK
Weight per Unit Volume: 0
Mass per Unit Volume: 0

Units: kip, in, F
Other Properties for Steel Materials
Minimum Yield Stress, Fy: 60
Minimum Tensile Stress, Fu: 60
Effective Yield Stress, Fye: 60
Effective Tensile Stress, Fue: 60

Advanced Material Property Data
Nonlinear Material Data
Hysteresis Type: Kinematic
Stress-Strain Curve Definition Options: User Defined
User Stress-Strain Curve Data
Number of Points in Stress-Strain Curve: 5

<table>
<thead>
<tr>
<th>Strain</th>
<th>Stress, ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.07E-02</td>
<td>-6.00E+01</td>
</tr>
<tr>
<td>-2.07E-03</td>
<td>-6.00E+01</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2.07E-03</td>
<td>6.00E+01</td>
</tr>
<tr>
<td>2.07E-02</td>
<td>6.00E+01</td>
</tr>
</tbody>
</table>

(Check stress is in the right units)
OK/OK/OK/OK

File/Save

Step 3. Define Area Sections

Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section

Section Name: M2-LIN
Type: Shell-Thick
Material
Material Name: M1215
Material Angle: 0
Thickness
Membrane: 2.0
Bending: 2.0
OK/OK

Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section

Section Name: M2-U22-A
Type: Shell-Layered/Nonlinear
Modify/Show Layer Definition

Layer Definition Data
Layer Name: M22N
Distance: 0
Thickness: 2.0
Type: Membrane
Num. Int. Points: 1
Material: M1215
Material Angle: 0
Material Component Behavior
S11    S22    S12
Linear  Nonlinear  Inactive
Modify

Layer Name: M12N
Distance: 0
Thickness: 2.0
Type: Membrane
Num. Int. Points: 1
Material: M1215v-A
Material Angle: 0
Material Component Behavior
S11    S22    S12
Inactive  Inactive  Nonlinear
Add
OK/OK/OK

Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section

Section Name: M2-U22-B
Type: Shell-Layered/Nonlinear
Modify/Show Layer Definition

Layer Definition Data
Layer Name: M22N
Distance: 0
Thickness: 2.0
Type: Membrane
Num. Int. Points: 1
Material: M1215
Material Angle: 0
Material Component Behavior
S11  S22  S12
Linear  Nonlinear  Inactive
Modify

Layer Name: M12N
Distance: 0
Thickness: 2.0
Type: Membrane
Num. Int. Points: 1
Material: M1215v-Coupling
Material Angle: 0
Material Component Behavior
S11  S22  S12
Inactive  Inactive  Nonlinear
Add
OK/OK/OK

Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section

Section Name: M2-U11-Coupling
Type: Shell-Layered/Nonlinear
Modify/Show Layer Definition

Layer Definition Data
Layer Name: M22N
Distance: 0
Thickness: 2.0
Type: Membrane
Num. Int. Points: 1
Material: M1215
Material Angle: 0
Material Component Behavior
S11  S22  S12
Nonlinear  Linear  Inactive
Modify

Layer Name: M12N
Distance: 0
Thickness: 2.0
Type: Membrane
Num. Int. Points: 1
Material: M1215v-B
Material Angle: 0
Material Component Behavior
S11  S22  S12
Inactive  Inactive  Nonlinear
Add
OK/OK/OK

Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section

Section Name: M2-R22-A
Type: Shell-Layered/Nonlinear
Modify/Show Layer Definition

Layer Definition Data
Layer Name: M22N
Distance: 0
Thickness: 2.0
Type: Membrane
Num. Int. Points: 1
Material: M1215
Material Angle: 0
Material Component Behavior
S11  S22  S12
Linear  Nonlinear  Inactive
Modify

Layer Name: M12N
Distance: 0
Thickness: 2.0
Type: Membrane
Num. Int. Points: 1
Material: M1215v-A
Material Angle: 0
Material Component Behavior
<table>
<thead>
<tr>
<th>Layer Name</th>
<th>Distance</th>
<th>Thickness</th>
<th>Type</th>
<th>Num. Int. Points</th>
<th>Material</th>
<th>Material Angle</th>
<th>Material Component Behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>R22N</td>
<td>0</td>
<td>0.00575</td>
<td>Membrane</td>
<td>1</td>
<td>WIRE</td>
<td>90</td>
<td>Nonlinear Inactive Inactive</td>
</tr>
<tr>
<td>M22N</td>
<td>0</td>
<td>2.0</td>
<td>Membrane</td>
<td>1</td>
<td>M1215</td>
<td>0</td>
<td>Nonlinear Linear Inactive</td>
</tr>
<tr>
<td>M12N</td>
<td>0</td>
<td>2.0</td>
<td>Membrane</td>
<td>1</td>
<td>M1215v-B</td>
<td>0</td>
<td>Nonlinear Linear Inactive</td>
</tr>
</tbody>
</table>

Layer Definition Data
Layer Name: M2-R22-B
Type: Shell-Layered/Nonlinear
Modify/Show Layer Definition

Layer Definition Data
Layer Name: M2-R11-Coupling-W
Type: Shell-Layered/Nonlinear
Modify/Show Layer Definition

Layer Definition Data
Layer Name: M12N
Distance: 0
Thickness: 2.0
Type: Membrane
Num. Int. Points: 1
Material: M1215v-B
Num. Int. Points: 1
Material: M1215v-Coupling
Material Angle: 0
Material Component Behavior
S11  S22  S12
Inactive  Inactive  Nonlinear
Add

Layer Name: R11N
Distance: 0
Thickness: 0.00575
Type: Membrane
Num. Int. Points: 1
Material: WIRE
Material Angle: 0
Material Component Behavior
S11  S22  S12
Nonlinear  Inactive  Inactive
Add
OK/OK/OK

Layer Name: M11N
Distance: 0
Thickness: 2.0
Type: Membrane
Num. Int. Points: 1
Material: M1215
Material Angle: 0
Material Component Behavior
S11  S22  S12
Nonlinear  Linear  Inactive
Modify

Layer Name: M12N
Distance: 0
Thickness: 2.0
Type: Membrane
Num. Int. Points: 1
Material: M1215v-Coupling

Material Angle: 0
Material Component Behavior
S11  S22  S12
Inactive  Inactive  Linear
Add

Layer Name: R11N
Distance: 0
Thickness: 0.0733
Type: Membrane
Num. Int. Points: 1
Material: R60
Material Angle: 0
Material Component Behavior
S11  S22  S12
Nonlinear  Inactive  Inactive
Add
OK/OK/OK

File/Save

Step 4. Draw Area Elements

(Draw Walls A, B, and C)
Click XZ View, Select X-Z Plane @ Y=1
Select Quick Draw Area on Side Toolbar
Fence regions between X=1, X=55, Z=0, and Z=93
Define window openings by deleting appropriate area elements
Click YZ View, Select Y-Z Plane @ X=1
Select Quick Draw Area on Side Toolbar
Select regions between Y=1, Y=14, Z=0, and Z=93
Select Y-Z Plane @ X=55
Select regions between Y=1, Y=14, Z=0, and Z=93
Select bottom joints, verify 12 Points are selected
Assign/Joint/Restraints/
Check boxes for all degrees of freedom (or on Fast Restraints, select fixed-end condition)
On side toolbar select all
Verify 156 Points 126 Areas and 504 Edges are selected
Edit/Edit Areas/Divide Areas
Divide Area into Objects of This Maximum Size
Along Edge from Point 1 to 2: 2 in.
Along Edge from Point 1 to 3: 2 in.
At bottom, on Restraints and Constraints for Added Points, select
Add on Edge when restraints/constraints exist at adjacent corner points
OK

On side toolbar select all, verify there are 1939 Points, 1776 Areas, and 7104 Edges
On side toolbar select clr

Click XZ View

Select checkmark icon (Set Display Options) on top toolbar
On Joints, uncheck: Invisible
On Joints, check: Labels
On Areas, check: Labels
OK

On side toolbar select all
Edit/Change Labels
Item Type: Element Labels – Area
Auto Relabel Control (use default values)
Edit/Auto Relabel/All in List
Item Type: Element Labels – Joint
Auto Relabel Control (use default values)
Edit/Auto Relabel/All in List
OK

Select checkmark icon (Set Display Options) on top toolbar
On Joints, uncheck: Labels
On Areas, uncheck: Labels
OK

File/Save

Step 5. Assign Area Elements
Select all area sections
Assign/Area/Sections
Sections: M2-LIN
OK

Select the area elements in between area sections M2-R22-A previously selected (4 area elements per story)
Verify 24 Areas and 96 Edges are selected
Assign/Area/Sections
Sections: M2-U22-A
OK

Select the corner area elements at clear heights of Wall B (4 elements per story)
Select the third (left to right) area element in between the previously selected areas (2 elements per story)
Verify 24 Areas and 96 Edges are selected
Assign/Area/Sections
Sections: M2-R22-B
OK

Select the area elements in between area sections M2-R22-B previously selected (8 area elements per story)
Verify 24 Areas and 96 Edges are selected
Assign/Area/Sections
Sections: M2-U22-B
OK

Click YZ View, Select Y-Z Plane @ X=1
Select the edge area elements located just above Z=6, Z=20, Z=37, Z=51, Z=68, and Z=82.
Select the third and the fifth (left to right) area elements at the same elevation of the previously selected (4 elements per story)
Select Y-Z Plane @ X=55
Select the edge area elements located just above Z=6, Z=20, Z=37, Z=51, Z=68, and Z=82.
Select the third and the fifth (left to right) area elements at the same elevation of the previously selected (4 elements per story)
Verify 48 Areas and 192 Edges are selected
Assign/Area/Sections
Sections: M2-R22-A
OK

Select Y-Z Plane @ X=1
Select the area sections located in between area sections M2-R22-A previously selected (6 elements per story)
Select Y-Z Plane at X=55
Select the area sections located in between area sections M2-R22-A previously assigned (6 elements per wall) on all stories
Verify 36 Areas and 144 Edges are selected
Assign/Area/Sections
Sections: M2-U22-A
OK

Select XZ View, Select X-Z Plane @ Y=1
Select two area elements between X=10, X=12, and Z=0, Z=4
Select two area elements between X=18, X=20, and Z=0, Z=4
Select two area elements between X=36, X=38, and Z=0, Z=4
Select two area elements between X=44, X=46, and Z=0, Z=4
Select two area elements between X=10, X=12, and Z=24, Z=28
Select two area elements between X=18, X=20, and Z=24, Z=28
Select two area elements between X=36, X=38, and Z=24, Z=28
Select two area elements between X=44, X=46, and Z=24, Z=28
Select two area elements between X=10, X=12, and Z=31, Z=35
Select two area elements between X=18, X=20, and Z=31, Z=35
Select two area elements between X=36, X=38, and Z=31, Z=35
Select two area elements between X=44, X=46, and Z=31, Z=35
Select two area elements between X=10, X=12, and Z=55, Z=59
Select two area elements between X=18, X=20, and Z=55, Z=59
Select two area elements between X=36, X=38, and Z=55, Z=59
Select two area elements between X=44, X=46, and Z=55, Z=59
Select two area elements between X=10, X=12, and Z=62, Z=66
Select two area elements between X=18, X=20, and Z=62, Z=66
Select two area elements between X=36, X=38, and Z=62, Z=66
Select two area elements between X=44, X=46, and Z=62, Z=66
Select two area elements between X=10, X=12, and Z=86, Z=90
Select two area elements between X=18, X=20, and Z=86, Z=90
Select two area elements between X=36, X=38, and Z=86, Z=90
Select two area elements between X=44, X=46, and Z=86, Z=90
Verify 48 Areas and 192 Edges are selected
Assign/Area/Sections
Sections: M2-U11-Coupling
Select two area elements between X=10, X=12, and Z=4, Z=6
Select two area elements between X=18, X=20, and Z=4, Z=6
Select two area elements between X=36, X=38, and Z=4, Z=6
Select two area elements between X=44, X=46, and Z=4, Z=6
Select two area elements between X=10, X=12, and Z=22, Z=24
Select two area elements between X=18, X=20, and Z=22, Z=24
Select two area elements between X=36, X=38, and Z=22, Z=24
Select two area elements between X=44, X=46, and Z=22, Z=24
Select two area elements between X=10, X=12, and Z=35, Z=37
Select two area elements between X=18, X=20, and Z=35, Z=37
Select two area elements between X=36, X=38, and Z=35, Z=37
Select two area elements between X=44, X=46, and Z=35, Z=37
Select two area elements between X=10, X=12, and Z=53, Z=55
Select two area elements between X=18, X=20, and Z=53, Z=55
Select two area elements between X=36, X=38, and Z=53, Z=55
Select two area elements between X=44, X=46, and Z=53, Z=55
Select two area elements between X=10, X=12, and Z=66, Z=68
Select two area elements between X=18, X=20, and Z=66, Z=68
Select two area elements between X=36, X=38, and Z=66, Z=68
Select two area elements between X=44, X=46, and Z=66, Z=68
Select two area elements between X=10, X=12, and Z=84, Z=86
Select two area elements between X=18, X=20, and Z=84, Z=86
Select two area elements between X=36, X=38, and Z=84, Z=86
Select two area elements between X=44, X=46, and Z=84, Z=86
Verify 24 Areas and 96 Edges are selected
Assign/Area/Sections
Sections: M2-R11-Coupling-W
Select two area elements between X=10, X=12, and Z=28, Z=31
Select two area elements between X=18, X=20, and Z=28, Z=31
Select two area elements between X=36, X=38, and Z=28, Z=31
Select two area elements between X=44, X=46, and Z=28, Z=31
Select two area elements between X=10, X=12, and Z=59, Z=62
Select two area elements between X=18, X=20, and Z=59, Z=62
Select two area elements between X=36, X=38, and Z=59, Z=62
Select two area elements between X=44, X=46, and Z=59, Z=62
Select two area elements between X=10, X=12, and Z=90, Z=93
Select two area elements between X=18, X=20, and Z=90, Z=93
Select two area elements between X=36, X=38, and Z=90, Z=93
Select two area elements between X=44, X=46, and Z=90, Z=93
Verify 24 Areas and 96 Edges are selected
Assign/Area/Sections
Sections: M2-R11-Coupling-R

File/Save

Step 6. Assign Constraints
Select all Joints at Z=29.5
Select all Joints at Z=60.5
Select all Joints at Z=91.5
Verify 123 Points are selected
Assign/Joint/Constraint
Choose Constraint Type to Add: Diaphragm
Add New Constraint
Constraint Name: DIAPH1
Coordinate System: Global
Constraint Axis: Z Axis
Check box Assign a different diaphragm constraint to each different selected Z level
OK/OK

File/Save

Step 7. Define Load Patterns and Load Cases

Define/Load Patterns
Load Pattern Name: SEISMIC
Type: Other
Self-Weight Multiplier: 0
Click to: Add New Load Pattern
OK

Define/Load Cases
Click to: Add New Load Case
Load Case Name: NSA+
Load Case Type: Static
Analysis Type: Nonlinear
Initial Conditions
Continue from State at End of Nonlinear Case: PRE-LOAD
Geometric Nonlinearity Parameters: None
Loads Applied
Load Type = Load Pattern
Load Name = SEISMIC
Scale Factor = 1
Add
Other Parameters
Load Application: Modify/Show
Load Application Control: Displacement Control
Control Displacement: Use Monitored Displacement
Load to a Monitored Displacement Magnitude of: 2.0 in.
Monitored Displacement DOF: U1
At Joint: 1868
OK
Results Saved: Modify/Show
Results Saved: Multiple States
For Each Stage
Minimum Number of Saved States: 75
Maximum Number of Saved States: 150
Select Save Positive Displacement Increments Only
OK
Nonlinear Parameters: Default
OK/OK

Step 8. Assign Loads

Select area elements between Z=28 and Z=31
Select area elements between Z=59 and Z=62

(Define Nonlinear Static Analysis - Eastward Loading)
Select area elements between Z=90 and Z=93
Verify 252 Areas, 1008 Edges are selected
Assign/Area Loads/Uniform (Shell)
Load Pattern Name: DEAD
Units: lb, in, F
Uniform Load
Load: 6.15
Coord System: Global
Direction: Gravity
Options: Replace Existing Loads
OK

Select the center joint at the roof diaphragm level (at X=28 in. Z=91.5 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in, F
Loads
Force Global X: 3 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the diaphragm level (at X=28 in. Z=60.5 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in, F
Loads
Force Global X: 2 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the diaphragm level (at X=28 in. Z=29.5 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in, F
Loads
Force Global X: 1 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

File/Save

Step 9. Analyze
Analyze/Set Analysis Options
FAST DOFs: Plane Frame - XZ Plane
OK

Analyze/Set Load Cases to Run
Highlight PRE-LOAD, NSA+, Click to: Run/Do Not Run Case
Verify the Nonlinear Static are marked as Do Not Run
Run Now

(On the top toolbar select the Show Deformed Shape icon)
Deformed Shape
Case/Combo
Case/Combo Name: SEISMIC
OK

Verify the displacement U1 at the roof diaphragm level is 0.0677 in.

Step 10. Program Output
Display
Show Forces/Stresses
Joints
Case/Combo Name: E
OK
Verify units are kip, in, F

Draw Section Cut (cut Wall A at Base)
Section Cutting Line
Start Point: X=−1, Y=1, Z=6.1
End Point: X=12, Y=1, Z=6.1
Click on Refresh button
Integrated Forces:
Left Side/Save Cut/OK
Close

Draw Section Cut (cut Wall B at Base)
Section Cutting Line
Start Point: X=18, Y=1, Z=6.1
End Point: X=38, Y=1, Z=6.1
Click on Refresh button
Integrated Forces:
Left Side/Save Cut/OK
Close

Draw Section Cut (cut Wall C at Base)
Section Cutting Line
Start Point: X=44, Y=1, Z=6.1
End Point: X=57, Y=1, Z=6.1
Click on Refresh button
Integrated Forces:
Left Side/Save Cut/OK
Close

Display/Show Plot Function
Define Plot Functions
Choose Function Type to Add: Add Base Functions
Click to: Add Plot Function
Base Functions: Base Shear X
OK/OK

Define Plot Functions
Choose Function Type to Add: Add Joint Disps/Forces
Click to: Add Plot Function
Joint ID: 1868
Vector Type: Displ
Component: UX

OK/OK

Define Plot Functions
Choose Function Type to Add: Add Section Cut Forces
Click to: Add Plot Function
Section Cut: SCUT1
Component: F1
OK/OK

Define Plot Functions
Choose Function Type to Add: Add Section Cut Forces
Click to: Add Plot Function
Section Cut: SCUT2
Component: F1
OK/OK

Define Plot Functions
Choose Function Type to Add: Add Section Cut Forces
Click to: Add Plot Function
Section Cut: SCUT3
Component: F1
OK/OK

Choose Plot Functions
List of Functions: Highlight Base Shear X, SCUT1, SCUT2, and SCUT3
Click the Add button
Verify Base Shear X, SCUT1, SCUT2, and SCUT3 show under Vertical Functions
Horizontal Plot Function: Joint1868

Load Case (Multi-Stepped Cases): NSA+
Click Display
File/Print Tables to File
File name: NSA+
Save
OK

File/Save
Done
B.4.4.2 Structure RM3

Step 1. Define Geometry

File/New Model
New Model Initialization
Initialize Model from Defaults with Units:
kip, in, F
Select Template: Grid Only

Cartesian
Coordinate System Name: GLOBAL

<table>
<thead>
<tr>
<th>Number of Grid Lines</th>
<th>Grid Spacing</th>
<th>First Grid Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>X direction: 6</td>
<td>48</td>
<td>0</td>
</tr>
<tr>
<td>Y direction: 2</td>
<td>48</td>
<td>0</td>
</tr>
<tr>
<td>Z direction: 13</td>
<td>48</td>
<td>0</td>
</tr>
</tbody>
</table>

OK

(Click on top tab of right window, close 3-D View)
(Select the XZ view in the top toolbar)

Step 2. Define Material Properties

Define/Materials
Check Show Advanced Properties
Click to: Add New Material
Material Name: M1228
Options
Material Type: Other
Directional Symmetry Type: Isotropic

Modify/Show Material Properties
Modulus of Elasticity: 864.5 ksi
Poisson’s Ratio: 0.25
Coeff. of Thermal Expansion: 5.5E-06
Shear Modulus: Auto (345.8 ksi)
Weight and Mass
Weight per Unit Volume: 0
Mass per Unit Volume: 0

Advanced Material Property Data
Nonlinear Material Data
Hysteresis Type: Kinematic
Drucker-Prager Parameters
Friction Angle: 0
Dilatational Angle: 0
User Stress-Strain Curve Data
Number of Points in Stress-Strain Curve: 5

<table>
<thead>
<tr>
<th>Strain</th>
<th>Stress, ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.08E-02</td>
<td>-9.33E-01</td>
</tr>
<tr>
<td>-1.08E-03</td>
<td>-9.33E-01</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.08E-03</td>
<td>9.33E-04</td>
</tr>
<tr>
<td>1.08E-03</td>
<td>9.33E-04</td>
</tr>
</tbody>
</table>

(Check stress is in the right units)
OK/OK/OK/OK

Define/Materials
Check Show Advanced Properties
Click to: Add New Material
Material Name: M1228v-A
Options
Material Type: Other
Directional Symmetry Type: Isotropic
Modify/Show Material Properties
Modulus of Elasticity: 768 ksi
Poisson’s Ratio: 0
Coeff. of Thermal Expansion: 5.5E–06
Shear Modulus: Auto (384 ksi)
Weight and Mass
Weight per Unit Volume: 0
Mass per Unit Volume: 0
Advanced Material Property Data
Nonlinear Material Data
Hysteresis Type: Kinematic
Drucker-Prager Parameters
Friction Angle: 0
Dilatational Angle: 0
User Stress-Strain Curve Data
Number of Points in Stress-Strain Curve: 5

<table>
<thead>
<tr>
<th>Strain</th>
<th>Stress, ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>-4.60E-03</td>
<td>-3.53E-01</td>
</tr>
<tr>
<td>-4.60E-04</td>
<td>-3.53E-01</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

(Check stress is in the right units)
OK/OK/OK/OK

Define/Materials
Check Show Advanced Properties
Click to: Add New Material
Material Name: M1228v-B
Options
Material Type: Other
Directional Symmetry Type: Isotropic
Modify/Show Material Properties
Modulus of Elasticity: 691.6 ksi
Poisson’s Ratio: 0
Coeff. of Thermal Expansion: 5.5E–06
Shear Modulus: Auto (345.8 ksi)
Weight and Mass
Weight per Unit Volume: 0
Mass per Unit Volume: 0
Advanced Material Property Data
Nonlinear Material Data
Hysteresis Type: Kinematic
Drucker-Prager Parameters
Friction Angle: 0
Dilatational Angle: 0
User Stress-Strain Curve Data
Number of Points in Stress-Strain Curve: 5

<table>
<thead>
<tr>
<th>Strain</th>
<th>Stress, ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>-4.60E-03</td>
<td>-3.18E-01</td>
</tr>
<tr>
<td>-4.60E-04</td>
<td>-3.18E-01</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

(Check stress is in the right units)
OK/OK/OK/OK

Define/Materials
Check Show Advanced Properties
Click to: Add New Material
Material Name: M1228v-C
<table>
<thead>
<tr>
<th>Options</th>
<th>Weight and Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Type: Other</td>
<td>Weight per Unit Volume: 0</td>
</tr>
<tr>
<td>Directional Symmetry Type: Isotropic</td>
<td>Mass per Unit Volume: 0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Modify/Show Material Properties</th>
<th>Advanced Material Property Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of Elasticity: 768 ksi</td>
<td>Nonlinear Material Data</td>
</tr>
<tr>
<td>Poisson’s Ratio: 0</td>
<td>Hysteresis Type: Kinematic</td>
</tr>
<tr>
<td>Coeff. of Thermal Expansion: 5.5E–06</td>
<td>Drucker-Prager Parameters</td>
</tr>
<tr>
<td>Shear Modulus: Auto (384 ksi)</td>
<td>Friction Angle: 0</td>
</tr>
<tr>
<td>Weight and Mass</td>
<td>Dilatational Angle: 0</td>
</tr>
<tr>
<td>Weight per Unit Volume: 0</td>
<td>User Stress-Strain Curve Data</td>
</tr>
<tr>
<td>Mass per Unit Volume: 0</td>
<td>Number of Points in Stress-Strain Curve: 5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Advanced Material Property Data</th>
<th>Strain</th>
<th>Stress, ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonlinear Material Data</td>
<td>-3.850E-03</td>
<td>-2.660E-01</td>
</tr>
<tr>
<td>Hysteresis Type: Kinematic</td>
<td>-3.850E-04</td>
<td>-2.660E-01</td>
</tr>
<tr>
<td>Drucker-Prager Parameters</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Friction Angle: 0</td>
<td>3.850E-04</td>
<td>2.660E-01</td>
</tr>
<tr>
<td>Dilatational Angle: 0</td>
<td>3.850E-03</td>
<td>2.660E-01</td>
</tr>
<tr>
<td>User Stress-Strain Curve Data</td>
<td>(Check stress is in the right units)</td>
<td></td>
</tr>
<tr>
<td>Number of Points in Stress-Strain Curve: 5</td>
<td>OK/OK/OK/OK</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Strain</th>
<th>Stress, ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3.82E-03</td>
<td>-2.93E-01</td>
</tr>
<tr>
<td>-3.82E-04</td>
<td>-2.93E-01</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3.82E-04</td>
<td>2.93E-01</td>
</tr>
<tr>
<td>3.82E-03</td>
<td>2.93E-01</td>
</tr>
</tbody>
</table>

(Train stress is in the right units)

OK/OK/OK/OK

<table>
<thead>
<tr>
<th>Define/Materials</th>
<th>Check Show Advanced Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Options</td>
<td>Click to: Add New Material</td>
</tr>
<tr>
<td>Material Name: M1228v-Coupling</td>
<td>Material Name: WIRE</td>
</tr>
<tr>
<td>Options</td>
<td>Material Type: Steel</td>
</tr>
<tr>
<td>Material Type: Other</td>
<td>Directional Symmetry Type: Uniaxial</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material Type: Other</th>
<th>Vector: 768 ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of Elasticity: 768 ksi</td>
<td>Nonlinear Material Data</td>
</tr>
<tr>
<td>Shear Modulus: Auto (384 ksi)</td>
<td>Hysteresis Type: Kinematic</td>
</tr>
<tr>
<td>Weight and Mass</td>
<td>Drucker-Prager Parameters</td>
</tr>
<tr>
<td>Weight per Unit Volume: 0</td>
<td>Friction Angle: 0</td>
</tr>
<tr>
<td>Mass per Unit Volume: 0</td>
<td>Dilatational Angle: 0</td>
</tr>
<tr>
<td>Units: kip, in, F</td>
<td>User Stress-Strain Curve Data</td>
</tr>
<tr>
<td>Minimum Yield Stress, Fy: 47</td>
<td>Number of Points in Stress-Strain Curve: 5</td>
</tr>
<tr>
<td>Minimum Tensile Stress, Fu: 47</td>
<td>Effective Yield Stress, Fye: 47</td>
</tr>
<tr>
<td>Effective Tensile Stress, Fue: 47</td>
<td>Other Properties for Steel Materials</td>
</tr>
<tr>
<td>Effective Yield Stress, Fye: 47</td>
<td>Other Properties for Steel Materials</td>
</tr>
<tr>
<td>Effective Tensile Stress, Fue: 47</td>
<td>Other Properties for Steel Materials</td>
</tr>
</tbody>
</table>
Advanced Material Property Data
Nonlinear Material Data
Hysteresis Type: Kinematic
Stress-Strain Curve Definition Options: User Defined
User Stress-Strain Curve Data
Number of Points in Stress-Strain Curve: 5

<table>
<thead>
<tr>
<th>Strain (ksi)</th>
<th>Stress, ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.07E-02</td>
<td>6.00E+01</td>
</tr>
<tr>
<td>2.07E-03</td>
<td>6.00E+01</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2.07E-02</td>
<td>6.00E+01</td>
</tr>
</tbody>
</table>

(Check stress is in the right units)
OK/OK/OK/OK

Step 3. Define Area Sections

Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section

Section Name: M2-LIN
Type: Shell-Thick
Material
Material Name: M1228
Material Angle: 0
Thickness
Membrane: 2.0
Bending: 2.0
OK/OK

Modify/Show Layer Definition
Layer Definition Data
Layer Name: M22N
Distance: 0
<table>
<thead>
<tr>
<th>Layer Name</th>
<th>Distance</th>
<th>Thickness</th>
<th>Type</th>
<th>Material</th>
<th>Material Angle</th>
<th>Num. Int. Points</th>
<th>Material Component Behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>M12N</td>
<td>0</td>
<td>2.0</td>
<td>Membrane</td>
<td>M1228</td>
<td>0</td>
<td>1</td>
<td>Linear Nonlinear Inactive</td>
</tr>
<tr>
<td>M12N</td>
<td>0</td>
<td>2.0</td>
<td>Membrane</td>
<td>M1228v-A</td>
<td>0</td>
<td></td>
<td>Inactive Inactive Nonlinear</td>
</tr>
<tr>
<td>M22N</td>
<td>0</td>
<td>2.0</td>
<td>Membrane</td>
<td>M1228v-C</td>
<td>0</td>
<td></td>
<td>Inactive Inactive Nonlinear</td>
</tr>
</tbody>
</table>

Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section

Section Name: M2-U22-C
Type: Shell-Layered/Nonlinear
Modify/Show Layer Definition

Layer Definition Data
Layer Name: M22N
Distance: 0
Thickness: 2.0
Type: Membrane
Num. Int. Points: 1
Material: M1228
Material Angle: 0
Material Component Behavior
S11 S22 S12
Linear Nonlinear Inactive
Modify

Layer Name: M12N
Distance: 0
Thickness: 2.0
Type: Membrane
Num. Int. Points: 1
Material: M1228v-A
Material Angle: 0
Material Component Behavior
S11 S22 S12
Inactive Inactive Nonlinear
Add
OK/OK/OK
Add
OK/OK/OK

Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section

Section Name: M2-U11-Coupling
Type: Shell-Layered/Nonlinear
Modify/Show Layer Definition

Layer Definition Data
Layer Name: M11N
Distance: 0
Thickness: 2.0
Type: Membrane
Num. Int. Points: 1
Material: M1228
Material Angle: 0
Material Component Behavior
S11 S22 S12
Nonlinear Linear Inactive
Modify

Layer Name: M12N
Distance: 0
Thickness: 2.0
Type: Membrane
Num. Int. Points: 1
Material: M1228v-A
Material Angle: 0
Material Component Behavior
S11 S22 S12
Inactive Inactive Nonlinear
Add

Layer Name: R22N
Distance: 0
Thickness: 0.00575
Type: Membrane
Num. Int. Points: 1
Material: WIRE
Material Angle: 90
Material Component Behavior
S11 S22 S12
Nonlinear Inactive Inactive
Add

OK/OK/OK

Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section

Section Name: M2-R22-A
Type: Shell-Layered/Nonlinear
Modify/Show Layer Definition

Layer Definition Data
Layer Name: M22N
Distance: 0
Thickness: 2.0
Type: Membrane
Num. Int. Points: 1
Material: M1228
Material Angle: 0
Material Component Behavior
S11 S22 S12
Linear Nonlinear Inactive
Modify

Layer Name: M12N
Distance: 0
Thickness: 2.0
Type: Membrane
Num. Int. Points: 1
Material: M1228v-A
Material Angle: 0
Material Component Behavior
S11 S22 S12
Inactive Inactive Nonlinear
Add

Layer Name: R22N
Distance: 0
Thickness: 0.00575
Type: Membrane
Num. Int. Points: 1
Material: WIRE
Material Angle: 90
Material Component Behavior
S11 S22 S12
Nonlinear Inactive Inactive
Add

OK/OK/OK

Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section

Section Name: M2-R22-B
Layer Name: M22N
Distance: 0
Thickness: 2.0
Type: Membrane
Num. Int. Points: 1
Material: M1228
Material Angle: 0
Material Component Behavior
S11  S22  S12
Linear  Nonlinear  Inactive

Layer Name: M12N
Distance: 0
Thickness: 2.0
Type: Membrane
Num. Int. Points: 1
Material: M1228v-B
Material Angle: 0
Material Component Behavior
S11  S22  S12
Inactive  Inactive  Nonlinear

Layer Name: R22N
Distance: 0
Thickness: 0.00575
Type: Membrane
Num. Int. Points: 1
Material: WIRE
Material Angle: 90
Material Component Behavior
S11  S22  S12
Nonlinear  Inactive  Inactive

---

Layer Name: M12N
Distance: 0
Thickness: 2.0
Type: Membrane
Num. Int. Points: 1
Material: M1228v-C
Material Angle: 0
Material Component Behavior
S11  S22  S12
Inactive  Inactive  Nonlinear

Layer Name: R22N
Distance: 0
Thickness: 0.00575
Type: Membrane
Num. Int. Points: 1
Material: WIRE
Material Angle: 90
Material Component Behavior
S11  S22  S12
Nonlinear  Inactive  Inactive

---

Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section

OK/OK/OK
Select Section Type to Add: Shell
Click to: Add New Section

Section Name: M2-R11-Coupling-W
Type: Shell-Layered/Nonlinear
Modify/Show Layer Definition

Layer Definition Data
Layer Name: M11N
Distance: 0
Thickness: 2.0
Type: Membrane
Num. Int. Points: 1
Material: M1228
Material Angle: 0
Material Component Behavior
S11   S22   S12
Nonlinear Linear Inactive
Modify

Layer Name: M12N
Distance: 0
Thickness: 2.0
Type: Membrane
Num. Int. Points: 1
Material: M1228v-Coupling
Material Angle: 0
Material Component Behavior
S11   S22   S12
Inactive Inactive Nonlinear
Add

Layer Name: R11N
Distance: 0
Thickness: 0.00575
Type: Membrane
Num. Int. Points: 1
Material: WIRE
Material Angle: 0
Material Component Behavior
S11   S22   S12
Nonlinear Inactive Inactive
Add
OK/OK/OK

Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section

Section Name: M2-R11-Coupling-R
Type: Shell-Layered/Nonlinear
Modify/Show Layer Definition

Layer Definition Data
Layer Name: M11N
Distance: 0
Thickness: 2.0
Type: Membrane
Num. Int. Points: 1
Material: M1228
Material Angle: 0
Material Component Behavior
S11   S22   S12
Nonlinear Inactive Linear
Add

Layer Name: M12N
Distance: 0
Thickness: 2.0
Type: Membrane
Num. Int. Points: 1
Material: M1228v-Coupling
Material Angle: 0
Material Component Behavior
S11   S22   S12
Inactive Inactive Linear
Add

Layer Name: R11N
Distance: 0
Thickness: 0.0733
Type: Membrane
Num. Int. Points: 1
Material: R60
Material Angle: 0
Material Component Behavior
S11   S22   S12
Nonlinear Inactive Inactive
Add
OK/OK/OK
Add
OK/OK/OK

File/Save

Step 4. Draw Area Elements

(Draw Walls A, B, and C)
Click XZ View, Select X-Z Plane @ Y=1
Select Quick Draw Area on side toolbar
Fence Regions between X=1, X=55, Z=0 and Z=93
Define window openings by deleting appropriate area elements
Click YZ view, select Y-Z Plane @ X=1
Select Quick Draw Area on side toolbar
Select Regions between Y=1, Y=10, Z=0, and Z=93
Select Y-Z Plane @ X=55
Select regions between Y=1, Y=10, Z=0, and Z=93

Select bottom joints, verify 12 Points are selected
Assign/Joint/Restraints/
Check boxes for all degrees of freedom (or on Fast Restraints, select fixed-end condition)
OK

On side toolbar select all
Verify 156 Points, 120 Areas and 480 Edges are selected
Edit/Edit Areas/Divide Areas
Divide Area into Objects of This Maximum Size
Along Edge from Point 1 to 2: 2 in.
Along Edge from Point 1 to 3: 2 in.
At bottom, on Restraints and Constraints for Added Points, select Add on Edge when restraints/constraints exist at adjacent corner points
OK
On side toolbar select all, verify there are 1646 Points, 1470 Areas, and 5880 Edges
On side toolbar select clr

Click XZ View
Select checkmark icon (Set Display Options) on top toolbar
On Joints, uncheck: Invisible
On Joints, check: Labels
On Areas, check: Labels
OK

On side toolbar select all
Edit/Change Labels
Item Type: Element Labels – Area
Auto Relabel Control (use default value)
Edit/Auto Relabel/All in List
Item Type: Element Labels – Joint
Auto Relabel Control (use default value)
Edit/Auto Relabel/All in List
OK

Select checkmark icon (Set Display Options) on top toolbar
On Joints, uncheck: Labels
On Areas, uncheck: Labels
OK

File/Save

Step 5. Assign Area Elements

Select all area sections
Assign/Area/Sections
Sections: M2-LIN
OK

(Assign nonlinear area elements to the potential hinge regions)
Select the corner area elements at clear heights of Wall A (4 area elements per story) Select the third (left to right) area
element at ends of clear heights (2 elements per story)
Verify 18 Areas and 72 Edges are selected
Assign/Area/Sections
Sections: M2-R22-A
OK

Select the area elements in between area sections M2-R22-A previously selected (4 area elements per story)
Verify 12 Areas and 48 Edges are selected
Assign/Area/Sections
Sections: M2-U22-A
OK

Select the corner area elements at clear heights of Wall B (4 area elements per story) Select the third (left to right) area element at ends of clear heights (2 elements per story)
Verify 18 Areas and 72 Edges are selected
Assign/Area/Sections
Sections: M2-R22-B
OK

Select the area elements in between area sections M2-R22-B previously selected (4 area elements per story)
Verify 12 Areas and 48 Edges are selected
Assign/Area/Sections
Sections: M2-U22-B
OK

Select the corner area elements at clear heights of Wall C (4 area elements per story) Select the third (left to right) area element at ends of clear heights (2 elements per story)
Verify 18 Areas and 72 Edges are selected
Assign/Area/Sections
Sections: M2-R22-C
OK

Select the area elements in between area sections M2-R22-C previously selected (4 area elements per story)
Verify 12 Areas and 48 Edges are selected
Assign/Area/Sections
Sections: M2-U22-C
OK

Click YZ view, select Y-Z Plane @ X=1
Select the two edge area elements located just above Z=8, Z=18, Z=39, Z=49, Z=70, and Z=80.
Select the third (left to right) area element at the same elevation of the previously selected area elements
Verify 18 Areas and 72 Edges are selected
Assign/Area/Sections
Sections: M2-R22-A
OK

Click YZ view, select Y-Z Plane @ X=55
Select area elements in between area sections M2-R22-A previously selected (4 elements per story)
Verify 12 Areas and 48 Edges are selected
Assign/Area/Sections
Sections: M2-U22-A
OK

Click YZ view, select Y-Z Plane @ X=1
Select the two edge area elements located just above Z=0, Z=26, Z=31, Z=57, Z=62, and Z=88.
Select the third (left to right) area element at the same elevation of the previously selected area elements
Verify 18 Areas and 72 Edges are selected
Assign/Area/Sections
Sections: M2-R22-C
OK

Select area elements in between area sections M2-R22-C previously selected (4 elements per story)
Verify 12 Areas and 48 Edges are selected
Assign/Area/Sections
Sections: M2-U22-C
OK

Select XZ View, Select X-Z Plane @ Y=1
Select three area elements between X=10, X=12 and Z=0, Z=6
Select three area elements between X=24, X=26 and Z=0, Z=6
Select three area elements between X=10, X=12 and Z=22, Z=28
Select three area elements between X=24, X=26 and Z=22, Z=28
Select three area elements between X=10, X=12 and Z=31, Z=37
Select three area elements between X=24, X=26 and Z=31, Z=37
Select three area elements between X=10, X=12 and Z=53, Z=59
Select three area elements between X=24, X=26 and Z=53, Z=59
Select three area elements between X=10, X=12 and Z=62, Z=68
Select three area elements between X=24, X=26 and Z=62, Z=68
Select three area elements between X=10, X=12 and Z=84, Z=90
Select three area elements between X=24, X=26 and Z=84, Z=90
Verify 36 Areas and 144 Edges are selected
Assign/Area/Sections
Sections: M2-U11-Coupling
Select one area element between X=10, X=12 and Z=6, Z=8
Select one area element between X=24, X=26 and Z=6, Z=8
Select one area element between X=10, X=12 and Z=28, Z=31
Select one area element between X=24, X=26 and Z=28, Z=31
Select one area element between X=10, X=12 and Z=44, Z=57
Select one area element between X=24, X=26 and Z=44, Z=57
Select one area element between X=10, X=12 and Z=68, Z=70
Select one area element between X=24, X=26 and Z=68, Z=70
Select one area element between X=10, X=12 and Z=88, Z=91
Select one area element between X=24, X=26 and Z=88, Z=91
Verify 12 Areas and 48 Edges are selected
Assign/Area/Sections
Sections: M2-R11-Coupling-W
Select two area elements between X=10, X=12 and Z=28, Z=31
Select two area elements between X=24, X=26 and Z=28, Z=31
Select two area elements between X=36, X=38 and Z=28, Z=31
Select two area elements between X=44, X=46 and Z=28, Z=31
Select two area elements between X=10, X=12 and Z=59, Z=61
Select two area elements between X=24, X=26 and Z=59, Z=61
Select two area elements between X=36, X=38 and Z=59, Z=61
Select two area elements between X=44, X=46 and Z=59, Z=61
Select two area elements between X=10, X=12 and Z=90, Z=93
Select two area elements between X=24, X=26 and Z=90, Z=93
Select two area elements between X=36, X=38 and Z=90, Z=93
Select two area elements between X=44, X=46 and Z=90, Z=93
Verify 24 Areas and 96 Edges are selected
Assign/Area/Sections
Sections: M2-R11-Coupling-R
File/Save

Step 6. Assign Constraints

Select all Joints at Z=29.5
Select all Joints at Z=60.5
Select all Joints at Z=91.5
Verify that 117 Points are selected
Assign/Joint/Constraints
Choose constraint Type to Add: Diaphragm
Add New Constraint
Constraint Name: DIAPH1
Coordinate System: Global
Constraint Axis: Z Axis
Check box: Assign a different diaphragm
Constraint to each different selected Z level
OK/OK

Select Joints at Z= 29.5 between X=36 and X=46
Select Joints at Z= 60.5 between X=36 and X=46
Select Joints at Z= 91.5 between X=36 and X=46
Verify that 18 Joints are selected
Assign/Joint/Constraints
Constraints: Null

File/Save

Step 7. Define Load Patterns and Load Cases

Define/Load Patterns
Load Pattern Name: SEISMIC
Type: Other
Self-Weight Multiplier: 0
Click to: Add New Load Pattern
OK

Define/Load Cases
Click to: Add New Load Case
Load Case Name: PRE-LOAD
Load Case Type: Static
Analysis Type: Nonlinear
Initial Conditions
Zero Initial Conditions - Start from Unstressed State
Geometric Nonlinearity Parameters: None
Loads Applied
Load Type = Load Pattern
Load Name = DEAD
Scale Factor = 1.0
Add
Other Parameters
Load Application: Full Load (Default)
Results Saved: Final State Only (Default)
Nonlinear Parameters: Default
OK/OK

(Define Nonlinear Static Analysis - Eastward Loading)
Define/Load Cases
Click to: Add New Load Case
Load Case Name: NSA+
Load Case Type: Static
Analysis Type: Nonlinear
Initial Conditions
Continue from State at End of Nonlinear Case: PRE-LOAD
Geometric Nonlinearity Parameters: None
Loads Applied
Load Type = Load Pattern
Load Name = SEISMIC
Scale Factor = 1
Add
Other Parameters
Load Application: Modify/Show Load Application Control: Displacement Control
Control Displacement: Use Monitored Displacement
Load to a Monitored Displacement Magnitude of: 2.0 in.
Monitored Displacement DOF: U1
At Joint: 1583
OK
Step 8. Assign Loads

Select area elements between Z=28 and Z=31
Select area elements between Z=59, and Z=62
Select area elements between Z=90, and Z=93
Verify 228 Areas and 912 Edges are selected
Assign/Area Loads/Uniform (Shell)
Load Pattern Name: DEAD
Units: lb, in, F
Uniform Load
Load: 6.60
Coord System: Global
Direction: Gravity
Options: Replace Existing Loads
OK

Select the center joint at the roof diaphragm level (at X=28 in. Z=91.5 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in, F
Loads
Force Global X: 3 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the diaphragm level (at X=28 in. Z=60.5 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in, F
Loads
Force Global X: 2 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the diaphragm level (at X=28 in. Z=29.5 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in, F
Loads
Force Global X: 1 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

File/Save

Step 9. Analyze

Analyze/Set Analysis Options
FAST DOFs: Plane Frame - XZ Plane
OK

Analyze/Set Load Cases to Run
Highlight PRE-LOAD, NSA+, NSA-
Click to: Run/Do Not Run Case
Verify the Nonlinear Static are marked as Run
Run Now

(On the top toolbar select the Show Deformed Shape icon)
Deformed Shape
Case/Combo
Case/Combo Name: SEISMIC
OK

Verify the displacement U1 at the roof diaphragm level is 0.117 in.

Analyze/Set Load Cases to Run
Highlight PRE-LOAD, NSA+, NSA-

Click to: Run/Do Not Run Case
Verify the Nonlinear Static are marked as Run
Run Now

Step 10. Program Output

Display
Show Forces/Stresses
Joints
Case/Combo Name: E
OK

Verify units are kip, in, F

Draw Section Cut (cut Wall A at Base)
Section Cutting Line
Start Point: X=0, Y=1, Z=8.1
End Point: X=11, Y=1, Z=8.1
Click on Refresh button
Integrated Forces:
Left Side/Save Cut/OK
Close

Draw Section Cut (cut Wall B at Base)
Section Cutting Line
Start Point: X=25, Y=1, Z=8.1
End Point: X=37, Y=1, Z=8.1
Click on Refresh button
Integrated Forces:
Left Side/Save Cut/OK
Close

Draw Section Cut (cut Wall C at Base)
Section Cutting Line
Start Point: X=45, Y=1, Z=0.1
End Point: X=56, Y=1, Z=0.1
Click on Refresh button
Integrated Forces:
Left Side/Save Cut/OK
Close

Display/Show Plot Function
Define Plot Functions
Choose Function Type to Add: Add Base Functions
Click to: Add Plot Function
Base Functions: Base Shear X
OK/OK

Define Plot Functions
Choose Function Type to Add: Add Joint Disps/Forces
Click to: Add Plot Function
Joint ID: 1583
Vector Type: Displ
Component: UX
OK/OK

Define Plot Functions
Choose Function Type to Add: Add Section Cut Forces
Click to: Add Plot Function
Section Cut: SCUT1
Component: F1
OK/OK

Define Plot Functions
Choose Function Type to Add: Add Section Cut Forces
Click to: Add Plot Function
Section Cut: SCUT2
Component: F1
OK/OK

Define Plot Functions
Choose Function Type to Add: Add Section Cut Forces
Click to: Add Plot Function
Section Cut: SCUT3
Component: F1
OK/OK

Choose Plot Functions
List of Functions: Highlight Base Shear X, SCUT1, SCUT2, and SCUT3
Click the Add button

Verify Base Shear X, SCUT1, SCUT2, and SCUT3 show under Vertical Functions
Horizontal Plot Function: Joint 1583

Load Case (Multi-Stepped Cases); NSA+
Click Display
File/Print Tables to File
File Name: NSA+
Save
OK

Load Case (Multi-Stepped Cases); NSA-
Click Display
File/Print Tables to File
File name: NSA-
Save
OK

File/Save
Done
B.5 Nonlinear Link Model for Selected Case Studies

B.5.1 Case Study A

Step 1. Define Geometry

File/New Model
New Model Initialization
Initialize Model from Defaults with Units: kip, in, F
Select Template: Grid Only

Cartesian
Coordinate System Name: GLOBAL

<table>
<thead>
<tr>
<th>Number of Grid Lines</th>
<th>Grid Spacing</th>
<th>First Grid Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>X direction:</td>
<td>6</td>
<td>48</td>
</tr>
<tr>
<td>Y direction:</td>
<td>1</td>
<td>48</td>
</tr>
<tr>
<td>Z direction:</td>
<td>4</td>
<td>48</td>
</tr>
</tbody>
</table>

OK (Click on top tab of right window, close 3-D View)
(Select Set XZ View in the top toolbar)

Right click/Edit Grid Data
Click to: Modify/Show System
(To modify grid lines using actual coordinates)

Units: Kip, ft, F

X Grid Data: 
- Grid ID: A1, Ordinate: 0 ft
- Grid ID: A2, Ordinate: 4 ft
- Grid ID: B1, Ordinate: 14 ft
- Grid ID: B2, Ordinate: 16 ft
- Grid ID: C1, Ordinate: 20 ft
- Grid ID: C2, Ordinate: 24 ft

Z Grid Data: 
- Grid ID: Z1, Ordinate: 0 ft
- Grid ID: Z2, Ordinate: 8 ft
- Grid ID: Z3, Ordinate: 10 ft

Step 2. Define Material Properties

Define/Materials
Check Show Advanced Properties
Click to: Add New Material
Material Name: M1500
Options
Material Type: Other
Directional Symmetry Type: Isotropic

Modulus of Elasticity: 1350 ksi
Poisson’s Ratio: 0.2
Coeff. of Thermal Expansion: 5.5E-06
Shear Modulus: Auto (562.5 ksi)
Weight and Mass
Weight per Unit Volume: 0.1259 (kip/ft³)
Mass per Unit Volume: 0

OK/OK/OK

File/Save

Step 3. Define Area Sections

Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section

Section Name: M8-LIN
Type: Membrane
Material
Material Name: M1500
Material Angle: 0
Thickness
Membrane: 7.625
Bending: 7.625

Z4  18 ft
OK/OK

View/Restore Full View
File/Save As
File name: R1-A-LNK
Save
Step 4. Draw Area Elements

(Draw walls A, B, and C)
- Draw/Draw Rectangular Area
- Click on bottom left of Wall A (at A1/Z1) and drag to top right of Wall A (at A2/Z3)
- Draw/Draw Rectangular Area
- Click on bottom left of Wall B (at B1/Z1) and drag mouse to top right of Wall B (at B2/Z2)
- Draw/Draw Rectangular Area
- Click on bottom left of Wall C (at C1/Z1) and drag mouse to top right of Wall C (at C2/Z2)

(Draw coupling wall segments)
- Draw/Draw Rectangular Area
- Click on top left of Wall A (at A1/Z3) and drag mouse to top of wall at Grid B1 (at B1/Z4)
- Draw/Draw Rectangular Area
- Click on top left of Wall B (at B1/Z2) and drag mouse to top of wall at Grid C2 (at C2/Z4)

Select checkmark icon (Set Display Options) on top toolbar
- On Joints, uncheck: Invisible
- On Joints, check: Labels
- On Areas, check: Labels
- OK

Select bottom joints, verify 6 Points are selected
- Assign/Joint/Restraints/
- Check boxes for all degrees of freedom (or on Fast Restraints, select fixed-end condition)
- OK

On side toolbar select all
- Verify 5 Areas and 20 Edges are selected
- Edit/Edit Areas/Divide Areas
- Divide Area into Objects of This Maximum Size
- Along Edge from Point 1 to 2: 8 in.
- Along Edge from Point 1 to 3: 8 in.
- At bottom, on Restraints and Constraints for Added Points, select
- Add on Edge when restraints/constraints exist at adjacent corner points
- OK

On side toolbar select all, verify there are 766 Points, 675 Areas, and 2700 Edges
- On side toolbar select clr

Step 5. Define Nonlinear Links

Define/Sections Properties
- Link/Support Properties
- Click to: Add New Property

Link/Support Type: MultiLinear Plastic
- Property Name: A24
- Total Mass and Weight
- Mass: 0
Weight: 0.0178 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0

Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line
Spring: 1
Property is Defined for This Area in Area
and Solid Springs: 1

Directional Properties
Select Direction U1 and check Nonlinear
Properties: Modify/Show for U1
Properties Used for Linear Analysis Cases
Effective Stiffness: 5147 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-8.280E-02</td>
<td>-4.260E+01</td>
</tr>
<tr>
<td>-8.280E-03</td>
<td>-4.260E+01</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>1.660E-02</td>
<td>6.000E+00</td>
</tr>
<tr>
<td>1.660E-01</td>
<td>6.000E+00</td>
</tr>
</tbody>
</table>

OK

Select Direction U2 and check Nonlinear
Properties: Modify/Show for U2
Properties Used for Linear Analysis Cases
Effective Stiffness: 10294 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-7.690E-02</td>
<td>-7.920E+01</td>
</tr>
<tr>
<td>-7.690E-03</td>
<td>-7.920E+01</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>1.660E-02</td>
<td>6.000E+00</td>
</tr>
<tr>
<td>1.660E-01</td>
<td>6.000E+00</td>
</tr>
</tbody>
</table>

OK

Total Mass and Weight
Mass: 0
Weight: 0.0356 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0

Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line
Spring: 1
Property is Defined for This Area in Area
and Solid Springs: 1

Directional Properties
Select Direction U2 and check Nonlinear
Properties: Modify/Show for U2
Properties Used for Linear Analysis Cases
Effective Stiffness: 3574 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.550E-02</td>
<td>-2.770E+00</td>
</tr>
<tr>
<td>-1.550E-03</td>
<td>-2.770E+00</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>1.550E-03</td>
<td>2.770E+00</td>
</tr>
</tbody>
</table>

OK
Shear Deformation Location
Distance from End-J: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition
Displ., in Force, kip
-1.550E-02 -5.530E+00
-1.550E-03 -5.530E+00
0.000E+00 0.000E+00
1.550E-03 5.530E+00
1.550E-02 5.530E+00
OK/OK

Define/Sections Properties
Link/Support Properties
Click to: Add New Property

Link/Support Type: MultiLinear Plastic
Property Name: A08
Total Mass and Weight
Mass: 0
Weight: 0.0356 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line
Spring: 1
Property is Defined for This Area in Area
and Solid Springs: 1

Directional Properties
Select Direction U1 and check Nonlinear
Properties: Modify/Show for U1
Properties Used for Linear Analysis Cases
Effective Stiffness: 10294 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition
Displ., in Force, kip
-7.110E-02 -7.320E+01
-7.110E-03 -7.320E+01

OK

Select Direction U2 and check Nonlinear Properties: Modify/Show for U2
Properties Used for Linear Analysis Cases
Effective Stiffness: 3574 ksi
Effective Damping: 0
Shear Deformation Location
Distance from End-J: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition
Displ., in Force, kip
-7.110E-02 -7.320E+01
-7.110E-03 -7.320E+01

OK

Define/Sections Properties
Link/Support Properties
Click to: Add New Property

Link/Support Type: MultiLinear Plastic
Property Name: A00
Total Mass and Weight
Mass: 0
Weight: 0.0356 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line
Spring: 1
Property is Defined for This Area in Area
and Solid Springs: 1

Directional Properties
Select Direction U1 and check Nonlinear
Properties: Modify/Show for U1
Properties Used for Linear Analysis Cases
Effective Stiffness: 10294 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition
Displ., in Force, kip
-7.110E-02 -7.320E+01
-7.110E-03 -7.320E+01

OK

Select Direction U1 and check Nonlinear
Properties: Modify/Show for U1
Properties Used for Linear Analysis Cases
Effective Stiffness: 10294 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-7.110E-02</td>
<td>-7.320E+01</td>
</tr>
<tr>
<td>-7.110E-03</td>
<td>-7.320E+01</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>1.660E-02</td>
<td>1.000E-03</td>
</tr>
<tr>
<td>1.660E-01</td>
<td>1.000E-03</td>
</tr>
</tbody>
</table>

OK

Select Direction U2 and check Nonlinear
Properties: Modify/Show for U2
Properties Used for Linear Analysis Cases
Effective Stiffness: 3574 ksi
Effective Damping: 0
Shear Deformation Location
Distance from End-J: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.550E-02</td>
<td>-5.530E+00</td>
</tr>
<tr>
<td>-1.550E-03</td>
<td>-5.530E+00</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>1.550E-03</td>
<td>5.530E+00</td>
</tr>
<tr>
<td>1.550E-02</td>
<td>5.530E+00</td>
</tr>
</tbody>
</table>

OK

Define/Sections Properties
Link/Support Properties
Click to: Add New Property

Link/Support Type: MultiLinear Plastic
Property Name: B12
Total Mass and Weight
Mass: 0
Weight: 0.0178 kip

Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line
Spring: 1
Property is Defined for This Area in Area
and Solid Springs: 1

Directional Properties
Select Direction U1 and check Nonlinear
Properties: Modify/Show for U1
Properties Used for Linear Analysis Cases
Effective Stiffness: 5147 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-8.280E-02</td>
<td>-4.260E+01</td>
</tr>
<tr>
<td>-8.280E-03</td>
<td>-4.260E+01</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>1.660E-02</td>
<td>6.000E+00</td>
</tr>
<tr>
<td>1.660E-01</td>
<td>6.000E+00</td>
</tr>
</tbody>
</table>

OK

Select Direction U2 and check Nonlinear
Properties: Modify/Show for U2
Properties Used for Linear Analysis Cases
Effective Stiffness: 1787 ksi
Effective Damping: 0
Shear Deformation Location
Distance from End-J: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.580E-02</td>
<td>-2.820E+00</td>
</tr>
<tr>
<td>-1.580E-03</td>
<td>-2.820E+00</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>1.580E-03</td>
<td>2.820E+00</td>
</tr>
<tr>
<td>1.580E-02</td>
<td>2.820E+00</td>
</tr>
</tbody>
</table>
OK/OK

Define/Sections Properties
Link/Support Properties
Click to: Add New Property

Link/Support Type: MultiLinear Plastic
Property Name: B04
Total Mass and Weight
Mass: 0
Weight: 0.0356 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line
Spring: 1
Property is Defined for This Area in Area
and Solid Springs: 1

Directional Properties
Select Direction U1 and check Nonlinear
Properties: Modify/Show for U1
Properties Used for Linear Analysis Cases
Effective Stiffness: 10294 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-7.690E-02</td>
<td>-7.920E+01</td>
</tr>
<tr>
<td>-7.690E-03</td>
<td>-7.920E+01</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>1.660E-02</td>
<td>6.000E+00</td>
</tr>
<tr>
<td>1.660E-01</td>
<td>6.000E+00</td>
</tr>
</tbody>
</table>

OK

Distance from End-J: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.580E-02</td>
<td>-5.630E+00</td>
</tr>
<tr>
<td>-1.580E-03</td>
<td>-5.630E+00</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>1.580E-03</td>
<td>5.630E+00</td>
</tr>
<tr>
<td>1.580E-02</td>
<td>5.630E+00</td>
</tr>
</tbody>
</table>

OK/OK

Define/Sections Properties
Link/Support Properties
Click to: Add New Property

Link/Support Type: MultiLinear Plastic
Property Name: CB-EXT-R
Total Mass and Weight
Mass: 0
Weight: 0.0178 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line
Spring: 1
Property is Defined for This Area in Area
and Solid Springs: 1

Directional Properties
Select Direction U1 and check Nonlinear
Properties: Modify/Show for U1
Properties Used for Linear Analysis Cases
Effective Stiffness: 5147 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-8.280E-02</td>
<td>-4.260E+01</td>
</tr>
<tr>
<td>-8.280E-03</td>
<td>-4.260E+01</td>
</tr>
</tbody>
</table>

OK

Select Direction U2 and check Nonlinear
Properties: Modify/Show for U2
Properties Used for Linear Analysis Cases
Effective Stiffness: 3574 ksi
Effective Damping: 0
Shear Deformation Location
0.000E+00  0.000E+00
1.660E-02  6.000E+00
1.660E-01  6.000E+00
OK

Effective Stiffness: 1787 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Multi-Linear Force-Deformation Definition

Displ., in. Force, kip
-2.360E-02 -4.210E+00
-2.360E-03 -4.210E+00
0.000E+00  0.000E+00
2.360E-03  4.210E+00
2.360E-02  4.210E+00
OK/OK

Select Direction U2 and check Nonlinear Properties: Modify/Show for U2
Properties Used for Linear Analysis Cases
Effective Stiffness: 10294 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

Displ., in. Force, kip
-2.360E-02 -8.420E+00
-2.360E-03 -8.420E+00
0.000E+00  0.000E+00
2.360E-03  8.420E+00
2.360E-02  8.420E+00
OK

Select Direction U2 and check Nonlinear Properties: Modify/Show for U2
Properties Used for Linear Analysis Cases
Effective Stiffness: 3574 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

Displ., in. Force, kip
-7.690E-02 -7.920E+01
-7.690E-03 -7.920E+01
0.000E+00  0.000E+00
1.660E-02  6.000E+00
1.660E-01  6.000E+00
OK/OK

Define/Sections Properties
Link/Support Properties
Click to: Add New Property

Link/Support Type: MultiLinear Plastic
Property Name: CB-INT-R
Total Mass and Weight
Mass: 0
Weight: 0.0356 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line
Spring: 1
Property is Defined for This Area in Area
and Solid Springs: 1
Directional Properties
Select Direction U1 and check Nonlinear Properties: Modify/Show for U1
Properties Used for Linear Analysis Cases
Effective Stiffness: 10294 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

Displ., in. Force, kip
-2.360E-02 -8.420E+00
-2.360E-03 -8.420E+00
0.000E+00  0.000E+00
2.360E-03  8.420E+00
2.360E-02  8.420E+00
OK/OK

Define/Sections Properties
Link/Support Properties
Click to: Add New Property

Link/Support Type: MultiLinear Plastic
Property Name: CB-INT-U
Total Mass and Weight
Mass: 0
Weight: 0.0356 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line Spring: 1
Property is Defined for This Area in Area and Solid Springs: 1

Directional Properties
Select Direction U1 and check Nonlinear Properties: Modify/Show for U1
Properties Used for Linear Analysis Cases
Effective Stiffness: 10294 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-7.110E-02</td>
<td>-7.320E+01</td>
</tr>
<tr>
<td>-7.110E-03</td>
<td>-7.320E+01</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>1.660E-02</td>
<td>1.000E-03</td>
</tr>
<tr>
<td>1.660E-01</td>
<td>1.000E-03</td>
</tr>
</tbody>
</table>

OK

Select Direction U2 and check Nonlinear Properties: Modify/Show for U2
Properties Used for Linear Analysis Cases
Effective Stiffness: 3574 ksi
Effective Damping: 0
Shear Deformation Location
Distance from End-J: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.360E-02</td>
<td>-8.420E+00</td>
</tr>
<tr>
<td>-2.360E-03</td>
<td>-8.420E+00</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>2.360E-03</td>
<td>8.420E+00</td>
</tr>
<tr>
<td>2.360E-02</td>
<td>8.420E+00</td>
</tr>
</tbody>
</table>

OK/OK

Step 6. Assign Nonlinear Links

OK/OK

File/Save

Draw/Draw 2 Joint Link
Property: A24
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>
(Assign Link A24 at base of Wall A, between Z=0 and Z=8 in., at X=0 and at X=48 in.)
(Assign Link A24 at base of Wall C, between Z=0 and Z=8 in., at X=240 and at X=288 in.)
Property: A16
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>
(Assign Link A16 at base of Wall A, between Z=0 and Z=8 in., at X=0 and at X=40 in.)
(Assign Link A16 at base of Wall C, between Z=0 and Z=8 in., at X=248 and at X=280 in.)
Property: A08
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>
(Assign Link A08 at base of Wall A, between Z=0 and Z=8 in., at X=16 and at X=32 in.)
(Assign Link A08 at base of Wall C, between Z=0 and Z=8 in., at X=256 and at X=272 in.)
Property: A00
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>
(Assign Link A00 at base of Wall A, between Z=0 and Z=8 in., at X=24 in.)
(Assign Link A00 at base of Wall C, between Z=0 and Z=8 in., at X=264 in.)
Property: B12
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>

(Assign Link B12 at base of Wall B, between Z=0 and Z=8 in., at X=168 and at X=192 in.)

Property: B04
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>

(Assign Link B04 at base of Wall B, between Z=0 and Z=8 in., at X=176 and at X=184 in.)

(Close the Properties of Object window)
(Select the area elements bounded by the Links at the base of Walls A, B, and C)
Verify 15 Areas and 60 Edges are selected and delete

(Select the Links at the base of Wall A)
Verify 7 Links are selected
Edit/Replicate/Linear Increments
dx: 0
dy: 0
dz: 112 in.
Increment Data
Number: 1
OK

(Select the Links at the base of Walls B and C)
Verify 11 Links are selected
Edit/Replicate/Linear Increments
dx: 0
dy: 0
dz: 88 in.
Increment Data
Number: 1
OK

(Select the area elements bounded by the Links at the top of Walls A, B, and C)
Verify 15 Areas and 60 Edges are selected and delete

Draw/Draw 2 Joint Link
Property: CB-EXT-R
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>

(Assign Link CB-EXT-R between X=48 and X=56 in., at Z=120 and at Z=216 in.)
(Assign Link CB-EXT-R between X=192 and X=200 in., at Z=96 and at Z=216 in.)

Property: CB-INT-R
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>

(Assign Link CB-INT-R between X=48 and X=56 in., at Z=128 and at Z=208 in.)
(Assign Link CB-INT-R between X=192 and X=200 in., at Z=104 and at Z=208 in.)

Property: CB-INT-U
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>

(Assign Link CB-INT-U between X=48 and X=56 in., at Z=136 and at Z=192 in.)
(Assign Link CB-INT-U between X=192 and X=200 in., at Z=112 and at Z=200 in.)
(Assign Link CB-INT-U between X=48 and X=56 in., at Z=144 and at Z=192 in.)
(Assign Link CB-INT-U between X=192 and X=200 in., at Z=120 and at Z=192 in.)
(Assign Link CB-INT-U between X=48 and X=56 in., at Z=152 and at Z=184 in.)
(Assign Link CB-INT-U between X=192 and X=200 in., at Z=128 and at Z=184 in.)
(Assign Link CB-INT-U between X=48 and X=56 in., at Z=160 and at Z=176 in.)
Step 7. Assign Constraints and Rigid Segments

Select all joints at roof level (2’-0” from the top of wall)
Verify 37 Points are selected
Assign/Joint/Constraints
Choose Constraint Type to Add: Diaphragm
Click to: Add New Constraint
Constraint Name: DIAPH1
Coordinate System: GLOBAL
Constraint Axis: Z Axis
OK/OK

Define/Section Properties/Frame Sections
Click to: Add New Property
Select Property Type
Frame Section Property Type: Other
Click to Add a Section: General
Properties
Cross-sectional Area = 0
Moment of Inertia about 3 axis = 1e6
Shear area in 2 direction = 1e6
All other properties = 1
OK

Section Name: RIGID
Material: M1500
Dimensions
Depth = 1
Width = 1
OK/OK

(Connect the ends of the Links with a transverse RIGID frame element, see Figure B.6)
Draw Frame/Cable/Tendon
Section: RIGID
Draw a Frame element from (X=0, Z=8) to (X=48, Z=8)
Draw a Frame element from (X=0, Z=112) to (X=48, Z=112)
Draw a Frame element from (X=168, Z=8) to (X=192, Z=8)
Draw a Frame element from (X=168, Z=88) to (X=192, Z=88)
Draw a Frame element from (X=240, Z=8) to (X=288, Z=8)
Draw a Frame element from (X=240, Z=88) to (X=288, Z=88)
Draw a Frame element from (X=56, Z=120) to (X=56, Z=216)
Draw a Frame element from (X=160, Z=120) to (X=160, Z=216)
Draw a Frame element from (X=200, Z=96) to (X=200, Z=216)
Draw a Frame element from (X=232, Z=96) to (X=232, Z=216)

(Close the Properties of Object window)
Select/Select/Properties/Frame Sections
Select: RIGID
OK
Verify 10 Frames are selected
Assign/Frame/Automatic Frame Mesh
Auto Mesh Frame: at Intermediate Joints
OK

Select Links at the base of the walls
Select Links along Grid A2
Select Links along Grid B2
Verify 47 Links are selected
Assign/Link/Support
Reverse Connectivity
Verify that the local 1 axis for the links point away from the RIGID frame elements

File/Save

Step 8. Define Load Patterns and Load Cases

Define/Load Patterns
Load Pattern Name: LIVE
Type: LIVE
Self-Weight Multiplier: 0
Click to: Add New Load Pattern
OK

Define/Load Patterns
Load Pattern Name: SEISMIC
Type: Other
Self-Weight Multiplier: 0
Click to: Add New Load Pattern
OK

Define/Load Cases
Click to: Add New Load Case
Load Case Name: E
Load Case Type: Static
Analysis Type: Linear
Stiffness to Use: Zero Initial Conditions - Unstressed State
Loads Applied
Load Type = Load Pattern
Load Name = SEISMIC
Scale Factor = 1
Add
OK/OK

Define/Load Cases
Click to: Add New Load Case
Load Case Name: PRE-LOAD
Load Case Type: Static
Analysis Type: Nonlinear
Initial Conditions
Zero Initial Conditions - Start from Unstressed State
Geometric Nonlinearity Parameters: None
Loads Applied
Load Type = Load Pattern
Load Name = DEAD
Scale Factor = 0.7
Add
Other Parameters
Load Application: Full Load (Default)
Results Saved: Final State Only (Default)
Nonlinear Parameters: Default
OK/OK
(Define Nonlinear Static Analysis - Eastward Loading)
Define/Load Cases
Click to: Add New Load Case
Load Case Name: NSA+
Load Case Type: Static
Analysis Type: Nonlinear
Initial Conditions
Continue from State at End of Nonlinear Case: PRE-LOAD
Geometric Nonlinearity Parameters: None
Loads Applied
Load Type = Load Pattern
Load Name = SEISMIC
Scale Factor = 1
Add
Other Parameters
Load Application: Modify/Show
Load Application Control: Displacement Control
Control Displacement: Use Monitored Displacement
Load to a Monitored Displacement Magnitude of: 1.0 in.
Monitored Displacement DOF: U1
At Joint: 495
OK
Results Saved: Modify/Show
Results Saved: Multiple States For Each Stage
Minimum Number of Saved States: 50
Maximum Number of Saved States: 100
Select Save Positive Displacement Increments Only
OK
Nonlinear Parameters: Default
OK/OK

(Define Nonlinear Static Analysis - Westward Loading)
Define/Load Cases
Click to: Add New Load Case
Load Case Name: NSA-
Load Case Type: Static
Analysis Type: Nonlinear
Initial Conditions
Continue from State at End of Nonlinear Case: PRE-LOAD
Geometric Nonlinearity Parameters: None
Loads Applied
Load Type = Load Pattern
Load Name = SEISMIC
Scale Factor = -1
Add
Other Parameters
Load Application: Modify/Show
Load Application Control: Displacement Control
Control Displacement: Use Monitored Displacement
Load to a Monitored Displacement Magnitude of: 1.0 in.
Monitored Displacement DOF: U1
At Joint: 495
OK
Results Saved: Modify/Show
Results Saved: Multiple States For Each Stage
Minimum Number of Saved States: 50
Maximum Number of Saved States: 100
Select Save Positive Displacement Increments Only
OK
Nonlinear Parameters: Default
OK/OK

Step 9. Assign Loads
Select all joints at the roof level except the edge joints
Verify 35 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: DEAD
Units: kip, in, F
Loads
Force Global Z: -0.10 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Click PS on the left side toolbar
Verify 35 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: LIVE
Units: kip, in, F
Loads
Force Global Z: -0.15 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the edge joints at Grid Lines A1 and C2 at the roof level (Z=192 in.)
Verify 2 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: DEAD
Units: kip, in, F
Loads
Force Global Z: -0.05 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Click PS on the left side toolbar
Verify 2 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in, F
Loads
Force Global X: 100 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

File/Save

Step 10. Analyze

Analyze/Set Analysis Options
FAST DOFs: Plane Frame - XZ Plane
OK

Analyze/Set Load Cases to Run
Highlight PRE-LOAD, NSA+, NSA-
Click to: Run/Do Not Run Case
Verify the Nonlinear Static are marked as Do Not Run
Run Now

(On the top toolbar select the Show Deformed Shape icon)
Deformed Shape
Case/Combo
Case/Combo Name: SEISMIC
OK

Verify the displacement U1 at the roof diaphragm level is 0.147 in.

Step 11. Program Output

Display
Show Forces/Stresses
Joints
Case/Combo Name: E
OK
Verify units are kip, in, F

Draw Section Cut (cut Wall A at Base)
Section Cutting Line
Start Point: X=−1, Y=0, Z=1
End Point: X=49, Y=0, Z=1
Click on Refresh button
Integrated Forces:
Left Side/Save Cut
Close

Draw Section Cut (cut Wall B at Base)
Section Cutting Line
Start Point: X=167, Y=0, Z=1
End Point: X=193, Y=0, Z=1
Click on Refresh button
Integrated Forces:
Left Side/Save Cut
Close

Draw Section Cut (cut Wall C at Base)
Section Cutting Line
Start Point: X=239, Y=0, Z=1
End Point: X=289, Y=0, Z=1
Click on Refresh button
Integrated Forces:
Left Side/Save Cut
Close

Display/Show Plot Function
Define Plot Functions
Choose Function Type to Add: Add Base Functions
Click to: Add Plot Function
Base Functions: Base Shear X
OK/OK

Define Plot Functions
Choose Function Type to Add: Add Joint Disps/Forces
Click to: Add Plot Function

Joint ID: 495
Vector Type: Displ
Component: UX
OK/OK

Define Plot Functions
Choose Function Type to Add: Add Section Cut Forces
Click to: Add Plot Function
Section Cut: SCUT1
Component: F1
OK/OK

Define Plot Functions
Choose Function Type to Add: Add Section Cut Forces
Click to: Add Plot Function
Section Cut: SCUT2
Component: F1
OK/OK

Define Plot Functions
Choose Function Type to Add: Add Section Cut Forces
Click to: Add Plot Function
Section Cut: SCUT3
Component: F1
OK/OK

Choose Plot Functions
List of Functions: Highlight Base Shear X, SCUT1, SCUT2, and SCUT3
Click the Add button
Verify Base Shear X, SCUT1, SCUT2, and SCUT3 show under Vertical Functions
Horizontal Plot Function: Joint495

Load Case (Multi-Stepped Cases); NSA+
Click Display
File/Print Tables to File
File name: NSA+
Save
OK
Load Case (Multi-Stepped Cases); NSA-
Click Display
File/Print Tables to File
File name: NSA-
Save
OK

File/Save
Done
B.5.2 Case Study B

Step 1. Define Geometry

File/New Model
New Model Initialization
Initialize Model from Defaults with Units:
kip, in, F
Select Template: Grid Only

Cartesian
Coordinate System Name: GLOBAL

<table>
<thead>
<tr>
<th>Number of Grid Lines</th>
<th>Grid Spacing</th>
<th>First Grid Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>X direction: 4</td>
<td>48</td>
<td>0</td>
</tr>
<tr>
<td>Y direction: 1</td>
<td>48</td>
<td>0</td>
</tr>
<tr>
<td>Z direction: 8</td>
<td>48</td>
<td>0</td>
</tr>
</tbody>
</table>

OK

(Click on top tab of right window, close 3-D View)
(Select the XZ view in the top toolbar)

Right click/Edit Grid Data
Click to: Modify/Show System
(To modify grid lines using actual coordinates)

Units: Kip, ft, F
X Grid Data: Grid ID Orinate
A1 0 ft
A2 8 ft
B1 32 ft
B2 40 ft

Z Grid Data: Grid ID Orinate
Z1 0 ft
Z2 10 ft
Z3 12 ft
Z4 22 ft
Z5 32 ft
Z6 42 ft
Z7 52 ft
Z8 54 ft

OK/OK

View/Restore Full View
File/Save As
File name: R1-B-LNK
Save

Step 2. Define Material Properties

Define/Materials
Check Show Advanced Properties
Click to: Add New Material
Material Name: M1500
Options
Material Type: Other
Directional Symmetry Type: Isotropic

Modify/Show Material Properties
Modulus of Elasticity: 1350 ksi
Poisson’s Ratio: 0.2
Coeff. of Thermal Expansion: 5.5E-06
Shear Modulus: Auto (562.5 ksi)
Weight and Mass
Weight per Unit Volume: 0.1259 (kip/ft$^3$)
Mass per Unit Volume: 0
OK/OK/OK

File/Save

Step 3. Define Area Sections

Define/Section Properties/Area Sections
Select Section Type to Add: Shell
Click to: Add New Section

Section Name: M8-LN
Type: Membrane
Material
Material Name: M1500
Material Angle: 0
Thickness
Membrane: 7.625
Bending: 7.625
OK/OK
Step 4. Draw Area Elements

(Draw walls A, and B)
Draw/Draw Rectangular Area
Click on bottom left of Wall A (at A1/Z1) and drag to top right of Wall A (at A2/Z2)
Draw/Draw Rectangular Area
Click on bottom left of Wall B (at B1/Z1) and drag mouse to top right of Wall B (at B2/Z2)

(Draw coupling wall segments)
Draw/Draw Rectangular Area
Click on top left of Wall A (at A1/Z2) and drag mouse to top of wall at Grid B1 (at B2/Z8)

Select checkmark icon (Set Display Options) on top toolbar
On Joints, uncheck: Invisible
On Joints, check: Labels
On Areas, check: Labels

OK

On side toolbar select all
Edit/Change Labels
Item Type: Element Labels – Area
Auto Relabel Control (use default values)
Edit/Auto Relabel/All in List
Item Type: Element Labels – Joint
Auto Relabel Control (use default values)
Edit/Auto Relabel/All in List
OK

Select checkmark icon (Set Display Options) on top toolbar
On Joints, uncheck: Labels
On Areas, uncheck: Labels

OK

Select bottom joints, verify 4 Points are selected

Assign/Joint/Restraints/
Check boxes for all degrees of freedom (or on Fast Restraints, select fixed-end condition)
OK

On side toolbar select all
Verify 3 areas and 12 edges are selected
Edit/Edit Areas/Divide Areas
Divide Area into Objects of This Maximum Size
Along Edge from Point 1 to 2: 8 in.
Along Edge from Point 1 to 3: 8 in.
At bottom, on Restraints and Constraints for Added Points, select
Add on Edge when restraints/constraints exist at adjacent corner points
OK

On side toolbar select all, verify there are 4477 Points, 4320 Areas, 17280 Edges
On side toolbar select clr

File/Save

Step 5. Define Nonlinear Links

Define/Sections Properties
Link/Support Properties
Click to: Add New Property

Link/Support Type: Multilinear Plastic
Property Name: A48
Mass: 0
Weight: 0.0178 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line Spring: 1
Property is Defined for This Area in Area and Solid Springs: 1
Selective Direction U1 and check Nonlinear Properties: Modify/Show for U1 Properties Used for Linear Analysis Cases
Effective Stiffness: 5147 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-8.92E-02</td>
<td>-4.59E+01</td>
</tr>
<tr>
<td>-8.92E-03</td>
<td>-4.59E+01</td>
</tr>
<tr>
<td>0.00E+00</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>1.66E-02</td>
<td>9.30E+00</td>
</tr>
<tr>
<td>1.66E-01</td>
<td>9.30E+00</td>
</tr>
</tbody>
</table>

OK

Select Direction U2 and check Nonlinear Properties: Modify/Show for U2 Properties Used for Linear Analysis Cases
Effective Stiffness: 1787 ksi
Effective Damping: 0
Shear Deformation Location
Distance from End-J: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-8.02E-02</td>
<td>-8.25E+01</td>
</tr>
<tr>
<td>-8.02E-03</td>
<td>-8.25E+01</td>
</tr>
<tr>
<td>0.00E+00</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>1.66E-02</td>
<td>9.30E+00</td>
</tr>
<tr>
<td>1.66E-01</td>
<td>9.30E+00</td>
</tr>
</tbody>
</table>

OK

Define/Sections Properties
Link/Support Properties
Click to: Add New Property
Link/Support Type: Multilinear Plastic
Property Name: A40
Mass: 0

Selective Direction U2 and check Nonlinear Properties: Modify/Show for U2 Properties Used for Linear Analysis Cases
Effective Stiffness: 10294 ksi
Effective Damping: 0
Shear Deformation Location
Distance from End-J: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.20E-02</td>
<td>-7.88E+00</td>
</tr>
<tr>
<td>-2.20E-03</td>
<td>-7.88E+00</td>
</tr>
<tr>
<td>0.00E+00</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>2.20E-03</td>
<td>7.88E+00</td>
</tr>
</tbody>
</table>

OK/OK
Define/Sections Properties
Link/Support Properties
Click to: Add New Property

Link/Support Type: Multilinear Plastic
Property Name: A32
Mass: 0
Weight: 0.0356 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line
Spring: 1
Property is Defined for This Area in Area and Solid Springs: 1

Directional Properties
Select Direction U1 and check Nonlinear Properties: Modify/Show for U1 Properties Used for Linear Analysis Cases Effective Stiffness: 10294 ksi Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

Displ., in. Force, kip
-7.110E-02 -7.320E+01
-7.110E-03 -7.320E+01
0.000E+00 0.000E+00
9.720E-08 1.000E-03
9.720E-07 1.000E-03
OK

Select Direction U2 and check Nonlinear Properties: Modify/Show for U2 Properties Used for Linear Analysis Cases Effective Stiffness: 3574 ksi Effective Damping: 0
Shear Deformation Location

Distance from End-J: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

Displ., in. Force, kip
-2.203E-02 -7.875E+00
-2.200E-03 -7.880E+00
0.000E+00 0.000E+00
2.200E-03 7.880E+00
2.200E-02 7.880E+00
OK

Define/Sections Properties
Link/Support Properties
Click to: Add New Property

Link/Support Type: Multilinear Plastic
Property Name: A24
Mass: 0
Weight: 0.0356 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line
Spring: 1
Property is Defined for This Area in Area and Solid Springs: 1

Directional Properties
Select Direction U1 and check Nonlinear Properties: Modify/Show for U1 Properties Used for Linear Analysis Cases Effective Stiffness: 10294 ksi Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

Displ., in. Force, kip
-7.110E-02 -7.320E+01
-7.110E-03 -7.320E+01
0.000E+00 0.000E+00
9.720E-08 1.000E-03
9.720E-07 1.000E-03
OK

Select Direction U2 and check Nonlinear Properties: Modify/Show for U2 Properties Used for Linear Analysis Cases Effective Stiffness: 3574 ksi Effective Damping: 0
Shear Deformation Location

Displ., in. Force, kip
-7.110E-02 -7.320E+01
-7.110E-03 -7.320E+01
0.000E+00 0.000E+00
Select Direction U2 and check Nonlinear Properties: Modify/Show for U2

Properties Used for Linear Analysis Cases

Effective Stiffness: 3574 ksi
Effective Damping: 0
Shear Deformation Location
Distance from End-J: 0

Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

Disp., in. Force, kip
-2.200E-02 -7.880E+00
-2.200E-03 -7.880E+00
0.000E+00 0.000E+00
2.200E-03 7.880E+00
2.200E-02 7.880E+00

OK/OK

Define/Sections Properties
Link/Support Properties
Click to: Add New Property

Link/Support Type: Multilinear Plastic
Property Name: A16
Mass: 0
Weight: 0.0356 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line Spring: 1
Property is Defined for This Area in Area and Solid Springs: 1

Directional Properties
Select Direction U1 and check Nonlinear Properties: Modify/Show for U1
Properties Used for Linear Analysis Cases

Effective Stiffness: 10294 ksi
Effective Damping: 0

Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

Disp., in. Force, kip
-7.110E-02 -7.320E+01
-7.110E-03 -7.320E+01
0.000E+00 0.000E+00
9.720E-08 1.000E-03
9.720E-07 1.000E-03

OK

Select Direction U2 and check Nonlinear Properties: Modify/Show for U2
Properties Used for Linear Analysis Cases
Effective Stiffness: 3574 ksi
Effective Damping: 0
Shear Deformation Location
Distance from End-J: 0

Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

Disp., in. Force, kip
-2.200E-02 -7.880E+00
-2.200E-03 -7.880E+00
0.000E+00 0.000E+00
2.200E-03 7.880E+00
2.200E-02 7.880E+00

OK/OK

Define/Sections Properties
Link/Support Properties
Click to: Add New Property

Link/Support Type: Multilinear Plastic
Property Name: A08R
Mass: 0
Weight: 0.0356 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line Spring: 1
Property is Defined for This Area in Area and Solid Springs: 1

Directional Properties
Select Direction U1 and check Nonlinear Properties: Modify/Show for U1
Properties Used for Linear Analysis Cases

Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line
Spring: 1
Property is Defined for This Area in Area
and Solid Springs: 1

Directional Properties
Select Direction U1 and check Nonlinear
Properties: Modify/Show for U1
Properties Used for Linear Analysis Cases
Effective Stiffness: 10294 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-8.020E-02</td>
<td>-8.250E+01</td>
</tr>
<tr>
<td>-8.020E-03</td>
<td>-8.250E+01</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>1.660E-02</td>
<td>9.300E+00</td>
</tr>
<tr>
<td>1.660E-01</td>
<td>9.300E+00</td>
</tr>
</tbody>
</table>

OK

Select Direction U2 and check Nonlinear
Properties: Modify/Show for U2
Properties Used for Linear Analysis Cases
Effective Stiffness: 3574 ksi
Effective Damping: 0
Shear Deformation Location
Distance from End-J: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-7.110E-02</td>
<td>-7.320E+01</td>
</tr>
<tr>
<td>-7.110E-03</td>
<td>-7.320E+01</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>9.720E-08</td>
<td>1.000E-03</td>
</tr>
<tr>
<td>9.720E-07</td>
<td>1.000E-03</td>
</tr>
</tbody>
</table>

OK

Define/Sections Properties
Disp., in.  Force, kip
-2.200E-02 -7.880E+00
-2.200E-03 -7.880E+00
0.000E+00 0.000E+00
2.200E-03 7.880E+00
2.200E-02 7.880E+00

OK/OK

Define/Sections Properties
Link/Support Properties
Click to: Add New Property

Link/Support Type: Multilinear Plastic
Property Name: A00
Mass: 0
Weight: 0.0356 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line
Spring: 1
Property is Defined for This Area in Area
and Solid Springs: 1

Directional Properties
Select Direction U1 and check Nonlinear
Properties: Modify/Show for U1
Properties Used for Linear Analysis Cases
Effective Stiffness: 10294 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

Disp., in.  Force, kip
-8.020E-02 -8.250E+01
-8.020E-03 -8.250E+01
0.000E+00 0.000E+00
1.660E-02 9.300E+00
1.660E-01 9.300E+00

OK

Define/Sections Properties
Link/Support Properties
Click to: Add New Property

Link/Support Type: Multilinear Plastic
Property Name: CB-EXT-R
Mass: 0
Weight: 0.0178 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line
Spring: 1
Property is Defined for This Area in Area
and Solid Springs: 1

Directional Properties
Select Direction U2 and check Nonlinear
Properties: Modify/Show for U2
Properties Used for Linear Analysis Cases
Effective Stiffness: 3574 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

Disp., in.  Force, kip
-2.200E-02 -7.880E+00
-2.200E-03 -7.880E+00
0.000E+00 0.000E+00
2.200E-03 7.880E+00
2.200E-02 7.880E+00

OK/OK

Define/Sections Properties
Link/Support Properties
Click to: Add New Property

Link/Support Type: Multilinear Plastic
Property Name: CB-EXT-R
Mass: 0
Weight: 0.0178 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line
Spring: 1
Property is Defined for This Area in Area
and Solid Springs: 1

Directional Properties
Select Direction U1 and check Nonlinear
Properties: Modify/Show for U1
Properties Used for Linear Analysis Cases
Effective Stiffness: 5147 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-8.280E-02</td>
<td>-4.260E+01</td>
</tr>
<tr>
<td>-8.280E-03</td>
<td>-4.260E+01</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>1.660E-03</td>
<td>6.000E+00</td>
</tr>
<tr>
<td>1.660E-02</td>
<td>6.000E+00</td>
</tr>
</tbody>
</table>

OK

Select Direction U2 and check Nonlinear Properties: Modify/Show for U2
Properties Used for Linear Analysis Cases
Effective Stiffness: 1787 ksi
Effective Damping: 0
Hysteresis Type and Parameters: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.360E-02</td>
<td>-4.210E+00</td>
</tr>
<tr>
<td>-2.360E-03</td>
<td>-4.210E+00</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>2.360E-03</td>
<td>4.210E+00</td>
</tr>
<tr>
<td>2.360E-02</td>
<td>4.210E+00</td>
</tr>
</tbody>
</table>

OK/OK

Define/Sections Properties
Link/Support Properties
Click to: Add New Property

Link/Support Type: Multilinear Plastic
Property Name: CB-INT-R
Mass: 0
Weight: 0.0356 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line
Spring: 1

OK/OK
Link/Support Type: Multilinear Plastic
Property Name: CB-INT-U
Mass: 0
Weight: 0.0356 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line
Spring: 1
Property is Defined for This Area in Area
and Solid Springs: 1

Directional Properties
Select Direction U1 and check Nonlinear
Properties: Modify/Show for U1
Properties Used for Linear Analysis Cases
Effective Stiffness: 10294 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition
Displ., in. Force, kip
-7.110E-02 -7.320E+01
-7.110E-03 -7.320E+01
0.000E+00 0.000E+00
1.660E-03 1.000E-03
1.660E-02 1.000E-03
OK

Select Direction U2 and check Nonlinear
Properties: Modify/Show for U2
Properties Used for Linear Analysis Cases
Effective Stiffness: 3874 ksi
Effective Damping: 0
Shear Deformation Location
Distance from End-J: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition
Disp., in. Force, kip
-2.360E-02 -8.420E+00
(Assign Link A40 at base of Wall B, between Z=0 and Z=8 in., at X=408 and X=456 in.)

Property: A16
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>

(Assign Link A40 at base of Wall A, between Z=0 and Z=8 in., at X=32 and X=64 in.)
(Assign Link A40 at base of Wall B, between Z=0 and Z=8 in., at X=416 and X=448 in.)

Property: A08R
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>

(Assign Link A40 at base of Wall A, between Z=0 and Z=8 in., at X=40 in.)
(Assign Link A40 at base of Wall B, between Z=0 and Z=8 in., at X=424 in.)

Property: A08U
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>

(Assign Link A40 at base of Wall A, between Z=0 and Z=8 in., at X=56 in.)
(Assign Link A40 at base of Wall B, between Z=0 and Z=8 in., at X=440 in.)

Property: A00
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>

(Assign Link A40 at base of Wall A, between Z=0 and Z=8 in., at X=48 in.)
(Assign Link A40 at base of Wall B, between Z=0 and Z=8 in., at X=432 in.)

(Close the Properties of Object window)
(Select the links at the base of Walls A, and B)
Verify 24 Areas and 96 Edges are selected and delete

(Select the area elements bounded by the Links at the top of Walls A, and B)
Verify 24 Areas and 96 Edges are selected

Draw/Draw 2 Joint Link
Property: CB-EXT-R
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>

(Assign Link CB-EXT-R between X=96 and X=104 in., at Z=120 and at Z=648 in.)
(Assign Link CB-EXT-R between X=376 and X=384 in., at Z=120 and at Z=648 in.)

Property: CB-INT-R
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>

(Assign Link CB-INT-R between X=96 and X=104 in., at Z=128 and at Z=640 in.)
(Assign Link CB-INT-R between X=376 and X=384 in., at Z=128 and at Z=640 in.)

Property: CB-INT-U
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>

(Assign Link CB-INT-U between X=96 and X=104 in., at Z=136 and at Z=632 in.)
(Assign Link CB-INT-U between X=376 and X=384 in., at Z=136 and at Z=632 in.)

(Close the Properties of Object window)
Select Link CB-INT-U between X=96 and X=104 in., at Z=136 in.
Select Link CB-INT-U between X=376 and X=384 in., at Z=136 in.
Verify 2 Links are selected
Edit/Replicate/Linear
Increments
dx: 0
dy: 0
dz: 8 in.
Increment Data
Number: 61
OK
(Select the area elements bounded by the Links along Grids A2 and B1)
Verify 132 Areas and 528 Edges are selected and delete

File/Save

Step 7. Assign Constraints and Rigid Segments

Select all joints at roof level (2'-0” from the top of the wall)
Verify 61 Points are selected
Assign/Joint/Constraints
Choose Constraint Type to Add: Diaphragm
Click to: Add New Constraint
Constraint Name: DIAPH5
Coordinate System: GLOBAL
Constraint Axis: Z Axis
OK/OK

Select joints at Story 3 elevation (Z=384 in.)
Verify 61 Points are selected
Assign/Joint/Constraints
Choose Constraint Type to Add: Diaphragm
Click to: Add New Constraint
Constraint Name: DIAPH4
Coordinate System: GLOBAL
Constraint Axis: Z Axis
OK/OK

Select joints at Story 2 elevation (Z=264 in.)
Verify 61 Points are selected
Assign/Joint/Constraints
Choose Constraint Type to Add: Diaphragm
Click to: Add New Constraint
Constraint Name: DIAPH2
Coordinate System: GLOBAL
Constraint Axis: Z Axis
OK/OK

Select joints at Story 1 elevation (Z=144 in.)
Verify 61 Points are selected
Assign/Joint/Constraints
Choose Constraint Type to Add: Diaphragm
Click to: Add New Constraint
Constraint Name: DIAPH1
Coordinate System: GLOBAL
Constraint Axis: Z Axis
OK/OK

Define/Section Properties/Frame Sections
Click to: Add New Property
Select Property Type
Frame Section Property Type: Other
Click to Add a Section: General Properties
Cross-sectional Area = 0
Moment of Inertia about 3 axis = 1e6
Shear area in 2 direction = 1e6
All other properties = 1
Section Name: RIGID  
Material: M1500  
Dimensions:  
Depth = 1 in.  
Width = 1 in.  
OK/OK

File/Save

Step 8. Define Load Patterns and Load Cases

Define/Load Patterns  
Load Pattern Name: LIVE  
Type: LIVE  
Self-Weight Multiplier: 0  
Click to: Add New Load Pattern  
OK

Define/Load Patterns  
Load Pattern Name: SEISMIC  
Type: Other  
Self-Weight Multiplier: 0  
Click to: Add New Load Pattern  
OK

Define/Load Cases  
Click to: Add New Load Case  
Load Case Name: E  
Load Case Type: Static  
Analysis Type: Linear  
Stiffness to Use: Zero Initial Conditions – Unstressed State  
Loads Applied  
Load Type = Load Pattern  
Load Name = SEISMIC  
Scale Factor = 1  
Add  
OK

Define/Load Cases  
Click to: Add New Load Case  
Load Case Name: PRE-LOAD  
Load Case Type: Static  
Analysis Type: Nonlinear  
Initial Conditions  
Zero Initial Conditions – Start from Unstressed State  
Geometric Nonlinearity Parameters: None  
Loads Applied  
Load Type = Load Pattern  
Load Name = DEAD
Scale Factor = 0.7
Add
Other Parameters
Load Application: Full Load (Default)
Results Saved: Final State Only (Default)
Nonlinear Parameters: Default
OK/OK

(Define Nonlinear Static Analysis - Eastward Loading)
Define/Load Cases
Click to: Add New Load Case
Load Case Name: NSA+
Load Case Type: Static
Analysis Type: Nonlinear
Initial Conditions
Continue from State at End of Nonlinear Case: PRE-LOAD
Geometric Nonlinearity Parameters: None
Loads Applied
Load Type = Load Pattern
Load Name = SEISMIC
Scale Factor = 1
Add
Other Parameters
Load Application: Modify-Show
Load Application Control: Displacement Control
Control Displacement: Use Monitored Displacement
Load to a Monitored Displacement
Magnitude of: 1.0 in.
Monitored Displacement
DOF: U1
At Joint: 2478
OK
Results Saved: Modify-Show
Results Saved: Multiple States
For Each Stage
Minimum Number of Saved States: 50
Maximum Number of Saved States: 100
Select Save Positive Displacement Increments Only
OK
Nonlinear Parameters: Default
OK/OK

(Define Nonlinear Static Analysis - Westward Loading)
Define/Load Cases
Click to: Add New Load Case
Load Case Name: NSA-
Load Case Type: Static
Analysis Type: Nonlinear
Initial Conditions
Continue from State at End of Nonlinear Case: PRE-LOAD
Geometric Nonlinearity Parameters: None
Loads Applied
Load Type = Load Pattern
Load Name = SEISMIC
Scale Factor = -1
Add
Other Parameters
Load Application: Modify-Show
Load Application Control: Displacement Control
Control Displacement: Use Monitored Displacement
Load to a Monitored Displacement
Magnitude of: 1.0 in.
Monitored Displacement
DOF: U1
At Joint: 2478
OK
Results Saved: Modify-Show
Results Saved: Multiple States
For Each Stage
Minimum Number of Saved States: 50
Maximum Number of Saved States: 100
Select Save Positive Displacement Increments Only
OK
Nonlinear Parameters: Default
OK/OK
File/Save
Step 9. Assign Loads

Select all joints at roof level (2'-0" from the top of wall) and at floor levels except edge joints
Verify 295 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: DEAD
Units: kip, in. F
Loads
Force Global Z: -0.5333 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Click PS on the left side toolbar
Verify 295 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: LIVE
Units: kip, in. F
Loads
Force Global Z: -0.2666 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the edge joints at Grid Lines A1 and B2 at each Story
Verify 10 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: DEAD
Units: kip, in. F
Loads
Force Global Z: -0.2666 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the roof level (at X=240 in. Z=624 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in. F
Loads
Force Global X: 53.35 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the roof level (at X=240 in. Z=504 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in. F
Loads
Force Global X: 42.68 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the roof level (at X=240 in. Z=384 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in. F
Loads
Force Global X: 32.00 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the roof level (at X=240 in. Z=264 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in. F
Loads
Force Global X: 21.34 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the roof level (at X=240 in. Z=144 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in. F
Loads
Force Global X: 10.67 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

File/Save

Step 10. Analyze

Analyze/Set Analysis Options
FAST DOFs: Plane Frame - XZ Plane
OK

Analyze/Set Load Cases to Run
Highlight PRE-LOAD, NSA+, NSA-
Click to: Run/Do Not Run Case
Verify the Nonlinear Static are marked as Run
Run Now

(On the top toolbar select the Show Deformed Shape icon)
Deformed Shape
Case/Combo
Case/Combo Name: SEISMIC
OK

Verify the displacement U1 at the roof diaphragm level is 0.198 in.

Analyze/Set Load Cases to Run
Highlight PRE-LOAD, NSA+, NSA-
Click to: Run/Do Not Run Case
Verify the Nonlinear Static are marked as Run
Run Now

Step 11. Program Output

Display
Show Forces/Stresses
Joints
Case/Combo Name: E
OK
Verify units are kip, in, F

Draw Section Cut (cut wall A at Base)
Section Cutting Line
Start Point: X=-1, Y=0, Z=1
End Point: X=97, Y=0, Z=1
Click on Refresh Button
Integrated Forces:
Left Side/Save Cut
Close

Draw Section Cut (cut wall B at Base)
Section Cutting Line
Start Point: X=383, Y=0, Z=1
End Point: X=481, Y=0, Z=1
Click on Refresh Button
Integrated Forces:
Left Side/Save Cut
Close

Display/Show Plot Functions
Define Plot Functions
Choose Function Type to Add: Add Base Functions
Click to: Add Plot Function
Base Functions: Base Shear X
OK/OK
Define Plot Functions
Choose Function Type to Add: Add Joint
Disps/Forces
Click to: Add Plot Function
Joint ID: 2478
Vector Type: Displ
Component: UX
OK/OK

Define Plot Functions
Choose Function Type to Add: Add Section
Cut Forces
Click to: Add Plot Functions
Section Cut: SCUT1
Component: F1
OK/OK

Define Plot Functions
Choose Function Type to Add: Add Section
Cut Forces
Click to: Add Plot Functions
Section Cut: SCUT2
Component: F1
OK/OK

Define Plot Functions
Choose Function Type to Add: Add Section
Cut Forces
Click to: Add Plot Functions
Section Cut: SCUT3
Component: F1
OK/OK

Choose Plot Functions
List of Functions: Highlight Base Shear X, SCUT1 and SCUT2
Click the Add button
Verify Base Shear X, SCUT1, and SCUT2 show under Vertical Functions
Horizontal Plot Function: Joint2478

Load Case (Multi-Stepped Cases); NSA+
Click Display

File/Print Tables to File
File name: NSA+
Save
OK

Load Case (Multi-Stepped Cases); NSA-
Click Display
File/Print Tables to File
File name: NSA-
Save
OK

File/Save
Done
**B.5.3 Case Study C**

**Step 1. Define Geometry**

File/New Model

New Model Initialization

Initialize Model from Defaults with Units: kip, in, F

Select Template: Grid Only

Cartesian

Coordinate System Name: GLOBAL

<table>
<thead>
<tr>
<th>Number of Grid Lines</th>
<th>Grid Spacing</th>
<th>First Grid Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>X direction:</td>
<td>4</td>
<td>48</td>
</tr>
<tr>
<td>Y direction:</td>
<td>1</td>
<td>48</td>
</tr>
<tr>
<td>Z direction:</td>
<td>16</td>
<td>48</td>
</tr>
</tbody>
</table>

OK

(Click on top tab of right window, close 3-D View)
(Select the XZ view in the top toolbar)

Right click/Edit Grid Data

Click to: Modify/Show System

(To modify grid lines using actual coordinates)

Units: Kip, ft, F

**X Grid Data:**

<table>
<thead>
<tr>
<th>Grid ID</th>
<th>Ordinate</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0 ft</td>
</tr>
<tr>
<td>A2</td>
<td>8 ft</td>
</tr>
<tr>
<td>B1</td>
<td>32 ft</td>
</tr>
<tr>
<td>B2</td>
<td>40 ft</td>
</tr>
</tbody>
</table>

**Z Grid Data:**

<table>
<thead>
<tr>
<th>Grid ID</th>
<th>Ordinate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z9</td>
<td>32 ft</td>
</tr>
<tr>
<td>Z10</td>
<td>34 ft</td>
</tr>
<tr>
<td>Z11</td>
<td>40 ft</td>
</tr>
<tr>
<td>Z12</td>
<td>42 ft</td>
</tr>
<tr>
<td>Z13</td>
<td>44 ft</td>
</tr>
<tr>
<td>Z14</td>
<td>50 ft</td>
</tr>
<tr>
<td>Z15</td>
<td>52 ft</td>
</tr>
<tr>
<td>Z16</td>
<td>54 ft</td>
</tr>
</tbody>
</table>

OK/OK

**Step 2. Define Material Properties**

Define/Materials

Check Show Advanced Properties

Click to: Add New Material

Material Name: M1500

Options

Material Type: Other

Directional Symmetry Type: Isotropic

Modulus of Elasticity: 1350 ksi

Poisson’s Ratio: 0.2

Coeff. of Thermal Expansion: 5.5E−06

Shear Modulus: Auto (562.5 ksi)

Weight and Mass

Weight per Unit Volume: 0.1259 (kip/ft^3)

Mass per Unit Volume: 0

OK/OK/OK

**Step 3. Define Area Sections**

Define/Section Properties/Area Sections

Select Section Type to Add: Shell

Click to: Add New Section

Section Name: M8-LIN

File/Save
Type: Membrane
Material
Material Name: M1500
Material Angle: 0
Thickness
Membrane: 7.625
Bending: 7.625
OK/OK

File/Save

Step 4. Draw Area Elements

(Draw walls A, and B)
Draw/Draw Rectangular Area
Click on bottom left of Wall A (at A1/Z1) and drag to top right of Wall A (at A2/Z16)

Draw/Draw Rectangular Area
Click on bottom left of Wall B (at B1/Z1) and drag mouse to top right of Wall B (at B2/Z16)

(Draw coupling wall segments)
Draw/Draw Rectangular Area
Click on top right of Wall A (at A2/Z2) and drag mouse to top of Wall B (at B1/Z4)

Draw/Draw Rectangular Area
Click on top right of Wall A (at A2/Z5) and drag mouse to top of Wall B (at B1/Z7)

Draw/Draw Rectangular Area
Click on top right of Wall A (at A2/Z8) and drag mouse to top of Wall B (at B1/Z10)

Draw/Draw Rectangular Area
Click on top right of Wall A (at A2/Z11) and drag mouse to top of Wall B (at B1/Z13)

Draw/Draw Rectangular Area
Click on top right of Wall A (at A2/Z14) and drag mouse to top of Wall B (at B1/Z16)

Select checkmark icon (Set Display Options) on top toolbar
On Joints, uncheck: Invisible
On Joints, check: Labels
On Areas, check: Labels
OK

On side toolbar select all
Edit/Change Labels
Item Type: Element Labels – Area
Auto Relabel Control (use default values)
Edit/Auto Relabel/All in List
Item Type: Element Labels – Joint
Auto Relabel Control (use default values)
Edit/Auto Relabel/All in List
OK

Select checkmark icon (Set Display Options) on top toolbar
On Joints, uncheck: Labels
On Areas, uncheck: Labels
OK

Select bottom joints, verify 4 Points are selected
Assign/Joint/Restraints/
Check boxes for all degrees of freedom (or on Fast Restraints, select fixed-end condition)
OK

On side toolbar select all
Verify 7 areas and 28 edges are selected
Edit/Edit Areas/Divide Areas
Divide Area into Objects of This Maximum Size
Along Edge from Point 1 to 2: 8 in.
Along Edge from Point 1 to 3: 8 in.
At bottom, on Restraints and Constraints for Added Points, select
Add on Edge when restraints/constraints exist at adjacent corner points
OK
On side toolbar select all, verify there are 3357 Points, 3024 Areas, 12096 Edges

On side toolbar select clr

File/Save

Step 5. Define Nonlinear Links

Define/Sections Properties
Link/Support Properties
Click to: Add New Property

Link/Support Type: Multilinear Plastic
Property Name: A48
Mass: 0
Weight: 0.0178 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line Spring: 1
Property is Defined for This Area in Area and Solid Springs: 1

Directional Properties
Select Direction U1 and check Nonlinear Properties: Modify/Show for U1
Properties Used for Linear Analysis Cases
Effective Stiffness:  5147 ksi
Effective Damping:  0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

Displ., in  Force, kip
1.870E-02  3.340E+00
1.870E-03  3.340E+00
0.000E+00  0.000E+00
-1.870E-03 -3.340E+00
-1.870E-02 -3.340E+00
OK

OK/OK

Define/Sections Properties
Link/Support Properties
Click to: Add New Property

Link/Support Type: Multilinear Plastic
Property Name: A40
Mass: 0
Weight: 0.0356 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line Spring: 1
Property is Defined for This Area in Area and Solid Springs: 1

Directional Properties
Select Direction U1 and check Nonlinear Properties: Modify/Show for U1
Properties Used for Linear Analysis Cases
Effective Stiffness:  10294 ksi
Effective Damping:  0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

Displ., in  Force, kip
1.870E-02  3.340E+00
1.870E-03  3.340E+00
0.000E+00  0.000E+00
-1.870E-03 -3.340E+00
-1.870E-02 -3.340E+00
OK

OK

Select Direction U2 and check Nonlinear

Select Direction U1 and check Nonlinear Properties: Modify/Show for U1
Properties Used for Linear Analysis Cases Effective Stiffness:  1787 ksi
Effective Damping:  0
Shear Deformation Location
Distance from End-J:  0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

Displ., in  Force, kip
-8.920E-03 -4.590E+01
-8.920E-03 -4.590E+01
0.000E+00  0.000E+00
1.660E-02  9.300E+00
1.660E-02  9.300E+00
-1.870E-03 -3.340E+00
-1.870E-02 -3.340E+00
OK
<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-8.020E-02</td>
<td>-8.250E+01</td>
</tr>
<tr>
<td>-8.020E-03</td>
<td>-8.250E+01</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>1.660E-02</td>
<td>9.300E+00</td>
</tr>
<tr>
<td>1.660E-01</td>
<td>9.300E+00</td>
</tr>
</tbody>
</table>

OK

Select Direction U2 and check Nonlinear Properties: Modify/Show for U2

Properties Used for Linear Analysis Cases

Effective Stiffness: 3574 ksi
Effective Damping: 0
Shear Deformation Location: 0
Distance from End-J: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.870E-02</td>
<td>-6.680E+00</td>
</tr>
<tr>
<td>-1.870E-03</td>
<td>-6.680E+00</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>1.870E-03</td>
<td>6.680E+00</td>
</tr>
<tr>
<td>1.870E-02</td>
<td>6.680E+00</td>
</tr>
</tbody>
</table>

OK/OK

Define/Sections Properties
Link/Support Properties
Click to: Add New Property

Link/Support Type: Multilinear Plastic
Property Name: A32
Mass: 0
Weight: 0.0356 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line Spring: 1
Property is Defined for This Area in Area and Solid Springs: 1

OK

Select Direction U2 and check Nonlinear Properties: Modify/Show for U2

Properties Used for Linear Analysis Cases

Effective Stiffness: 10294 ksi
Effective Damping: 0
Shear Deformation Location: 0
Distance from End-J: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-7.110E-02</td>
<td>-7.320E+01</td>
</tr>
<tr>
<td>-7.110E-03</td>
<td>-7.320E+01</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>9.720E-08</td>
<td>1.000E-03</td>
</tr>
<tr>
<td>9.720E-07</td>
<td>1.000E-03</td>
</tr>
</tbody>
</table>

OK

Select Direction U2 and check Nonlinear Properties: Modify/Show for U2

Properties Used for Linear Analysis Cases

Effective Stiffness: 3574 ksi
Effective Damping: 0
Shear Deformation Location: 0
Distance from End-J: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.870E-02</td>
<td>-6.680E+00</td>
</tr>
<tr>
<td>-1.870E-03</td>
<td>-6.680E+00</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>1.870E-03</td>
<td>6.680E+00</td>
</tr>
<tr>
<td>1.870E-02</td>
<td>6.680E+00</td>
</tr>
</tbody>
</table>

OK/OK

Define/Sections Properties
Link/Support Properties
Click to: Add New Property

Link/Support Type: Multilinear Plastic
Property Name: A24
Mass: 0
Weight: 0.0356 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line Spring: 1
Property is Defined for This Area in Area and Solid Springs: 1

Directional Properties
Select Direction U1 and check Nonlinear Properties: Modify/Show for U1
Properties Used for Linear Analysis Cases
Effective Stiffness: 10294 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-7.110E-02</td>
<td>-7.320E+01</td>
</tr>
<tr>
<td>-7.110E-03</td>
<td>-7.320E+01</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>9.720E-08</td>
<td>1.000E-03</td>
</tr>
<tr>
<td>9.720E-07</td>
<td>1.000E-03</td>
</tr>
</tbody>
</table>

OK

Select Direction U2 and check Nonlinear Properties: Modify/Show for U2
Properties Used for Linear Analysis Cases
Effective Stiffness: 3574 ksi
Effective Damping: 0
Shear Deformation Location
Distance from End-J: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.870E-02</td>
<td>-6.680E+00</td>
</tr>
<tr>
<td>-1.870E-03</td>
<td>-6.680E+00</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
</tbody>
</table>

OK

Select Direction U2 and check Nonlinear Properties: Modify/Show for U2
Properties Used for Linear Analysis Cases
Effective Stiffness: 3574 ksi
Effective Damping: 0
Shear Deformation Location
Distance from End-J: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Disp., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.870E-02</td>
<td>-6.680E+00</td>
</tr>
<tr>
<td>-1.870E-03</td>
<td>-6.680E+00</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>1.870E-03</td>
<td>6.680E+00</td>
</tr>
<tr>
<td>1.870E-02</td>
<td>6.680E+00</td>
</tr>
</tbody>
</table>

OK/OK

Define/Sections Properties
Link/Support Properties
Click to: Add New Property
Link/Support Type: Multilinear Plastic
Property Name: A08R
Mass: 0
Weight: 0.0356 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line
Spring: 1
Property is Defined for This Area in Area
and Solid Springs: 1

Directional Properties
Select Direction U1 and check Nonlinear
Properties: Modify/Show for U1
Properties Used for Linear Analysis Cases
Effective Stiffness: 10294 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Disp., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-8.020E-02</td>
<td>-8.250E+01</td>
</tr>
<tr>
<td>-8.020E-03</td>
<td>-8.250E+01</td>
</tr>
</tbody>
</table>

OK/OK

Define/Sections Properties
Link/Support Properties
Click to: Add New Property
Link/Support Type: Multilinear Plastic
Property Name: A08U
Mass: 0
Weight: 0.0356 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line
Spring: 1
Property is Defined for This Area in Area
and Solid Springs: 1

Directional Properties
Select Direction U1 and check Nonlinear
Properties: Modify/Show for U1
Properties Used for Linear Analysis Cases
Effective Stiffness: 3574 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Disp., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-8.020E-02</td>
<td>-8.250E+01</td>
</tr>
<tr>
<td>-8.020E-03</td>
<td>-8.250E+01</td>
</tr>
</tbody>
</table>

OK/OK
Properties Used for Linear Analysis Cases
Effective Stiffness: 10294 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-7.110E-02</td>
<td>-7.320E+01</td>
</tr>
<tr>
<td>-7.110E-03</td>
<td>-7.320E+01</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>9.720E-08</td>
<td>1.000E-03</td>
</tr>
<tr>
<td>9.720E-07</td>
<td>1.000E-03</td>
</tr>
</tbody>
</table>

OK

Select Direction U2 and check Nonlinear Properties: Modify/Show for U2
Properties Used for Linear Analysis Cases
Effective Stiffness: 3574 ksi
Effective Damping: 0
Shear Deformation Location
Distance from End-J: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.870E-02</td>
<td>-6.680E+00</td>
</tr>
<tr>
<td>-1.870E-03</td>
<td>-6.680E+00</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>1.870E-03</td>
<td>6.680E+00</td>
</tr>
<tr>
<td>1.870E-02</td>
<td>6.680E+00</td>
</tr>
</tbody>
</table>

OK/OK

Select Direction U2 and check Nonlinear Properties: Modify/Show for U2
Properties Used for Linear Analysis Cases
Effective Stiffness: 10294 ksi
Effective Damping: 0
Shear Deformation Location
Distance from End-J: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.870E-02</td>
<td>-6.680E+00</td>
</tr>
<tr>
<td>-1.870E-03</td>
<td>-6.680E+00</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>1.870E-03</td>
<td>6.680E+00</td>
</tr>
<tr>
<td>1.870E-02</td>
<td>6.680E+00</td>
</tr>
</tbody>
</table>

OK/OK

Select Direction U2 and check Nonlinear Properties: Modify/Show for U2
Properties Used for Linear Analysis Cases
Effective Stiffness: 3574 ksi
Effective Damping: 0
Shear Deformation Location
Distance from End-J: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-8.020E-02</td>
<td>-8.250E+01</td>
</tr>
<tr>
<td>-8.020E-03</td>
<td>-8.250E+01</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>1.660E-02</td>
<td>9.300E+00</td>
</tr>
<tr>
<td>1.660E-01</td>
<td>9.300E+00</td>
</tr>
</tbody>
</table>

OK/OK
Define/Sections Properties
Link/Support Properties
Click to: Add New Property

Link/Support Type: Multilinear Plastic
Property Name: CB-EXT-R
Mass: 0
Weight: 0.0178 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line
Spring: 1
Property is Defined for This Area in Area
and Solid Springs: 1

Directional Properties
Select Direction U1 and check Nonlinear
Properties: Modify/Show for U1
Properties Used for Linear Analysis Cases
Effective Stiffness: 5147 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Multi-Linear Force-Deformation Definition

Displ., in. Force, kip
-1.070E-01 -5.520E+01
-1.070E-02 -5.520E+01
0.000E+00 0.000E+00
1.660E-03 1.860E+01
1.660E-02 1.860E+01
OK

Select Direction U2 and check Nonlinear
Properties: Modify/Show for U2
Properties Used for Linear Analysis Cases
Effective Stiffness: 10294 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

Displ., in. Force, kip
-8.920E-02 -9.180E+01
-8.920E-03 -9.180E+01
0.000E+00 0.000E+00
1.660E-03 1.860E+01
1.660E-02 1.860E+01
OK

Define/Sections Properties
Link/Support Properties
Click to: Add New Property

Link/Support Type: Multilinear Plastic
Property Name: CB-INT-R
Mass: 0
Weight: 0.0356 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line
Spring: 1
Property is Defined for This Area in Area
and Solid Springs: 1

Directional Properties
Select Direction U1 and check Nonlinear
Properties: Modify/Show for U1
Properties Used for Linear Analysis Cases
Effective Stiffness: 1787 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

Displ., in. Force, kip
-8.920E-02 -9.180E+01
-8.920E-03 -9.180E+01
0.000E+00 0.000E+00
1.660E-03 1.860E+01
1.660E-02 1.860E+01
OK

Select Direction U2 and check Nonlinear
Properties: Modify/Show for U2
Properties Used for Linear Analysis Cases
Effective Stiffness: 10294 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition
Select Direction U2 and check Nonlinear Properties: Modify/Show for U2
Properties Used for Linear Analysis Cases
Effective Stiffness: 3574 ksi
Effective Damping: 0
Shear Deformation Location
Distance from End-J: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.640E-02</td>
<td>-9.450E+00</td>
</tr>
<tr>
<td>-2.640E-03</td>
<td>-9.450E+00</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>2.640E-03</td>
<td>9.450E+00</td>
</tr>
<tr>
<td>2.640E-02</td>
<td>9.450E+00</td>
</tr>
</tbody>
</table>

OK/OK

Define/Sections Properties
Link/Support Properties
Click to: Add New Property

Link/Support Type: Multilinear Plastic
Property Name: CB-INT-U
Mass: 0
Weight: 0.0356 kip
Rotational Inertia 1: 0
Rotational Inertia 2: 0
Rotational Inertia 3: 0
Factors for Line, Area and Solid Springs
Property is Defined for This Length In a Line Spring: 1
Property is Defined for This Area in Area and Solid Springs: 1

Directional Properties
Select Direction U1 and check Nonlinear Properties: Modify/Show for U1
Properties Used for Linear Analysis Cases
Effective Stiffness: 10294 ksi
Effective Damping: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-7.110E-02</td>
<td>-7.320E+01</td>
</tr>
<tr>
<td>-7.110E-03</td>
<td>-7.320E+01</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>1.660E-03</td>
<td>1.000E-03</td>
</tr>
<tr>
<td>1.660E-02</td>
<td>1.000E-03</td>
</tr>
</tbody>
</table>

OK

Select Direction U2 and check Nonlinear Properties: Modify/Show for U2
Properties Used for Linear Analysis Cases
Effective Stiffness: 3574 ksi
Effective Damping: 0
Shear Deformation Location
Distance from End-J: 0
Hysteresis Type and Parameters
Hysteresis Type: Kinematic
Multi-Linear Force-Deformation Definition

<table>
<thead>
<tr>
<th>Displ., in.</th>
<th>Force, kip</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.440E-02</td>
<td>-9.450E+00</td>
</tr>
<tr>
<td>-2.440E-03</td>
<td>-9.450E+00</td>
</tr>
<tr>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>2.440E-03</td>
<td>9.450E+00</td>
</tr>
<tr>
<td>2.440E-02</td>
<td>9.450E+00</td>
</tr>
</tbody>
</table>

OK/OK

File/Save

Step 6. Assign Nonlinear Links

Draw/Draw 2 Joint Link
Property: A48
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>

(Assign Link A48 at base of Wall A, between Z=0 and Z=8 in., at X=0 and X=96 in.)

(Assign Link A48 at base of Wall B, between Z=0 and Z=8 in., at X=384 and X=480 in.)
Property: A40
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>

(Assign Link A40 at base of Wall A, between Z=0 and Z=8 in., at X=8 and X=88 in.)
(Assign Link A40 at base of Wall B, between Z=0 and Z=8 in., at X=392 and X=472 in.)

Property: A32
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>

(Assign Link A40 at base of Wall A, between Z=0 and Z=8 in., at X=16 and X=80 in.)
(Assign Link A40 at base of Wall B, between Z=0 and Z=8 in., at X=400 and X=464 in.)

Property: A24
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>

(Assign Link A40 at base of Wall A, between Z=0 and Z=8 in., at X=24 and X=72 in.)
(Assign Link A40 at base of Wall B, between Z=0 and Z=8 in., at X=408 and X=456 in.)

Property: A16
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>

(Assign Link A40 at base of Wall A, between Z=0 and Z=8 in., at X=32 and X=64 in.)
(Assign Link A40 at base of Wall B, between Z=0 and Z=8 in., at X=416 and X=448 in.)

Property: A08R
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>

(Assign Link A40 at base of Wall A, between Z=0 and Z=8 in., at X=40 in.)
(Assign Link A40 at base of Wall B, between Z=0 and Z=8 in., at X=424 in.)

Property: A08U
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>

(Assign Link A40 at base of Wall A, between Z=0 and Z=8 in., at X=56 in.)
(Assign Link A40 at base of Wall B, between Z=0 and Z=8 in., at X=440 in.)

Property: A00
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>

(Assign Link A40 at base of Wall A, between Z=0 and Z=8 in., at X=48 in.)
(Assign Link A40 at base of Wall B, between Z=0 and Z=8 in., at X=432 in.)

(Close the Properties of Object window)
(Select the area elements bounded by the Links at the base of Walls A, and B)
Verify 24 Areas and 96 Edges are selected and delete

(Select the links at the base of Walls A, and B)
Verify 26 Links are selected
Edit/Replicate/Linear Increments
dx: 0
dy: 0
dz: 112 in.
Increment Data Number: 1 OK

(Select the area elements bounded by the Links at the top of Walls A, and B)
Verify 24 Areas and 96 Edges are selected and delete

Draw/Draw 2 Joint Link
Property: CB-EXT-R
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>

(Assign Link CB-EXT-R between X=96 and X=104 in., at Z=120 in.)
(Assign Link CB-EXT-R between X=376 and X=384 in., at Z=120 in.)

(Assign Link CB-EXT-R between X=96 and X=104 in., at Z=168 in.)
(Assign Link CB-EXT-R between X=376 and X=384 in., at Z=168 in.)

Draw/Draw 2 Joint Link
Property: CB-INT-R
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>

(Assign Link CB-INT-R between X=96 and X=104 in., at Z=128 in.)
(Assign Link CB-INT-R between X=376 and X=384 in., at Z=128 in.)

(Assign Link CB-INT-R between X=96 and X=104 in., at Z=160 in.)
(Assign Link CB-INT-R between X=376 and X=384 in., at Z=160 in.)

Draw/Draw 2 Joint Link
Property: CB-INT-U
XY Plane Offset Normal: 0
Drawing Control Type: None <space bar>

(Assign Link CB-INT-U between X=96 and X=104 in., at Z=136, Z=144, Z=152 in.)
(Assign Link CB-INT-U between X=376 and X=384 in., at Z=136, Z=144, Z=152 in.)

(Close the Properties of Object window)
Select Links CB-XXX-XX between X=96 and X= 104 in., from Z=120 to Z=168 in.
Verify 14 Links are selected

Edit/Replicate/Linear
Increments
dx: 0
dy: 0
dz: 120 in.
Increment Data
Number: 4
OK

(Select the area elements bounded by the Links along Grids A2 and B1)
Verify 60 Areas and 240 Edges are selected and delete

File/Save

Step 7. Assign Rigid Segments

Define/Section Properties/Frame Sections
Click to: Add New Property
Select Property Type
Frame Section Property Type: Other
Click to Add a Section: General Properties
Cross-sectional Area = 0
Moment of Inertia about 3 axis = 1e6
Shear area in 2 direction = 1e6
All other properties = 1
OK

Section Name: RIGID
Material: M1500
Dimensions:
Depth = 1 in.
Width = 1 in.
OK/OK

(Connect the ends of the Links with a transverse RIGID frame element)
Draw Frame/Cable/Tendon
Section: RIGID
Draw a Frame element from (X=0, Z=8) to (X=96, Z=8)
Draw a Frame element from (X=0, Z=112) to (X=96, Z=112)
Draw a Frame element from (X=384, Z=8) to (X=480, Z=8)
Draw a Frame element from (X=384, Z=112) to (X=480, Z=112)
Draw a Frame element from (X=104, Z=120) to (X=104, Z=168)
Draw a Frame element from (X=376, Z=120) to (X=376, Z=168)
Draw a Frame element from (X=104, Z=240) to (X=104, Z=288)
Draw a Frame element from (X=376, Z=240) to (X=376, Z=288)
Draw a Frame element from (X=104, Z=360) to (X=104, Z=408)
Draw a Frame element from (X=376, Z=360) to (X=376, Z=408)
Draw a Frame element from (X=104, Z=480) to (X=104, Z=528)
Draw a Frame element from (X=376, Z=480) to (X=376, Z=528)
Draw a Frame element from (X=104, Z=600) to (X=104, Z=648)
Draw a Frame element from (X=376, Z=600) to (X=376, Z=648)

(Close the Properties of Object window)
Select/Select/Properties/Frame Sections
Select; RIGID
OK
Verify 14 Frames are selected
Assign/Frame/Automatic Frame Mesh
Auto Mesh Frame at Intermediate Joints
OK

Select Links at the base of the walls
Select Links along Grid A2
Verify 61 Links are selected
Assign/Link/Support
Reverse Connectivity
Verify that the local 1 axis for the links point away from the Rigid Frame elements

File/Save

Step 8. Define Load Patterns and Load Cases

Define/Load Patterns
Load Pattern Name: LIVE
Type: LIVE
Self-Weight Multiplier: 0
Click to: Add New Load Pattern
OK

Define/Load Patterns
Load Pattern Name: SEISMIC
Type: Other
Self-Weight Multiplier: 0
Click to: Add New Load Pattern
OK

Define/Load Cases
Click to: Add New Load Case
Load Case Name: E
Load Case Type: Static
Analysis Type: Linear
Stiffness to Use: Zero Initial Conditions – Unstressed State
Loads Applied
Load Type = Load Pattern
Load Name = SEISMIC
Scale Factor = 1
Add
OK/OK

Define/Load Cases
Click to: Add New Load Case
Load Case Name: PRE-LOAD
Load Case Type: Static
Analysis Type: Nonlinear
Initial Conditions
Zero Initial Conditions – Start from Unstressed State
Geometric Nonlinearity Parameters: None
Loads Applied
Load Type = Load Pattern
Load Name = DEAD
Scale Factor = 0.7
Add
Other Parameters
Load Application: Full Load (Default)
Results Saved: Final State Only (Default)
Nonlinear Parameters: Default
OK/OK

(Define Nonlinear Static Analysis - Eastward Loading)
Define/Load Cases
Click to: Add New Load Case
Load Case Name: NSA+
Load Case Type: Static
Analysis Type: Nonlinear
Initial Conditions
Continue from State at End of Nonlinear Case: PRE-LOAD
Geometric Nonlinearity Parameters: None
Loads Applied
Load Type = Load Pattern
Load Name = SEISMIC
Scale Factor = 1
Add
Other Parameters
Load Application: Modify-Show
Load Application Control: Displacement Control
Control Displacement: Use Monitored Displacement
Load to a Monitored Displacement Magnitude of: 5.0 in.
Monitored Displacement DOF: U1
At Joint: 3235
OK
Results Saved: Modify-Show
Results Saved: Multiple States
For Each Stage
Minimum Number of Saved States: 250
Maximum Number of Saved States: 500
Select Save Positive Displacement Increments Only
OK
Nonlinear Parameters: Default
OK/OK

(Define Nonlinear Static Analysis - Westward Loading)
Define/Load Cases
Click to: Add New Load Case
Load Case Name: NSA-
Load Case Type: Static
Analysis Type: Nonlinear
Initial Conditions
Continue from State at End of Nonlinear Case: PRE-LOAD
Geometric Nonlinearity Parameters: None
Loads Applied
Load Type = Load Pattern
Load Name = SEISMIC
Scale Factor = -1
Add
Other Parameters
Load Application: Modify-Show
Load Application Control: Displacement Control
Control Displacement: Use Monitored Displacement
Load to a Monitored Displacement Magnitude of: 5.0 in.
Monitored Displacement DOF: U1
At Joint: 3235
OK
Results Saved: Modify-Show
Results Saved: Multiple States
For Each Stage
Minimum Number of Saved States: 250
Maximum Number of Saved States: 500
Select Save Positive Displacement Increments Only
OK
Nonlinear Parameters: Default
OK/OK

File/Save
Step 9. Assign Loads
Select all joints at roof level (2’-0” from the top of wall) and at floor levels except edge joints. Verify 295 Points are selected.

Assign/Joint Loads/Forces
Load Pattern Name: DEAD
Units: kip, in. F
Loads
Force Global Z: -0.2666 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Click PS on the left side toolbar
Verify 295 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: LIVE
Units: kip, in. F
Loads
Force Global Z: -0.2666 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the edge joints at Grid Lines A1 and B2 at each Story
Verify 10 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: DEAD
Units: kip, in. F
Loads
Force Global Z: -0.1333 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the edge joints at Grid Lines A1 and B2 at each Story
Verify 10 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: LIVE
Units: kip, in. F
Loads
Force Global Z: -0.1333 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the edge joints at Grid Lines A1 and B2 at each Story
Verify 10 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in. F
Loads
Force Global X: 53.35 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the edge joints at Grid Lines A1 and B2 at each Story
Verify 10 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in. F
Loads
Force Global X: 42.68 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the edge joints at Grid Lines A1 and B2 at each Story
Verify 10 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in. F
Loads
Force Global X: 32.00 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the edge joints at Grid Lines A1 and B2 at each Story
Verify 10 Points are selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in. F
Loads
Force Global X: 22.00 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the roof level (at X=240 in. Z=624 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in. F
Loads
Force Global X: 53.35 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the roof level (at X=240 in. Z=504 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in. F
Loads
Force Global X: 42.68 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the roof level (at X=240 in. Z=384 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in. F
Loads
Force Global X: 32.00 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the roof level (at X=240 in. Z=264 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in. F
Loads
Force Global X: 22.00 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK
Units: kip, in. F

Loads

Force Global X: 21.34 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Select the center joint at the roof level (at X=240 in. Z=144 in.)
Verify 1 Point is selected
Assign/Joint Loads/Forces
Load Pattern Name: SEISMIC
Units: kip, in. F
Loads
Force Global X: 10.67 kip (all others zero)
Coordinate System: GLOBAL
Options: Replace Existing Loads
OK

Verify units are kip, in, F

File/Save

Step 10. Analyze

Analyze/Set Analysis Options
FAST DOFs: Plane Frame - XZ Plane
OK

Analyze/Set Load Cases to Run
Highlight PRE-LOAD, NSA+, NSA-
Click to: Run/Do Not Run Case
Verify the Nonlinear Static are marked as Run
Run Now

(On the top toolbar select the Show Deformed Shape icon)
Deformed Shape
Case/Combo
Case/Combo Name: SEISMIC
OK

Verify the displacement U1 at the roof diaphragm level is 1.215 in.

Step 11. Program Output

Draw Section Cut (cut wall A at Base)
Section Cutting Line
Start Point: X=-1, Y=0, Z=1
End Point: X=97, Y=0, Z=1
Click on Refresh Button
Integrated Forces:
Left Side/Save Cut
Close

Draw Section Cut (cut wall B at Base)
Section Cutting Line
Start Point: X=383, Y=0, Z=1
End Point: X=481, Y=0, Z=1
Click on Refresh Button
Integrated Forces:
Left Side/Save Cut
Close

Draw Section Cut (cut coupling beams at ends)
Section Cutting Line
Start Point: X=100, Y=0, Z=119
End Point: X=100, Y=0, Z=169
Click on Refresh Button
Integrated Forces:
Left Side/Save Cut
Close
Draw Section Cut (cut coupling beams at ends)
Section Cutting Line
Start Point: X=100, Y=0, Z=239
End Point: X=100, Y=0, Z=289
Click on Refresh Button
Integrated Forces:
Left Side/Save Cut
Close

Draw Section Cut (cut coupling beams at ends)
Section Cutting Line
Start Point: X=100, Y=0, Z=359
End Point: X=100, Y=0, Z=409
Click on Refresh Button
Integrated Forces:
Left Side/Save Cut
Close

Draw Section Cut (cut coupling beams at ends)
Section Cutting Line
Start Point: X=100, Y=0, Z=479
End Point: X=100, Y=0, Z=529
Click on Refresh Button
Integrated Forces:
Left Side/Save Cut
Close

Draw Section Cut (cut coupling beams at ends)
Section Cutting Line
Start Point: X=100, Y=0, Z=599
End Point: X=100, Y=0, Z=649
Click on Refresh Button
Integrated Forces:
Left Side/Save Cut
Close

Draw Section Cut (cut coupling beams at ends)
Section Cutting Line
Start Point: X=380, Y=0, Z=119
End Point: X=380, Y=0, Z=169
Click on Refresh Button
Integrated Forces:
Left Side/Save Cut
Close

Draw Section Cut (cut coupling beams at ends)
Section Cutting Line
Start Point: X=380, Y=0, Z=239
End Point: X=380, Y=0, Z=289
Click on Refresh Button
Integrated Forces:
Left Side/Save Cut
Close

Draw Section Cut (cut coupling beams at ends)
Section Cutting Line
Start Point: X=380, Y=0, Z=359
End Point: X=380, Y=0, Z=409
Click on Refresh Button
Integrated Forces:
Left Side/Save Cut
Close

Draw Section Cut (cut coupling beams at ends)
Section Cutting Line
Start Point: X=380, Y=0, Z=479
End Point: X=380, Y=0, Z=529
Click on Refresh Button
Integrated Forces:
Left Side/Save Cut
Close

Draw Section Cut (cut coupling beams at ends)
Section Cutting Line
Start Point: X=380, Y=0, Z=599
End Point: X=380, Y=0, Z=649
Click on Refresh Button
Integrated Forces:
Left Side/Save Cut
Close

Display/Show Plot Functions
Define Plot Functions
Choose Function Type to Add: Add Base Functions
Click to: Add Plot Function
Base Functions: Base Shear X
OK/OK

Define Plot Functions
Choose Function Type to Add: Add Joint Disps/Forces
Click to: Add Plot Function
Joint ID: 2478
Vector Type: Displ
Component: UX
OK/OK

Choose Function Type to Add: Add Section Cut Forces
Click to: Add Plot Functions
Section Cut: SCUT1
Component: F1
OK/OK

Choose Function Type to Add: Add Section Cut Forces
Click to: Add Plot Functions
Section Cut: SCUT2
Component: F1
OK/OK

Choose Function Type to Add: Add Section Cut Forces
Click to: Add Plot Functions
Section Cut: SCUT3
Component: F1
OK/OK

Choose Plot Functions
List of Functions: Highlight Base Shear X, SCUT1 and SCUT2
Click the Add button

Verify Base Shear X, SCUT1, and SCUT2 show under Vertical Functions
Horizontal Plot Function: Joint2478

Load Case (Multi-Stepped Cases); NSA+
Click Display
File/Print Tables to File
File name: NSA+
Save
OK

Load Case (Multi-Stepped Cases); NSA-
Click Display
File/Print Tables to File
File name: NSA-
Save
OK

File/Save
Done
APPENDIX C
SPREADSHEET FORMULATIONS FOR TRIAL DESIGNS

Representative trial designs are presented in this Appendix. The calculations were
developed using spreadsheet formulations for the reinforcement options considered in case
studies A, B, and C.

For each case study, a spreadsheet was programmed using separate worksheets for each
of the three design methods considered: Allowable Stress Design (ASD) and Strength Design (SD)
according to MSJC code (2011), and Limit Design (LD) following Chapter 2 of this thesis.

This appendix only includes the calculations involved in case study A reinforcement
option 10. For each design method, the controlling seismic base shear was determined by trial
and error after adjusting the total applied lateral force so that the code provisions in MSJC
(2011) were satisfied.

C.1 Case Study A Reinforcement Option 10, Allowable Stress Design

<table>
<thead>
<tr>
<th>Reinforcement</th>
<th>(Assumed sufficient for all non-seismic load combinations)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall A Flexural Reinforcement</td>
<td></td>
</tr>
<tr>
<td>$A_{v,1}$</td>
<td>(1) #6 = 0.44 in$^2$ @ $d_1$ = 4 in</td>
</tr>
<tr>
<td>$A_{v,2}$</td>
<td>(1) #6 = 0.44 in$^2$ @ $d_2$ = 12 in</td>
</tr>
<tr>
<td>$A_{v,3}$</td>
<td>(1) #6 = 0.44 in$^2$ @ $d_3$ = 36 in</td>
</tr>
<tr>
<td>$A_{v,4}$</td>
<td>(1) #6 = 0.44 in$^2$ @ $d_4$ = 44 in</td>
</tr>
<tr>
<td>Wall A Shear Reinforcement</td>
<td></td>
</tr>
<tr>
<td>$A_s$</td>
<td>(2) #4 = 0.4 in$^2$ @ 16 in o.c.</td>
</tr>
<tr>
<td>$(A_s/s)$</td>
<td>0.025 in$^2$/in</td>
</tr>
<tr>
<td>Wall B Flexural Reinforcement</td>
<td></td>
</tr>
<tr>
<td>$A_{v,1}$</td>
<td>(1) #5 = 0.31 in$^2$ @ $d_1$ = 4 in</td>
</tr>
<tr>
<td>$A_{v,2}$</td>
<td>(1) #5 = 0.31 in$^2$ @ $d_2$ = 20 in</td>
</tr>
<tr>
<td>Wall B Shear Reinforcement</td>
<td></td>
</tr>
<tr>
<td>$A_s$</td>
<td>None = 0 in$^2$ @ 8 in o.c.</td>
</tr>
<tr>
<td>$(A_s/s)$</td>
<td>0.000 in$^2$/in</td>
</tr>
<tr>
<td>Wall C Flexural Reinforcement</td>
<td></td>
</tr>
<tr>
<td>$A_{v,1}$</td>
<td>(1) #6 = 0.44 in$^2$ @ $d_1$ = 4 in</td>
</tr>
<tr>
<td>$A_{v,2}$</td>
<td>(1) #6 = 0.44 in$^2$ @ $d_2$ = 12 in</td>
</tr>
<tr>
<td>$A_{v,3}$</td>
<td>(1) #6 = 0.44 in$^2$ @ $d_3$ = 36 in</td>
</tr>
<tr>
<td>$A_{v,4}$</td>
<td>(1) #6 = 0.44 in$^2$ @ $d_4$ = 44 in</td>
</tr>
<tr>
<td>Wall C Shear Reinforcement</td>
<td></td>
</tr>
</tbody>
</table>
\[ A_v = (2) \#4 = 0.4 \text{ in}^2 \] @ 16 in o.c.

\[ (A_v/s) = 0.025 \text{ in}^2/\text{in} \]

**Material Properties**

\[ f'_m = 1500 \text{ psi} \]
\[ f_y = 60 \text{ ksi} \]
\[ E_s = 29000 \text{ ksi} \]
\[ E_m = 1350 \text{ ksi} \]
\[ F_M = 667 \text{ psi} \]
\[ F_s = 32 \text{ ksi} \]

**Seismic Design Parameters**

\[ S_{DS} = 1 \]
\[ R = 5 \]
\[ C_d = 3.5 \] (ASCE/SEI 7-10 Table 12.2-1)
\[ E_s = 0.2 \times S_{DS} \] (ASCE/SEI 7-10 Eq. 12.14-6)

**F.E.M. Model Assumptions**

\[ E = E_m/2 = 675 \text{ ksi} \]
\[ G = 281 \text{ ksi} \]
\[ \nu = 0.2 \]

**Gravity Loading**

- **DL (Self Weight)**: 80 psf
- **DL (Tributary)**: 150 plf
- **LL (Tributary)**: 230 plf

(Determined using program SAP2000)

(Wall A)

\[ P_{D(Top)} = 7.7 \text{ kip} \]
\[ P_{D(Bot)} = 10.9 \text{ kip} \]
\[ V_o = 0.0 \text{ kip} \]
\[ M_{D(Top)} = 0.0 \text{ kip-ft} \]
\[ M_{D(Bot)} = 0.0 \text{ kip-ft} \]
\[ P_t = 2.2 \text{ kip} \]
\[ V_t = 0.0 \text{ kip} \]
\[ M_{D(Top)} = 0.0 \text{ kip-ft} \]
\[ M_{D(Bot)} = 0.0 \text{ kip-ft} \]

(Wall B)

\[ P_{D(Top)} = 5.6 \text{ kip} \]
\[ P_{D(Bot)} = 6.9 \text{ kip} \]
\[ V_o = 0.0 \text{ kip} \]
\[ M_{D(Top)} = 0.0 \text{ kip-ft} \]
\[ M_{D(Bot)} = 0.0 \text{ kip-ft} \]
\[ P_t = 1.5 \text{ kip} \]
\[ V_t = 0.0 \text{ kip} \]
\[ M_{D(Top)} = 0.0 \text{ kip-ft} \]
\[ M_{D(Bot)} = 0.0 \text{ kip-ft} \]

(Wall C)

\[ P_{D(Top)} = 7.2 \text{ kip} \]
\[ P_{D(Bot)} = 9.8 \text{ kip} \]
\[ V_o = 0.0 \text{ kip} \]
\[ M_{D(Top)} = 0.0 \text{ kip-ft} \]
\[ M_{D(Bot)} = 0.0 \text{ kip-ft} \]
\[
\begin{align*}
\text{Wall A:} & \\
& P_1 = 1.8 \text{ kip} \\
& V_1 = 0.0 \text{ kip} \\
& M_{L\text{(top)}} = 0.0 \text{ kip-ft} \\
& M_{L\text{(bot)}} = 0.0 \text{ kip-ft} \\
& \text{Wall B:} & \\
& P_2 = 16.2 \text{ kip} \\
& V_2 = 12.5 \text{ kip} \\
& M_{L\text{(top)}} = 48.4 \text{ kip-ft} \\
& M_{L\text{(bot)}} = 76.7 \text{ kip-ft} \\
& \text{Wall C:} & \\
& P_3 = 20.7 \text{ kip} \\
& V_3 = 17.5 \text{ kip} \\
& M_{L\text{(top)}} = 49.1 \text{ kip-ft} \\
& M_{L\text{(bot)}} = 90.9 \text{ kip-ft} \\
\end{align*}
\]

**Seismic Forces and Displacement**

(Determined using program SAP2000)

Base Shear, \( E = 33.8 \) kip

Roof Displacement, \( \delta_R = 0.09 \) in

**Load Combo (1.0D+1.0L+E/1.4)**

(Including \( E_v \))

**Wall A**

\[
\begin{align*}
P_{L\text{(top)}} &= 22.6 \text{ kip} \\
P_{L\text{(bot)}} &= 26.2 \text{ kip} \\
V &= 8.9 \text{ kip} \\
M_{L\text{(top)}} &= 34.5 \text{ kip-ft} \\
M_{L\text{(bot)}} &= 54.8 \text{ kip-ft} \\
\end{align*}
\]

**Wall B**

\[
\begin{align*}
P_{L\text{(top)}} &= 11.0 \text{ kip} \\
P_{L\text{(bot)}} &= 12.5 \text{ kip} \\
V &= 2.7 \text{ kip} \\
M_{L\text{(top)}} &= 9.1 \text{ kip-ft} \\
M_{L\text{(bot)}} &= 12.5 \text{ kip-ft} \\
\end{align*}
\]

**Wall C**

\[
\begin{align*}
P_{L\text{(top)}} &= 24.8 \text{ kip} \\
P_{L\text{(bot)}} &= 27.8 \text{ kip} \\
V &= 12.5 \text{ kip} \\
M_{L\text{(top)}} &= 35.1 \text{ kip-ft} \\
M_{L\text{(bot)}} &= 64.9 \text{ kip-ft} \\
\end{align*}
\]

**Load Combo (0.9D-1.0E/1.4)**

(Including \( E_v \))

**Wall A**

\[
\begin{align*}
P_{L\text{(top)}} &= -5.8 \text{ kip} \\
P_{L\text{(bot)}} &= -3.3 \text{ kip} \\
V &= 8.9 \text{ kip} \\
M_{L\text{(top)}} &= 34.5 \text{ kip-ft} \\
M_{L\text{(bot)}} &= 54.8 \text{ kip-ft} \\
\end{align*}
\]

**Wall B**
Combined Axial and Flexure Design

**Wall C**

\[ P^{(\text{Top})} = 1.1 \text{ kip} \]
\[ P^{(\text{Bot})} = 2.1 \text{ kip} \]
\[ V = 2.7 \text{ kip} \]
\[ M^{(\text{Top})} = 9.1 \text{ kip-ft} \]
\[ M^{(\text{Bot})} = 12.5 \text{ kip-ft} \]

**Combined Axial and Flexure Design**

**Top of Wall A**

\[ P = 22.6 \text{ kip} \]
\[ M = 34.5 \text{ kip-ft} \]
\[ M_{\text{allow}} = 98.4 \text{ kip-ft} > M \text{ OK} \]

**Bottom of Wall A**

\[ P = -5.8 \text{ kip} \]
\[ M = 34.5 \text{ kip-ft} \]
\[ M_{\text{allow}} = 67.4 \text{ kip-ft} > M \text{ OK} \]

Wall A - Interaction Diagram
Top of Wall B

\[ P = 11.0 \text{ kip} \quad (1.0D+1.0L+E/1.4, \text{ incl. } E_v) \]
\[ M = 9.1 \text{ kip-ft} \]
\[ M_{\text{allow}} = 21.0 \text{ kip-ft} \quad > \quad M \quad \text{OK} \]

\[ P = 1.1 \text{ kip} \quad (0.9D-E/1.4, \text{ incl. } E_v) \]
\[ M = 9.1 \text{ kip-ft} \]
\[ M_{\text{allow}} = 15.9 \text{ kip-ft} \quad > \quad M \quad \text{OK} \]

Bottom of Wall B

\[ P = 12.5 \text{ kip} \quad (1.0D+1.0L+E/1.4, \text{ incl. } E_v) \]
\[ M = 12.5 \text{ kip-ft} \]
\[ M_{\text{allow}} = 21.2 \text{ kip-ft} \quad > \quad M \quad \text{OK} \]

\[ P = 2.1 \text{ kip} \quad (0.9D-E/1.4, \text{ incl. } E_v) \]
\[ M = 12.5 \text{ kip-ft} \]
\[ M_{\text{allow}} = 16.7 \text{ kip-ft} \quad > \quad M \quad \text{OK} \]

Wall B - Interaction Diagram

Combined Axial and Flexure Design (cont.)

Top of Wall C

\[ P = 24.8 \text{ kip} \quad (1.0D+1.0L+E/1.4, \text{ incl. } E_v) \]
\[ M = 35.1 \text{ kip-ft} \]
\[ M_{\text{allow}} = 98.6 \text{ kip-ft} \quad > \quad M \quad \text{OK} \]

\[ P = -9.3 \text{ kip} \quad (0.9D-E/1.4, \text{ incl. } E_v) \]
\[ M = 35.1 \text{ kip-ft} \]
\[ M_{\text{allow}} = 62.0 \text{ kip-ft} \quad > \quad M \quad \text{OK} \]

Bottom of Wall C

\[ P = 27.8 \text{ kip} \quad (1.0D+1.0L+E/1.4, \text{ incl. } E_v) \]
\[ M = 64.9 \text{ kip-ft} \]
\[ M_{\text{allow}} = 98.9 \text{ kip-ft} \quad > \quad M \quad \text{OK} \]
168

\[ P = -7.4 \text{ kip} \quad (0.9D-E/1.4, \text{ incl. } E_v) \]
\[ M = 64.9 \text{ kip-ft} \]
\[ M_{allow} = 65.0 \text{ kip-ft} > M \quad \text{OK} \]

Wall C - Interaction Diagram

Shear Design
Top of Wall A
\[ P = 22.6 \text{ kip} \quad (1.0D+1.0L+E/1.4, \text{ incl. } E_v) \]
\[ V = 8.9 \text{ kip} \]
\[ M = 34.5 \text{ kip-ft} \]
\[ d = 44.00 \text{ in} \]
\[ t_{wall} = 7.625 \text{ in} \]
\[ M/Vd = 1.055 \]
\[ f_r = 1.5^2V/(t_{wall}d) \quad (2011 \text{ MSJC } 1.18.3.2.6.1.2 \text{ and Eq. 2-24}) \]
\[ f_s = 36.6 \text{ psi} \]
\[ F_{v,max} = 2.00 \text{ psi} \quad (2011 \text{ MSJC } 2.3.6.1.2) \]
\[ F_{v,max} = 77.5 \text{ psi} \]
\[ f_r < F_{v,max} \quad \text{OK} \]
\[ F_{vm} = 37.2 \text{ psi} \quad (2011 \text{ MSJC Eq. } 2-29) \]
\[ (A_v/s) = 0.025 \text{ in}^2/\text{in} \]
\[ F_{av} = 48.1 \text{ psi} \quad (2011 \text{ MSJC Eq. } 2-30) \]
\[ F_v = 85.3 \text{ psi} \quad (2011 \text{ MSJC Eq. } 2-25) \]
\[ V_{A5D} = 28.4 \text{ kip} \quad > (1.5 V = 13.4 \text{ kip}) \quad \text{OK} \]
Top of Wall A

\[ P = -5.8 \text{ kip} \]
\[ V = 8.9 \text{ kip} \]
\[ M = 34.5 \text{ kip-ft} \]
\[ d = 44.00 \text{ in} \]
\[ t_{\text{wall}} = 7.625 \text{ in} \]
\[ M/Vd = 1.055 \]
\[ f_s = 1.5*V/(t_{\text{wall}}*d) \]
\[ f_s = 36.6 \text{ psi} \]
\[ F_{v,\text{max}} = 2.00 \text{ kip} \]
\[ F_{v,\text{max}} = 77.5 \text{ psi} \]
\[ f_v < F_{v,\text{max}} \text{ OK} \]
\[ F_{v,\text{max}} = 17.9 \text{ psi} \]
\[ (A/s) = 0.025 \text{ in}^2/\text{in} \]
\[ F_{v} = 48.1 \text{ psi} \]
\[ F_v = 65.9 \text{ psi} \]
\[ V_{\text{ASD}} = 24.1 \text{ kip} \]
\[ > (1.5 V = 13.4 \text{ kip}) \text{ OK} \]

Bottom of Wall A

\[ P = 26.3 \text{ kip} \]
\[ V = 8.9 \text{ kip} \]
\[ M = 54.8 \text{ kip-ft} \]
\[ d = 44.00 \text{ in} \]
\[ t_{\text{wall}} = 7.625 \text{ in} \]
\[ M/Vd = 1.673 \]
\[ f_s = 1.5*V/(t_{\text{wall}}*d) \]
\[ f_s = 36.6 \text{ psi} \]
\[ F_{v,\text{max}} = 2.00 \text{ kip} \]
\[ F_{v,\text{max}} = 77.5 \text{ psi} \]
\[ f_v < F_{v,\text{max}} \text{ OK} \]
\[ F_{v,\text{max}} = 39.7 \text{ psi} \]
\[ (A/s) = 0.025 \text{ in}^2/\text{in} \]
\[ F_{v} = 48.1 \text{ psi} \]
\[ F_v = 87.8 \text{ psi} \]
\[ V_{\text{ASD}} = 28.4 \text{ kip} \]
\[ > (1.5 V = 13.4 \text{ kip}) \text{ OK} \]

Bottom of Wall A

\[ P = -3.3 \text{ kip} \]
\[ V = 8.9 \text{ kip} \]
\[ M = 54.8 \text{ kip-ft} \]
\[ d = 44.00 \text{ in} \]
\[ t_{\text{wall}} = 7.625 \text{ in} \]
\[ M/V_d = 1.673 \]

\[ f_s = 1.5 \frac{V}{(t_{w,1} \cdot d)} \quad (2011 \text{ MSJC } 1.18.3.2.6.1.2 \text{ and Eq. } 2-24) \]

\[ f_s = 36.6 \text{ psi} \]

\[ F_{u, \text{max}} = 2.00 \text{ psi} \quad (2011 \text{ MSJC } 2.3.6.1.2) \]

\[ F_{u, \text{max}} = 77.5 \text{ psi} \]

\[ f_s < F_{u, \text{max}} \text{ OK} \]

\[ f_s = 19.5 \text{ psi} \quad (2011 \text{ MSJC } 2-29) \]

\[ (A_v/s) = 0.025 \text{ in}^2/\text{in} \]

\[ F_{c} = 48.1 \text{ psi} \quad (2011 \text{ MSJC } 2-30) \]

\[ F_{c} = 67.6 \text{ psi} \quad (2011 \text{ MSJC } 2-25) \]

\[ V_{\text{ASD}} = 24.7 \text{ kip} > (1.5 V = 13.4 \text{ kip}) \text{ OK} \]

**Shear Design (cont.)**

*Top of Wall B*

\[ P = 11.0 \text{ kip} \]

\[ V = 2.7 \text{ kip} \]

\[ M = 9.1 \text{ kip-ft} \]

\[ d = 20.00 \text{ in} \]

\[ t_{\text{wall}} = 7.625 \text{ in} \]

\[ M/V_d = 2.021 \]

\[ f_s = 1.5 \frac{V}{(t_{w,1} \cdot d)} \quad (2011 \text{ MSJC } 1.18.3.2.6.1.2 \text{ and Eq. } 2-24) \]

\[ f_s = 22.1 \text{ psi} \]

\[ F_{u, \text{max}} = 2.00 \text{ psi} \quad (2011 \text{ MSJC } 2.3.6.1.2) \]

\[ F_{u, \text{max}} = 77.5 \text{ psi} \]

\[ f_s < F_{u, \text{max}} \text{ OK} \]

\[ f_s = 36.8 \text{ psi} \quad (2011 \text{ MSJC } 2-29) \]

\[ (A_v/s) = 0.000 \text{ in}^2/\text{in} \]

\[ F_{c} = 0.0 \text{ psi} \quad (2011 \text{ MSJC } 2-30) \]

\[ F_{c} = 36.8 \text{ psi} \quad (2011 \text{ MSJC } 2-25) \]

\[ V_{\text{ASD}} = 6.7 \text{ kip} > (1.5 V = 4.1 \text{ kip}) \text{ OK} \]

*Top of Wall B*

\[ P = 1.1 \text{ kip} \]

\[ V = 2.7 \text{ kip} \]

\[ M = 9.1 \text{ kip-ft} \]

\[ d = 20.00 \text{ in} \]

\[ t_{\text{wall}} = 7.625 \text{ in} \]

\[ M/V_d = 2.021 \]

\[ f_s = 1.5 \frac{V}{(t_{w,1} \cdot d)} \quad (2011 \text{ MSJC } 1.18.3.2.6.1.2 \text{ and Eq. } 2-24) \]

\[ f_s = 22.1 \text{ psi} \]

\[ F_{u, \text{max}} = 2.00 \text{ psi} \quad (2011 \text{ MSJC } 2.3.6.1.2) \]

\[ F_{u, \text{max}} = 77.5 \text{ psi} \]

\[ f_s < F_{u, \text{max}} \text{ OK} \]

\[ f_s = 36.8 \text{ psi} \quad (2011 \text{ MSJC } 2-29) \]
\[ F_{v,max} = 2.00 \ \text{psi} \]  
\[ F_{v,\text{max}} = 77.5 \ \text{psi} \]  
\[ f_v < F_{v,\text{max}} \text{ OK} \]

\[ F_{vm} = 23.3 \ \text{psi} \]  
\[ f_v < F_{v,\text{max}} \text{ OK} \]

\[ (A_v/s) = 0.000 \ \text{in}^2/\text{in} \]  
\[ F_{v} = 0.0 \ \text{psi} \]  
\[ F_{v} = 23.3 \ \text{psi} \]  
\[ V_{\text{ASD}} = 4.3 \ \text{kip} \]  
\[ V_{\text{ASD}} > (1.5 \ V = 4.1 \ \text{kip}) \text{ OK} \]

**Bottom of Wall B**

\[ P = 12.5 \ \text{kip} \]  
\[ V = 2.7 \ \text{kip} \]  
\[ M = 12.5 \ \text{kip-ft} \]  
\[ d = 20.00 \ \text{in} \]  
\[ t_{\text{wall}} = 7.625 \ \text{in} \]  
\[ M/Vd = 2.782 \]

\[ f_e = 1.5*V/(f_{\text{vm}}*d) \]  
\[ f_v = 22.1 \ \text{psi} \]  
\[ f_v < F_{v,\text{max}} \text{ OK} \]

\[ F_{vm} = 38.8 \ \text{psi} \]  
\[ (A_v/s) = 0.000 \ \text{in}^2/\text{in} \]  
\[ F_{v} = 0.0 \ \text{psi} \]  
\[ F_{v} = 38.8 \ \text{psi} \]  
\[ V_{\text{ASD}} = 7.1 \ \text{kip} \]  
\[ V_{\text{ASD}} > (1.5 \ V = 4.1 \ \text{kip}) \text{ OK} \]

**Bottom of Wall B**

\[ P = 2.1 \ \text{kip} \]  
\[ V = 2.7 \ \text{kip} \]  
\[ M = 12.5 \ \text{kip-ft} \]  
\[ d = 20.00 \ \text{in} \]  
\[ t_{\text{wall}} = 7.625 \ \text{in} \]  
\[ M/Vd = 2.782 \]

\[ f_e = 1.5*V/(f_{\text{vm}}*d) \]  
\[ f_v = 22.1 \ \text{psi} \]  
\[ f_v < F_{v,\text{max}} \text{ OK} \]

\[ F_{vm} = 24.6 \ \text{psi} \]  
\[ (A_v/s) = 0.000 \ \text{in}^2/\text{in} \]
Shear Design (cont.)

Top of Wall C

\[ F_{vs} = 0.0 \text{ psi} \quad (2011 \text{ MSJC Eq. 2-30}) \]

\[ F_v = 24.6 \text{ psi} \quad (2011 \text{ MSJC Eq. 2-25}) \]

\[ V_{ASD} = 4.5 \text{ kip} > (1.5 V = 4.1 \text{ kip}) \quad \text{OK} \]

\[ V_{ASD} = 32.8 \text{ kip} > (1.5 V = 18.8 \text{ kip}) \quad \text{OK} \]
Bottom of Wall C

\[ P = 27.8 \text{ kip} \]
\[ V = 12.5 \text{ kip} \]
\[ M = 64.9 \text{ kip-ft} \]
\[ d = 44.0 \text{ in} \]
\[ t_{\text{wall}} = 7.625 \text{ in} \]
\[ M/Vd = 1.416 \]

\[ f_s = 1.5V/(t_{\text{wall}} d_v) \]
\[ f_s = 51.3 \text{ psi} \]
\[ F_{v,\text{max}} = 2.00 \text{ psi} \]
\[ F_{v,\text{max}} = 77.5 \text{ psi} \]
\[ f_v < F_{v,\text{max}} \text{ OK} \]
\[ f_v = 51.3 \text{ psi} \]

\( (A_v/s) = 0.025 \text{ in}^2/\text{in} \)
\[ F_{vs} = 48.1 \text{ psi} \]
\[ F_{v} = 88.9 \text{ psi} \]
\[ F_{v,\text{max}} = 77.5 \text{ psi} \]
\[ V_{ASD} = 23.7 \text{ kip} \]
\[ > (1.5 V = 18.8 \text{ kip}) \text{ OK} \]

Bottom of Wall C

\[ P = -7.4 \text{ kip} \]
\[ V = 12.5 \text{ kip} \]
\[ M = 64.9 \text{ kip-ft} \]
\[ d = 44.0 \text{ in} \]
\[ t_{\text{wall}} = 7.625 \text{ in} \]
\[ M/Vd = 1.416 \]

\[ f_s = 1.5V/(t_{\text{wall}} d_v) \]
\[ f_s = 51.3 \text{ psi} \]
\[ F_{v,\text{max}} = 2.00 \text{ psi} \]
\[ F_{v,\text{max}} = 77.5 \text{ psi} \]
\[ f_v < F_{v,\text{max}} \text{ OK} \]
\[ f_v = 51.3 \text{ psi} \]

\( (A_v/s) = 0.025 \text{ in}^2/\text{in} \)
\[ F_{vs} = 48.1 \text{ psi} \]
\[ F_{v} = 64.8 \text{ psi} \]
\[ F_{v,\text{max}} = 77.5 \text{ psi} \]
\[ V_{ASD} = 23.7 \text{ kip} \]
\[ > (1.5 V = 18.8 \text{ kip}) \text{ OK} \]

Rho Max Check

(1.0D+1.0L+E/1.4, incl. E)

(2011 MSJC 1.18.3.2.6.1.2 and Eq. 2-24)

(2011 MSJC 2.3.6.1.2)

(2011 MSJC Eq. 2-29)

(2011 MSJC Eq. 2-30)

(2011 MSJC Eq. 2-25)
Wall A

\[ P = 26.3 \text{ kip} \]  
\[ \rho = 0.048 \times f_m' A_n \quad \text{<} \quad 0.05 f_m' A_n \quad \text{Do not check rho max} \]

\[ M = 54.8 \text{ kip-ft} \]
\[ V = 8.9 \text{ kip-ft} \]
\[ d = 44 \text{ in} \]
\[ t_{wall} = 7.625 \text{ in} \]
\[ \rho = 2.62E-03 \]
\[ M/Vd = 1.67 \quad > \quad 1 \]
\[ \rho_{\text{max}} = n*f_m'/\left(2*f_y(n*f_y/f_m')\right) \]
\[ \rho_{\text{max}} = \text{No Limit} \quad \text{OK} \]

Wall B

\[ P = 12.5 \text{ kip} \]  
\[ \rho = 0.046 \times f_m' A_n \quad \text{<} \quad 0.05 f_m' A_n \quad \text{Do not check rho max} \]

\[ M = 12.5 \text{ kip-ft} \]
\[ V = 2.7 \text{ kip-ft} \]
\[ d = 20 \text{ in} \]
\[ t_{wall} = 7.6 \text{ in} \]
\[ \rho = 2.03E-03 \]
\[ M/Vd = 2.78 \quad > \quad 1 \]
\[ \rho_{\text{max}} = n*f_m'/\left(2*f_y(n*f_y/f_m')\right) \]
\[ \rho_{\text{max}} = \text{No Limit} \quad \text{OK} \]

Wall C

\[ P = 27.8 \text{ kip} \]  
\[ \rho = 0.051 \times f_m' A_n \quad \text{>} \quad 0.05 f_m' A_n \]

\[ M = 64.9 \text{ kip-ft} \]
\[ V = 12.5 \text{ kip-ft} \]
\[ d = 44 \text{ in} \]
\[ t_{wall} = 7.625 \text{ in} \]
\[ \rho = 2.62E-03 \]
\[ M/Vd = 1.42 \quad > \quad 1 \quad \text{Check rho max} \]
\[ \rho_{\text{max}} = n*f_m'/\left(2*f_y(n*f_y/f_m')\right) \]
\[ \rho_{\text{max}} = 4.37E-03 \quad > \quad 2.62E-03 \quad \text{OK} \]
### C.2 Case Study A Reinforcement Option 10, Strength Design

#### Reinforcement

**Wall A Flexural Reinforcement**

- $A_{s,1} = (1) \#6 = 0.44 \text{ in}^2 @ d_1 = 4 \text{ in}$
- $A_{s,2} = (1) \#6 = 0.44 \text{ in}^2 @ d_2 = 12 \text{ in}$
- $A_{s,3} = (1) \#6 = 0.44 \text{ in}^2 @ d_3 = 36 \text{ in}$
- $A_{s,4} = (1) \#6 = 0.44 \text{ in}^2 @ d_4 = 44 \text{ in}$

**Wall A Shear Reinforcement**

- $A_v = (2) \#4 = 0.4 \text{ in}^2 @ 16 \text{ in} \text{ o.c.}$
- $(A_v/s) = 0.025 \text{ in}^2/\text{in}$

**Wall B Flexural Reinforcement**

- $A_{s,1} = (1) \#5 = 0.31 \text{ in}^2 @ d_1 = 4 \text{ in}$
- $A_{s,2} = (1) \#5 = 0.31 \text{ in}^2 @ d_2 = 20 \text{ in}$

**Wall B Shear Reinforcement**

- $A_v = \text{None} = 0.0 \text{ in}^2 @ 8 \text{ in} \text{ o.c.}$
- $(A_v/s) = 0.000 \text{ in}^2/\text{in}$

**Wall C Flexural Reinforcement**

- $A_{s,1} = (1) \#6 = 0.44 \text{ in}^2 @ d_1 = 4 \text{ in}$
- $A_{s,2} = (1) \#6 = 0.44 \text{ in}^2 @ d_2 = 12 \text{ in}$
- $A_{s,3} = (1) \#6 = 0.44 \text{ in}^2 @ d_3 = 36 \text{ in}$
- $A_{s,4} = (1) \#6 = 0.44 \text{ in}^2 @ d_4 = 44 \text{ in}$

**Wall C Shear Reinforcement**

- $A_v = (2) \#4 = 0.4 \text{ in}^2 @ 16 \text{ in} \text{ o.c.}$
- $(A_v/s) = 0.025 \text{ in}^2/\text{in}$

#### Material Properties

- $f'_m = 1500 \text{ psi}$
- $f_y = 60 \text{ ksi}$
- $E_s = 29000 \text{ ksi}$
- $E_m = 1350 \text{ ksi}$
- $\varepsilon_{mu} = 0.0025 \text{ in/in}$
- $\varepsilon_{sy} = 0.0021 \text{ in/in}$

#### Seismic Design Parameters

- $S_{DS} = 1$
- $R = 5$
- $C_a = 3.5$
- $E_s = 0.2 * S_{DS}$

#### F.E.M. Model Assumptions

- $E = E_s/2 = 675 \text{ ksi}$
- $G = 281 \text{ ksi}$
- $\nu = 0.2$

#### Gravity Loading

- $D_{L\text{Self Weight}} = 80 \text{ psf}$
- $D_{L\text{Tributary}} = 150 \text{ plf}$
- $L_{L\text{Tributary}} = 230 \text{ plf}$

**Wall A**

- $P_{D\text{(Top)}} = 7.7 \text{ kip}$
- $P_{D\text{(Bottom)}} = 10.9 \text{ kip}$
- $V_D = 0.0 \text{ kip}$

(Determined using program SAP2000)

(Shear and moment in walls due to gravity loads assumed zero)
Wall B

- \( P_{2(Bot)} = 5.6 \text{ kip} \)
- \( V_{2(Bot)} = 0.0 \text{ kip} \)
- \( M_{2(Bot)} = 0.0 \text{ kip-ft} \)
- \( M_{2(Top)} = 0.0 \text{ kip-ft} \)

- \( P_{1} = 1.5 \text{ kip} \)
- \( V_{1} = 0.0 \text{ kip} \)
- \( M_{1(Top)} = 0.0 \text{ kip-ft} \)
- \( M_{1(Bot)} = 0.0 \text{ kip-ft} \)

Wall C

- \( P_{2(Top)} = 7.2 \text{ kip} \)
- \( P_{2(Bot)} = 9.8 \text{ kip} \)
- \( V_{2} = 0.0 \text{ kip} \)
- \( M_{2(Top)} = 0.0 \text{ kip-ft} \)
- \( M_{2(Bot)} = 0.0 \text{ kip-ft} \)

- \( P_{1} = 1.8 \text{ kip} \)
- \( V_{1} = 0.0 \text{ kip} \)
- \( M_{1(Top)} = 0.0 \text{ kip-ft} \)
- \( M_{1(Bot)} = 0.0 \text{ kip-ft} \)

**Seismic Forces and Displacement**

- **Base Shear,** \( E = 43.8 \text{ kip} \)
- **Roof Displacement,** \( \delta_{R} = 0.12 \text{ in} \)

**Wall A**

- \( P_{1} = 21.0 \text{ kip} \)
- \( V_{1} = 16.2 \text{ kip} \)
- \( M_{1(Top)} = 62.6 \text{ kip-ft} \)
- \( M_{1(Bot)} = 99.4 \text{ kip-ft} \)

**Wall B**

- \( P_{1} = 5.7 \text{ kip} \)
- \( V_{1} = 4.9 \text{ kip} \)
- \( M_{1(Top)} = 16.5 \text{ kip-ft} \)
- \( M_{1(Bot)} = 22.7 \text{ kip-ft} \)

**Wall C**

- \( P_{1} = 26.8 \text{ kip} \)
- \( V_{1} = 22.7 \text{ kip} \)
- \( M_{1(Top)} = 63.6 \text{ kip-ft} \)
- \( M_{1(Bot)} = 117.8 \text{ kip-ft} \)

**Load Combo \( (1.2D+0.5L+1.0E)\)**

- **Wall A**
  - \( P_{11(Top)} = 32.9 \text{ kip} \)
  - \( P_{11(Bot)} = 37.4 \text{ kip} \)
  - \( V_{u} = 16.2 \text{ kip} \)

**Note:** (Include \( E_{u} \))
\[ M_{u}(\text{Top}) = 62.6 \text{ kip-ft} \]
\[ M_{u}(\text{Bot}) = 99.4 \text{ kip-ft} \]

\textbf{Wall B}
\[ P_{u}(\text{Top}) = 14.3 \text{ kip} \]
\[ P_{u}(\text{Bot}) = 16.1 \text{ kip} \]
\[ V_{u} = 4.9 \text{ kip} \]
\[ M_{u}(\text{Top}) = 16.5 \text{ kip-ft} \]
\[ M_{u}(\text{Bot}) = 22.7 \text{ kip-ft} \]

\textbf{Wall C}
\[ P_{u}(\text{Top}) = 37.8 \text{ kip} \]
\[ P_{u}(\text{Bot}) = 41.4 \text{ kip} \]
\[ V_{u} = 22.7 \text{ kip} \]
\[ M_{u}(\text{Top}) = 63.6 \text{ kip-ft} \]
\[ M_{u}(\text{Bot}) = 117.8 \text{ kip-ft} \]

\textbf{Load Combo (0.9D-1.0E)} (Include \( E_v \))

\textbf{Wall A}
\[ P_{u}(\text{Top}) = -15.6 \text{ kip} \]
\[ P_{u}(\text{Bot}) = -13.4 \text{ kip} \]
\[ V_{u} = 16.2 \text{ kip} \]
\[ M_{u}(\text{Top}) = 62.6 \text{ kip-ft} \]
\[ M_{u}(\text{Bot}) = 99.4 \text{ kip-ft} \]

\textbf{Wall B}
\[ P_{u}(\text{Top}) = -1.8 \text{ kip} \]
\[ P_{u}(\text{Bot}) = -0.9 \text{ kip} \]
\[ V_{u} = 4.9 \text{ kip} \]
\[ M_{u}(\text{Top}) = 16.5 \text{ kip-ft} \]
\[ M_{u}(\text{Bot}) = 22.7 \text{ kip-ft} \]

\textbf{Wall C}
\[ P_{u}(\text{Top}) = -21.7 \text{ kip} \]
\[ P_{u}(\text{Bot}) = -20.0 \text{ kip} \]
\[ V_{u} = 22.7 \text{ kip} \]
\[ M_{u}(\text{Top}) = 63.6 \text{ kip-ft} \]
\[ M_{u}(\text{Bot}) = 117.8 \text{ kip-ft} \]

\textbf{Combined Axial and Flexure Design}

\textbf{Top of Wall A}
\[ P_{u} = 32.9 \text{ kip} \]
\[ M_{u} = 62.6 \text{ kip-ft} \]
\[ \phi M_{u} = 195 \text{ kip-ft} > M_{u} \quad \text{OK} \]
\[ P_{u} = -15.6 \text{ kip} \]
\[ M_{u} = 62.6 \text{ kip-ft} \]
\[ \phi M_{u} = 138 \text{ kip-ft} > M_{u} \quad \text{OK} \]

\textbf{Bottom of Wall A}
\[ P_{u} = 37.4 \text{ kip} \]
\[ M_{u} = 99.4 \text{ kip-ft} \]
\[ \phi M_{u} = 201 \text{ kip-ft} > M_{u} \quad \text{OK} \]
\[ P_{u} = -13.4 \text{ kip} \]
\[ M_{u} = 99.4 \text{ kip-ft} \]
\[ \phi M_{u} = 141 \text{ kip-ft} > M_{u} \quad \text{OK} \]
Combined Axial and Flexure Design (cont.)

Top of Wall B

\[ P_u = 14.3 \text{ kip} \]
\[ M_u = 16.5 \text{ kip-ft} \]
\[ \phi M_u = 36.2 \text{ kip-ft} > M_u \text{ OK} \]

\[ P_u = -1.8 \text{ kip} \]
\[ M_u = 16.5 \text{ kip-ft} \]
\[ \phi M_u = 26.0 \text{ kip-ft} > M_u \text{ OK} \]

Bottom of Wall B

\[ P_u = 16.1 \text{ kip} \]
\[ M_u = 22.7 \text{ kip-ft} \]
\[ \phi M_u = 37.4 \text{ kip-ft} > M_u \text{ OK} \]

\[ P_u = -0.9 \text{ kip} \]
\[ M_u = 22.7 \text{ kip-ft} \]
\[ \phi M_u = 26.6 \text{ kip-ft} > M_u \text{ OK} \]
**Combined Axial and Flexure Design (cont.)**

*Top of Wall C*

\[
P_u = 37.8 \text{ kip} \quad (1.2D+0.5L+E, \text{ incl. } E_v)
\]
\[
M_u = 63.6 \text{ kip-ft}
\]
\[
\phi M_u = 201.4 \text{ kip-ft} > M_u \quad \text{OK}
\]
\[
P_u = -21.7 \text{ kip} \quad (0.9D-E, \text{ incl. } E_v)
\]
\[
M_u = 63.6 \text{ kip-ft}
\]
\[
\phi M_u = 130.9 \text{ kip-ft} > M_u \quad \text{OK}
\]

*Bottom of Wall C*

\[
P_u = 41.4 \text{ kip} \quad (1.2D+0.5L+E, \text{ incl. } E_v)
\]
\[
M_u = 117.8 \text{ kip-ft}
\]
\[
\phi M_u = 205.4 \text{ kip-ft} > M_u \quad \text{OK}
\]
\[
P_u = -20.0 \text{ kip} \quad (0.9D-E, \text{ incl. } E_v)
\]
\[
M_u = 117.8 \text{ kip-ft}
\]
\[
\phi M_u = 133.4 \text{ kip-ft} > M_u \quad \text{OK}
\]
**Shear Design**

*Top of Wall A (1.2D+0.5L+E, incl. E*)

\[
\begin{align*}
\tau_{\text{wall}} & = 7.625 \text{ in} \\
d_v & = 48 \text{ in} \\
P_u & = 32.9 \text{ kip} \\
V_u & = 16.2 \text{ kip} \\
M_u & = 62.6 \text{ kip-ft} \\
\frac{M_u}{V_u d_v} & = 0.97 \\
V_n & = V_{nm} + V_{ns} \leq V_{n,\text{max}} \quad \text{(2011 MSJC 3.3.4.1.2)} \\
V_{nm} & = [4-1.75*(M_u/V_u d_v)]*A_v*f_m' + 0.25*P_u \quad \text{(2011 MSJC Eq. 3-23)} \\
V_{nm} & = 40.9 \text{ kip} \\
V_{ns} & = 0.5*(A_v/s)*f_y \quad \text{(2011 MSJC Eq. 3-24)} \\
(A_v/s) & = 0.025 \text{ in}^2/\text{in} \\
V_{ns} & = 36.0 \text{ kip} \\
V_{n,\text{max}} & = 4.1 *A_v*f_m' \quad \text{(2011 MSJC Eq. 3-21 and 3-22)} \\
V_{n,\text{max}} & = 58.0 \text{ kip} \\
V_e & = 58.0 \text{ kip} \quad \text{(2011 MSJC 3.3.4.1.2)} \\
\phi & = 0.8 \\
\phi V_e & = 46.4 \text{ kip} > 16.2 \text{ kip} \quad \text{OK} \\
\end{align*}
\]

Check \(\phi V_e \geq \min(2.0*V_e + V_{ap}, 1.25*V_{nh} + V_{ap})\) \quad \text{(2011 MSJC 1.18.3.2.6.1.1)}

\[
\begin{align*}
V_e & = 16.2 \text{ kip} \quad \text{(E)} \\
M_e & = 62.6 \text{ kip-ft} \quad \text{(E)} \\
V_{ap} & = V_e - V_t = 0.0 \text{ kip} \quad \text{(1.2D+0.5L incl. E)} \\
\end{align*}
\]
\[ M_s = 217.5 \text{ kip-ft} \]
\[ V_{sh} = M_s \cdot V_e / M_e = 56.3 \text{ kip} \]
\[ 2.0 \cdot V_e + V_{ap} = 32.4 \text{ kip} \]
\[ 1.25 \cdot V_{sh} + V_{ap} = 70.3 \text{ kip} \]
\[ \phi V_e = 46.4 \text{ kip} > 32.4 \text{ kip} \quad \text{OK} \]

**Top of Wall A**

\[ t_{wall} = 7.625 \text{ in} \]
\[ d_v = 48 \text{ in} \]
\[ P_u = -15.6 \text{ kip} \]
\[ V_e = 16.2 \text{ kip} \]
\[ M_e = 62.6 \text{ kip-ft} \]
\[ M_s / V_e d_v = 0.97 \]
\[ V_e = V_{nm} + V_n \leq V_{n,\text{max}} \]
\[ V_{nm} = [4 - 1.75 \cdot (M_s / V_e d_v)] \cdot A_n \cdot \sqrt{f_m'} + 0.25 \cdot P_u \]
\[ V_{nm} = 28.8 \text{ kip} \]
\[ V_n = 0.5 \cdot (A_s / s) \cdot f_y \cdot d_v \]
\[ (A_s / s) = 0.025 \text{ in}^2 / \text{in} \]
\[ V_n = 36.0 \text{ kip} \]
\[ V_{n,\text{max}} = 4.1 \cdot A_n \cdot \sqrt{f_m'} \]
\[ V_{n,\text{max}} = 58.0 \text{ kip} \]
\[ V_e = 58.0 \text{ kip} \]
\[ \phi = 0.8 \]
\[ \phi V_e = 46.4 \text{ kip} > 16.2 \text{ kip} \quad \text{OK} \]

Check \( \phi V_e \geq \min(2.0 \cdot V_e + V_{ap}, 1.25 \cdot V_{sh} + V_{ap}) \)

\[ V_e = 16.2 \text{ kip} \]
\[ M_e = 62.6 \text{ kip-ft} \]
\[ V_{ap} = V_e - V_i = 0.0 \text{ kip} \]
\[ M_{ap} = 154.1 \text{ kip-ft} \]
\[ V_{sh} = M_s \cdot V_e / M_e = 39.9 \text{ kip} \]
\[ 2.0 \cdot V_e + V_{ap} = 32.4 \text{ kip} \]
\[ 1.25 \cdot V_{sh} + V_{ap} = 49.8 \text{ kip} \]
\[ \phi V_e = 46.4 \text{ kip} > 32.4 \text{ kip} \quad \text{OK} \]

**Bottom of Wall A**

\[ t_{wall} = 7.625 \text{ in} \]
\[ d_v = 48 \text{ in} \]
\[ P_u = 37.4 \text{ kip} \]
\[ V_e = 16.2 \text{ kip} \]
\[ M_e = 99.4 \text{ kip-ft} \]
\[ M_s / V_e d_v = 1.53 \]
\[ V_e = V_{nm} + V_n \leq V_{n,\text{max}} \]
\[ V_{nm} = [4 - 1.75 \cdot (M_s / V_e d_v)] \cdot A_n \cdot \sqrt{f_m'} + 0.25 \cdot P_u \]
\[ V_{nm} = 41.2 \text{ kip} \]
\[ V_n = 0.5 \cdot (A_s / s) \cdot f_y \cdot d_v \]

\[ V_n = 41.2 \text{ kip} \]
\( (A_v/s) = 0.025 \text{ in}^2/\text{in} \)
\( V_{ns} = 36.0 \text{ kip} \)

\[ V_{s,\text{max}} = 4.0 \times A_v \times v(V_{ns}) \quad (2011 \text{ MSJC Eq. 3-21 and 3-22}) \]
\[ V_s = 56.7 \text{ kip} \quad (2011 \text{ MSJC 3.3.4.1.2}) \]
\[ \phi = 0.8 \]
\[ \phi V_s = 45.4 \text{ kip} \geq 16.2 \text{ kip} \quad \text{OK} \]

Check \( \phi V_s \geq \min(2.0 \times V_s + V_{ug}, 1.25 \times V_{sm} + V_{ug}) \) (2011 MSJC 1.18.3.2.6.1.1)

\[ V_s = 16.2 \text{ kip} \quad (E_s) \]
\[ M_s = 99.4 \text{ kip-ft} \quad (E_s) \]
\[ V_{ug} = V_s - V_t = 0.0 \text{ kip} \quad (1.2D+0.5L, \text{ incl. } E_s) \]
\[ V_{sm} = M_s \times V_s / M_s = 36.4 \text{ kip} \]
\[ 2.0 \times V_s + V_{ug} = 32.4 \text{ kip} \]
\[ 1.25 \times V_{sm} + V_{ug} = 45.5 \text{ kip} \]
\[ \phi V_s = 45.4 \text{ kip} \geq 32.4 \text{ kip} \quad \text{OK} \]

**Bottom of Wall A**

\[ t_{wall} = 7.625 \text{ in} \]
\[ d_r = 48 \text{ in} \]
\[ P_u = -13.4 \text{ kip} \]
\[ V_s = 16.2 \text{ kip} \]
\[ M_s = 99.4 \text{ kip-ft} \]

\[ M_s / V_s d_r = 1.53 \]

\[ V_s = V_{sm} + V_v \leq V_{s,\text{max}} \quad (2011 \text{ MSJC 3.3.4.1.2}) \]

\[ V_{sm} = 28.5 \text{ kip} \]

\[ V_v = 0.5 \times (A_v/s) \times f_s \times d_r \]
\[ (A_v/s) = 0.025 \text{ in}^2/\text{in} \]
\[ V_v = 36.0 \text{ kip} \]

\[ V_{s,\text{max}} = 4.0 \times A_v \times v(V_{ns}) \quad (2011 \text{ MSJC Eq. 3-21 and 3-22}) \]
\[ V_{s,\text{max}} = 56.7 \text{ kip} \]
\[ V_v = 56.7 \text{ kip} \quad (2011 \text{ MSJC 3.3.4.1.2}) \]
\[ \phi = 0.8 \]
\[ \phi V_v = 45.4 \text{ kip} \geq 16.2 \text{ kip} \quad \text{OK} \]

Check \( \phi V_v \geq \min(2.0 \times V_v + V_{ug}, 1.25 \times V_{sm} + V_{ug}) \) (2011 MSJC 1.18.3.2.6.1.1)

\[ V_v = 16.2 \text{ kip} \quad (E_v) \]
\[ M_v = 99.4 \text{ kip-ft} \quad (E_v) \]
\[ V_{ug} = V_v - V_t = 0.0 \text{ kip} \quad (0.9D-E, \text{ incl. } E_v) \]
\[ M_v = 157.1 \text{ kip-ft} \]
\[ V_{sm} = M_v \times V_v / M_v = 25.6 \text{ kip} \]
\[ 2.0 \times V_v + V_{ug} = 32.4 \text{ kip} \]
\[ 1.25 \times V_{sm} + V_{ug} = 32.0 \text{ kip} \]
\[ \phi V_v = 45.4 \text{ kip} \geq 32.0 \text{ kip} \quad \text{OK} \]
Shear Design (cont.)

Top of Wall B

\[ t_{\text{wall}} = 7.625 \text{ in} \]
\[ d_v = 24 \text{ in} \]
\[ P_u = 14.3 \text{ kip} \]
\[ V_u = 4.9 \text{ kip} \]
\[ M_u = 16.5 \text{ kip-ft} \]

\[ M_u/V_u d_v = 1.68 \]

\[ V_v = V_{vm} + V_{ns} \leq V_{n,\text{max}} \]

\[ V_{vm} = [4-1.75*(M_u/V_u d_v)]*A_v*\sqrt{f_m'} + 0.25*P_u \]

\[ V_{vm} = 19.5 \text{ kip} \]

\[ V_{ns} = 0.5*(A_v/s)*f_y*d_v \]
\[ (A_v/s) = 0.000 \text{ in}^2/\text{in} \]
\[ V_{ns} = 0.0 \text{ kip} \]

\[ V_{n,\text{max}} = 4.0*A_v*\sqrt{f_m'} \]
\[ V_{n,\text{max}} = 28.4 \text{ kip} \]
\[ \phi = 0.8 \]
\[ \phi V_v = 15.6 \text{ kip} \]

Check \( \phi V_v \geq \min(2.0*V_v + V_{ug}, 1.25*V_{sn} + V_{ug}) \)

\[ V_v = 4.9 \text{ kip} \]
\[ M_v = 16.5 \text{ kip-ft} \]
\[ V_{ug} = V_v - V_e = 0.0 \text{ kip} \]
\[ M_v = 40.3 \text{ kip-ft} \]
\[ V_{sn} = M_v*V_v/M_e = 12.0 \text{ kip} \]

\[ 2.0*V_v + V_{ug} = 9.8 \text{ kip} \]
\[ 1.25*V_{sn} + V_{ug} = 14.9 \text{ kip} \]
\[ \phi V_v = 15.6 \text{ kip} \]

Top of Wall B

\[ t_{\text{wall}} = 7.625 \text{ in} \]
\[ d_v = 24 \text{ in} \]
\[ P_u = -1.8 \text{ kip} \]
\[ V_u = 4.9 \text{ kip} \]
\[ M_u = 16.5 \text{ kip-ft} \]

\[ M_u/V_u d_v = 1.68 \]

\[ V_v = V_{vm} + V_{ns} \leq V_{n,\text{max}} \]

\[ V_{vm} = [4-1.75*(M_u/V_u d_v)]*A_v*\sqrt{f_m'} + 0.25*P_u \]

\[ V_{vm} = 15.5 \text{ kip} \]

\[ V_{ns} = 0.5*(A_v/s)*f_y*d_v \]
\[ (A_v/s) = 0.000 \text{ in}^2/\text{in} \]
\[ V_{ns} = 0.0 \text{ kip} \]

\[ V_{n,\text{max}} = 4.0*A_v*\sqrt{f_m'} \]
\[ V_{n,\text{max}} = 28.4 \text{ kip} \]
\(V_n = 15.5\) kip \quad \text{(2011 MSJC 3.3.4.1.2)}

\(\phi = 0.8\)

\[\phi V_n = 12.4 \text{ kip} > 4.9 \text{ kip} \quad \text{OK}\]

Check \(\phi V_n \geq \min(2.0*V_c+V_{up}, 1.25*V_{sn}+V_{aq})\) \quad \text{(2011 MSJC 1.18.3.2.6.1.1)}

\(V_c = 4.9\) kip \quad \text{(E)}

\(M_c = 16.5\) kip-ft \quad \text{(E)}

\(V_{up} = V_c - V_i = 0.0\) kip \quad \text{(0.9D-E, incl. \(E\))}

\(M_{sn} = 28.9\) kip-ft \quad \text{(E)}

\[V_{sn} = M_{sn} V_i/M_c = 8.6\] kip

\[2.0*V_c+V_{up} = 9.8\] kip

\[1.25*V_{sn}+V_{aq} = 10.7\] kip

\[\phi V_n = 12.4 \text{ kip} > 9.8 \text{ kip} \quad \text{OK}\]

**Bottom of Wall B** \quad \text{(1.2D+0.5L+\(E\), incl. \(E\))}

\(t_{wall} = 7.625\) in

\(d_v = 24\) in

\(P_u = 16.1\) kip

\(V_u = 4.9\) kip

\(M_u = 22.7\) kip-ft

\[M_c/V_c d_v = 2.32\]

\(V_{sn} = V_{sn} + V_{u} \leq V_{n,\text{max}}\) \quad \text{(2011 MSJC 3.3.4.1.2)}

\[V_{sn} = [4-1.75*(M_c/V_c d_v)]*A_n*\sqrt{(f'_{m})} + 0.25*P_u\] \quad \text{(2011 MSJC Eq. 3-23)}

\[V_{sn} = 20.0\] kip

\(V_{n,\text{max}} = 0.5*(A_n/s)^{1/2} d_v\) \quad \text{(2011 MSJC Eq. 3-24)}

\(A_n/s = 0.000\) in²/in

\[V_{n,\text{max}} = 0.0\] kip

\[V_{n,\text{max}} = 4.0 \times A_n*\sqrt{(f'_{m})}\] \quad \text{(2011 MSJC Eq. 3-21 and 3-22)}

\[V_{n,\text{max}} = 28.4\] kip

\(V_n = 20.0\) kip \quad \text{(2011 MSJC 3.3.4.1.2)}

\(\phi = 0.8\)

\[\phi V_n = 16.0 \text{ kip} > 4.9 \text{ kip} \quad \text{OK}\]

Check \(\phi V_n \geq \min(2.0*V_c+V_{up}, 1.25*V_{sn}+V_{aq})\) \quad \text{(2011 MSJC 1.18.3.2.6.1.1)}

\(V_c = 4.9\) kip \quad \text{(E)}

\(M_c = 22.7\) kip-ft \quad \text{(E)}

\(V_{up} = V_c - V_i = 0.0\) kip \quad \text{(1.2D+0.5L, incl. \(E\))}

\(M_{sn} = 41.5\) kip-ft \quad \text{(E)}

\[V_{sn} = M_{sn} V_i/M_c = 9.0\] kip

\[2.0*V_c+V_{up} = 9.8\] kip

\[1.25*V_{sn}+V_{aq} = 11.2\] kip

\[\phi V_n = 16.0 \text{ kip} > 9.8 \text{ kip} \quad \text{OK}\]

**Bottom of Wall B** \quad \text{(0.9D-E, incl. \(E\))}

\(t_{wall} = 7.625\) in

\(d_v = 24\) in

\(P_u = -0.9\) kip

\(V_n = 4.9\) kip

\(M_u = 22.7\) kip-ft
\[
\frac{M_u}{V_u d_v} = 2.32
\]
\[
V_v = V_{vm} + V_n \leq V_{n,max} \quad (2011 \text{ MSJC 3.3.4.1.2})
\]
\[
V_{vm} = [4-1.75 \times (M_u/V_u d_v)] \times A_e \times v(f'_{cm}) + 0.25 \times P_u \quad (2011 \text{ MSJC Eq. 3-23})
\]
\[
V_n = 15.7 \text{ kip} \quad (2011 \text{ MSJC Eq. 3-24})
\]
\[
\frac{V_n}{V_{n,max}} = 0.5 \times (A/s) \times f' \times d_v \quad (2011 \text{ MSJC Eq. 3-21 and 3-22})
\]
\[
\phi = 0.8
\]
\[
\psi V_v = 12.6 \text{ kip} > 4.9 \text{ kip} \quad \text{OK}
\]
\[
\text{Check } \psi V_v \geq \min(2.0 \times V_E + V_{ug}, 1.25 \times V_{sn} + V_{ug}) \quad (2011 \text{ MSJC 1.18.3.2.6.1.1})
\]
\[
V_v = 4.9 \text{ kip} \quad (E_i)
\]
\[
M_v = 22.7 \text{ kip-ft} \quad (E_i)
\]
\[
V_{eg} = V_v - V_e = 0.0 \text{ kip} \quad (0.9D-E, \text{ incl. } E_i)
\]
\[
M_e = 29.5 \text{ kip-ft}
\]
\[
V_{sn} = M_e \times V_E / M_E = 6.4 \text{ kip}
\]
\[
2.0 \times V_v + V_{eg} = 9.8 \text{ kip}
\]
\[
1.25 \times V_{sn} + V_{eg} = 8.0 \text{ kip}
\]
\[
\psi V_v = 12.6 \text{ kip} > 8.0 \text{ kip} \quad \text{OK}
\]

Shear Design (cont.)

Top of Wall C

\[
\begin{align*}
t_{wall} & = 7.625 \text{ in} \\
d_v & = 48 \text{ in} \\
P_u & = 37.8 \text{ kip} \\
V_v & = 22.7 \text{ kip} \\
M_e & = 63.6 \text{ kip-ft} \\
M_u/V_u d_v & = 0.70
\end{align*}
\]
\[
V_v = V_{vm} + V_n \leq V_{n,max} \quad (2011 \text{ MSJC 3.3.4.1.2})
\]
\[
V_{vm} = [4-1.75 \times (M_u/V_u d_v)] \times A_e \times v(f'_{cm}) + 0.25 \times P_u \quad (2011 \text{ MSJC Eq. 3-23})
\]
\[
V_n = 48.8 \text{ kip} \quad (2011 \text{ MSJC Eq. 3-24})
\]
\[
\frac{V_n}{V_{n,max}} = 4.8 \times (A/s) \times f' \times d_v \quad (2011 \text{ MSJC Eq. 3-21 and 3-22})
\]
\[
\psi V_v = 54.4 \text{ kip} > 22.7 \text{ kip} \quad \text{OK}
\]
\[
\text{Check } \psi V_v \geq \min(2.0 \times V_v + V_{eg}, 1.25 \times V_{sn} + V_{eg}) \quad (2011 \text{ MSJC 1.18.3.2.6.1.1})
\]
\[
V_v = 22.7 \text{ kip} \quad (E_i)
\]
\[ M_E = 63.6 \text{ kip-ft} \quad (E_1) \]
\[ V_{ap} = V_u - V_e = 0.0 \text{ kip} \quad (1.2D+0.5L, \text{incl. } E_1) \]
\[ M_S = 223.8 \text{ kip-ft} \]
\[ V_{sh} = M_S \cdot V_e / M_E = 79.8 \text{ kip} \]

\[ 2.0 \cdot V_e + V_{ap} = 45.4 \text{ kip} \]
\[ 1.25 \cdot V_{sh} + V_{ap} = 99.7 \text{ kip} \]
\[ \phi V_e = 54.4 \text{ kip} > 45.4 \text{ kip} \quad \text{OK} \]

**Top of Wall C**

\[ t_{wall} = 7.625 \text{ in} \]
\[ d_s = 48 \text{ in} \]
\[ P_o = -21.7 \text{ kip} \]
\[ V_e = 22.7 \text{ kip} \]
\[ M_S = 63.6 \text{ kip-ft} \]

\[ M_e / V_e d_s = 0.70 \]

\[ V_e = V_{rm} + V_e \leq V_{e,\text{max}} \quad (2011 \text{ MSJC 3.3.4.1.2}) \]

\[ V_{rm} = [4-1.75 \cdot (d_s / A_e) \cdot f'_{m}] \cdot A_e \cdot (f'_{m}) + 0.25 \cdot P_o \quad (2011 \text{ MSJC Eq. 3-23}) \]

\[ V_{e,\text{max}} = 4.8 \cdot A_e \cdot (f'_{m}) \quad (2011 \text{ MSJC Eq. 3-21 and 3-22}) \]

\[ V_{e,\text{max}} = 68.0 \text{ kip} \]
\[ V_e = 68.0 \text{ kip} \quad (2011 \text{ MSJC 3.3.4.1.2}) \]
\[ \phi = 0.8 \]
\[ \phi V_e = 54.4 \text{ kip} > 22.7 \text{ kip} \quad \text{OK} \]

Check \[ \phi V_e \geq \min(2.0 \cdot V_e + V_{ap}, 1.25 \cdot V_{sh} + V_{ap}) \quad (2011 \text{ MSJC 1.18.3.2.6.1.1}) \]

\[ V_e = 22.7 \text{ kip} \quad (E_2) \]
\[ M_e = 63.6 \text{ kip-ft} \quad (E_2) \]
\[ V_{ap} = V_u - V_e = 0.0 \text{ kip} \quad (0.9D-\epsilon, \text{incl. } E_2) \]
\[ M_S = 145.4 \text{ kip-ft} \]
\[ V_{sh} = M_S \cdot V_e / M_e = 51.8 \text{ kip} \]

\[ 2.0 \cdot V_e + V_{ap} = 45.4 \text{ kip} \]
\[ 1.25 \cdot V_{sh} + V_{ap} = 64.8 \text{ kip} \]
\[ \phi V_e = 54.4 \text{ kip} > 45.4 \text{ kip} \quad \text{OK} \]

**Bottom of Wall C**

\[ t_{wall} = 7.625 \text{ in} \]
\[ d_s = 48 \text{ in} \]
\[ P_o = 41.4 \text{ kip} \]
\[ V_e = 22.7 \text{ kip} \]
\[ M_S = 117.8 \text{ kip-ft} \]

\[ M_e / V_e d_s = 1.30 \]

\[ V_e = V_{rm} + V_e \leq V_{e,\text{max}} \quad (2011 \text{ MSJC 3.3.4.1.2}) \]

\[ V_{rm} = [4-1.75 \cdot (d_s / A_e) \cdot f'_{m}] \cdot A_e \cdot (f'_{m}) + 0.25 \cdot P_o \quad (2011 \text{ MSJC Eq. 3-23}) \]

\[ V_{rm} = 42.2 \text{ kip} \]
\[ V_{ns} = 0.5 \cdot (A/v) \cdot f_y \cdot d_v \]  
(2011 MSJC Eq. 3-24)

\[ (A/v) = 0.025 \text{ in}^2/\text{in} \]

\[ V_{ns} = 36.0 \text{ kip} \]

\[ V_{n, \text{max}} = 4.0 \cdot A \cdot v(f'_{\text{mn}}) \]  
(2011 MSJC Eq. 3-21 and 3-22)

\[ V_{n, \text{max}} = 56.7 \text{ kip} \]

\[ V_e = 56.7 \text{ kip} \]  
(2011 MSJC 3.3.4.1.2)

\[ \phi = 0.8 \]

\[ \phi V_e = 45.4 \text{ kip} > 22.7 \text{ kip} \]

OK

Check \( \phi V_e \geq \min(2.0 V_e + V_{ug}, 1.25 V_{n, \text{max}} + V_{ug}) \)  
(2011 MSJC 1.18.3.2.6.1.1)

\[ V_e = 22.7 \text{ kip} \]

\[ M_e = 117.8 \text{ kip-ft} \]

\[ V_{ug} = V_u - V_e = 0.0 \text{ kip} \]  
(1.2D+0.5L, incl. \( E_s \))

\[ V_{n, \text{max}} = 228.2 \text{ kip-ft} \]

\[ \frac{V_e \cdot V_e}{M_e} = 44.0 \text{ kip} \]

\[ 2.0 V_e + V_{ug} = 45.4 \text{ kip} \]

\[ 1.25 V_{n, \text{max}} + V_{ug} = 55.0 \text{ kip} \]

\[ \phi V_e = 45.4 \text{ kip} < 45.4 \text{ kip} \]

NG

Bottom of Wall C  
(0.9D-\( E_s \), incl. \( E_s \))

\[ t_{wall} = 7.625 \text{ in} \]

\[ d_v = 48 \text{ in} \]

\[ P_u = -20.0 \text{ kip} \]

\[ V_e = 22.7 \text{ kip} \]

\[ M_e = 117.8 \text{ kip-ft} \]

\[ M_e/V_d = 1.30 \]

\[ V_e = \frac{V_{n, \text{min}} + V_{ns}}{V_{n, \text{max}}} \]  
(2011 MSJC 3.3.4.1.2)

\[ V_{n, \text{min}} = [4 - 1.75 \cdot (M_e/V_d) \cdot A \cdot v(f'_{\text{mn}}) + 0.25 \cdot P_u] \]  
(2011 MSJC Eq. 3-23)

\[ V_{n, \text{min}} = 26.9 \text{ kip} \]

\[ V_{n, \text{max}} = 0.5 \cdot (A/v) \cdot f_y \cdot d_v \]  
(2011 MSJC Eq. 3-24)

\[ (A/v) = 0.025 \text{ in}^2/\text{in} \]

\[ V_{n, \text{max}} = 36.0 \text{ kip} \]

\[ V_{n, \text{max}} = 4.0 \cdot A \cdot v(f'_{\text{mn}}) \]  
(2011 MSJC Eq. 3-21 and 3-22)

\[ V_{n, \text{max}} = 56.7 \text{ kip} \]

\[ V_e = 56.7 \text{ kip} \]  
(2011 MSJC 3.3.4.1.2)

\[ \phi = 0.8 \]

\[ \phi V_e = 45.4 \text{ kip} > 22.7 \text{ kip} \]

OK

Check \( \phi V_e \geq \min(2.0 V_e + V_{ug}, 1.25 V_{n, \text{max}} + V_{ug}) \)  
(2011 MSJC 1.18.3.2.6.1.1)

\[ V_e = 22.7 \text{ kip} \]

\[ M_e = 117.8 \text{ kip-ft} \]

\[ V_{ug} = V_u - V_e = 0.0 \text{ kip} \]  
(0.9D-\( E_s \), incl. \( E_s \))

\[ M_e = 148.2 \text{ kip-ft} \]

\[ \frac{V_e \cdot V_e}{M_e} = 28.6 \text{ kip} \]

\[ 2.0 V_e + V_{ug} = 45.4 \text{ kip} \]

\[ 1.25 V_{n, \text{max}} + V_{ug} = 35.7 \text{ kip} \]

\[ \phi V_e = 45.4 \text{ kip} > 35.7 \text{ kip} \]

OK
Wall A Boundary Element Check
Rapid Screening

$P_u = 37.4$ kip

$0.10A_g*f_m = 54.9$ kip

$V_u = 16.2$ kip

$M_u = 99.4$ kip-ft

$h_w = 120$ in

$M_u/(V_u*V) = 1.53 > 1 < 3$

$3*A_g*V(f_m) = 42.5$ kip

Neutral Axis Depth

$c = 10.35$ in

$\delta_{ne} = 0.12$ in

$C_d = 3.5$

$c_{max} = l_w/(600*C_d*\delta_{ne}/h_w) = 22.43$ in

$3*An*\sqrt{f_m} = 42.5$ kip

Extreme Fiber Compressive Stress

$f_{max} = 300.0$ psi

$f_{max} = P_u/A_g+M_u/S = 509.3$ psi

Wall B Boundary Element Check
Rapid Screening

$P_u = 16.1$ kip

$0.10A_g*f_m = 54.9$ kip

$V_u = 4.9$ kip

$M_u = 22.7$ kip-ft

$h_w = 96$ in

$M_u/(V_u*V) = 2.3 > 1 < 3$

$3*An*V(f_m) = 21.3$ kip

Neutral Axis Depth

$c = 4.43$ in

$\delta_{ne} = 0.12$ in

$C_d = 3.5$

$c_{max} = l_w/(600*C_d*\delta_{ne}/h_w) = 8.97$ in

$3*An*\sqrt{f_m} = 21.3$ kip

NG
Extreme Fiber Compressive Stress

\[ 0.2* f'_{m} = 300.0 \text{ psi} \]  
\[ f_{\text{max}} = \frac{P_u}{A_g} + \frac{M_u}{S} \]
\[ P_u = 16.1 \text{ kip} \]
\[ M_u = 22.7 \text{ kip-ft} \]
\[ A_g = 183 \text{ in}^2 \]
\[ S = 732 \text{ in}^3 \]
\[ f_{\text{max}} = 460.0 \text{ psi} > 300.0 \text{ psi} \text{ NG} \]

Wall C Boundary Element Check

Rapid Screening
\[ P_u = 41.4 \text{ kip} \]
\[ 0.10* A_g* f'_{m} = 54.9 \text{ kip} > 41.4 \text{ kip} \text{ OK} \]
\[ V_u = 22.7 \text{ kip} \]
\[ M_u = 117.8 \text{ kip-ft} \]
\[ t_o = 48 \text{ in} \]
\[ h_o = 96 \text{ in} \]
\[ M_u/(V_u* f'_{m}) = 1.3 \text{ > 1 and < 3} \]
\[ 3* A_g* V(f'_{m}) = 42.5 \text{ kip} > 22.7 \text{ kip} \text{ OK} \]

Neutral Axis Depth
\[ c = 10.69 \text{ in} \]
\[ \delta_{\text{nc}} = 0.12 \text{ in} \]
\[ C_d = 3.5 \]
\[ c_{\text{max}} = \frac{L_o/(600* C_d* \delta_{\text{nc}}/h_o)} \]
\[ c_{\text{max}} = 17.94 \text{ in} > 10.69 \text{ in} \text{ OK} \]

Extreme Fiber Compressive Stress
\[ 0.2* f'_{m} = 300.0 \text{ psi} \]
\[ f_{\text{max}} = \frac{P_u}{A_g} + \frac{M_u}{S} \]
\[ P_u = 41.4 \text{ kip} \]
\[ M_u = 117.8 \text{ kip-ft} \]
\[ A_g = 366 \text{ in}^2 \]
\[ S = 2928 \text{ in}^3 \]
\[ f_{\text{max}} = 595.7 \text{ psi} > 300.0 \text{ psi} \text{ NG} \]

Rho Max Check
\[ (D+0.75L+0.525E, \text{ not incl. } E_v) \]

Wall A
\[ P_u = 23.6 \text{ kip} \]
\[ V_u = 8.5 \text{ kip} \]
\[ M_u = 52.2 \text{ kip-ft} \]
\[ d_o = 48 \text{ in} \]
\[ M_u/V_d_o = 1.53 \]
\[ \varepsilon_{\text{max}} = 4.00 \varepsilon_{\text{sp}} \]
\[ \varepsilon_{\text{max}} = -8.28E-03 \text{ in/in} \]
\[ P_u = 35.8 \text{ kip} > 23.6 \text{ kip} \text{ OK} \]
Wall B

\[ P_u = 11.0 \text{ kip} \]
\[ V_u = 2.6 \text{ kip} \]
\[ M_u = 11.9 \text{ kip*ft} \]
\[ d_u = 24 \text{ in} \]
\[ M_u/V_u d_u = 2.32 \]
\[ \varepsilon_{s,max} = 4.00 \times \varepsilon_{sy} \]
\[ \varepsilon_{s,max} = -8.28 \times 10^{-3} \text{ in/in} \]
\[ P_n = 18.5 \text{ kip} \]
\[ > 11.0 \text{ kip} \quad \text{OK} \]

Wall C

\[ P_u = 25.2 \text{ kip} \]
\[ V_u = 11.9 \text{ kip} \]
\[ M_u = 61.8 \text{ kip*ft} \]
\[ d_u = 48 \text{ in} \]
\[ M_u/V_u d_u = 1.30 \]
\[ \varepsilon_{s,max} = 4.00 \times \varepsilon_{sy} \]
\[ \varepsilon_{s,max} = -8.28 \times 10^{-3} \text{ in/in} \]
\[ P_n = 35.8 \text{ kip} \]
\[ > 25.2 \text{ kip} \quad \text{OK} \]
### C.3 Case Study A Reinforcement Option 10, Limit Design

**Reinforcement**

(Assumed sufficient for all non-seismic load combinations)

#### Wall A Flexural Reinforcement

- **Wall A Flexural Reinforcement**
  
  - $A_{s,1}$ = (1) #6 = 0.44 in$^2$ @ $d_1$ = 4 in
  
  - $A_{s,2}$ = (1) #6 = 0.44 in$^2$ @ $d_2$ = 12 in
  
  - $A_{s,3}$ = (1) #6 = 0.44 in$^2$ @ $d_3$ = 36 in
  
  - $A_{s,4}$ = (1) #6 = 0.44 in$^2$ @ $d_4$ = 44 in

#### Wall A Shear Reinforcement

- **Wall A Shear Reinforcement**
  
  - $A_v$ = (2) #4 = 0.4 in$^2$ @ 16 in o.c.
  
  - $(A_v/s)_A$ = 0.025 in$^2$/in

#### Wall B Flexural Reinforcement

- **Wall B Flexural Reinforcement**
  
  - $A_{s,1}$ = (1) #5 = 0.31 in$^2$ @ $d_1$ = 4 in
  
  - $A_{s,2}$ = (1) #5 = 0.31 in$^2$ @ $d_2$ = 20 in

#### Wall B Shear Reinforcement

- **Wall B Shear Reinforcement**
  
  - $A_v$ = None = 0 in$^2$ @ 8 in o.c.
  
  - $(A_v/s)_A$ = 0.000 in$^2$/in

#### Wall C Flexural Reinforcement

- **Wall C Flexural Reinforcement**
  
  - $A_{s,1}$ = (1) #6 = 0.44 in$^2$ @ $d_1$ = 4 in
  
  - $A_{s,2}$ = (1) #6 = 0.44 in$^2$ @ $d_2$ = 12 in
  
  - $A_{s,3}$ = (1) #6 = 0.44 in$^2$ @ $d_3$ = 36 in
  
  - $A_{s,4}$ = (1) #6 = 0.44 in$^2$ @ $d_4$ = 44 in

#### Wall C Shear Reinforcement

- **Wall C Shear Reinforcement**
  
  - $A_v$ = (2) #4 = 0.4 in$^2$ @ 16 in o.c.
  
  - $(A_v/s)_A$ = 0.025 in$^2$/in

**Material Properties**

- $f' = 1500$ psi
- $f_y = 60$ ksi
- $E_s = 29000$ ksi
- $E_m = 1350$ ksi
- $\varepsilon_{mu} = 0.0025$ in/in (2011 MSJC 3.3.2(c))
- $\varepsilon_{sy} = 0.0021$ in/in

**Seismic Design Parameters**

- $S_{DS} = 1$
- $R = 5$ (ASCE/SEI 7-10 Table 12.2-1)
- $C_s = 3.5$ (ASCE/SEI 7-10 Table 12.2-1)
- $E_v = 0.2 * S_{DS}$ (ASCE/SEI 7-10 Eq. 12.14-6)

**F.E.M. Model Assumptions**

- (Stiffness properties are based on 50% of gross section properties)
- $E = E_{s}/2 = 675$ ksi
- $G = 281$ ksi
- $\nu = 0.2$

**Gravity Loading**

- (Determined using program SAP2000)
- $DL_{Self Weight} = 80$ psf
- $DL_{Tributary} = 150$ plf
- $LL_{Tributary} = 230$ plf

**Wall A**

- $P_{20\text{in}} = 7.7$ kip
- $P_{20\text{out}} = 10.9$ kip
- $V_0 = 0.0$ kip

(Shear and moment in walls due to gravity loads assumed zero)
Seismic Forces and Displacement

(Determined using program SAP2000)

Base Shear, $E = 49.1$ kip

Roof Displacement, $\delta_R = 0.14$ in

Wall A

$P_A = 23.57$ kip

$V_A = 18.17$ kip

$M_{ELA+} = 70.26$ kip-ft

$M_{ELB+} = 111.48$ kip-ft

Wall B

$P_B = 6.38$ kip

$V_B = 5.49$ kip

$M_{ELA+} = 18.51$ kip-ft

$M_{ELB+} = 25.48$ kip-ft

Wall C

$P_C = 30.08$ kip

$V_C = 25.45$ kip

$M_{ELA+} = 71.39$ kip-ft

$M_{ELB+} = 132.11$ kip-ft

Load Combo (1.2$D+0.5E+1.0E$) (Include $E_\text{v}$)

Wall A

$P_{uA+} = 35.5$ kip

$P_{uB+} = 39.9$ kip

$V_{u} = 18.2$ kip
\[ M_{u\text{top}} = 70.3 \text{ kip-ft} \]
\[ M_{u\text{bot}} = 111.5 \text{ kip-ft} \]

**Wall B**
\[ P_{u\text{top}} = 15.0 \text{ kip} \]
\[ P_{u\text{bot}} = 16.7 \text{ kip} \]
\[ V_u = 5.5 \text{ kip} \]
\[ M_{u\text{top}} = 18.5 \text{ kip-ft} \]
\[ M_{u\text{bot}} = 25.5 \text{ kip-ft} \]

**Wall C**
\[ P_{u\text{top}} = 41.1 \text{ kip} \]
\[ P_{u\text{bot}} = 44.7 \text{ kip} \]
\[ V_u = 25.4 \text{ kip} \]
\[ M_{u\text{top}} = 71.4 \text{ kip-ft} \]
\[ M_{u\text{bot}} = 132.1 \text{ kip-ft} \]

**Load Combo (0.9D-1.0E)**
(Include \( E_u \))

**Wall A**
\[ P_{u\text{top}} = -18.2 \text{ kip} \]
\[ P_{u\text{bot}} = -15.9 \text{ kip} \]
\[ V_u = 18.2 \text{ kip} \]
\[ M_{u\text{top}} = 70.3 \text{ kip-ft} \]
\[ M_{u\text{bot}} = 111.5 \text{ kip-ft} \]

**Wall B**
\[ P_{u\text{top}} = -2.5 \text{ kip} \]
\[ P_{u\text{bot}} = -1.6 \text{ kip} \]
\[ V_u = 5.5 \text{ kip} \]
\[ M_{u\text{top}} = 18.5 \text{ kip-ft} \]
\[ M_{u\text{bot}} = 25.5 \text{ kip-ft} \]

**Wall C**
\[ P_{u\text{top}} = -25.0 \text{ kip} \]
\[ P_{u\text{bot}} = -23.2 \text{ kip} \]
\[ V_u = 25.4 \text{ kip} \]
\[ M_{u\text{top}} = 71.4 \text{ kip-ft} \]
\[ M_{u\text{bot}} = 132.1 \text{ kip-ft} \]
**Interaction Diagrams**

**Wall A - Interaction Diagram**

- Compression (kip) vs. Moment (k-ft)

**Wall B - Interaction Diagram**

- Compression (kip) vs. Moment (k-ft)
Wall A Hinge Strength

$M_n$ and $V_n$ determined for gravity load of 0.9D - 0.2*S_D*D  
(Not to include $E_s$)

**Shear Corresponding to Flexural Hinge Development ($V_{ Mn}$)**

- $P_{u(top)} = 5.4$ kip
- $M_{n(top)} = 182.1$ kip-ft
- $P_{u(bottom)} = 7.6$ kip
- $M_{n(bottom)} = 185.0$ kip-ft

$V_{Mn} = \sum (M_n)/L = (182.1 \text{ kip-ft} + 185.0 \text{ kip-ft})/10 \text{ ft}$

$V_{Mn} = 36.7$ kip

**Shear Strength Provided ($V_{n,prov}$)**

Assume $M_n/V_d \geq 1.00$

- $t_{wall} = 7.625$ in
- $d_v = 48$ in
- $P_u = 5.4$ kip
- $(A_v/s) = 0.025$ in$^3$/in

$V_{vm} = [4-1.75*1]*A_v*\sqrt{f_m'} + 0.25*P_u$  
(2011 MSJC Eq. 3-23)

$V_{vm} = 33.2$ kip

$V_{m} = 0.5*(A_v/s)*f_m'*d_v$  
(2011 MSJC Eq. 3-24)

$V_{m} = 36.0$ kip

$V_{(max)} = 4.0* A_v*\sqrt{f_m'}$  
(2011 MSJC Eq. 3-21 and 3-22)

$V_{(max)} = 56.7$ kip

$V_{n,prov} = 56.7$ kip  
(2011 MSJC 3.3.4.1.2)

**Shear Demand**

Assuming $V_{uE} = 0.0$ kip

$V_{uE} = 18.2$ kip

**Check if Shear Controlled**

$\phi_{vo} = \frac{\text{max}(V_{cm},(2V_{cm},(V_{cm}-(R*V_{cm}))))}{(2V_{cm},(V_{cm}-(R*V_{cm}))))} \leq 1$

If $\phi_{vo} < 1.0$ then Shear Controlled

$\phi_{vo} = 0.77$  
Shear Controlled
Hinge Strength @ Top of Wall A

Hinge Strength = \( \phi_v \cdot M_{n(top)} \)

Hinge Strength = 140.6 kip-ft

Hinge Strength @ Bottom of Wall A

Hinge Strength = \( \phi_v \cdot M_{n(top)} \)

Hinge Strength = 142.9 kip-ft

Wall B Hinge Strength

\( M_n \) and \( V_n \) determined for gravity load of 0.9\( D - 0.2 \cdot S_{Im} \cdot D \) (Not to include \( E_h \))

Shear Corresponding to Flexural Hinge Development \( (V_{Mn}) \)

\( P_{u(top)} = 3.9 \) kip

\( M_{n(top)} = 33.0 \) kip-ft

\( P_{u(btm)} = 4.8 \) kip

\( M_{n(btm)} = 33.6 \) kip-ft

\( V_{Mn} = \Sigma(M_j)/L = (33.0 \text{ kip-ft} + 33.6 \text{ kip-ft}) / 8 \text{ ft} \)

\( V_{Mn} = 8.3 \) kip

Shear Strength Provided \( (V_{n,pov}) \)

Assume \( M_u/V_u \geq 1.0 \)

\( t_{wall} = 7.625 \) in

\( d_v = 24.00 \) in

\( P_u = 3.9 \) kip

\( (A_v/s) = 0.000 \) in\(^2\)/in

\( V_{sn} = [4-1.75*1] \cdot A_v \cdot V_{f_m} + 0.25 \cdot P_u \) (2011 MSJC Eq. 3-23)

\( V_{sn} = 16.9 \) kip

\( V_n = 0.5 \cdot (A_v/s) \cdot f_{vm} \) (2011 MSJC Eq. 3-24)

\( V_n = 28.4 \) kip

\( V_{n,pov} = 16.9 \) kip

(2011 MSJC 3.3.4.1.2)

Shear Demand

Assuming \( V_{ug} \approx 0.0 \) kip

\( V_{as} = 5.5 \) kip

Check if Shear Controlled

\( \phi_v = \max((V_n - V_{as})/(2V_{sn}), (V_n - V_{as})/(R \cdot V_{sn})) \leq 1 \)

If \( \phi_v < 1.0 \) then Shear Controlled

\( \phi_v = 1.00 \)

Not Shear Controlled

Hinge Strength @ Top of Wall B

Hinge Strength = \( \phi_v \cdot M_{n(top)} \)

Hinge Strength = 33.0 kip-ft

Hinge Strength @ Bottom of Wall B

Hinge Strength = \( \phi_v \cdot M_{n(top)} \)

Hinge Strength = 33.6 kip-ft

Wall C Hinge Strength

\( M_n \) and \( V_n \) determined for gravity load of 0.9\( D - 0.2 \cdot S_{Im} \cdot D \) (Not to include \( E_h \))

Shear Corresponding to Flexural Hinge Development \( (V_{Mn}) \)

\( P_{u(top)} = 5.1 \) kip

\( M_{n(top)} = 181.6 \) kip-ft

\( P_{u(btm)} = 6.9 \) kip

\( M_{n(btm)} = 184.0 \) kip-ft

\( V_{Mn} = \Sigma(M_j)/L = (181.6 \text{ kip-ft} + 184.0 \text{ kip-ft}) / 8 \text{ ft} \)

\( V_{Mn} = 45.7 \) kip
Shear Strength Provided ($V_{u,prov}$)

Assume $M_u/V_d \geq 1.00$

$V_{u,prov} = 56.7$ kip

$V_{n,prov} = 56.7$ kip

Shear Demand

Assuming $V_{u,E} = 25.4$ kip

Check if Shear Controlled

If $\phi_{s,E} < 1.0$ then Shear Controlled

Hinge Strength @ Top of Wall C

Hinge Strength = $\phi_{s,E} \times M_{n(top)}$

Hinge Strength = 112.7 kip-ft

Hinge Strength @ Bottom of Wall C

Hinge Strength = $\phi_{s,E} \times M_{n(foot)}$

Hinge Strength = 114.1 kip-ft

Mechanism Strength

Virtual External Work = Virtual Internal Work

Virtual External Work = $V_{lim} \times \delta$

Virtual Internal Work = $\delta \times (\sum (M_d)/h_w)_{wallA} + (\sum (M_d)/h_w)_{wallB} + (\sum (M_d)/h_w)_{wallC}$

$V_{lim} = 65.0$ kip

$\phi_{lim} = 0.8$

$\phi V_{lim} = 52.0$ kip

Base Shear, $E = 49.1$ kip

$V_{lim} = 90.7$ kip if not Shear Controlled

$\phi V_{lim} = OK$
Wall A Deformation Capacity Check

Displacement Demand
\[ \delta_e = 0.14 \text{ in} \]
\[ C_d = 3.5 \]
\[ \delta_m = \delta_e C_d = 0.48 \text{ in} \]

Displacement Capacity
Base Shear, \( E = 49.1 \text{ kip} \)
For \( P_u = 39.9 \text{ kip} \)
\[ c = 10.56 \text{ in} \]
\[ 0.5 h_w^* \varepsilon_m/c = 0.68 \text{ in} \]
\[ h/200 = 0.6 \text{ in} \]
\[ \delta_{cap} = 0.60 \text{ in} > 0.48 \text{ in} \text{ OK} \]

Wall B Deformation Capacity Check

Displacement Demand
\[ \delta_e = 0.14 \text{ in} \]
\[ C_d = 3.5 \]
\[ \delta_m = \delta_e C_d = 0.48 \text{ in} \]

Displacement Capacity
Base Shear, \( E = 49.1 \text{ kip} \)
For \( P_u = 16.7 \text{ kip} \)
\[ c = 4.49 \text{ in} \]
\[ 0.5 h_w^* \varepsilon_m/c = 0.64 \text{ in} \]
\[ \delta_{cap} = 0.64 \text{ in} > 0.48 \text{ in} \text{ OK} \]
**Wall C Deformation Capacity Check**

*(Load Case 1.2* + 0.5* + 1.0*E)*

*(Include *E)*

**Displacement Demand**

\[ \delta_r = 0.14 \text{ in} \]

\[ C_d = 3.5 \]

\[ \delta_m = \delta_r C_d = 0.48 \text{ in} \]

**Displacement Capacity**

Shear Controlled

Base Shear, *E* = 49.1 kip

For *P* = 44.7 kip

\[ c = 10.97 \text{ in} \]

\[ 0.5 h_w \varepsilon E_{md}/c = 0.53 \text{ in} \]

\[ h/200 = 0.48 \text{ in} \]

\[ \delta_{cap} = 0.48 \text{ in} \]

\[ \delta_{cap} < 0.48 \text{ in} \text{ NG} \]
Table 2.1 – Limit Design Code

Code

LIMIT DESIGN OF SPECIAL REINFORCED MASONRY SHEAR WALLS

X General — The Limit Design method shall be permitted to be applied to a line of lateral load resistance consisting of Special Reinforced Masonry Shear Walls that are designed per the Strength Design provisions of Chapter 3, except that the provisions of Section 3.3.3.5 and Section 3.3.6.5 shall not apply.

X.1 Yield mechanism — It shall be permitted to use limit analysis to determine the controlling yield mechanism and its corresponding base-shear strength, \(V_{lim}\), for a line of lateral load resistance, provided (a) through (d) are satisfied:

(a) The relative magnitude of lateral seismic forces applied at each floor level shall correspond to the loading condition producing the maximum base shear at the line of resistance in accordance with analytical procedures permitted in Section 12.6 of ASCE 7.
(b) In the investigation of potential yield mechanisms induced by seismic loading, plastic hinges shall be considered to form at the faces of joints and at the interface between masonry components and the foundation.
(c) The axial forces associated with load combination 7 per Section 2.3.2 of ASCE 7 shall be used when determining the strength of plastic hinges, except that axial loads due to horizontal seismic forces are permitted to be neglected.
(d) The strength assigned to plastic hinges shall be based on the nominal flexural strength, \(M_n\), but shall not exceed the moment associated with one-half of the nominal shear strength, \(V_n\), calculated using MSJC Section 3.3.4.1.2.

X.2 Mechanism strength — The yield mechanism associated with the limiting base-shear strength, \(V_{lim}\), shall satisfy the following:

\[ \phi V_{lim} \geq V_{sh} \]

The value of \( \phi \) assigned to the mechanism strength shall be taken as 0.8. The base-shear demand, \(V_{sh}\), shall be determined from analytical procedures permitted in Section 12.6 of ASCE 7.

X.3 Mechanism deformation — The deformation demand on plastic hinges shall be determined by imposing the design displacement, \(\delta_d\), at the roof level of the yield mechanism. The deformation capacity of plastic hinges shall satisfy X.3.1 to X.3.3.

X.3.1 The deformation capacity of plastic hinges shall be taken as \(0.5 \cdot \ell_u \cdot h_u \cdot e_{max} / c\). The value of \(c\) shall be calculated for the \(P_u\) corresponding to load combination 5 per Section 2.3.2 of ASCE 7.

X.3.2 The deformation capacity of masonry components where the plastic hinge strengths are limited by shear as specified in X.1(d), shall be taken as \(h_u / 400\), except that \(h_u / 200\) shall be used for masonry components satisfying the following requirements:

(a) Transverse and longitudinal reinforcement ratios shall exceed 0.001;
(b) Spacing of transverse and longitudinal reinforcement shall not exceed the smallest of 24 in. (610 mm), \(\ell_u / 2\), and \(h_u / 2\);
(c) Reinforcement ending at a free edge of masonry shall terminate in a standard hook.

X.3.3 The \(P_u\) corresponding to load combination 5 of Section 2.3.2 of ASCE 7 shall not exceed a compressive stress of \(0.3 f'_{m} A_e\) at plastic hinges in the controlling mechanism.
Table 2.2 – Commentary to Limit Design Code

Commentary

X  General — This section provides alternative design provisions for special reinforced masonry shear walls subjected to in-plane seismic loading. The Limit Design method is presented as an alternative to the requirements of 3.3.3.5 and 3.3.6.5. All other sections in Chapter 3 are applicable. Limit Design is considered to be particularly useful for perforated wall configurations for which a representative yield mechanism can be determined.

X.1 Yield mechanism — This section defines the basic conditions for allowing the use of limit analysis to determine the base-shear strength of a line of resistance subjected to seismic loading.

Item (a) allows the use of conventional methods of analysis permitted in ASCE 7 to determine the distribution of lateral loads. The designer should use the seismic loading condition that produces the maximum base-shear demand at the line of resistance.

Item (b) allows the location of yielding regions at the interfaces between wall segments and their supporting members.

Item (c) prescribes the use of the loading condition that induces the lowest axial force due to gravity loads. For wall segments loaded with axial forces below the balanced point, this loading condition gives the lowest flexural strength and therefore leads to lower mechanism strengths.

Item (d) limits the flexural strength that is assigned to a plastic hinge so that the maximum shear that can be developed does not exceed one-half the shear strength of the wall segment. This stratagem effectively reduces the strength of the controlling yield mechanism involving wall segments vulnerable to shear failure. In addition to a reduction in strength there is a reduction in deformation capacity as indicated in X.3.2.

X.2 Mechanism strength — Because the controlling yield mechanism is investigated using nominal strengths, an overall strength reduction factor of $\phi = 0.8$ is applied to the limiting base-shear strength. For simplicity, a single value of $\phi$ is adopted.

X.3 Mechanism deformation — This section defines the ductility checks required by the Limit Design method. The deformation demands at locations of plastic hinges are determined by imposing the calculated design roof displacement to the controlling yield mechanism.

X.3.1 The deformation capacity is calculated assuming an ultimate curvature of $\varepsilon_{\text{eq}} / c$ acts on a plastic hinge length of $0.5 L_w$ with an effective shear span of $h_w$. The resulting expression is similar to that used in 3.3.6.5.3(a) to determine the need for special boundary elements. The value of $P_u$ includes earthquake effects and may be calculated using a linearly elastic model.

X.3.2 At locations where the hinge strength is assigned a value lower than the nominal flexural strength due to limitations in X.1(d), the deformation capacity is limited to $h_w / 400$ or $h_w / 200$ depending on the amount of transverse and longitudinal reinforcement.

X.3.3 The limit of 30% of $f_m'$ is intended to ensure that all yielding components respond below the balanced point of the P-M interaction diagram.
Table 3.1 – Reinforcement Options

<table>
<thead>
<tr>
<th>Reinforcement Option</th>
<th>Walls A and C Reinforcement</th>
<th>Wall B Reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flexural $^a$ @ ea. end</td>
<td>Flexural $^a$ @ ea. end</td>
</tr>
<tr>
<td></td>
<td>Shear $^b$ @ 16” o.c.</td>
<td>Shear $^b$ @ 16” o.c.</td>
</tr>
<tr>
<td>R1</td>
<td>(1) #4</td>
<td>(1) #4</td>
</tr>
<tr>
<td>R2</td>
<td>(1) #5</td>
<td>(1) #4</td>
</tr>
<tr>
<td>R3</td>
<td>(1) #6</td>
<td>(1) #4</td>
</tr>
<tr>
<td>R4</td>
<td>(2) #5</td>
<td>(1) #4</td>
</tr>
<tr>
<td>R5</td>
<td>(2) #6</td>
<td>(1) #4</td>
</tr>
<tr>
<td>R6</td>
<td>(1) #5</td>
<td>(1) #4</td>
</tr>
<tr>
<td>R7</td>
<td>(1) #6</td>
<td>(1) #4</td>
</tr>
<tr>
<td>R8</td>
<td>(2) #5</td>
<td>(1) #4</td>
</tr>
<tr>
<td>R9</td>
<td>(2) #6</td>
<td>(1) #4</td>
</tr>
<tr>
<td>R10</td>
<td>(2) #6</td>
<td>(1) #5</td>
</tr>
</tbody>
</table>

$^a$ – All vertical reinforcement is placed one bar per cell

$^b$ – Additional horizontal reinforcement to satisfy MSJC (2011) § 1.18.3.2.6 is neglected in analysis
Table 3.2 – Member Forces due to Dead, Live, and Earthquake Loads

<table>
<thead>
<tr>
<th>Member</th>
<th>Section</th>
<th>Load Case</th>
<th>Forces(^c)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Axial, kip</td>
<td>Shear, kip</td>
</tr>
<tr>
<td>Wall A</td>
<td>Top</td>
<td>Dead, D</td>
<td>7.7</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Live, L</td>
<td>2.2</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Earthquake, E</td>
<td>24.0</td>
<td>18.5</td>
</tr>
<tr>
<td></td>
<td>Bot</td>
<td>Dead, D</td>
<td>10.9</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Live, L</td>
<td>2.2</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Earthquake, E</td>
<td>24.0</td>
<td>18.5</td>
</tr>
<tr>
<td>Wall B</td>
<td>Top</td>
<td>Dead, D</td>
<td>5.6</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Live, L</td>
<td>1.5</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Earthquake, E</td>
<td>6.5</td>
<td>5.6</td>
</tr>
<tr>
<td></td>
<td>Bot</td>
<td>Dead, D</td>
<td>6.9</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Live, L</td>
<td>1.5</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Earthquake, E</td>
<td>6.5</td>
<td>5.6</td>
</tr>
<tr>
<td>Wall C</td>
<td>Top</td>
<td>Dead, D</td>
<td>7.2</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Live, L</td>
<td>2.2</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Earthquake, E</td>
<td>30.6</td>
<td>25.9</td>
</tr>
<tr>
<td></td>
<td>Bot</td>
<td>Dead, D</td>
<td>9.8</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Live, L</td>
<td>2.2</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Earthquake, E</td>
<td>30.6</td>
<td>25.9</td>
</tr>
</tbody>
</table>

\(^a\) – Forces are reported at ends of member clear length
\(^b\) – Forces due to earthquake loads are reported without signs (absolute values) and correspond to a base shear of 50 kip. Lateral story forces due to earthquake loads are applied at roof level
\(^c\) – Dead and live loads induce axial forces in compression. Shear and moments due to dead and live loads are neglected
Table 3.3 – Lateral Stiffness for Different Mesh Sizes

<table>
<thead>
<tr>
<th>Mesh Size (in.)</th>
<th>Lateral Force at Roof (kip)</th>
<th>Roof Displacement (in.)</th>
<th>Stiffness (kip/in.)</th>
<th>Relative Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1x1</td>
<td>100</td>
<td>0.144</td>
<td>696</td>
<td>0.00</td>
</tr>
<tr>
<td>2x2</td>
<td>100</td>
<td>0.143</td>
<td>699</td>
<td>0.35</td>
</tr>
<tr>
<td>4x4</td>
<td>100</td>
<td>0.142</td>
<td>704</td>
<td>1.06</td>
</tr>
<tr>
<td>8x8</td>
<td>100</td>
<td>0.140</td>
<td>716</td>
<td>2.87</td>
</tr>
<tr>
<td>12x12</td>
<td>100</td>
<td>0.127</td>
<td>789</td>
<td>13.3</td>
</tr>
</tbody>
</table>
Table 3.4–Controlling Provisions and Seismic Base Shear per Design Method

<table>
<thead>
<tr>
<th>Condition</th>
<th>Walls A and C Reinforcement</th>
<th>Wall B Reinforcement</th>
<th>Allowable Stress Design</th>
<th>Strength Design</th>
<th>Limit Design</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flexural Shear</td>
<td>Flexural Shear</td>
<td>Flexural Shear</td>
<td>Flexural Shear</td>
<td>Flexural Shear</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1</td>
<td>(1) #4 @ each end</td>
<td>None</td>
<td>(1) #4 @ each end</td>
<td>None</td>
<td>13.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R2</td>
<td>(1) #5 @ each end</td>
<td>None</td>
<td>(1) #4 @ each end</td>
<td>None</td>
<td>14.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R3</td>
<td>(1) #6 @ each end</td>
<td>None</td>
<td>(1) #4 @ each end</td>
<td>None</td>
<td>14.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R4</td>
<td>(2) #5 @ each end</td>
<td>None</td>
<td>(1) #4 @ each end</td>
<td>None</td>
<td>14.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R5</td>
<td>(2) #6 @ each end</td>
<td>None</td>
<td>(1) #4 @ each end</td>
<td>None</td>
<td>14.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R6</td>
<td>(1) #6 @ each end</td>
<td>(2) #4 @ 16&quot; o.c.</td>
<td>(1) #4 @ each end</td>
<td>None</td>
<td>17.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R7</td>
<td>(1) #6 @ each end</td>
<td>(2) #4 @ 16&quot; o.c.</td>
<td>(1) #6 @ each end</td>
<td>None</td>
<td>22.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R8</td>
<td>(2) #5 @ each end</td>
<td>(2) #4 @ 16&quot; o.c.</td>
<td>(1) #6 @ each end</td>
<td>None</td>
<td>26.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R9</td>
<td>(2) #6 @ each end</td>
<td>(2) #4 @ 16&quot; o.c.</td>
<td>(1) #6 @ each end</td>
<td>None</td>
<td>31.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R10</td>
<td>(2) #6 @ each end</td>
<td>(2) #4 @ 16&quot; o.c.</td>
<td>(1) #6 @ each end</td>
<td>None</td>
<td>33.8</td>
</tr>
</tbody>
</table>

✓ Provision passes  □ Provision controls
Code requirement is met when one of three provisions passes
○ Alternate provision passes  ○ Alternate provision fails

---

*a*–Effects of compression reinforcement were included in axial and flexural strength. Slenderness effects were ignored

*b*–Base shear reported as $1.0E$, ASD provisions were checked using $E/1.4$
Table 3.5 – Base Shear Strength for Nonlinear Static Analyses

<table>
<thead>
<tr>
<th>Reinforcement Option</th>
<th>Layer Model (kip)</th>
<th>Link Model (kip)</th>
<th>Mechanism Strength, $V_{lim}^a$ (kip)</th>
<th>Limit Design, $V'_{lim}^b$ (kip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>31.2</td>
<td>31.2</td>
<td>31.0</td>
<td>24.8</td>
</tr>
<tr>
<td>R2</td>
<td>41.1</td>
<td>40.3</td>
<td>38.3</td>
<td>24.5</td>
</tr>
<tr>
<td>R3</td>
<td>50.1</td>
<td>49.0</td>
<td>39.2</td>
<td>24.5</td>
</tr>
<tr>
<td>R4</td>
<td>54.8</td>
<td>55.9</td>
<td>44.2</td>
<td>24.5</td>
</tr>
<tr>
<td>R5</td>
<td>65.4</td>
<td>65.7</td>
<td>59.4</td>
<td>24.5</td>
</tr>
<tr>
<td>R6</td>
<td>41.5</td>
<td>40.3</td>
<td>41.1</td>
<td>32.9</td>
</tr>
<tr>
<td>R7</td>
<td>52.6</td>
<td>51.4</td>
<td>52.9</td>
<td>42.3</td>
</tr>
<tr>
<td>R8</td>
<td>64.2</td>
<td>62.8</td>
<td>62.0</td>
<td>49.1</td>
</tr>
<tr>
<td>R9</td>
<td>82.9</td>
<td>82.3</td>
<td>62.7</td>
<td>49.1</td>
</tr>
<tr>
<td>R10</td>
<td>84.9</td>
<td>85.1</td>
<td>65.0</td>
<td>49.1</td>
</tr>
</tbody>
</table>

- $V_{lim}$ is based on proposed Limit Design code provisions in Table 2.1, using $\phi=1.0$
- $V'_{lim}$ is obtained from $V_{lim}$ after adjustments due to displacement capacities of walls

Table 3.6 – Base Shear Strength and Displacement Capacity

<table>
<thead>
<tr>
<th>Reinforcement Option</th>
<th>$V_{lim}$ (kip)</th>
<th>$\delta_{cap}^b$ (in.)</th>
<th>$V'_{lim}^c$ (kip)</th>
<th>$V_p^d$ (kip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>31.0</td>
<td>0.5 $h_w/\ell_w \varepsilon_{mu}/c = 0.78$</td>
<td>31.0</td>
<td>31.2</td>
</tr>
<tr>
<td>R1$^e$</td>
<td>31.0</td>
<td>0.5 $h_w/\ell_w \varepsilon_{mu}/c = 0.78$</td>
<td>31.0</td>
<td>31.5</td>
</tr>
<tr>
<td>R2</td>
<td>38.3</td>
<td>$h_w/400 = 0.24$</td>
<td>24.5</td>
<td>40.3</td>
</tr>
<tr>
<td>R3</td>
<td>39.2</td>
<td>$h_w/400 = 0.24$</td>
<td>24.5</td>
<td>49.0</td>
</tr>
<tr>
<td>R4</td>
<td>44.2</td>
<td>$h_w/400 = 0.24$</td>
<td>24.5</td>
<td>54.8</td>
</tr>
<tr>
<td>R5</td>
<td>59.3</td>
<td>$h_w/400 = 0.24$</td>
<td>24.5</td>
<td>65.4</td>
</tr>
<tr>
<td>R6</td>
<td>41.1</td>
<td>0.5 $h_w/\ell_w \varepsilon_{mu}/c = 0.76$</td>
<td>41.1</td>
<td>40.3</td>
</tr>
<tr>
<td>R7</td>
<td>52.9</td>
<td>0.5 $h_w/\ell_w \varepsilon_{mu}/c = 0.74$</td>
<td>52.9</td>
<td>51.4</td>
</tr>
<tr>
<td>R8</td>
<td>62.0</td>
<td>$h_w/200 = 0.48$</td>
<td>49.0</td>
<td>62.8</td>
</tr>
<tr>
<td>R9</td>
<td>62.7</td>
<td>$h_w/200 = 0.48$</td>
<td>49.0</td>
<td>82.3</td>
</tr>
<tr>
<td>R10</td>
<td>65.0</td>
<td>$h_w/200 = 0.48$</td>
<td>49.0</td>
<td>84.9</td>
</tr>
<tr>
<td>R10$^e$</td>
<td>65.0</td>
<td>$h_w/200 = 0.48$</td>
<td>49.0</td>
<td>78.2</td>
</tr>
</tbody>
</table>

- $V_{lim}$ is based on Limit Design code in Table 2.1
- $\delta_{cap}$ is displacement capacity
- $V'_{lim}$ is obtained from $V_{lim}$ after adjustments due to displacement capacities of walls
- $V_p$ is minimum value obtained from Nonlinear Layer model and Nonlinear Link model
# Table 3.7 – Selected Nonlinear Static Analysis Observations

<table>
<thead>
<tr>
<th>Figure</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6, 3.8</td>
<td>All three walls yield in flexure at the top and bottom of the clear height defined by the openings. Shear in wall C is higher than walls A and B due to an increase in the flexural strength of wall C after an increase in axial forces induced by seismic overturning.</td>
</tr>
<tr>
<td>3.7, 3.9</td>
<td>All three walls yield in flexure at the top and bottom of the clear height defined by the openings. Shear in wall A is higher than walls B and C due to an increase in the flexural strength of wall A after an increase in axial forces induced by seismic overturning.</td>
</tr>
<tr>
<td>3.26, 3.28</td>
<td>All three walls yield in flexure at the top and bottom of the clear height defined by the openings. Shear in wall C is higher than walls A and B due to an increase in the flexural strength of wall C after an increase in axial forces induced by seismic overturning.</td>
</tr>
<tr>
<td>3.27, 3.29</td>
<td>All three walls yield in flexure at the top and bottom of the clear height defined by the openings. Shear in wall A is higher than walls B and C due to an increase in the flexural strength of wall A after an increase in axial forces induced by seismic overturning.</td>
</tr>
<tr>
<td>3.42, 3.44</td>
<td>Walls A and B yield in flexure at the top and bottom of the clear height defined by the openings while wall C reaches its nominal shear strength (calculated based on Limit Design code provisions, using ϕ=1). Shear in wall C is higher than walls A and B due to decrease in flexural strength of walls A and B after decrease in axial forces induced by seismic overturning.</td>
</tr>
<tr>
<td>3.43, 3.45</td>
<td>All three walls yield in flexure at the top and bottom of the clear height defined by the openings. Shear in wall C is higher than walls A and B due to an increase in the flexural strength of wall C after an increase in axial forces induced by seismic overturning.</td>
</tr>
</tbody>
</table>
Table 4.1 – Reinforcement Options

<table>
<thead>
<tr>
<th>Reinforcement Option</th>
<th>Flexural&lt;sup&gt;a&lt;/sup&gt; @ ea. end</th>
<th>Shear&lt;sup&gt;b&lt;/sup&gt; @ 24&quot; o.c.</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>(1) #5</td>
<td>None</td>
</tr>
<tr>
<td>R2</td>
<td>(2) #5</td>
<td>None</td>
</tr>
<tr>
<td>R3</td>
<td>(2) #5</td>
<td>(2) #4</td>
</tr>
<tr>
<td>R4</td>
<td>(2) #6</td>
<td>(2) #4</td>
</tr>
<tr>
<td>R5</td>
<td>(2) #7</td>
<td>(2) #4</td>
</tr>
</tbody>
</table>

<sup>a</sup> – All vertical reinforcement is placed one bar per cell. Walls 8-ft long have #5 vertical bar at 44 in. from one edge of wall

<sup>b</sup> – Additional horizontal reinforcement to satisfy MSJC (2011) § 1.18.3.2.6 is neglected in analysis
Table 4.2 – Member Forces due to Dead, Live, and Earthquake Loads

<table>
<thead>
<tr>
<th>Member</th>
<th>Section&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Load Case&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Forces&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Axial, kip</td>
</tr>
<tr>
<td>Wall A</td>
<td>Top</td>
<td>Dead, D</td>
<td>150.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Live, L</td>
<td>40.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Earthquake, E</td>
<td>48.4</td>
</tr>
<tr>
<td></td>
<td>Bot</td>
<td>Dead, D</td>
<td>156.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Live, L</td>
<td>40.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Earthquake, E</td>
<td>48.4</td>
</tr>
<tr>
<td>Wall B</td>
<td>Top</td>
<td>Dead, D</td>
<td>150.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Live, L</td>
<td>40.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Earthquake, E</td>
<td>48.4</td>
</tr>
<tr>
<td></td>
<td>Bot</td>
<td>Dead, D</td>
<td>156.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Live, L</td>
<td>40.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Earthquake, E</td>
<td>48.4</td>
</tr>
<tr>
<td>Wall AB</td>
<td>Top</td>
<td>Dead, D</td>
<td>300.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Live, L</td>
<td>80.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Earthquake, E</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Bot</td>
<td>Dead, D</td>
<td>313.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Live, L</td>
<td>80.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Earthquake, E</td>
<td>0.0</td>
</tr>
</tbody>
</table>

<sup>a</sup> – Forces are reported for the first story at ends of member clear length

<sup>b</sup> – Forces due to earthquake loads are reported without signs (absolute values) and correspond to a base shear of 50 kip. Lateral story forces due to earthquake loads are assumed proportional to story elevations and are applied at floor and roof levels

<sup>c</sup> – Dead and live loads induce axial forces in compression. Shear and moments due to dead and live loads are neglected
Table 4.3 – Controlling Provisions and Seismic Base Shear per Design Method

<table>
<thead>
<tr>
<th>Condition</th>
<th>Wall Reinforcement</th>
<th>Flexural Shear</th>
<th>Allowable Stress Design&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Strength Design&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Limit Design&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Allowable Stress Design&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Strength Design&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Limit Design&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Shear Strength</td>
<td>Flexural Strength</td>
<td>Rho Max</td>
<td>Seismic Base Shear&lt;sup&gt;d&lt;/sup&gt;</td>
<td>Rho Max Check</td>
<td>Seismic Base Shear&lt;sup&gt;d&lt;/sup&gt;</td>
<td>Rho Max Check</td>
</tr>
<tr>
<td>R1</td>
<td>(1) 5 (2) each end</td>
<td>None</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>R2</td>
<td>(2) 5 (2) each end</td>
<td>None</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>R3</td>
<td>(2) 5 (2) each end</td>
<td>#4 @ 24&quot; O.C.</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>R4</td>
<td>(2) #6 (2) each end</td>
<td>#4 @ 24&quot; O.C.</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>R5</td>
<td>(2) #7 (2) each end</td>
<td>#4 @ 24&quot; O.C.</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

✓ Provision passes  ☐ Provision controls

Code requirement is met when one of three provisions passes
☐ Alternate provision passes  ☐ Alternate provision fails

<sup>a</sup> Effects of compression reinforcement were included in axial and flexural strength. Slenderness effects were ignored

<sup>b</sup> Base shear reported as 1.0E, ASD provisions were checked using E/1.4
### Table 4.4 – Base Shear Strength for Nonlinear Static Analyses

<table>
<thead>
<tr>
<th>Reinforcement Option</th>
<th>Layer Model (kip)</th>
<th>Link Model (kip)</th>
<th>Mechanism Strength, $V_{lim}^{a}$ (kip)</th>
<th>Limit Design, $V'_{lim}^{b}$ (kip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>124.4</td>
<td>123.2</td>
<td>94.5</td>
<td>35.5</td>
</tr>
<tr>
<td>R2</td>
<td>138.4</td>
<td>136.9</td>
<td>94.5</td>
<td>0.0</td>
</tr>
<tr>
<td>R3</td>
<td>154.5</td>
<td>153.0</td>
<td>118.3</td>
<td>70.9</td>
</tr>
<tr>
<td>R4</td>
<td>169.6</td>
<td>164.8</td>
<td>118.3</td>
<td>70.9</td>
</tr>
<tr>
<td>R5</td>
<td>187.8</td>
<td>180.0</td>
<td>118.3</td>
<td>0.0</td>
</tr>
</tbody>
</table>

$^{a}$ – Based on proposed Limit Design code provisions in Table 2.1, using $\phi=1.0$

$^{b}$ – $V'_{lim}$ is obtained from $V_{lim}$ after adjustments due to displacement capacities of walls

### Table 4.5 – Base Shear Strength and Displacement Capacity

<table>
<thead>
<tr>
<th>Reinforcement Option</th>
<th>Limit Design Code$^{a}$</th>
<th>Nonlinear Static Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$V_{lim}$ (kip)</td>
<td>$\delta_{cap}^{b}$ (in.)</td>
</tr>
<tr>
<td>R1</td>
<td>94.5</td>
<td>$h_w/400 = 0.30$</td>
</tr>
<tr>
<td>R1$^e$</td>
<td>94.5</td>
<td>$h_w/400 = 0.30$</td>
</tr>
<tr>
<td>R2</td>
<td>94.5</td>
<td>$h_w/400 = 0.30$</td>
</tr>
<tr>
<td>R3</td>
<td>118.3</td>
<td>$h_w/200 = 0.60$</td>
</tr>
<tr>
<td>R4</td>
<td>118.3</td>
<td>$h_w/200 = 0.60$</td>
</tr>
<tr>
<td>R5</td>
<td>118.3</td>
<td>$h_w/200 = 0.60$</td>
</tr>
<tr>
<td>R5$^e$</td>
<td>118.3</td>
<td>$h_w/200 = 0.60$</td>
</tr>
</tbody>
</table>

$^{a}$ – Based on Limit Design code in Table 2.1

$^{b}$ – Displacement Capacity

$^{c}$ – $V'_{lim}$ is obtained from $V_{lim}$ after adjustments due to displacement capacities of walls

$^{d}$ – Minimum value obtained from Nonlinear Layer model and Nonlinear Link model

$^{e}$ – Refined Nonlinear Layer model

$^{f}$ – $V_{Min} > V_n$
Table 4.6 – Selected Nonlinear Static Analysis Observations

<table>
<thead>
<tr>
<th>Figure</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.6, 4.7</td>
<td>Wall A yields in flexure before wall B at the bottom of the clear height defined by the opening. Flexural strength of wall B is higher than wall A due to axial forces induced by seismic overturning. Wall B reaches its nominal shear strength before yielding in flexure.</td>
</tr>
<tr>
<td>4.10, 4.11</td>
<td>Wall A yields in flexure before wall B at the bottom of the clear height defined by the opening. Flexural strength of wall B is higher than wall A due to axial forces induced by seismic overturning. Wall B reaches its nominal shear strength before yielding in flexure.</td>
</tr>
<tr>
<td>4.14, 4.15</td>
<td>Wall A yields in flexure before wall B at the bottom of the clear height defined by the opening. Flexural strength of wall B is higher than wall A due to axial forces induced by seismic overturning. Wall B reaches its nominal shear strength before yielding in flexure.</td>
</tr>
</tbody>
</table>
Table 5.1 – Reinforcement Options

| Reinforcement Option | Wall Reinforcement |  | Beam Reinforcement |  |
|----------------------|--------------------|--------------------------|------------------|
|                      | Flexural<sup>a</sup> @ ea. end | Shear<sup>b</sup> @ 16” o.c. | Flexural<sup>c</sup> Top & bot | Shear @ 8” o.c. |
| R1                   | (1) #5             | None                     | (2) #5           | (1) #4           |
| R2                   | (1) #5             | None                     | (4) #4           | (1) #4           |
| R3                   | (1) #5             | (2) #4                   | (4) #4           | (1) #4           |
| R4                   | (2) #5             | (2) #4                   | (4) #4           | (1) #4           |
| R5                   | (2) #6             | (2) #4                   | (4) #4           | (1) #4           |
| R6                   | (2) #6             | (2) #4                   | (4) #5           | (1) #4           |
| R7                   | (2) #6             | (2) #4                   | (4) #6           | (1) #4           |

<sup>a</sup> – All vertical reinforcement is placed one bar per cell. Walls 8-ft long have #5 vertical bar at 44 in. from one edge of wall.

<sup>b</sup> – Additional horizontal reinforcement to satisfy MSJC (2011) § 1.18.3.2.6 is neglected in analysis.

<sup>c</sup> – Beams have two bars per cell; i.e., (4) #4 indicate two bars in the top two cells and two bars in the bottom two cells.
Table 5.2 – Member Forces due to Dead, Live, and Earthquake Loads

<table>
<thead>
<tr>
<th>Member</th>
<th>Section</th>
<th>Load Case</th>
<th>Forces&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Axial, kip</th>
<th>Shear, kip</th>
<th>Moment, kip-ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall A</td>
<td>Top</td>
<td>Dead, D</td>
<td>87.4</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Live, L</td>
<td>40.0</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Earthquake, E</td>
<td>36.5</td>
<td>25.0</td>
<td>126.8</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Bot</td>
<td>Dead, D</td>
<td>93.8</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Live, L</td>
<td>40.0</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Earthquake, E</td>
<td>36.5</td>
<td>25.0</td>
<td>383.3</td>
<td>–</td>
</tr>
<tr>
<td>Wall B</td>
<td>Top</td>
<td>Dead, D</td>
<td>87.4</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Live, L</td>
<td>40.0</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Earthquake, E</td>
<td>36.5</td>
<td>25.0</td>
<td>126.8</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Bot</td>
<td>Dead, D</td>
<td>93.8</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Live, L</td>
<td>40.0</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Earthquake, E</td>
<td>36.5</td>
<td>25.0</td>
<td>383.3</td>
<td>–</td>
</tr>
<tr>
<td>Beams</td>
<td>Left</td>
<td>Dead, D</td>
<td>–</td>
<td>8.6</td>
<td>31.1</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Live, L</td>
<td>–</td>
<td>4.8</td>
<td>17.3</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Earthquake, E</td>
<td>–</td>
<td>8.5</td>
<td>101.7</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>Dead, D</td>
<td>–</td>
<td>8.6</td>
<td>31.1</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Live, L</td>
<td>–</td>
<td>4.8</td>
<td>17.3</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Earthquake, E</td>
<td>–</td>
<td>8.5</td>
<td>101.7</td>
<td>–</td>
</tr>
</tbody>
</table>

<sup>a</sup> – Forces are reported for the first story at ends of member clear length

<sup>b</sup> – Forces due to earthquake loads are reported without signs (absolute values) and correspond to a base shear of 50 kip. Lateral story forces due to earthquake loads are assumed proportional to story elevations and are applied at floor and roof levels

<sup>c</sup> – Dead and live loads induce axial forces in compression. Shear and moments due to dead and live loads are neglected except for beams
Table 5.3 – Controlling Provisions and Seismic Base Shear per Design Method

<table>
<thead>
<tr>
<th>Condition</th>
<th>Wall Reinforcement</th>
<th>Beam Reinforcement</th>
<th>Allowable Stress Design(^a)</th>
<th>Strength Design(^a)</th>
<th>Limit Design(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flexural Shear</td>
<td>Flexural Shear</td>
<td>Flexural Shear</td>
<td>Walls Beams</td>
<td>Walls Beams</td>
</tr>
<tr>
<td>R1</td>
<td>[1] #5 @ each end</td>
<td>None</td>
<td>[2] #4 @ top &amp; bot</td>
<td>(1) #4 @ 8&quot; o.c.</td>
<td>✓</td>
</tr>
<tr>
<td>R2</td>
<td>[1] #5 @ each end</td>
<td>None</td>
<td>[2] #4 @ top &amp; bot</td>
<td>(1) #4 @ 8&quot; o.c.</td>
<td>✓</td>
</tr>
<tr>
<td>R3</td>
<td>[1] #5 @ each end</td>
<td>None</td>
<td>[2] #4 @ 16&quot; o.c.</td>
<td>(1) #4 @ 8&quot; o.c.</td>
<td>✓</td>
</tr>
<tr>
<td>R4</td>
<td>[2] #5 @ each end</td>
<td>None</td>
<td>[2] #4 @ 16&quot; o.c.</td>
<td>(1) #4 @ 8&quot; o.c.</td>
<td>✓</td>
</tr>
<tr>
<td>R5</td>
<td>[2] #5 @ each end</td>
<td>None</td>
<td>[2] #4 @ 16&quot; o.c.</td>
<td>(1) #4 @ 8&quot; o.c.</td>
<td>✓</td>
</tr>
<tr>
<td>R6</td>
<td>[2] #5 @ each end</td>
<td>None</td>
<td>[2] #4 @ 16&quot; o.c.</td>
<td>(1) #4 @ 8&quot; o.c.</td>
<td>✓</td>
</tr>
<tr>
<td>R7</td>
<td>[2] #5 @ each end</td>
<td>None</td>
<td>[2] #4 @ 10&quot; o.c.</td>
<td>(1) #4 @ 8&quot; o.c.</td>
<td>✓</td>
</tr>
</tbody>
</table>

\[✓\] Provision passes \[✗\] Provision controls

Code requirement is met when one of three provisions passes

\(\bigcirc\) Alternate provision passes \(\bigcirc\) Alternate provision fails \(\bigcirc\) Alternate provision controls

\(^a\) – Effects of compression reinforcement were included in axial and flexural strength. Slenderness effects were ignored

\(^b\) – Base shear reported as 1.0E, ASD provisions were checked using E/1.4
Table 5.4 – Base Shear Strength for Nonlinear Static Analyses

<table>
<thead>
<tr>
<th>Reinforcement Option</th>
<th>Layer Model (kip)</th>
<th>Link Model (kip)</th>
<th>Mechanism Strength, $V_{\text{lim}}$ a (kip)</th>
<th>Limit Design, $V'_{\text{lim}}$ b (kip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>70.6</td>
<td>71.0</td>
<td>68.0</td>
<td>51.5</td>
</tr>
<tr>
<td>R2</td>
<td>79.7</td>
<td>79.8</td>
<td>78.8</td>
<td>51.5</td>
</tr>
<tr>
<td>R3</td>
<td>79.5</td>
<td>79.9</td>
<td>78.8</td>
<td>51.5</td>
</tr>
<tr>
<td>R4</td>
<td>85.8</td>
<td>86.2</td>
<td>84.8</td>
<td>50.5</td>
</tr>
<tr>
<td>R5</td>
<td>92.3</td>
<td>91.9</td>
<td>90.2</td>
<td>50.1</td>
</tr>
<tr>
<td>R6</td>
<td>120.2</td>
<td>118.1</td>
<td>111.4</td>
<td>44.5</td>
</tr>
<tr>
<td>R7</td>
<td>149.7</td>
<td>146.0</td>
<td>139.7</td>
<td>44.5</td>
</tr>
</tbody>
</table>

a – Based on proposed Limit Design code provisions in Table 2.1, using $\phi$=1.0
b – $V'_{\text{lim}}$ is obtained from $V_{\text{lim}}$ after adjustments due to displacement capacities of walls

Table 5.5 – Base Shear Strength and Displacement Capacity

<table>
<thead>
<tr>
<th>Reinforcement Option</th>
<th>$V_{\text{lim}}$ (kip)</th>
<th>$\delta_{\text{cap}}$ b (in.)</th>
<th>$V'_{\text{lim}}$ c (kip)</th>
<th>$V_p$ d (kip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>68.0</td>
<td>$0.5 h_w \ell_w \varepsilon_{\text{mu}}/c = 2.71$</td>
<td>51.5</td>
<td>70.6</td>
</tr>
<tr>
<td>R1$^e$</td>
<td>68.0</td>
<td>$0.5 h_w \ell_w \varepsilon_{\text{mu}}/c = 2.71$</td>
<td>51.5</td>
<td>66.0</td>
</tr>
<tr>
<td>R2</td>
<td>78.8</td>
<td>$0.5 h_w \ell_w \varepsilon_{\text{mu}}/c = 2.71$</td>
<td>51.5</td>
<td>79.7</td>
</tr>
<tr>
<td>R3</td>
<td>78.8</td>
<td>$0.5 h_w \ell_w \varepsilon_{\text{mu}}/c = 2.71$</td>
<td>51.5</td>
<td>79.5</td>
</tr>
<tr>
<td>R4</td>
<td>84.8</td>
<td>$0.5 h_w \ell_w \varepsilon_{\text{mu}}/c = 2.65$</td>
<td>50.5</td>
<td>85.8</td>
</tr>
<tr>
<td>R5</td>
<td>90.2</td>
<td>$0.5 h_w \ell_w \varepsilon_{\text{mu}}/c = 2.63$</td>
<td>50.1</td>
<td>91.9</td>
</tr>
<tr>
<td>R6</td>
<td>114.4</td>
<td>$h_w/200 = 1.44$</td>
<td>44.5</td>
<td>118.1</td>
</tr>
<tr>
<td>R7</td>
<td>139.7</td>
<td>$h_w/200 = 1.44$</td>
<td>44.5</td>
<td>146.0</td>
</tr>
<tr>
<td>R7$^e$</td>
<td>139.7</td>
<td>$h_w/200 = 1.44$</td>
<td>44.5</td>
<td>143.2</td>
</tr>
</tbody>
</table>

a – Based on Limit Design code in Table 2.1
b – Displacement capacity
c – $V'_{\text{lim}}$ is obtained from $V_{\text{lim}}$ after adjustments due to displacement capacities of walls
d – Minimum value obtained from Nonlinear Layer model and Nonlinear Link model
e – Refined Nonlinear Layer model
Table 5.6 – Selected Nonlinear Static Analysis Observations

<table>
<thead>
<tr>
<th>Figure</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.6, 5.7</td>
<td>Wall A yields in flexure before wall B at the bottom of the clear height defined by the opening. Flexural Strength of wall B is higher than wall A due to axial forces induced by seismic overturning. Both walls experience flexural yielding. Coupling beams in all stories yield in flexure indicating the development of a full structural mechanism.</td>
</tr>
<tr>
<td>5.22, 5.23</td>
<td></td>
</tr>
<tr>
<td>5.14, 5.15</td>
<td>Wall A yields in flexure before wall B at the bottom of the clear height defined by the opening. Flexural strength of wall B is higher than wall A due to axial forces induced by seismic overturning. Both walls experience flexural yielding. Coupling beams in all stories yield in flexure indicating the development of a full structural mechanism.</td>
</tr>
<tr>
<td>5.30, 5.31</td>
<td></td>
</tr>
<tr>
<td>5.18, 5.19</td>
<td>Wall A yields in flexure before wall B at the bottom of the clear height defined by the opening. Flexural strength of wall B is higher than wall A due to axial forces induced by seismic overturning. Wall B reaches its nominal shear strength before yielding in flexure. Coupling beams in all stories yield in flexure indicating the development of a full structural mechanism.</td>
</tr>
<tr>
<td>5.34, 5.35</td>
<td></td>
</tr>
</tbody>
</table>
Table 6.1 – Reinforcement Schedules

<table>
<thead>
<tr>
<th>Structure</th>
<th>Wall A</th>
<th>Wall B</th>
<th>Wall C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flexural Shear</td>
<td>Flexural Shear</td>
<td>Flexural Shear</td>
</tr>
<tr>
<td>RM1</td>
<td>#11g @ 4in.</td>
<td>#11g @ 4in.</td>
<td>#11g @ 4in.</td>
</tr>
<tr>
<td>RM2</td>
<td>#11g @ 4in.</td>
<td>#11g @ 4in.</td>
<td>#11g @ 4in.</td>
</tr>
<tr>
<td>RM3</td>
<td>#11g @ 4in.</td>
<td>#11g @ 2in.</td>
<td>#11g @ 4in.</td>
</tr>
</tbody>
</table>

\[ ^a \text{– Paulson and Abrams (1990)} \]

Table 6.2 – Material Properties

<table>
<thead>
<tr>
<th>Structure</th>
<th>Mean ( f'_m ) (psi)</th>
<th>Initial Tangent Modulus ( E_m ) (psi)</th>
<th>Shear Modulus ( G ) (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RM1-RM2</td>
<td>1215</td>
<td>720000</td>
<td>288000</td>
</tr>
<tr>
<td>RM3</td>
<td>1228</td>
<td>910000</td>
<td>364000</td>
</tr>
</tbody>
</table>

\[ ^a \text{– Paulson and Abrams (1990)} \]

Table 6.3 – Measured First-Mode Frequency of Vibration

<table>
<thead>
<tr>
<th>Structure</th>
<th>Measured(^a) (Hz)</th>
<th>Calculated(^b) (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RM1</td>
<td>15.5</td>
<td>17.0</td>
</tr>
<tr>
<td>RM3</td>
<td>13.2</td>
<td>13.3</td>
</tr>
</tbody>
</table>

\[ ^a \text{– By Paulson and Abrams (1990), before first earthquake simulation test.} \\
^b \text{– Using the models described in Appendix B, Section B.4.4. Mass sources are defined based on the applied dead loads} \]

Table 6.4 – Measured Base Shear Strength

<table>
<thead>
<tr>
<th>Structure</th>
<th>Load Direction</th>
<th>Measured Peak Base Shear(^b) (kip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RM1</td>
<td>Eastward</td>
<td>12.9</td>
</tr>
<tr>
<td></td>
<td>Westward</td>
<td>14.6</td>
</tr>
<tr>
<td>RM2</td>
<td>Northward</td>
<td>9.4</td>
</tr>
<tr>
<td></td>
<td>Southward</td>
<td>9.3</td>
</tr>
<tr>
<td>RM3</td>
<td>Eastward</td>
<td>11.2</td>
</tr>
<tr>
<td></td>
<td>Westward</td>
<td>12.8</td>
</tr>
</tbody>
</table>

\[ ^a \text{– Paulson and Abrams (1990)} \\
^b \text{– Structures RM1 and RM3 subjected to dynamic tests (Earthquake Simulations). Structure RM2 subjected to static tests} \]
Table 6.5 – Calculated Base Shear Strength, Structures RM1 and RM2

<table>
<thead>
<tr>
<th>Wall</th>
<th>$\delta_{cap}^a$ (in.)</th>
<th>Base Shear$^b$ (kip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$h_w/200 = 0.08$</td>
<td>8.7</td>
</tr>
<tr>
<td>B</td>
<td>$h_w/200 = 0.08$</td>
<td>2.0</td>
</tr>
<tr>
<td>C</td>
<td>$h_w/200 = 0.08$</td>
<td></td>
</tr>
</tbody>
</table>

$^a - \delta_{cap} = 0.5 \, h_w \, \epsilon_{mu}/c$  (for shear-controlled walls, $\delta_{cap} = h_w/200$)

$^b - V'_{lim}$ is obtained from $V_{lim}$ after adjustments due to displacement capacities of walls

Table 6.6 – Calculated Base Shear Strength, Structure RM3

<table>
<thead>
<tr>
<th>Wall</th>
<th>$\delta_{cap}^a$ (in.)</th>
<th>Base Shear$^b$ (kip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$h_w/200 = 0.06$</td>
<td>7.7</td>
</tr>
<tr>
<td>B</td>
<td>$h_w/200 = 0.06$</td>
<td>0.9</td>
</tr>
<tr>
<td>C</td>
<td>$h_w/200 = 0.14$</td>
<td></td>
</tr>
</tbody>
</table>

$^a - \delta_{cap} = 0.5 \, h_w \, \epsilon_{mu}/c$  (for shear-controlled walls, $\delta_{cap} = h_w/200$)

$^b - V'_{lim}$ is obtained from $V_{lim}$ after adjustments due to displacement capacities of walls

Table 6.7 – Base Shear Strength for Nonlinear Static Analyses

<table>
<thead>
<tr>
<th>Structure</th>
<th>Layer Model$^a$ (kip)</th>
<th>Mechanism Strength, $V_{lim}^{a,b}$ (kip)</th>
<th>Limit Design, $V'_{lim}^{a,c}$ (kip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RM1</td>
<td>9.6</td>
<td>8.7</td>
<td>2.0</td>
</tr>
<tr>
<td>RM2</td>
<td>9.6</td>
<td>8.7</td>
<td>2.0</td>
</tr>
<tr>
<td>RM3</td>
<td>7.4</td>
<td>7.7</td>
<td>0.9</td>
</tr>
</tbody>
</table>

$^a -$ Applied gravity loads are unfactored and based on the measured weight

$^b -$ Based on proposed Limit Design code provisions in Table 2.1, using $\phi=1.0$

$^c - V'_{lim}$ is obtained from $V_{lim}$ after adjustments due to displacement capacities of walls
Table 6.8 – Selected Nonlinear Static Analysis Observations

<table>
<thead>
<tr>
<th>Figure</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.17</td>
<td>All three walls yield in flexure in the first story at the top and bottom of the clear height defined by the openings. Flexural strength in wall C is higher than wall A due to axial forces induced by seismic overturning. Wall A yields in pure tension causing zero flexural strength and zero shear demand. Wall B reaches higher flexural strength than wall C (wall B is longer).</td>
</tr>
<tr>
<td>6.18</td>
<td>All three walls yield in flexure in the first story at the top and bottom of the clear height defined by the openings. Wall A yields in pure tension causing zero flexural strength and zero shear demand. At the onset of developing the structure yield mechanism, wall B resists the largest fraction of the base shear because is stiffer than wall C. Wall C increases its flexural strength due to forces induced by the coupling slabs.</td>
</tr>
<tr>
<td>6.19</td>
<td>Walls B and C yield in flexure at the top and bottom of the clear height defined by the openings while wall A reaches its nominal shear strength (calculated based on Limit Design code provisions, using ( \phi = 1 )). Seismic overturning increases compression forces in wall A leading to an increase in its flexural strength and stiffness. Wall C yields in pure tension due to forces induced by the coupling slabs, leading to zero flexural strength and zero shear demand.</td>
</tr>
</tbody>
</table>
Table A.1 - Experimental Data

<table>
<thead>
<tr>
<th>Author</th>
<th>ID</th>
<th>Failure Type</th>
<th>$h_w$ (in.)</th>
<th>$h_w/l_w$</th>
<th>$\rho_s$ (%)</th>
<th>$\rho_s/f_s A_g$ (%)</th>
<th>$\delta_{u, exp}$ (in.)</th>
<th>$V_{lm}$ (kip)</th>
<th>$V_n$ (kip)</th>
<th>Shear Controlled</th>
<th>$\delta_{cap}$ (in.)</th>
<th>$\delta_{cap}/\delta_{u, exp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shing et al.</td>
<td>3 (+)</td>
<td>Shear</td>
<td>72</td>
<td>1</td>
<td>0.74</td>
<td>0.14</td>
<td>8.9</td>
<td>1.12</td>
<td>124</td>
<td>89</td>
<td>YES</td>
<td>0.34</td>
</tr>
<tr>
<td>Shing et al.</td>
<td>3 (-)</td>
<td>Shear</td>
<td>72</td>
<td>1</td>
<td>0.74</td>
<td>0.14</td>
<td>8.9</td>
<td>1.00</td>
<td>124</td>
<td>89</td>
<td>YES</td>
<td>0.34</td>
</tr>
<tr>
<td>Shing et al.</td>
<td>4 (+)</td>
<td>Shear</td>
<td>72</td>
<td>1</td>
<td>0.74</td>
<td>0.14</td>
<td>0.0</td>
<td>0.41</td>
<td>80</td>
<td>60</td>
<td>YES</td>
<td>0.36</td>
</tr>
<tr>
<td>Shing et al.</td>
<td>4 (-)</td>
<td>Shear</td>
<td>72</td>
<td>1</td>
<td>0.74</td>
<td>0.14</td>
<td>0.0</td>
<td>0.58</td>
<td>80</td>
<td>60</td>
<td>YES</td>
<td>0.36</td>
</tr>
<tr>
<td>Shing et al.</td>
<td>5 (+)</td>
<td>Shear</td>
<td>72</td>
<td>1</td>
<td>0.74</td>
<td>0.14</td>
<td>3.8</td>
<td>0.48</td>
<td>102</td>
<td>70</td>
<td>YES</td>
<td>0.36</td>
</tr>
<tr>
<td>Shing et al.</td>
<td>5 (-)</td>
<td>Shear</td>
<td>72</td>
<td>1</td>
<td>0.74</td>
<td>0.14</td>
<td>3.8</td>
<td>0.50</td>
<td>102</td>
<td>70</td>
<td>YES</td>
<td>0.36</td>
</tr>
<tr>
<td>Shing et al.</td>
<td>7 (+)</td>
<td>Shear</td>
<td>72</td>
<td>1</td>
<td>0.74</td>
<td>0.14</td>
<td>3.3</td>
<td>0.62</td>
<td>104</td>
<td>74</td>
<td>YES</td>
<td>0.36</td>
</tr>
<tr>
<td>Shing et al.</td>
<td>7 (-)</td>
<td>Shear</td>
<td>72</td>
<td>1</td>
<td>0.74</td>
<td>0.14</td>
<td>3.3</td>
<td>0.71</td>
<td>104</td>
<td>74</td>
<td>YES</td>
<td>0.36</td>
</tr>
<tr>
<td>Shing et al.</td>
<td>9 (+)</td>
<td>Shear</td>
<td>72</td>
<td>1</td>
<td>0.38</td>
<td>0.14</td>
<td>8.9</td>
<td>0.45</td>
<td>85</td>
<td>89</td>
<td>YES</td>
<td>0.36</td>
</tr>
<tr>
<td>Shing et al.</td>
<td>9 (-)</td>
<td>Shear</td>
<td>72</td>
<td>1</td>
<td>0.38</td>
<td>0.14</td>
<td>8.9</td>
<td>0.47</td>
<td>85</td>
<td>89</td>
<td>YES</td>
<td>0.36</td>
</tr>
<tr>
<td>Shing et al.</td>
<td>13 (+)</td>
<td>Shear</td>
<td>72</td>
<td>1</td>
<td>0.54</td>
<td>0.24</td>
<td>8.1</td>
<td>0.74</td>
<td>102</td>
<td>93</td>
<td>YES</td>
<td>0.36</td>
</tr>
<tr>
<td>Shing et al.</td>
<td>13 (-)</td>
<td>Shear</td>
<td>72</td>
<td>1</td>
<td>0.54</td>
<td>0.24</td>
<td>8.1</td>
<td>0.70</td>
<td>102</td>
<td>93</td>
<td>YES</td>
<td>0.36</td>
</tr>
<tr>
<td>Shing et al.</td>
<td>14 (+)</td>
<td>Shear</td>
<td>72</td>
<td>1</td>
<td>0.54</td>
<td>0.24</td>
<td>8.1</td>
<td>0.63</td>
<td>102</td>
<td>93</td>
<td>YES</td>
<td>0.36</td>
</tr>
<tr>
<td>Shing et al.</td>
<td>14 (-)</td>
<td>Shear</td>
<td>72</td>
<td>1</td>
<td>0.54</td>
<td>0.24</td>
<td>8.1</td>
<td>0.40</td>
<td>102</td>
<td>93</td>
<td>YES</td>
<td>0.36</td>
</tr>
<tr>
<td>Shing et al.</td>
<td>16 (+)</td>
<td>Shear</td>
<td>72</td>
<td>1</td>
<td>0.74</td>
<td>0.24</td>
<td>10.7</td>
<td>0.70</td>
<td>117</td>
<td>81</td>
<td>YES</td>
<td>0.31</td>
</tr>
<tr>
<td>Shing et al.</td>
<td>16 (-)</td>
<td>Shear</td>
<td>72</td>
<td>1</td>
<td>0.74</td>
<td>0.24</td>
<td>10.7</td>
<td>0.70</td>
<td>117</td>
<td>81</td>
<td>YES</td>
<td>0.31</td>
</tr>
<tr>
<td>Voon and Ingham</td>
<td>2 (+)</td>
<td>Shear</td>
<td>71</td>
<td>1</td>
<td>0.62</td>
<td>0.01</td>
<td>0.0</td>
<td>0.38</td>
<td>51</td>
<td>45</td>
<td>YES</td>
<td>0.18</td>
</tr>
<tr>
<td>Voon and Ingham</td>
<td>2 (-)</td>
<td>Shear</td>
<td>71</td>
<td>1</td>
<td>0.62</td>
<td>0.01</td>
<td>0.0</td>
<td>0.33</td>
<td>51</td>
<td>45</td>
<td>YES</td>
<td>0.18</td>
</tr>
<tr>
<td>Voon and Ingham</td>
<td>4 (+)</td>
<td>Shear</td>
<td>71</td>
<td>1</td>
<td>0.62</td>
<td>0.06</td>
<td>0.0</td>
<td>0.43</td>
<td>51</td>
<td>51</td>
<td>YES</td>
<td>0.18</td>
</tr>
<tr>
<td>Voon and Ingham</td>
<td>4 (-)</td>
<td>Shear</td>
<td>71</td>
<td>1</td>
<td>0.62</td>
<td>0.06</td>
<td>0.0</td>
<td>0.31</td>
<td>51</td>
<td>51</td>
<td>YES</td>
<td>0.18</td>
</tr>
<tr>
<td>Voon and Ingham</td>
<td>7 (+)</td>
<td>Shear</td>
<td>71</td>
<td>1</td>
<td>0.62</td>
<td>0.05</td>
<td>2.7</td>
<td>0.33</td>
<td>62</td>
<td>57</td>
<td>YES</td>
<td>0.18</td>
</tr>
<tr>
<td>Voon and Ingham</td>
<td>7 (-)</td>
<td>Shear</td>
<td>71</td>
<td>1</td>
<td>0.62</td>
<td>0.05</td>
<td>2.7</td>
<td>0.34</td>
<td>62</td>
<td>57</td>
<td>YES</td>
<td>0.18</td>
</tr>
<tr>
<td>Voon and Ingham</td>
<td>8 (+)</td>
<td>Shear</td>
<td>71</td>
<td>1</td>
<td>0.62</td>
<td>0.05</td>
<td>1.3</td>
<td>0.26</td>
<td>57</td>
<td>54</td>
<td>YES</td>
<td>0.18</td>
</tr>
<tr>
<td>Voon and Ingham</td>
<td>8 (-)</td>
<td>Shear</td>
<td>71</td>
<td>1</td>
<td>0.62</td>
<td>0.05</td>
<td>1.3</td>
<td>0.34</td>
<td>57</td>
<td>54</td>
<td>YES</td>
<td>0.18</td>
</tr>
<tr>
<td>Voon and Ingham</td>
<td>9 (+)</td>
<td>Shear</td>
<td>142</td>
<td>2</td>
<td>0.62</td>
<td>0.05</td>
<td>1.0</td>
<td>1.00</td>
<td>42</td>
<td>60</td>
<td>YES</td>
<td>0.35</td>
</tr>
<tr>
<td>Voon and Ingham</td>
<td>9 (-)</td>
<td>Shear</td>
<td>142</td>
<td>2</td>
<td>0.62</td>
<td>0.05</td>
<td>1.0</td>
<td>1.04</td>
<td>42</td>
<td>60</td>
<td>YES</td>
<td>0.35</td>
</tr>
</tbody>
</table>

$^a$ $\delta_{cap} = 0.5 \frac{h_w l_w}{c_{md}}$ (except for shear-controlled walls where $h_w/200$ or $h_w/400$ governs, see Table 2.1)
<table>
<thead>
<tr>
<th>Author</th>
<th>ID</th>
<th>Failure Type</th>
<th>$h_w$ (in.)</th>
<th>$h_{sl}/h_w$</th>
<th>$\rho_r$ (%)</th>
<th>$P_{cl}/f_{w}A_0$ (%)</th>
<th>$\delta_{s, S}$ (in.)</th>
<th>$V_{MN}$ (kip)</th>
<th>$V_n$ (kip)</th>
<th>Shear Controlled</th>
<th>$\delta_{s, S}^a$</th>
<th>$\delta_{s, S}/\delta_{s, S}^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shing et al.</td>
<td>1 (+)</td>
<td>Flexure</td>
<td>72</td>
<td>1</td>
<td>0.38</td>
<td>0.24</td>
<td>6.8</td>
<td>0.90</td>
<td>76</td>
<td>87</td>
<td>YES</td>
<td>0.36</td>
</tr>
<tr>
<td>Shing et al.</td>
<td>1 (-)</td>
<td>Flexure</td>
<td>72</td>
<td>1</td>
<td>0.38</td>
<td>0.24</td>
<td>6.8</td>
<td>0.61</td>
<td>76</td>
<td>87</td>
<td>YES</td>
<td>0.36</td>
</tr>
<tr>
<td>Shing et al.</td>
<td>2 (+)</td>
<td>Flexure</td>
<td>72</td>
<td>1</td>
<td>0.38</td>
<td>0.24</td>
<td>9.2</td>
<td>0.92</td>
<td>85</td>
<td>87</td>
<td>YES</td>
<td>0.36</td>
</tr>
<tr>
<td>Shing et al.</td>
<td>2 (-)</td>
<td>Flexure</td>
<td>72</td>
<td>1</td>
<td>0.38</td>
<td>0.24</td>
<td>9.2</td>
<td>0.90</td>
<td>85</td>
<td>87</td>
<td>YES</td>
<td>0.36</td>
</tr>
<tr>
<td>Shing et al.</td>
<td>10 (+)</td>
<td>Flexure</td>
<td>72</td>
<td>1</td>
<td>0.38</td>
<td>0.14</td>
<td>3.1</td>
<td>1.14</td>
<td>62</td>
<td>75</td>
<td>YES</td>
<td>0.36</td>
</tr>
<tr>
<td>Shing et al.</td>
<td>10 (-)</td>
<td>Flexure</td>
<td>72</td>
<td>1</td>
<td>0.38</td>
<td>0.14</td>
<td>3.1</td>
<td>1.17</td>
<td>62</td>
<td>75</td>
<td>YES</td>
<td>0.36</td>
</tr>
<tr>
<td>Shing et al.</td>
<td>12 (+)</td>
<td>Flexure</td>
<td>72</td>
<td>1</td>
<td>0.38</td>
<td>0.24</td>
<td>3.1</td>
<td>1.14</td>
<td>62</td>
<td>92</td>
<td>YES</td>
<td>0.36</td>
</tr>
<tr>
<td>Shing et al.</td>
<td>12 (-)</td>
<td>Flexure</td>
<td>72</td>
<td>1</td>
<td>0.38</td>
<td>0.24</td>
<td>3.1</td>
<td>1.15</td>
<td>62</td>
<td>92</td>
<td>YES</td>
<td>0.36</td>
</tr>
<tr>
<td>Shing et al.</td>
<td>15 (+)</td>
<td>Flexure</td>
<td>72</td>
<td>1</td>
<td>0.54</td>
<td>0.24</td>
<td>3.0</td>
<td>1.30</td>
<td>80</td>
<td>93</td>
<td>YES</td>
<td>0.36</td>
</tr>
<tr>
<td>Shing et al.</td>
<td>15 (-)</td>
<td>Flexure</td>
<td>72</td>
<td>1</td>
<td>0.54</td>
<td>0.24</td>
<td>3.0</td>
<td>1.42</td>
<td>80</td>
<td>93</td>
<td>YES</td>
<td>0.36</td>
</tr>
<tr>
<td>Shedid et al.</td>
<td>1 (+)</td>
<td>Flexure</td>
<td>142</td>
<td>2</td>
<td>0.29</td>
<td>0.08</td>
<td>0.0</td>
<td>3.15</td>
<td>26</td>
<td>76</td>
<td>NO</td>
<td>1.83</td>
</tr>
<tr>
<td>Shedid et al.</td>
<td>1 (-)</td>
<td>Flexure</td>
<td>142</td>
<td>2</td>
<td>0.29</td>
<td>0.08</td>
<td>0.0</td>
<td>2.87</td>
<td>26</td>
<td>76</td>
<td>NO</td>
<td>1.83</td>
</tr>
<tr>
<td>Shedid et al.</td>
<td>2 (+)</td>
<td>Flexure</td>
<td>142</td>
<td>2</td>
<td>0.78</td>
<td>0.13</td>
<td>0.0</td>
<td>2.64</td>
<td>61</td>
<td>84</td>
<td>YES</td>
<td>0.71</td>
</tr>
<tr>
<td>Shedid et al.</td>
<td>2 (-)</td>
<td>Flexure</td>
<td>142</td>
<td>2</td>
<td>0.78</td>
<td>0.13</td>
<td>0.0</td>
<td>2.64</td>
<td>61</td>
<td>84</td>
<td>YES</td>
<td>0.71</td>
</tr>
<tr>
<td>Shedid et al.</td>
<td>3 (+)</td>
<td>Flexure</td>
<td>142</td>
<td>2</td>
<td>0.73</td>
<td>0.13</td>
<td>0.0</td>
<td>2.72</td>
<td>58</td>
<td>78</td>
<td>YES</td>
<td>0.71</td>
</tr>
<tr>
<td>Shedid et al.</td>
<td>3 (-)</td>
<td>Flexure</td>
<td>142</td>
<td>2</td>
<td>0.73</td>
<td>0.13</td>
<td>0.0</td>
<td>1.69</td>
<td>58</td>
<td>78</td>
<td>YES</td>
<td>0.71</td>
</tr>
<tr>
<td>Shedid et al.</td>
<td>4 (+)</td>
<td>Flexure</td>
<td>142</td>
<td>2</td>
<td>1.31</td>
<td>0.26</td>
<td>0.0</td>
<td>2.21</td>
<td>88</td>
<td>105</td>
<td>YES</td>
<td>0.65</td>
</tr>
<tr>
<td>Shedid et al.</td>
<td>4 (-)</td>
<td>Flexure</td>
<td>142</td>
<td>2</td>
<td>1.31</td>
<td>0.26</td>
<td>0.0</td>
<td>2.01</td>
<td>88</td>
<td>105</td>
<td>YES</td>
<td>0.65</td>
</tr>
<tr>
<td>Shedid et al.</td>
<td>5 (+)</td>
<td>Flexure</td>
<td>142</td>
<td>2</td>
<td>1.31</td>
<td>0.26</td>
<td>5.0</td>
<td>1.77</td>
<td>94</td>
<td>105</td>
<td>YES</td>
<td>0.57</td>
</tr>
<tr>
<td>Shedid et al.</td>
<td>5 (-)</td>
<td>Flexure</td>
<td>142</td>
<td>2</td>
<td>1.31</td>
<td>0.26</td>
<td>5.0</td>
<td>1.64</td>
<td>94</td>
<td>105</td>
<td>YES</td>
<td>0.57</td>
</tr>
<tr>
<td>Shedid et al.</td>
<td>6 (+)</td>
<td>Flexure</td>
<td>142</td>
<td>2</td>
<td>1.31</td>
<td>0.26</td>
<td>10.0</td>
<td>1.93</td>
<td>99</td>
<td>105</td>
<td>YES</td>
<td>0.51</td>
</tr>
<tr>
<td>Shedid et al.</td>
<td>6 (-)</td>
<td>Flexure</td>
<td>142</td>
<td>2</td>
<td>1.31</td>
<td>0.26</td>
<td>10.0</td>
<td>2.32</td>
<td>99</td>
<td>105</td>
<td>YES</td>
<td>0.51</td>
</tr>
<tr>
<td>Voon and Ingham</td>
<td>1 (+)</td>
<td>Flexure</td>
<td>71</td>
<td>1</td>
<td>0.62</td>
<td>0.05</td>
<td>0.0</td>
<td>0.47</td>
<td>51</td>
<td>49</td>
<td>YES</td>
<td>0.18</td>
</tr>
<tr>
<td>Voon and Ingham</td>
<td>1 (-)</td>
<td>Flexure</td>
<td>71</td>
<td>1</td>
<td>0.62</td>
<td>0.05</td>
<td>0.0</td>
<td>0.57</td>
<td>51</td>
<td>49</td>
<td>YES</td>
<td>0.18</td>
</tr>
</tbody>
</table>

\(a\) – $\delta_{s, S}^a = 0.5 \frac{h_w}{\ell_w} \frac{\varepsilon_{mu}}{c}$ (except for shear-controlled walls where $h_{sl}/200$ or $h_{sl}/400$ governs, see Table 2.1)
Materials:
\( f_y = 60 \text{ ksi} \)
\( f_m' = 1500 \text{ psi} \)
8-in. concrete masonry units fully grouted

Loads:
Self Weight = 80 psf
Trib. Dead = 150 plf
Trib. Live = 230 plf

Seismic Design Parameters:
\( S_{DS} = 1.0 \)
\( S_{D1} = 0.6 \)
\( R = 5.0 \)
\( C_d = 3.5 \)
\( \delta_{e,\text{Roof}} = 0.14'' \text{ for } V_b = 50 \text{ kip} \)

Figure 3.1 – Single-Story Wall with Openings

Figure 3.2 – Lateral Stiffness for Different Mesh Sizes, after Linear-Elastic Analysis
Figure 3.3 – Controlling Yield Mechanism

Figure 3.4 – Base Shear per Design Method
Figure 3.5 – Base Shear Strength for Nonlinear Static Analyses
Figure 3.6 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 1, Eastward Loading

Figure 3.7 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 1, Westward Loading
Figure 3.8 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 1, Eastward Loading

Figure 3.9 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 1, Westward Loading
Figure 3.10 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 2, Eastward Loading

Figure 3.11 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 2, Westward Loading
Figure 3.12 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 2, Eastward Loading

Figure 3.13 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 2, Westward Loading
Figure 3.14 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 3, Eastward Loading

Figure 3.15 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 3, Westward Loading
Figure 3.16 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 3, Eastward Loading

Figure 3.17 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 3, Westward Loading
Figure 3.18 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 4, Eastward Loading

Figure 3.19 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 4, Westward Loading
Figure 3.20 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 4, Eastward Loading

Figure 3.21 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 4, Westward Loading
Figure 3.22 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 5, Eastward Loading

Figure 3.23 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 5, Westward Loading
Figure 3.24 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 5, Eastward Loading

Figure 3.25 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 5, Westward Loading
Figure 3.26 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 6, Eastward Loading

Figure 3.27 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 6, Westward Loading
Figure 3.28 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 6, Eastward Loading

Figure 3.29 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 6, Westward Loading
Figure 3.30 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 7, Eastward Loading

Figure 3.31 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 7, Westward Loading
Figure 3.32 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 7, Eastward Loading

Figure 3.33 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 7, Westward Loading
Figure 3.34 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 8, Eastward Loading

Figure 3.35 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 8, Westward Loading
Figure 3.36 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 8, Eastward Loading

Figure 3.37 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 8, Westward Loading
Figure 3.38 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 9, Eastward Loading

Figure 3.39 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 9, Westward Loading
Figure 3.40 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 9, Eastward Loading

Figure 3.41 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 9, Westward Loading
Figure 3.42 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 10, Eastward Loading

Figure 3.43 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 10, Westward Loading
Figure 3.44 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 10, Eastward Loading

Figure 3.45 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 10, Westward Loading
Figure 3.46 – Wall Shear vs. Roof Displacement for Refined Nonlinear Layer Model, Reinforcement Option 1, Eastward Loading

Figure 3.47 – Wall Shear vs. Roof Displacement for Refined Nonlinear Layer Model, Reinforcement Option 1, Westward Loading
Figure 3.48 – Wall Shear vs. Roof Displacement for Refined Nonlinear Layer Model, Reinforcement Option 10, Eastward Loading

Figure 3.49 – Wall Shear vs. Roof Displacement for Refined Nonlinear Layer Model, Reinforcement Option 10, Westward Loading
Materials:

\[ f_y = 60 \text{ ksi} \]
\[ f'_m = 1500 \text{ psi} \]

8-in. concrete masonry units
fully grouted

Loads:

Self Weight = 80 psf
Trib. Dead = 800 plf
Trib. Live = 400 plf

Seismic Design Parameters:

\[ S_{DS} = 1.0 \]
\[ S_{D1} = 0.6 \]
\[ R = 5.0 \]
\[ C_d = 3.5 \]
\[ \delta_{e,\text{Roof}} = 0.387'' \text{ for } V_b = 160 \text{ kip} \]

Figure 4.1 – Multi-Story Wall with Large Opening at Base

Figure 4.2 – Linear-Elastic Model with 8 in. by 8 in. Mesh
Figure 4.3 – Controlling Yield Mechanism

Figure 4.4 – Base Shear per Design Method

- As Two Walls
- As Single Wall
Figure 4.5 – Base Shear Strength for Nonlinear Static Analyses
Figure 4.6 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 1

Figure 4.7 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 1
Figure 4.8 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 2

Figure 4.9 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 2
Figure 4.10 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 3

Figure 4.11 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 3
Figure 4.12 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 4

Figure 4.13 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 4
Figure 4.14 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 5

Figure 4.15 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 5
Figure 4.16 – Wall Shear vs. Roof Displacement for Refined Nonlinear Layer Model, Reinforcement Option 1

Figure 4.17 – Wall Shear vs. Roof Displacement for Refined Nonlinear Layer Model, Reinforcement Option 5
Materials:
\[ f_y = 60 \text{ ksi} \]
\[ f_m' = 1500 \text{ psi} \]
8-in. concrete masonry units
fully grouted

Loads:
Self Weight = 80 psf
Trib. Dead = 400 plf
Trib. Live = 400 plf

Seismic Design Parameters:
\[ S_{DS} = 1.0 \]
\[ S_{D1} = 0.6 \]
\[ R = 5.0 \]
\[ C_d = 3.5 \]
\[ \delta_{e,\text{Roof}} = 2.40'' \text{ for } V_b = 160 \text{ kip} \]

Figure 5.1 – Multi-Story Coupled Shear Walls

Figure 5.2 – Linear-Elastic Model with 8 in. by 8 in. Mesh
Figure 5.3 – Controlling Yield Mechanism

Figure 5.4 – Base Shear per Design Method
Figure 5.5 – Base Shear Strength for Nonlinear Static Analyses

![Bar Chart]

- LAYER
- LINK
- LIMIT MECHANISM ($V_{lim}$)
- LIMIT DESIGN CODE ($\phi=1$)
Figure 5.6 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 1

Figure 5.7 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 1
Figure 5.8 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 2

Figure 5.9 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 2
Figure 5.10 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 3

Figure 5.11 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 3
Figure 5.12 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 4

Figure 5.13 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 4
Figure 5.14 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 5

Figure 5.15 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 5
Figure 5.16 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 6

Figure 5.17 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 6
Figure 5.18 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 7

Figure 5.19 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 7
Figure 5.20 – Wall Shear vs. Roof Displacement for Refined Nonlinear Layer Model, Reinforcement Option 1

Figure 5.21 – Wall Shear vs. Roof Displacement for Refined Nonlinear Layer Model, Reinforcement Option 7
Figure 5.22 – Beam Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 1

Figure 5.23 – Beam Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 1
Figure 5.24 – Beam Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 2

Figure 5.25 – Beam Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 2
Figure 5.26 – Beam Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 3

Figure 5.27 – Beam Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 3
Figure 5.28 – Beam Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 4

Figure 5.29 – Beam Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 4
Figure 5.30 – Beam Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 5

Figure 5.31 – Beam Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 5
Figure 5.32 – Beam Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 6

Figure 5.33 – Beam Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 6
Figure 5.34 – Beam Shear vs. Roof Displacement for Nonlinear Layer Model, Reinforcement Option 7

Figure 5.35 – Beam Shear vs. Roof Displacement for Nonlinear Link Model, Reinforcement Option 7
Figure 5.36 – Beam Shear vs. Roof Displacement for Refined Nonlinear Layer Model, Reinforcement Option 1

Figure 5.37 – Beam Shear vs. Roof Displacement for Refined Nonlinear Layer Model, Reinforcement Option 7
Figure 6.1 – Structural Configurations and Direction of Lateral Force (after Paulson and Abrams, 1990)

Materials:
- $f_y = 47$ ksi
- $f'_{m} = 1215$ psi; $E_m = 720$ ksi
- 1.9-in. Concrete Masonry Units fully grouted

Loads:
- Total Weight = 8850 lb (full structure)
- 2950 lb (per story)

Seismic Design Parameters:
- $\delta_{e,\text{Roof}} = 0.14''$ for $V_b = 12$ kip (full structure)
- (50% gross section properties)

Figure 6.2 – Configuration of Structures RM1 and RM2
Materials:
\[ f_y = 47 \text{ ksi} \]
\[ f'_m = 1228 \text{ psi}; \quad E_m = 910 \text{ ksi} \]
1.9-in. Concrete Masonry Units fully grouted

Loads:
Total Weight = 8550 lb (full structure)
2850 lb (per story)

Seismic Design Parameters:
\[ \delta_{e,\text{Roof}} = 0.24'' \text{ for } V_b = 12 \text{ kip (full structure)} \]
(50% gross section properties)

Figure 6.3 – Configuration of Structure RM3

Figure 6.4 – Typical Construction of Test Structures (after Paulson and Abrams, 1990)
Figure 6.5 – Configuration and Layout of Reinforcement for Structures RM1 and RM2

Figure 6.6 – Configuration and Layout of Reinforcement for Structure RM3
Figure 6.7 – Measured Base Shear and Roof Displacement Histories for Structure RM1, Run 4 (after Paulson and Abrams, 1990)

Figure 6.8 – Measured Base Shear and Roof Displacement Histories for Structure RM3, Run 6 (after Paulson and Abrams, 1990)
Figure 6.9 – RM1 Final Crack Pattern (after Paulson and Abrams, 1990)

Figure 6.10 – RM2 Final Crack Pattern (after Paulson and Abrams, 1990)
Figure 6.11 – RM3 Final Crack Pattern (after Paulson and Abrams, 1990)

Figure 6.12 – Controlling Yield Mechanism for Structures RM1 and RM2
Figure 6.13 – Controlling Yield Mechanism for Structure RM3

Figure 6.14 – Nonlinear Layer Model, Structure RM1 View from Southwest
Figure 6.15 – Nonlinear Layer Model, Structure RM3 View from Southwest

Figure 6.16 – Nonlinear Layer Model, Structure RM3 View from Southeast
Figure 6.17 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model of Structures RM1 and RM2, Eastward Loading

Figure 6.18 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model of Structure RM3, Eastward Loading
Figure 6.19 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model of Structure RM3, Westward Loading

Figure 6.20 – Measured and Calculated Base Shear vs. Roof Displacement for Structure RM1
Figure 6.21 – Measured and Calculated Base Shear vs. Roof Displacement for Structure RM2

Figure 6.22 – Measured and Calculated Base Shear vs. Roof Displacement for Structure RM3
Figure A.1 – Definition of Displacement Capacity for Experimental Data

<table>
<thead>
<tr>
<th>Failure Type</th>
<th>Shear</th>
<th>Flexure</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho h %$</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>$(\geq 0.21, 0.28)$</td>
<td>□</td>
<td>✷</td>
</tr>
<tr>
<td>$(\geq 0.14, 0.21)$</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>$(\geq 0.07, 0.14)$</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>$(\geq 0, 0.07)$</td>
<td>□</td>
<td>△</td>
</tr>
</tbody>
</table>

Figure A.2 – Key for Experimental Data Shown in Figure A.3 to Figure A.6
Figure A.3 – Drift Capacity of Specimens Failing in Shear (Effects of Shear Force)

Figure A.4 – Drift Capacity of Specimens Failing in Shear (Effects of Axial Force)
Figure A.5 – Drift Capacity of Specimens Failing in Flexure (Effects of Shear Force)

Figure A.6 – Drift Capacity of Specimens Failing in Flexure (Effects of Axial Force)
Figure A.7 – Displacement Capacity of Flexure-Controlled Walls

\[ \theta_u = \frac{\delta_{\text{cap}}}{h_w} = \phi_u \frac{l_p}{c} = \frac{\varepsilon_{\text{mu}}}{2} \]

Figure A.8 – Measured vs. Calculated Deformation Capacity, All Data
Figure B.1 – Linear-Elastic Model with 8 in. by 8 in. Mesh, Case Study A

Figure B.2 – Nonlinear Layer Model, Case Study A
Figure B.3 – Masonry Model, Axial Direction

- Stress, ksi:
  - 0.8f’ m
  - E_m = 1350 ksi

Figure B.4 – Reinforcement Steel Model, Axial Direction

- Stress, ksi:
  - f_y
  - E_s = 29000 ksi

- Strain:
  - -0.004 to 0.004
Figure B.5 – Representative Shear Model, Walls A and C (Case Study A, Reinforcement Option 1)

Figure B.6 – Nonlinear Link Model, Case Study A
Figure B.7 – Nonlinear Link Definition, Axial Direction, Interior Links in Walls A and C (Case Study A, Reinforcement Option 1)

Figure B.8 – Nonlinear Link Definition, Shear Direction, Interior Links in Walls A and C (Case Study A, Reinforcement Option 1)
Figure B.9 – Wall Shear vs. Roof Displacement for Nonlinear Layer Model, Eastward Loading (Case Study A, Reinforcement Option 1)

Figure B.10 – Wall Shear vs. Roof Displacement for Nonlinear Link Model, Eastward Loading (Case Study A, Reinforcement Option 1)
LIST OF REFERENCES


BIOGRAPHICAL SKETCH

REYNALDO E. SANCHEZ BRAVO

Reynaldo Sanchez was born on December 2nd 1988, in Maracaibo, Venezuela. He began his undergraduate studies at the Universidad Rafael Urdaneta in fall of 2006. In summer 2010 he graduated from Universidad Rafael Urdaneta with a Bachelor of Science in Civil Engineering. He enrolled at The Pennsylvania State University in fall 2010 as a graduate student in the Department of Architectural Engineering, College of Engineering. Reynaldo worked with Dr. Andres Lepage as a grader in AE 402 (Design of Concrete Structures for Buildings) and in AE 530 (Computer Modeling of Building Structures). He received a full research assistantship during spring 2011 and fall 2011. He is expected to graduate in summer 2012 with an M.S. in Architectural Engineering.