OUT-OF-PLANE CAPACITY AND REHABILITATION OF PARTIAL HEIGHT MASONRY PARTITIONS

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FINAL REPORT

MAE PROJECT ST-9
PERFORMANCE OBJECTIVES FOR ESSENTIAL FACILITIES

March 2003

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Acknowledgement

The work reported in this document was supported by the Mid America Earthquake Center which is funded in part by the National Science Foundation under grant ECC-97010785 and is headquartered at the University of Illinois at Urbana-Champaign. The authors would like to thank the researchers throughout the MAE Center who have provided information for this report.

Summary

This project examined the behavior of nonstructural components present in essential facilities in Mid-America. School buildings were chosen for detailed studies because of the vulnerability of their occupants and the importance of these particular facilities to post earthquake emergency response. An inventory of nonstructural components was made for this class of essential facilities using the categorization of components developed by FEMA. In addition, the results of an inventory of schools and other essential facilities from Project SE-1 (Inventories of Essential Facilities in Mid-America) were used in this study. Partial height interior unreinforced masonry walls were found in many schools and because of their clear vulnerability to seismic forces were selected as the focus of this study. The primary objective of the present investigation was to evaluate and then suggest retrofit strategies for these components to enable them to meet the life safety and/or immediate occupancy performance levels specified in current FEMA guidelines. Additional objectives were to assess the accuracy of current evaluation methods recommended by FEMA and if necessary to develop improved analysis procedures, rehabilitation guidelines, and performance measures.

1. Introduction

1.1 Background

Failure of nonstructural components in essential facilities such as hospitals, schools, police and fire stations, may adversely impact building function and endanger occupants, especially if those components are massive and are constructed of brittle materials such as unreinforced masonry. Nonstructural components are an integral part of a building system, and include architectural, mechanical and electrical components and contents whose value may exceed that of the structure alone. Seismic evaluation and rehabilitation guidelines must be provided for these components. Preliminary surveys have shown that collapse of selected nonstructural components can be fatal to building occupants (Boussabah [1992]). Failures out-of-plane of massive elements such as URM walls have been reported in past earthquakes by Bruneau [1990, 1994, 1995] and Paquette [2001]. Such failures of heavy partial height partitions in buildings may block exits and cause injury or death. Failure of nonstructural components may also be associated with significant financial loss and prevent continuation of building function.

At present, there is only limited information on how to determine the capacity of nonstructural components in documents such as the Guidelines for the Seismic Rehabilitation of Buildings (FEMA Publication 273/274/356/357). The Federal Emergency Management Agency (FEMA) has sponsored continued development of these documents since 1991. These guidelines are expected to serve as a primary resource on the seismic rehabilitation of buildings for use by design professionals, educators, model code and standards organizations, and state and local building regulatory personnel. A more comprehensive inventory of building nonstructural components is needed for the continued development of these documents and more detailed analytical studies should be performed to better understand and represent expected performance of nonstructural components.

The work reported in this study includes an inventory of selected buildings to identify the types of nonstructural components found in typical essential facilities. Performance objectives for various categories of essential facilities were defined for life safety (LS), immediate occupancy (IO) and operational performance (OP) levels. Results from this investigation were used to develop improved rehabilitation guidelines that are specific to the type of facility selected for study.

To increase the applicability and potential for use of analytical models developed in this research program, efforts were made to collaborate with research teams on MAE Center projects ST-4 (Response Modification Applications for Essential Facilities) and ST-5 (MDOF Response of Low-Rise Buildings). The simplified models for nonstructural components developed as part of this research program are intended to be included in three-dimensional models for low-rise URM buildings developed in these companion projects: project ST-4 investigators developed passive devices to dissipate energy in low-rise URM buildings, and ST-5 researchers assembled simplified three-dimensional models for URM low-rise buildings. Project ST-4 also developed simplified 2-D models of low-rise unreinforced masonry (URM) buildings using Drain2-DX software, while Project ST-5 formulated simplified 3-D models which incorporate improved nonlinear models for the wood diaphragms often present as floor and roof systems in unreinforced masonry buildings. These two companion projects provide the floor spectra needed as input to this project to be used to perform dynamic analyses of selected nonstructural components.

1.2 Research Objectives

This project is concerned with the investigation of the behavior of nonstructural components present in essential facilities in Mid-America. The most critical essential facilities such as school buildings were chosen for detailed studies because of the vulnerability of their occupants and their importance to post earthquake emergency response. An inventory of nonstructural components was made for this class of essential facilities using the categorization of components listed in Table 11-1 of FEMA 273/356, FEMA273 [1997], FEMA356 [2000]. In addition, the results of an inventory of schools and other essential facilities in Project SE-1 (Inventories of Essential Facilities in Mid-America) were used in this investigation. The primary objective of the present investigation was to evaluate and then suggest retrofit strategies for these components to enable them to meet the life safety and/or immediate occupancy performance levels specified in FEMA 273.

The specific objectives of this research work are as follows:

1. Conduct a preliminary survey of selected essential facilities to determine what kinds, amounts and arrangements of nonstructural components may be found in essential facilities in Mid-America.

   Nonstructural component information such as number, size and material of construction was collected. The various types of nonstructural components in these buildings include architectural, mechanical and electrical components. After some initial investigations, the decision was made to focus the survey efforts on architectural components only; ceilings and partial height heavy weight partitions were then of primary interest.

2. Perform analyses on selected components using FEMA 273/356 Prescriptive and Analytical Procedures.

   Selected nonstructural components in Atlanta area schools were investigated to assess their performance for various earthquake response levels. Deformation (displacement), velocity, and acceleration sensitive nonstructural components were considered. Out-of-plane behavior of partial height URM partitions was of primary interest.

3. Confirm results of FEMA 273/356 evaluations using more complex models and analysis (linear, nonlinear) procedures and existing software.

   Detailed finite element models of URM partitions were developed using ABAQUS software as appropriate to simulate linear and nonlinear responses of selected nonstructural components for selected earthquake ground motion inputs.

4. Develop simplified analysis procedures, improved rehabilitation guidelines, and performance measures.

   This research has expanded the existing evaluation methodology presented in FEMA 273/356 for selected categories of nonstructural components so that improved performance of these secondary systems will contribute to meeting the life safety and/or immediate occupancy performance levels required for essential facilities in Mid-America.

1.3 Report Organization

This report begins with a summary and review of past work on the out-of-plane behavior of partial height masonry partitions, then presents analytical studies of several different wall configurations. Preliminary surveys of essential facilities in the New Madrid Seismic Zone

(NMSZ) and some of the schools in the Atlanta metropolitan area are presented in Chapter 2. The information on partial height partitions provided by FEMA 273/356 is summarized in Chapter 3. Methods recommended by FEMA 273/356 to determine the out-of-plane capacity of walls, referred to as prescriptive and analytical procedures, are also presented in Chapter 3. Linear static pushover analysis was used to study various types of partial height partitions and simplified models are presented along with sample results in Chapter 4. Both ABAQUS and Drain-2dx models of freestanding walls were also developed and are described in Chapter 5. Nonlinear static pushover analysis was used to evaluate the capacity of these partitions, and methods and results are also described in Chapter 5. Simplified analysis procedures, improved rehabilitation guidelines and performance measures are described in Chapter 6. Possible rehabilitation methods for various types of partial height URM walls are proposed in Chapter 7. Finally, overall conclusions of the study and possible directions for follow-on research are presented in Chapter 8.

2. Survey of Partial Height Walls in Local Schools

Preliminary surveys of essential facilities in the New Madrid Seismic Zone (NMSZ) conducted under Mid-America Earthquake Center (MAE Center) sponsorship have considered both the overall region (Project SE-1, Inventories of Essential Facilities in Mid-America), French [2000], and the specific cities of Carbondale, IL and Sikeston, MO (Project SE-5, Loss Estimates for Essential Facilities). After reviewing these surveys, it was determined that the schools included in these surveys were quite similar to selected schools in the Atlanta metropolitan area. During the Summer of 1999, an in-depth evaluation of nonstructural components and support details in two schools within the Fulton County School District in Atlanta was completed. Use of these local schools meant that nonstructural systems could be studied in more detail and travel time and expense could be reduced.

2.1 Survey Results from Atlanta Schools

The purpose of this project was to generate information about the nonstructural elements within essential facilities in the New Madrid Seismic Zone by study of several representative school buildings in the Atlanta region. The research in Atlanta was carried out assuming that the school buildings available in this region are similar to those in the NMSZ.

Project SE-1 previously developed basic inventory information on the number, type and location of essential facilities. The following types of essential facilities were included: hospitals, health care facilities, police and fire stations, emergency operations centers, schools, and nodes in utility systems. The project produced descriptive statistics of the size (floor area), year built, function, and structural type of these facilities by location. Priority was placed on identifying as many facilities as possible in the regions of highest potential seismic hazard. Facilities were geolocated in a GIS database. The GIS database was developed to be compatible with the MAE Center hazard maps. The Project SE-1 survey included 1306 buildings, approximately 20% of the essential facilities in the New Madrid Seismic Zone. This study was carried out to provide a basic understanding of the types of buildings that exist in Mid-America and includes information on 635 schools. Most of the survey information was taken by telephone and, unfortunately, the survey does not include detailed information on the structural and nonstructural systems. This information must be obtained by studying building design and construction documents and drawings visiting, and/or entering promising school buildings to gather additional information by visual inspection.

A survey of essential facilities in Sikeston, MO was conducted in connection with Project SE-5, and researchers completed this work in the summer of 1999. In some cases, the data collected from the Sikeston survey is incomplete. For example, the ATC-21 (FEMA154 [1988]) survey forms (see Appendix D) identify the type of building but neither the square footage nor the year of construction could be determined. In contrast, the data for the city of Carbondale school system is more comprehensive and provides all essential data that is needed to compare buildings.

The data from Project SE-1 covering schools was compared to similar inventory data obtained for both the Atlanta City School System and the Fulton County School System in order to determine if building types like those in the survey were available in the Atlanta area. The criteria used for comparison were structural system type, year built, and size (floor area) of the structure. When comparing the data in these three categories, these local buildings show similar characteristics to structures in the New Madrid Seismic Zone. As a result, the Atlanta survey identified the seven candidate schools list in Table 2.1 and shown in Figure 2.1 and Figure 2.2

below. Officials at the Fulton County School District were very cooperative in giving the researchers access (during the summer break) to both the schools, and also in providing access to available structural and architectural drawings for these schools.

Table 2.1 Atlanta Schools

Name	Frame Type*	Built	Stories	Area (sq.ft.)
McNair Middle School	C3	1969	2	129,462
Parklane Elementary	RM	1954	1	80,710
Conley Hills Elementary	RM	1952	2	101,096
Harriet Tubman Elementary	C3	1961	2	111,575
Paul West Middle School	C3	1957	2	139,111
Frank McClarin High School	C3	1943	2	97,789
Alpharetta Elementary	C3/RM	1956	1	102,655

**NOTE: Frame types are those defined in ATC-21 (see Table 2.2)* —

Table 2.2 ATC-21 Building Identifiers

Building Identifier	General Description
W	Wood buildings of all types
S1	Steel moment resisting frames
S2	Braced steel frames
S3	Light metal buildings
S4	Steel frames with cast-in-place concrete shear walls
C1	Concrete moment resisting frames
C2	Concrete shear wall buildings
C3/S5	Tilt-up buildings
PC1	Concrete or steel frame buildings with unreinforced masonry infill walls
PC2	Precast concrete frame buildings
RM	Reinforced masonry
URM	Unreinforced masonry

NOTE: Taken from FEMA 154, Rapid Visual Screening of Buildings for Potential Seismic Hazards

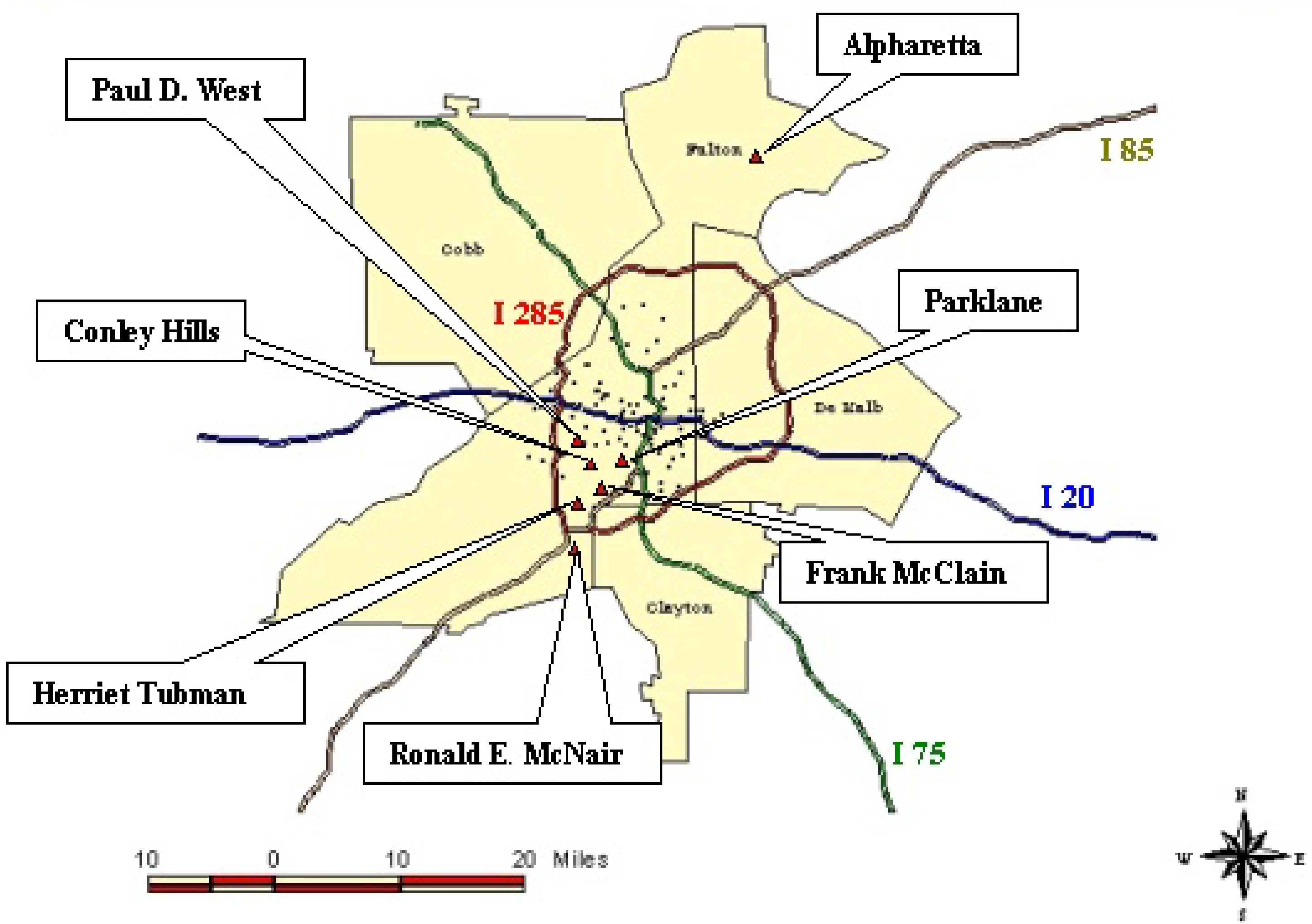

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Figure 2.1 Location of Selected Schools for Local Survey in Metro-Atlanta Area

a) Paul D. West Middle School

b) Conley Hills Elementary School

c) Harriet Tubman Elementary School

d) Alpharetta Elementary School

e) Parklane Elementary School

f) Frank Mc Clain High School

g) Ronald E. McNair Middle School

Figure 2.2 Selected Schools for Local Survey in Metro-Atlanta Area

2.2 Matching Atlanta Schools with Schools in Study Region

It was considered desirable to select Atlanta schools which were most similar to Memphis schools as the basis for further study of their nonstructural systems. General information from the SE-1 survey indicated structural frame type matches between Memphis, TN, and Atlanta, GA, school survey results for four schools, as shown in Table 2.3. After taking into account the decade built along with the square footage, the matches were reduced to two. Knight Road Elementary (TN) was built in 1963, which is the same decade as the construction of the McNair Middle School (GA), Figure 2.1. A second match was found between Saint Louis Church School (TN) and Alpharetta Elementary (GA), Figure 2.1; both of these schools were also built in the same decade.

Square footage is approximate on both SE-1 structures because the SE-1 study does not report how close these estimates are to the actual size of the building. This survey information was taken in a phone interview and could not provide more definitive data. In spite of this, close matches can be made between the two more modern schools, Saint Louis Church School (TN) and Knight Road Elementary (TN). These schools have the same frame type and were built in the same decade as two schools that had similar characteristics in Atlanta, namely Alpharetta Elementary and McNair Middle School. Once again, since the square footage is estimated from the SE-1 survey, the exact size of the Memphis schools as they compare to those in Atlanta could not be determined. All of the Memphis buildings shown in the chart below have a concrete frame with a masonry infill, and are likely to have partial height partitions. Based on the Atlanta school survey results, partial height partitions usually exist in a concrete frame type building of this size and vintage.

Table 2.3 Sample Schools in Memphis, TN

Name	Frame Type	Built	Stories	Area (sq.ft)
Florida Elementary	C3	1923	2	50000*
Knight Road Elementary	C3	1963	1	100000*
The Wesley School	C3	1933	1	N/A
Saint Louis Church School	C3	1959	1	30000*

** NOTE: indicates estimated data*

The SE-5 data includes five possible additional matches, as shown in Table 2.4. In Carbondale, IL, both high schools match the frame criteria. Of these two schools, Carbondale East High School (IL) was built in the 1960's which is the same decade as McNair Middle School (GA). The Sikeston data brings a possible match in Southeast Elementary School (MO) because the school has a concrete frame with masonry infill type construction; however, the exact date of construction could not be determined from the given data. Despite these inconsistencies, the existence of partial height partitions is quite possible within these structures. Partial height partitions are often used in buildings with a concrete frame and masonry infill, and this is the frame type for the Southeast Elementary School (MO) and both of the Atlanta Schools.

Table 2.4 Comparison with SE-5

Name	Frame Type	Built	Stories	Area (sq.ft)
Carbondale, IL, Central High School	S3/C5	1920s	3	85017
Carbondale, IL, East High School	S3/C5	1960s	1	70423
Lee Hunter Elementary (Sikeston, MO)	S5	N/a	1	N/A
Southeast Elementary (Sikeston, MO)	C3	N/a	1	N/A
Southwest School (Sikeston, MO)	S5	N/a	1	N/A

2.3 Nonstructural Components in Atlanta Schools

The initial purpose of the field survey for this report was to determine the different kinds of nonstructural components with seismic vulnerability that might be found in school buildings. This rather broad objective was subsequently narrowed to consider specifically the existence of so-called “partial-height walls” in the schools. Partial-height walls are interior walls that do not extend fully from the floor to the ceiling above. Instead, such walls are continued for only a few inches above the typical suspended ceilings used in these buildings as shown in Figure 2.3. Partial-height walls are acceleration-sensitive and hence very vulnerable to out of plane inertia forces which may cause them to topple over during an earthquake. Since most partial-height walls in schools are constructed from concrete block, the potential injury to students from heavy falling masonry is considerable. Partial height walls are also likely to be found in hallways, and their collapse may also further hinder emergency exit from the building. The most typical partition configurations are illustrated in Figure 2.4 and Figure 2.5. Partial height partitions supported on two edges can be found as party walls dividing the classrooms. The partition is supported on its two vertical edges by columns or by adjacent partitions in perpendicular directions. The other typical configuration is the partition supported only on one edge. This type is usually found along hallways and includes one or more door openings. The doors divide a two-edge supported partition into two one-edge supported partitions.

The research group evaluated architectural and structural plans for schools in order to identify the presence of partial-height walls in classrooms, hallways or other areas. These studies showed that two buildings definitely meet the requirements for this study. It is possible that a third school had the same types of walls; however the plans were unavailable (i.e., in use as part of local construction activities), and so a conclusion could not be made on the structural and architectural details used in the third school structure.

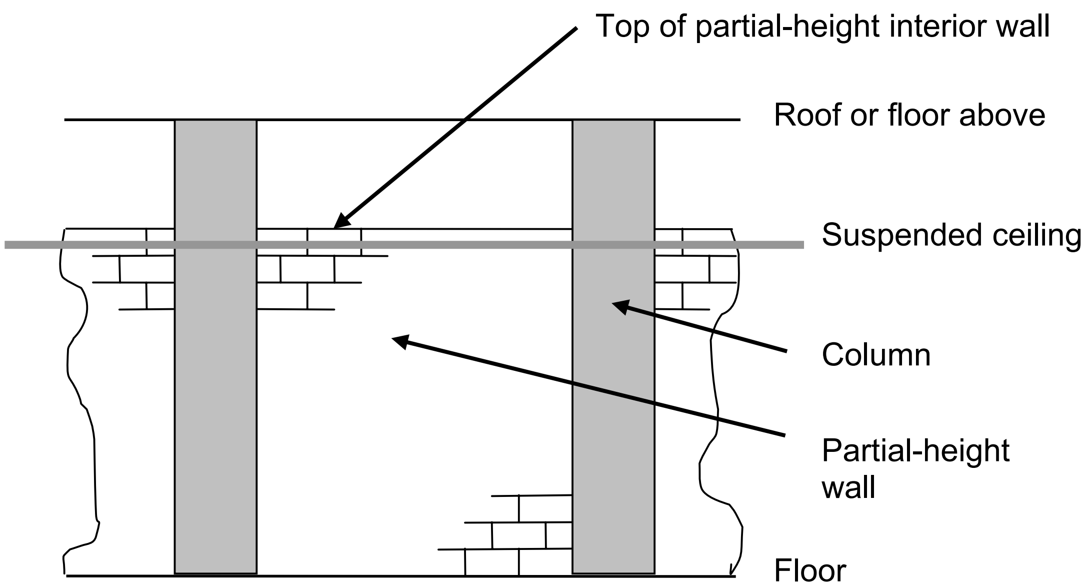


Figure 2.3 Elevation of a Typical Partial-Height Wall

Figure 2.4 Partial Height Partition Supported Along Two Edges

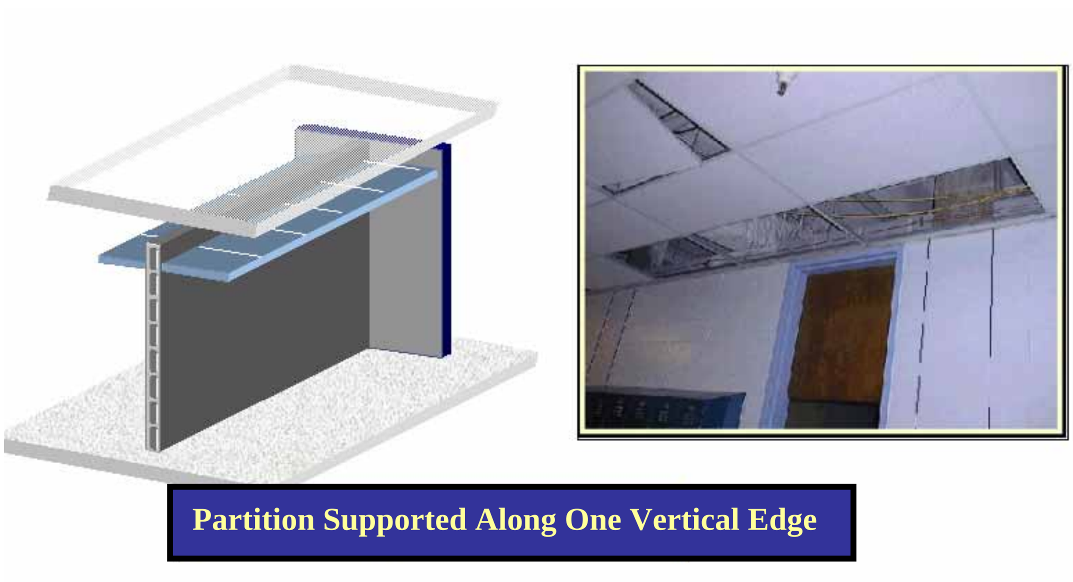


Figure 2.5 Partial Height Partition Supported Along One Edge

2.4 Selected Atlanta Schools

Out of seven original buildings, two buildings were identified as having partial height partitions. The two schools in the Fulton County School District were Alpharetta Elementary School and McNair Middle School. Alpharetta Elementary was built in 1956; however, the school underwent a major expansion in 1989. Both the original and new addition to the Alpharetta School contain partial height partitions. McNair Middle School was built in 1969 and also has partial height partitions throughout the structure. More detailed descriptions of each of these schools are presented below.

2.4.1 McNair Middle School

McNair Middle School is a cross-shaped building with 129,426 square feet of space and a courtyard in the center (see Figure 2.6 and Figure 2.7 below). It was built in 1969 and has a concrete frame with unreinforced masonry infill. Portions of the building have two stories (the gymnasium and a section containing two floors of classrooms). The size and spacing of the rooms is relatively uniform, however the column spacing does not correspond to that of the rooms. This means that some of the walls run between columns, while others end at intermediate points. Partial-height walls running along column lines between columns indicates that the wall can be assumed to be laterally supported over the height of the column on each end, leaving only the upper edge unsupported. The support provided by the attachment to the columns is similar to what would be provided if the wall made a 90 degree bend at the same point. In either case, the result is a degree of lateral support similar to what is defined as a simply supported edge condition (restrained lateral displacement, no restraint on bending along the edge). These are referred to as H walls in this report: the partial height wall is assumed to be the horizontal leg of the H and, the columns or 90 degree walls are represented as the left and right legs of the H. If only one vertical edge of the wall is supported by attachment to a column and the other edge is essentially free of any lateral support, the arrangement is referred to as an L configuration. The walls observed in this study ranged in length from approximately 10 feet to about 28 feet. The columns are spaced at similar varying distances. The vertical heights of these partitions is approximately 11 feet with the story height (distance to the underside of the floor above or to the roof structure) equal to approximately 14 feet, leaving a three foot gap above the suspended ceilings. Such partial-height walls are located both in the hallways and also as party walls between classrooms.

Figure 2.6 Photo of McNair Middle School

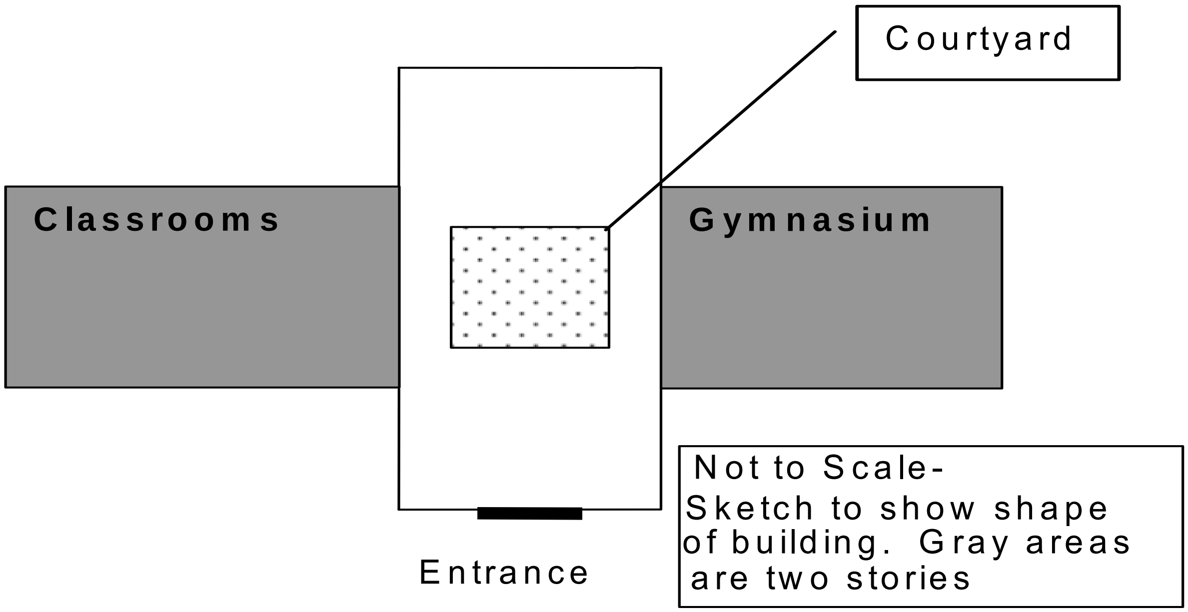


Figure 2.7 McNair Middle School Floor Plan

2.4.2 Alpharetta Elementary School

Alpharetta Elementary with 102,665 square feet of space was built in 1956 and had a major addition in 1989. Figure 2.8 shows the structure, and Figure 2.9 presents the layout of the building. The original part of the building has partial-height partitions in the party walls of the classrooms and also in the hallways. Originally, the hallways had operable windows on the top of the partitions to allow for ventilation. When the school added air conditioning, the windows were replaced with drywall to cover up the void left by the removal of the windows. In the original part of the building the columns are evenly spaced along the hallways at approximately 16 feet on center. The 1989 addition is reinforced masonry and the hallway partitions in the addition are full height. However, the party walls are still partial height in this part of the structure. A major difference in the party walls in the addition to the original structure is that concrete block cores are reinforced.

Figure 2.8 Alpharetta Elementary School

The information gathered from McNair Middle School and Alpharetta Elementary is considered to be representative of a large number of school buildings in the SE region for purposes of this investigation. It is likely (based on comparison to Memphis, Sikeston and Carbondale schools noted above) that schools in the New Madrid Seismic Zone have very similar characteristics depending on the construction date. It is recognized that the surveys used to identify these school buildings contain incomplete and, in some cases, inaccurate information. It is assumed that detailed evaluation of any structure would occur before any widespread rehabilitation measures were implemented.

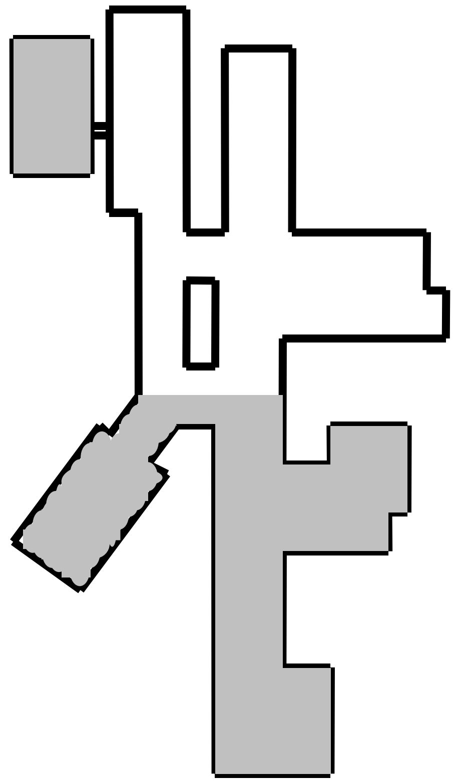


Figure 2.9 Alpharetta Elementary School Floor Plan

Study of the two Atlanta schools provides some indication of how similar buildings in the New Madrid Seismic Zone might perform in an earthquake. This study provides information that may be useful in deciding how to upgrade a building to be more earthquake resistant. It is vital that such buildings survive an earthquake since they are likely to be places where individuals would gather for emergency services and assistance after an earthquake.

3. Nonstructural Components in FEMA 273/356

FEMA 273/356 provides national guidelines for the seismic rehabilitation of buildings. These documents are intended to serve as a ready tool for design professionals and a foundation for the future development and implementation of building code provisions and standards. This document is intended for architects, engineers and building officials, especially those in the technical community responsible for developing and using codes and standards and for carrying out the design and analysis of buildings. The engineering expertise of a design professional is a prerequisite to the appropriate use of the guidelines.

FEMA 273/356 applies to the seismic resistance of both the overall structural system of a building and its elements, such as shear walls or frames and the constituent components of elements, such as a column in a frame or a boundary member in a wall. It also applies to architectural nonstructural components of existing buildings such as ceilings, heavy partial height partitions, as well as to mechanical and electrical systems. In addition to techniques for increasing strength and ductility of systems, this document provides rehabilitation techniques for reducing seismic demand, such as the introduction of isolation or damping devices. Although this document is not intended to address the design of new buildings, it does cover new components or elements to be added to existing buildings.

3.1 Information on Partial Height Partitions in FEMA273/356

A part of FEMA 273/356 establishes rehabilitation criteria for nonstructural comments such as architectural, mechanical and electrical components including heavy partial height partitions. Guidance for rehabilitating existing nonstructural components is emphasized, but new nonstructural components must conform to the material, detailing and construction requirements for similar elements in new buildings. It provides general requirements and discussion of rehabilitation objectives, performance levels and performance ranges as they pertain to nonstructural components. An extensive discussion in the Commentary, FEMA 274, reviews all of the issues involved in rehabilitation of nonstructural components; this will not be repeated here. FEMA 274 also offers a brief discussion of structural-nonstructural interaction and provides general requirements for acceptance criteria for acceleration-sensitive and deformation-sensitive components to both kinds of input. Sets of equations for simple force analyses are offered, as well as an extended analysis method that considers a number of additional factors. Another set of equations sets out the Analytical Procedure for determining drift ratios and relative displacements. The general requirements for prescriptive procedures are also presented. Moreover, appropriate rehabilitation criteria for each component category are provided. More detailed analysis procedures and examples which illustrate proper use of these various equations will be provided below.

While FEMA 273/356 contains rehabilitation criteria for a broad class of nonstructural components as noted above and is widely used for seismic evaluation, there is very little information on determination of the capacity and rehab of out-of-plane partial height partitions. The analysis procedures for nonstructural components recommended in FEMA 273/356 are based on those applicable to freestanding components. In general, heavy partial height partitions, which have some degree of lateral support along their vertical edges but are free along the support edge, are not specifically addressed. As a result, the equations provided to calculate capacity of generic nonstructural components are found to be too conservative for existing partition configurations and more detailed models and analyses are required to obtain accurate results for the specific class of walls considered here. The present study will evaluate the strengths and limitations of present analysis procedures in FEMA 273/356 and will propose a more effective way to calculate the capacity of partial height partitions.

3.2 Deficiencies in Chapter 11

As noted above, information on behavior of out-of-plane partial height partitions is very limited in this document. A part of Chapter 7 in FEMA 273/356 addresses out-of-plane behavior of URM walls. However, information in this section is based on experiments conducted more than twenty years ago (ABK [1981]). The walls tested were full height (floor to floor) and were not laterally supported along the vertical edges, so this information does not directly apply to the partial height partitions under investigation in this study.

Chapter 11 provides information on architectural, mechanical and electrical nonstructural elements and recommends the analysis method that should be used for each nonstructural component. These analysis methods are described in the following section of this report. General information on out-of-plane behavior of partitions is included at the end of Chapter 11 of FEMA 273/356 where it is recommended that partitions shall meet the requirements given in Chapter 4. While application of the procedure in Chapter 4 results in an evaluation of the capacity of the partition in the out-of-plane direction, it is unnecessarily complex and in need of simplification. A simplified model and analysis approach which leads to a prediction of the ultimate capacity of URM partial height partitions is presented in Chapter 6 of this report.

However, for practical purposes, performing detailed analyses (e.g., using finite element analysis) on each component may not be the most effective way to evaluate the variety of walls and support conditions found in a representative school building. Since the wall configurations considered herein are assumed to be freestanding, one-edge supported or two-edge supported, general solutions to find the capacity of partial height partitions in various configurations will simplify the overall analysis procedures (making them more useful in a code or standard context) and reduce the time for the overall analysis.

3.3 Capacity of Out of Plane Walls by FEMA 273/356

In this study, the seismic force was simplified to an equivalent static force. Time history analysis requires substantial computational time especially when the model is complex or has a large number of finite elements. Nonlinear dynamic analysis requires even more computational resources because the stiffness matrix is usually updated at each calculation step. As a result, static pushover analysis using an equivalent static force is preferable especially for a document specifying rehabilitation guidelines.

Chapter 11 of FEMA 273/356 provides two computational procedures to find the design equivalent static force for various partial height partitions. These procedures are referred to as the prescriptive and analytical procedures. The details of each procedure will be described in the next section. The design equivalent static force for each partial height partition will be checked against its capacity at a specified performance level. A detailed evaluation of the behavior of partial height partitions under the computed equivalent static force will be more fully explained in Chapters 4 and 5 of this report.

3.4 Two Methods to Determine the Out-of-Plane Capacity of Walls

3.4.1 Prescriptive Procedure

The Prescriptive Procedure is based on published standards and references that describe the design concepts and construction features that must be present for a given nonstructural component to be judged seismically adequate. No engineering calculations are required in the

Prescriptive Procedure, although in some cases an engineering review of the design and installation of the component is required. More details of the procedure are presented in subsequent chapters of this report.

3.4.2 Analytical Procedure

Two formulas are presented for use in calculating forces under the Analytical Procedure contained within FEMA 273/356. The first is a simple conservative equation containing three factors (defined below) to calculate an equivalent seismic lateral force, F_P:

$$F_p = 1.6 S_{XS} I_p W_p \tag{3.1}$$

where

F_p = Seismic design force applied horizontally at the component's center of gravity and distributed according to the component's mass distribution (as shown in Figure 3.1)

S_{XS} = Spectral response acceleration at short periods for any hazard level

I_p = Component Performance factor (either 1.0 for Life Safety Performance Level or 1.5 for Immediate Occupancy Performance Level)

W_p = Component operating weight.

The second equation in the Analytical Procedure is also an equivalent lateral force (F_P) equation but it incorporates additional factors which account for the component's geometry, flexibility and location within the structure; it also establishes a minimum lateral force value. This second equation is as follows:

$$F_p = \frac{0.4 a_p S_{XS} I_p W_p (1 + \frac{2x}{h})}{R_p} \tag{3. 2}$$

$$F_p(\text{minimum}) = 0.3 S_{XS} I_p W_p \tag{3. 3}$$

where

F_p = Seismic design force applied horizontally at the component's center of gravity and distributed relative to the component's mass distribution (as shown in Figure 3.1)

a_p = Component amplification factor, related to the rigidity of the component (varies from 1.00 to 2.50)

S_{XS} = Spectral response acceleration at short periods for any hazard level

h = Average roof elevation of structure, relative to grade elevation

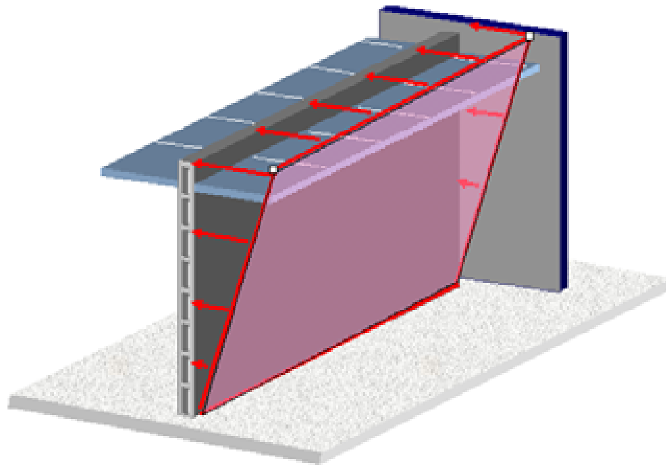
I_p = Component Performance Factor (either 1.0 for Life Safety (LS) Performance Level or 1.5 for Immediate Occupancy (IO) Performance Level)

R_p = Component response modification factor (related to ductility of anchorage; varies from 1.25 to 6.0)

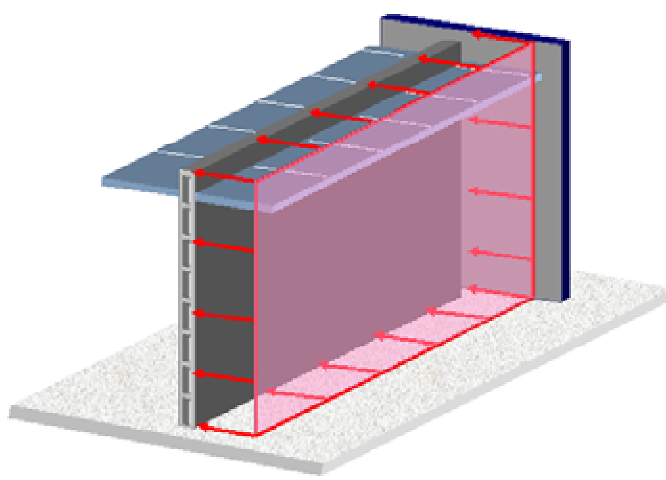
W_p = Component operating weight

x = Elevation in structure of component relative to grade elevation.

The Analytical Procedure is considered by FEMA 273/356 as always acceptable. However, the Prescriptive Procedure is only acceptable for certain combinations of seismicity, performance level and only for selected nonstructural components. After calculating the equivalent seismic force, any structural analysis method may be used to check if the designated nonstructural component can resist the required force.



a) Structural Component



b) Nonstructural Component

Figure 3.1 Equivalent Seismic Force Distribution

3.5 Acceptance Criteria

Partitions are vertical non-load-bearing interior elements that provide for division of space within the structure. They may span vertically from floor to the underside of the floor or roof above, with connections at the top that may or may not allow for isolation from in-plane drift motions. Some partitions may extend only partial height, and may or may not have lateral bracing at the top.

Heavy partitions are constructed of masonry materials such as hollow clay tile or concrete block, or are assemblies that weigh five pounds per square foot or more. Light partitions are constructed of metal or wood studs surfaced with lath and plaster, gypsum board, wood or other facing materials and weigh less than five pounds per square foot. Glazed partitions that span from floor to ceiling or to the underside of floor or roof above consist of wall assemblies that are made up from structural subframes attached to the main structure. The subframes may be assembled in the field, or prefabricated in sections and assembled in the field.

Partitions which extend from floor-to-floor are both acceleration and deformation sensitive. Partitions loaded out-of-plane can experience flexural cracking, failure of connections to the structure, and even collapse. The widespread use of unsupported block partitions in schools in low and moderate seismic zones (as noted in the survey presented in Chapter 2) represents a significant collapse threat.

Heavy partitions, whether infill or freestanding and constructed of masonry materials such as hollow clay tile or concrete block, must be proportioned to meet the out-of-plane force requirements of Eq. 3.1, 3.2 and 3.3, as appropriate, in applying the Analytical Procedure of FEMA 273/356.

3.6 Sample Results

An illustration of how to calculate the seismic lateral force for nonstructural partial height partitions is shown below. The design lateral force values point up the differences between application of Equation 3.1 (Method 2) and either 3.2/3.3 (Method 1) of the Analytical Procedure.

Partition properties:

- 72”x144”x6” (height x width x thickness)
- density = 124 lb/cu.ft.
- located in high seismic zone: Ss = 0.5g
- installed in 20 foot tall structure
- elevation = 10 ft. above the grade
- stiff soil

Assumed Parameters:

a_p	=	1.0	(FEMA 273 Table 11-2)
S_s	=	0.5g	
F_a	=	1.4	Soil type D (stiff soil)
S_{xs}	=	F_aS_s = 0.7	
h	=	20 ft.	height of the building
x	=	10 ft.	elevation of the partition
Wp	=	4.464 kips.	
R_p	=	1.5	(FEMA 273 Table 11-2)

I_p = 1.5 (Life Safety)

Method (1) $F_p(\text{minimum}) = 0.3 S_{XS} I_p W_p$ = 1.4 kips (using Eq. 3.2)

$$F_p = \frac{0.4 a_p S_{XS} I_p W_p (1 + \frac{2x}{h})}{R_p}$$ = 2.5 kips (using Eq. 3.3)

Method (2) $F_p(\text{maximum}) = 1.6 S_{XS} I_p W_p$ = 7.5 kips (using Eq. 3.1)

In Method (1), the partition must have a capacity at 2.5 kips or greater (the controlling value between equations 3.2 and 3.3) to resist the earthquake generated forces while Method (2) gives a much higher and much more conservative equivalent seismic force. Note that the above calculations ignore the support conditions of the partial height partitions. If static pushover analysis (to be presented later in Chapters 4 and 5 of this report) is used to predict the capacity of the partition for free standing, one edge supported and two edge supported configurations, the capacity values are 1.8, 2.1 and 3.1 kips, respectively. Hence, only the two edge supported partition will survive the loading in this case.

More detailed examples will be provided in subsequent chapters.

4. Linear Static Analysis

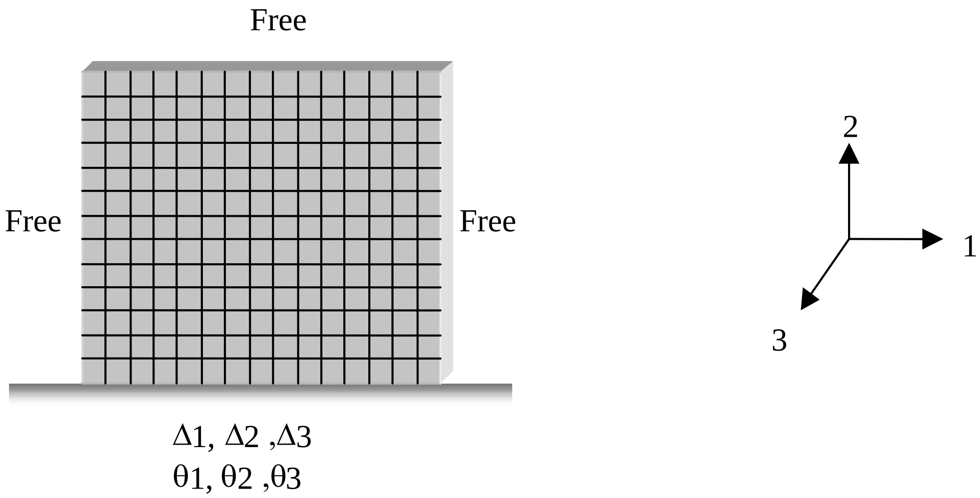
4.1 Linear Analysis

Linear static analysis was used to investigate the behavior of partial height partitions in the linear range, before first cracking occurs in the walls. Hence the partial height partition will be expected to have a linear relationship between the transverse displacement and the corresponding applied lateral load. The partition will be loaded with an equivalent earthquake static load until the maximum principle tensile stress reaches the tensile strength of the masonry.

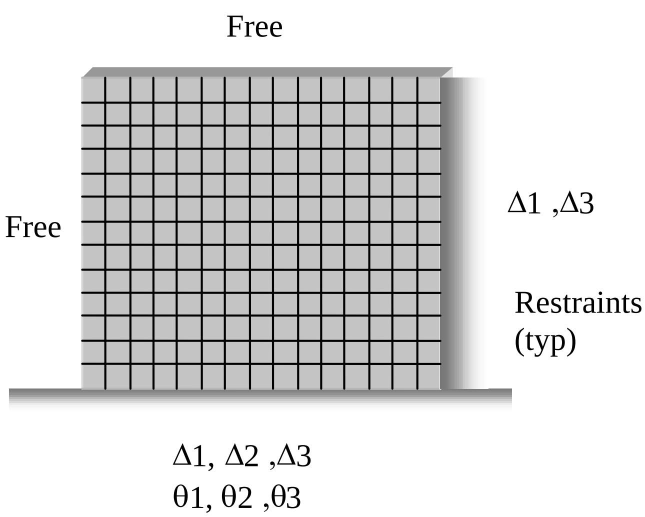
The lateral strain will be very small in this linear analysis so that linear elasticity will be appropriate. The analysis was performed using ABAQUS and several different finite element models were used to compare computed results to theoretical values. Parameter studies were performed to evaluate the effect of partition size on computed values. The maximum load at the point at which cracking occurred in the partition was the main concern in this analysis sequence. Results are compared below to those obtained from a Drain-2dx model developed by project investigators on MAE Project ST-10, Dynamic Tests of Low-Rise Building Systems.

4.2 Geometry and Model

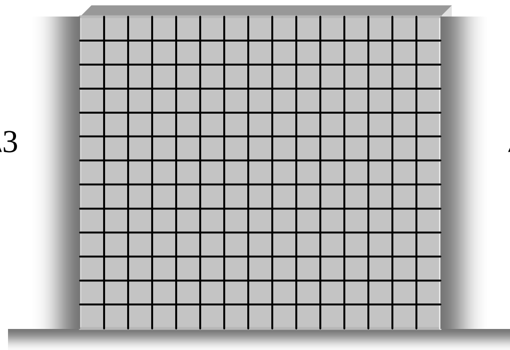
The three types of partial height partitions under study here are: freestanding, one edge-supported and two edge-supported partitions. Three dimensional shell elements were used in this linear analysis. The appropriate edge restraints (i.e., restrained degrees of freedom along an edge) for each of these models are summarized below in Fig. 4.1.



a) Free Standing Model



b) One Edge Supported Model



c) Two Edge Supported Model

Figure 4.1 Restrained Degrees of Freedom in Freestanding, One Edge Supported and Two Edge Supported Models

4.3 Comparing Displacements Computed by ABAQUS to Hand Calculations

The analysis results were compared to the existing theory to ensure that the linear model was reliable. If a concentrated load is applied at the free edge of a very long plate, the deflection along the free edge can be computed by the formula

$$(w)_{y=b} = \alpha \frac{Pb^2}{D} \tag{4.1}$$

$$D = \frac{Eh^3}{12(1-\nu^2)} \tag{4.2}$$

where

w = lateral deflection at free edge

P = concentrated load

b = height of the partial height partition

D = flexural rigidity

E = Young's modulus

h = thickness of the partition

ν = Poison's ratio

The factor α in Eq. 4.1 rapidly diminishes as the distance from point A (point of application of the load P) increases. For ease of reference, several values of this factor are given Table 4.1.

Table 4.1 Factor α at Various Points

x =	0	b/4	B/2	b	2b
α =	0.168	0.15	0.121	0.068	0.016

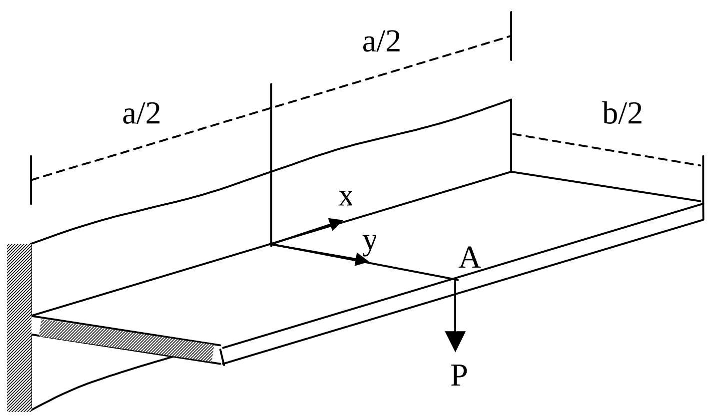


Figure 4.2 Very Long Plate Subjected to Concentrated Load, P

Results for a sample freestanding partition are now presented. The partition size was taken as 84:1000:6 (height:width:thickness, inches). Young's modulus and Poison's ratio were taken as 5.5 ksi and 0.25, respectively, in this comparison. The width is very long compared to the height to simulate a long plate as shown in Figure 4.2. A 1 kip point load was applied at the middle-top of the partition as shown in Figure 4.3. The number of the elements was varied until the finite analysis results converged to the plate theory solution. The displacements at selected points along the top of the wall were compared to the results from Eq. 4.1 (see Table 4.2) and the displaced wall model is shown in Figure 4.4.

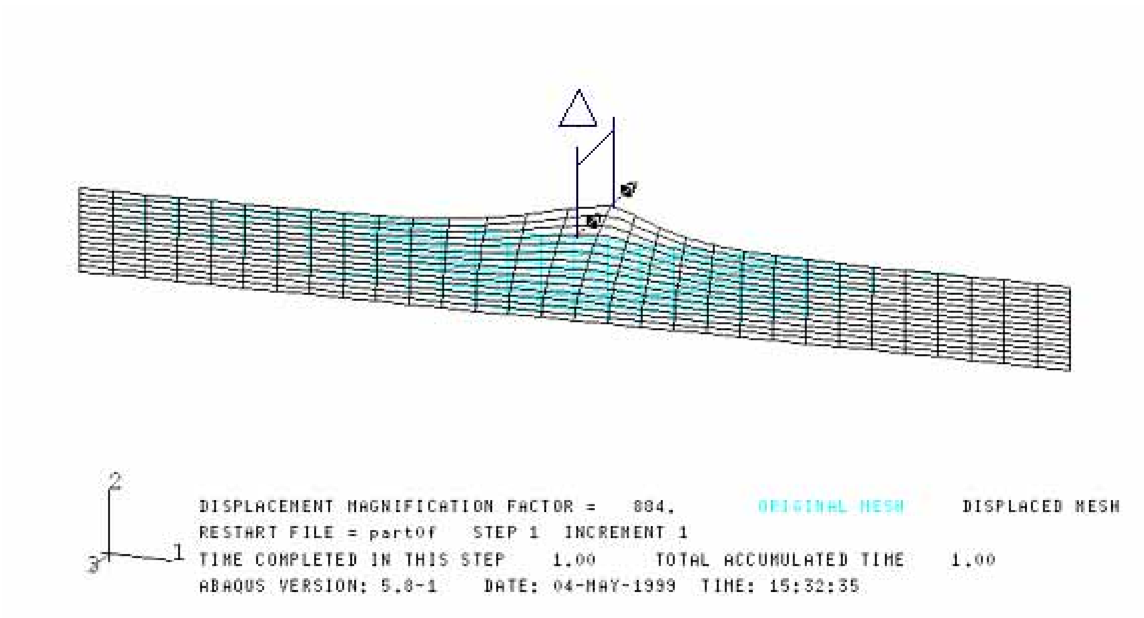


Figure 4.3 Infinite Plate Subjected to Concentrated Load at the Middle-Top of the Wall

Table 4.2 Comparison of Displacements at Top of Wall

x	0	b/4	b/2	b	2b
x (in.)	0	21	42	84	168
α	0.168	0.15	0.121	0.068	0.016
Displacement (in.) (at y = 84 in.)					

Hand Calculation	0.120	0.107	0.086	0.049	0.011
ABAQUS result	0.119	0.109	0.085	0.049	0.011

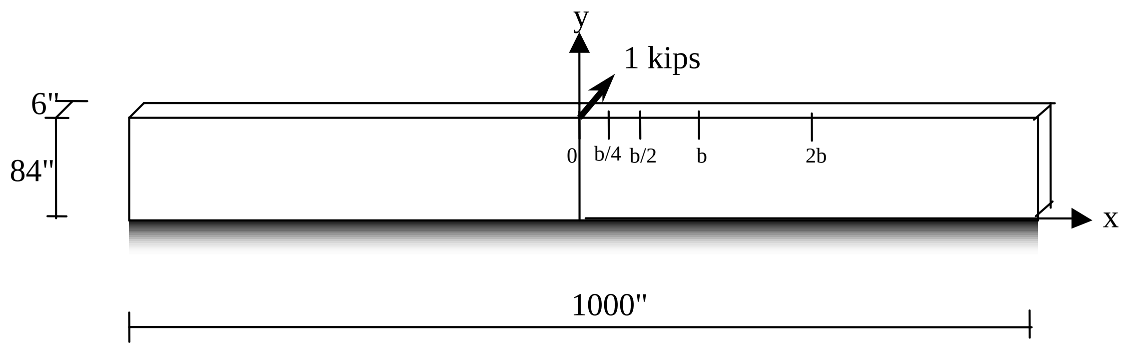


Figure 4.4 ABAQUS Long Plate Model

4.4 Parameter Study

The effect of different aspect ratios (B/H, H/t) for the partial height partitions was evaluated in a set of parameter studies to find a general relationship between the capacity of the partition at the onset of the first crack and its aspect ratio(s). Assume that Eqs. 3.1-3.3 from the FEMA 273/356 Analytical Procedure can be rewritten as:

$$F_p = \alpha W_p \tag{4.3}$$
$$W_p = \rho BHt \tag{4.4}$$

where

F_p = Seismic design force applied horizontally at the component's center of gravity and distributed relative to the component's mass distribution

α = Site parameter

W_p = Component operating weight

ρ = Density of the partition

H = Height of the partition

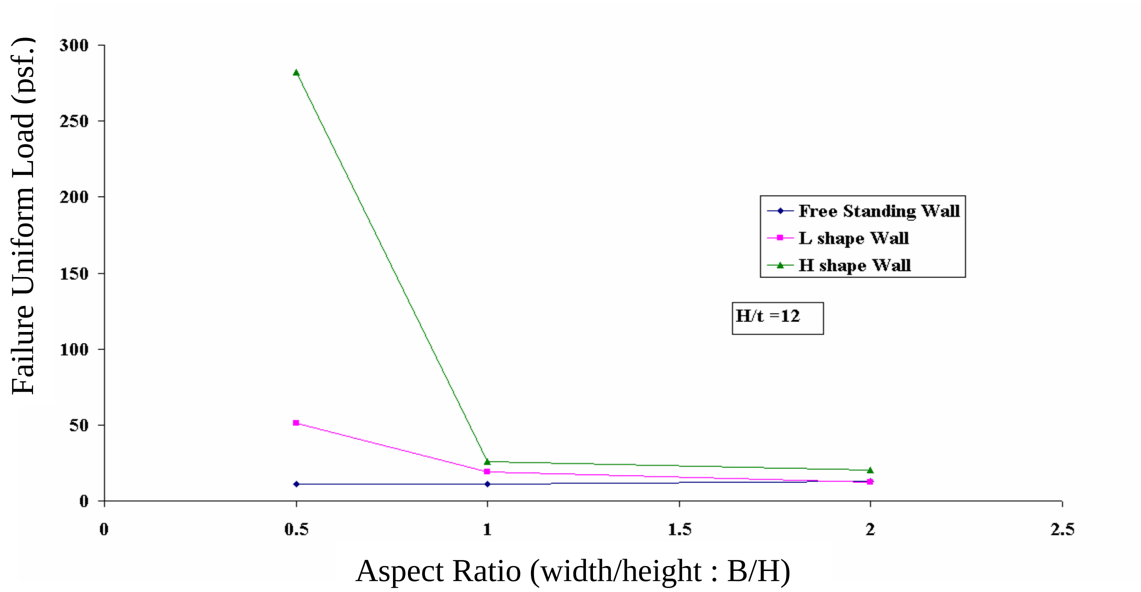
B = Width of the partition

t = Thickness of the partition

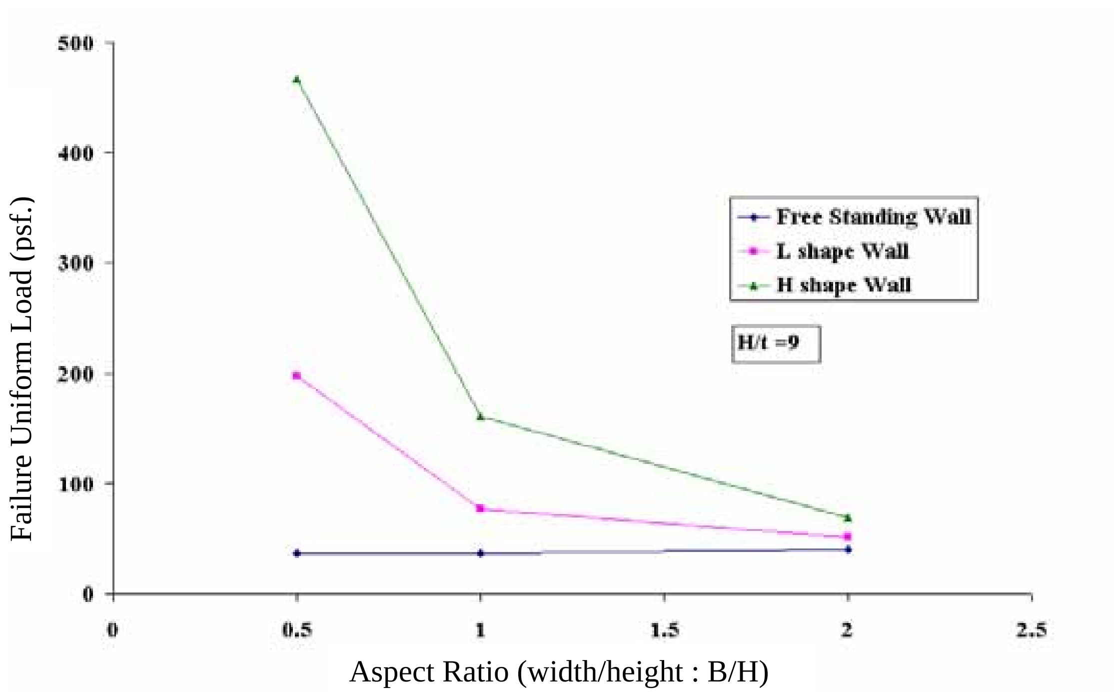
If Eqs. 4.3 and 4.4 are rewritten as shown in Eq. 4.5 below, it is apparent that partitions with the same thickness (and at the same location but with different dimensions) require the same uniform pressure to reach the first crack.

$$\frac{F_P}{\rho BH} := \alpha t \tag{4.5}$$

However, these equations are based on the freestanding condition so parameter studies were carried out to evaluate a variety of other conditions. Two sets of models were considered; both sets have the same H/t and B/H ratios but B, H and t are each different. Further analyses were also performed for one-edge and two-edge support partial height partition. Practical values of B, H and t were selected for partitions from the local school survey information presented in Chapter 2. Results for all cases are shown in Figure 4.5



a) B/H = 12



b) B/H = 9

Figure 4.5 Capacity of Partial Height Partition at First Crack

As shown in Figure 4.5, as B/H is increased, all partitions converge to the same failure pressure. In the case of one-edge and two-edge support partitions, the capacity is relatively high for smaller B/H values. However, ss B/H increases, the partitions behavior is closer to that of the freestanding condition.

4.5 ST-10 Out-of-Plane Model

MAE Project ST-10, Dynamic Tests of Low-Rise Building Systems, investigated nonlinear dynamic response of structural systems used in low-rise essential facilities, using reduced-scale idealized structures subjected to simulated seismic motions on a shake table. A companion mathematical and computer model was created to plan the testing program and to predict experimental results. The out-of-plane wall model component of the overall test fixture assemblage was of primary interest here. The associated computer model for the URM building structure is shown in Figure 4.6. This model includes brick and mortar as separate elements in a Drain-2dx model. Translational springs were also used to represent the diaphragm and in-plane wall components of a typical low rise URM structure. A beam-column element was used to represent the brick and elastic panel and gap elements were used to represent mortar (zero stiffness when in tension). The general ST-10 experiment set up is illustrated in Appendix C; the Project ST-10 final report should be consulted for further details of the experimental setup and for results of both computer and laboratory test models.

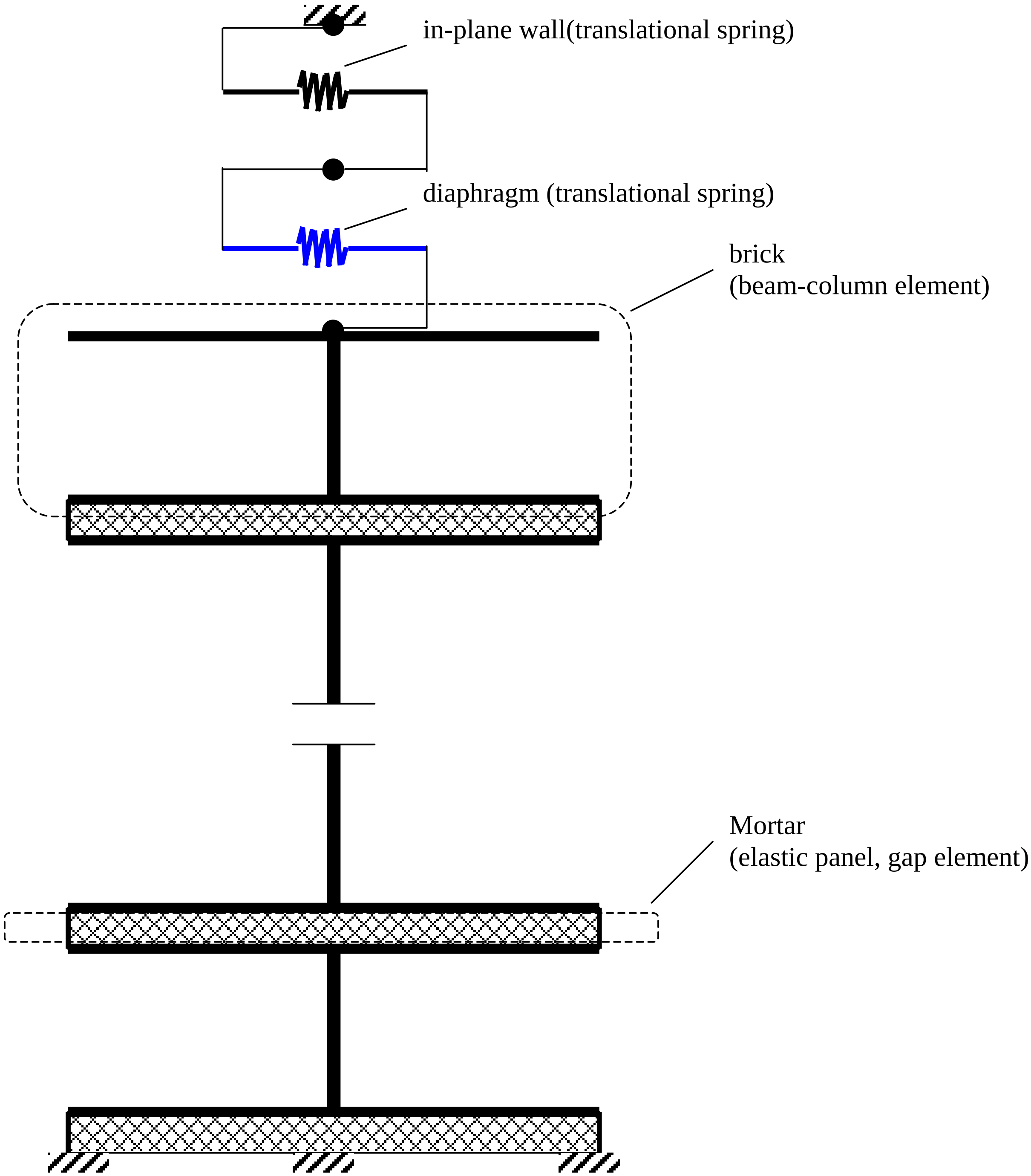


Figure 4.6 ST-10 Drain-2dx Model

5. Nonlinear Static Pushover Analysis

5.1 Nonlinear Analysis

After a partial height URM partition experiences the first crack at any point, the behavior of the structure is no longer linear. The wall stiffness changes (decreases) as it displaces out of plane. Linear analysis is a convenient approximation but is inadequate for detailed analysis in the nonlinear range.

Since stiffness is no longer linearly related to displacement, the initial flexibility can no longer be multiplied by the applied load to calculate the spring displacement for any load. In nonlinear analysis the stiffness matrix of the structure has to be assembled and inverted many times during the course of the incremental analysis, making it much more expensive to solve the system equations than for a linear analysis.

Since the response of the nonlinear system depends on the magnitude of the applied load, it is not possible to create solutions for different load cases by superposition. Each load case must be defined and solved as a separate analysis.

5.2 Geometry and Model

As for the linear analysis discussed in Chapter 4, three boundary condition cases will be considered: free standing, one edge supported and two edge supported URM partial height partitions. Since URM is a composite material, the FE model could be developed using two different material types, one each for the masonry unit and the mortar (Lofti [1994] and Martini [1997, 1998]). However, it is assumed herein that the wall is homogeneous to simplify the problem (Anand [1993, 1996]), and the wall FE mesh was refined until results converged. The partitions were modeled using small-strain shell elements (S8R) as illustrated in Figure 5.1.

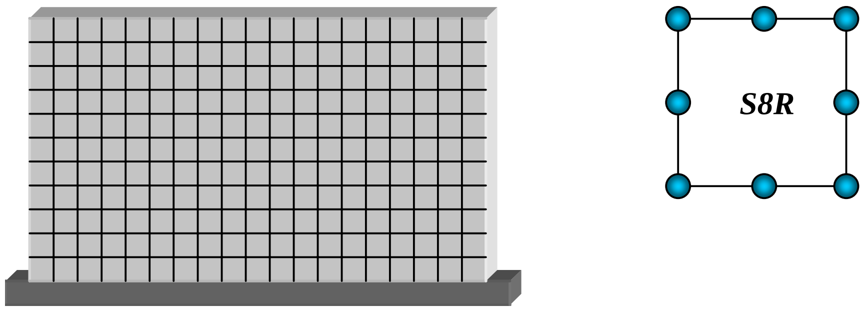


Figure 5.1 Finite Element and Mesh

5.3 Material Properties

5.3.1 Compressive Behavior

When material is loaded in compression, it initially exhibits elastic response. As the stress increases, some nonrecoverable (inelastic) straining occurs and the response of the material softens. An ultimate stress is reached, after which the material loses strength until it can no longer carry any stress. If the load is removed at some point after inelastic straining has occurred, the unloading response is softer than the initial elastic response: the damaged material is no longer elastic (Fig. 5.2). This effect is ignored in the present model since it is assumed here that the applications involve primarily monotonic straining, with only occasional, minor unloading. When a uniaxial specimen is loaded in tension, it responds elastically until, at a stress that is typically 7%-10% of the ultimate compressive stress, cracks form. Cracks form so quickly that, even in the stiffest testing machines available, it is very difficult to observe the actual behavior. The model assumes that cracking causes damage, in the sense that open cracks can be represented by a loss of elastic stiffness. It is also assumed that there is no permanent strain associated with cracking. This will allow cracks to close completely if the stress across them becomes compressive.

Since partial height partitions usually fail in tension in the out of plane direction, the compressive behavior is assumed to be linear while the wall is loaded. In the present study, the ultimate compressive stress is assumed to be a large number to keep compressive behavior linear.

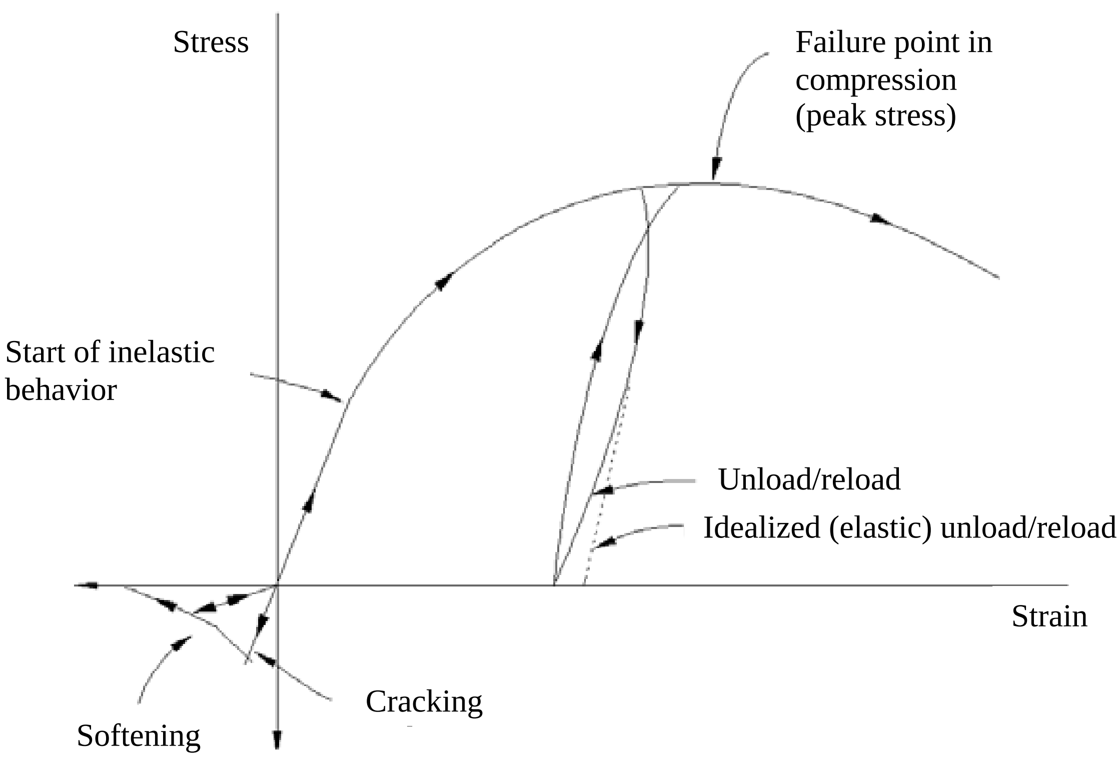


Figure 5.2 Uniaxial Behavior

5.3.2 Postfailure Stress-Strain Relation

Specification of strain softening behavior generally means specifying the postfailure stress as a function of strain across the crack.

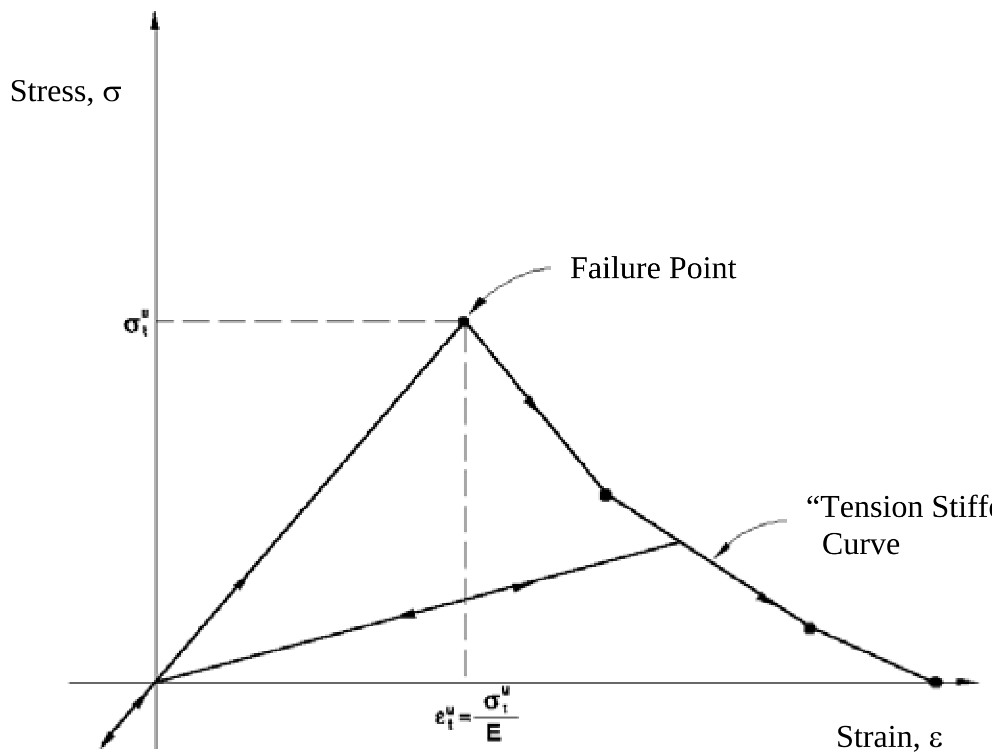


Figure 5.3 Tension Stiffening Model

Tension stiffening characteristics (Fig. 5.3) (Lourenco [1996, 2000]) are important in computational analysis since, generally, more tension stiffening makes it easier to obtain numerical solutions. Too little tension stiffening will cause the local cracking failure in the material to introduce numerical instability into the calculation of the overall response of the model. Few practical designs exhibit such unstable behavior, so the presence of this type of numerical instability in the analysis model usually indicates that tension stiffening is unreasonably low.

5.3.3 Crack Detection

Cracking is assumed to be the most important aspect of the behavior, and representation of cracking and of postcracking behavior dominates the model. Cracking is assumed to occur when the stress reaches a failure surface that is called the "crack detection surface" illustrated in Figure 5.4. When a crack has been detected, its orientation is stored for subsequent calculations. Subsequent cracking at the same point is restricted to being orthogonal to this direction since stress components associated with an open crack are not included in the definition of the failure surface used for detecting the additional cracks.

Cracks are irrecoverable: they remain for the rest of the calculation (but may open and close). No more than three cracks can occur at any point (two in a plane stress case, one in a uniaxial stress case). Following crack detection, the crack affects the calculations because a damaged elasticity model is used.

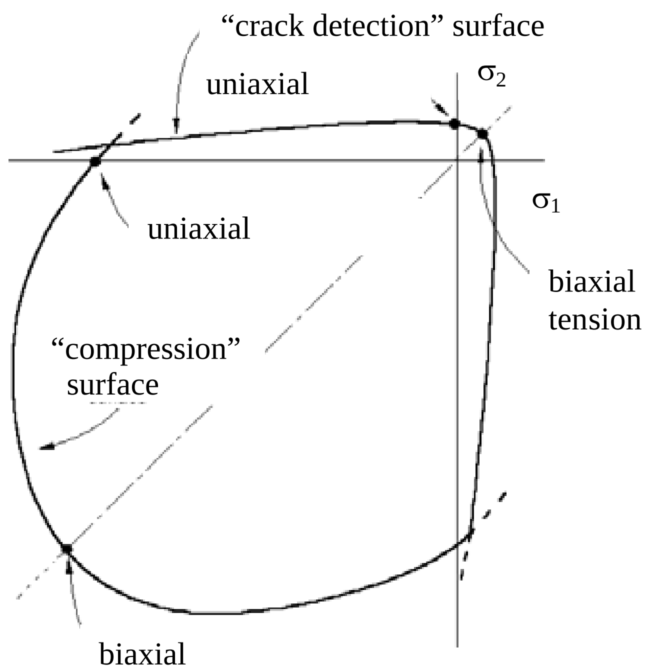


Figure 5.4 Yield and Failure Surfaces in Plane Stress

The concrete model is a smeared crack model in the sense that it does not track individual "macro" cracks. Constitutive calculations are performed independently at each integration point of the finite element model. The presence of cracks enters into these calculations by the way in which the cracks affect the stress and material stiffness associated with the integration point.

5.4 Loading and Solution Control

According to FEMA 273/274, the equivalent seismic force on the nonstructural component will be distributed in proportion to the mass distribution of the component in horizontal direction. Thus, the equivalent seismic force of the partial height partition will be uniformly distributed normal to the surface of the wall as illustrated in Figure 5.5 if the ground motion is shaking the wall in out of plane direction. The loading will be divided into two load steps. In the first step, the weight of the partition will be introduced, and in the second step, the equivalent seismic load will be gradually applied to the surface of the partition.

The load-displacement path for the partial height partition subjected to uniform surface load in the out of plane direction is an unstable problem, as sketched in Figure 5.6. During the period of response, the load and/or the displacement may decrease as the solution evolves. The Riks Method (Crisfield [1981]) provides an algorithm that allows effective solution in this case. ABAQUS uses the Riks iteration technique to stabilize the calculation process after the walls fail. This approach provides solutions regardless of whether the response is stable or unstable. It is assumed that the response is reasonably smooth so that sudden bifurcations do not occur.

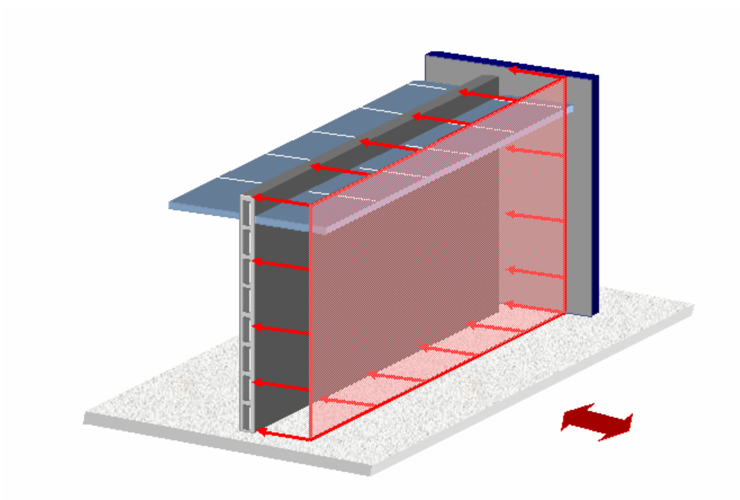


Figure 5.5 Equivalent Earthquake Load Pattern

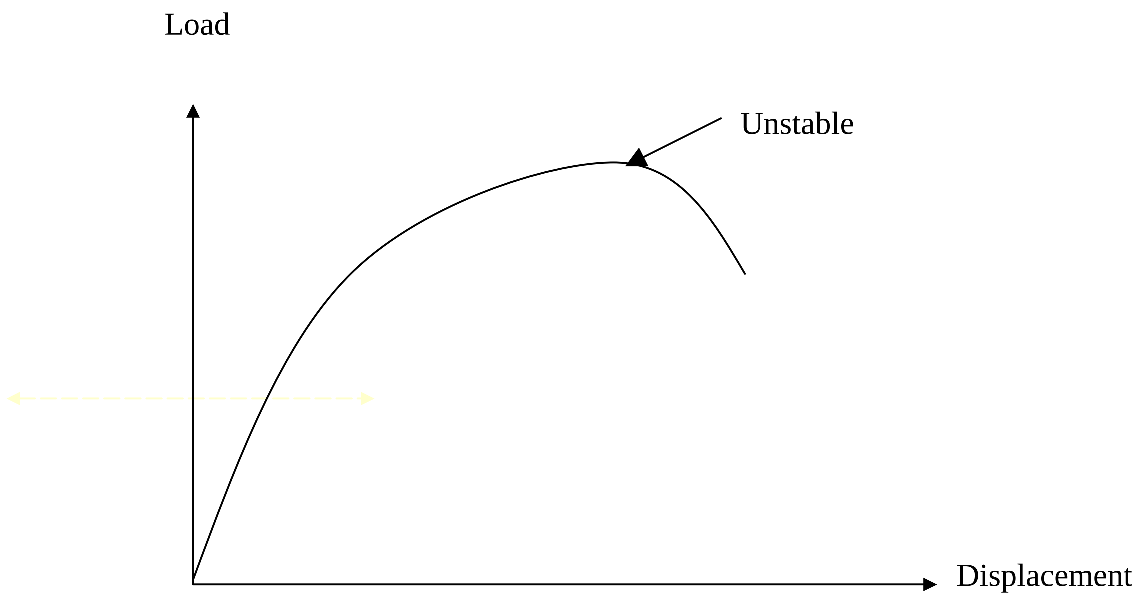


Figure 5.6 Load Displacement Path of Partial Height Partition Loaded in Out-of-Plane Direction

5.5 Verification of FE Model

Analysis results were confirmed by comparison to experimental results (Drysdale [1988]) using the case of the two edge supported partial height partition. The two edge supported partition was referred to as the "WF wall" to be consistent with Drysdale's nomenclature. The width, height and thickness were set at 280, 520 and 19 cm respectively. A bond wrench apparatus (Hughes [1980]) was used to determine flexural tensile strengths. The mean tensile strength of 86 specimens was found to be 68. Simple support conditions were used to facilitate the development and verification of the analysis models. The resulting analysis produced load-displacement values in excellent agreement with experimental findings, as shown in Figure 5.7. For additional verification, experimental results were also compared to results of yield line analysis (Sinha [1978], Zhang [2001]). Once again, very good agreement was achieved as shown in Table 5.1.

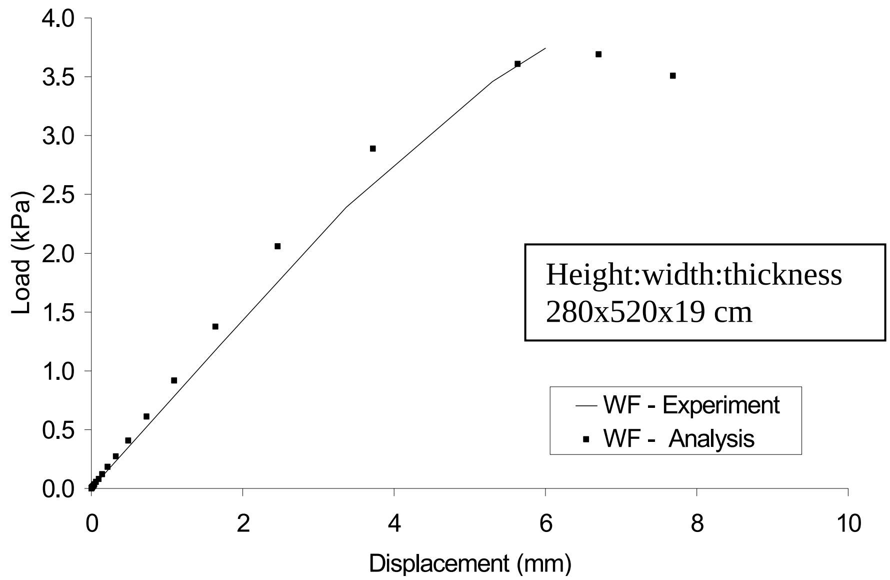


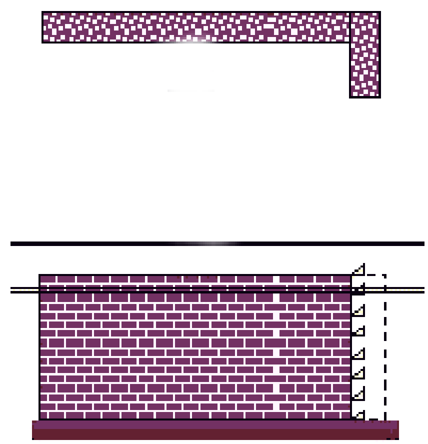
Figure 5.7 Out-of-Plane Load-Displacement Relationship from FE Analysis and Experiment

Table 5.1 Comparison of Experiment and Predicted Out-of-Plane Capacity of WF Wall

	Experimental Results	Yield Line Analysis	Nonlinear Static Pushover Analysis
Failure Load (psf)	78.3	79.3	76.2

5.6 Reserve Capacity after Occurrence of First Crack

Static pushover analysis allows one to predict the detailed behavior of the partition after it cracks. Either piece-wise linear (Henderson [1993, 1994]) or iterative nonlinear analysis are required to fully capture nonlinear behavior. An L-shaped wall model was studied (Fig. 5.8) and its displacement response computed using pushover analysis (Fig. 5.9). Results of this analysis show that the reserve capacity of the partition after the first crack can be as much as 30% of the capacity from linear analysis.



72 x 144 x 6
(height x width x thickness)

Figure 5.8 L-shape Wall Model

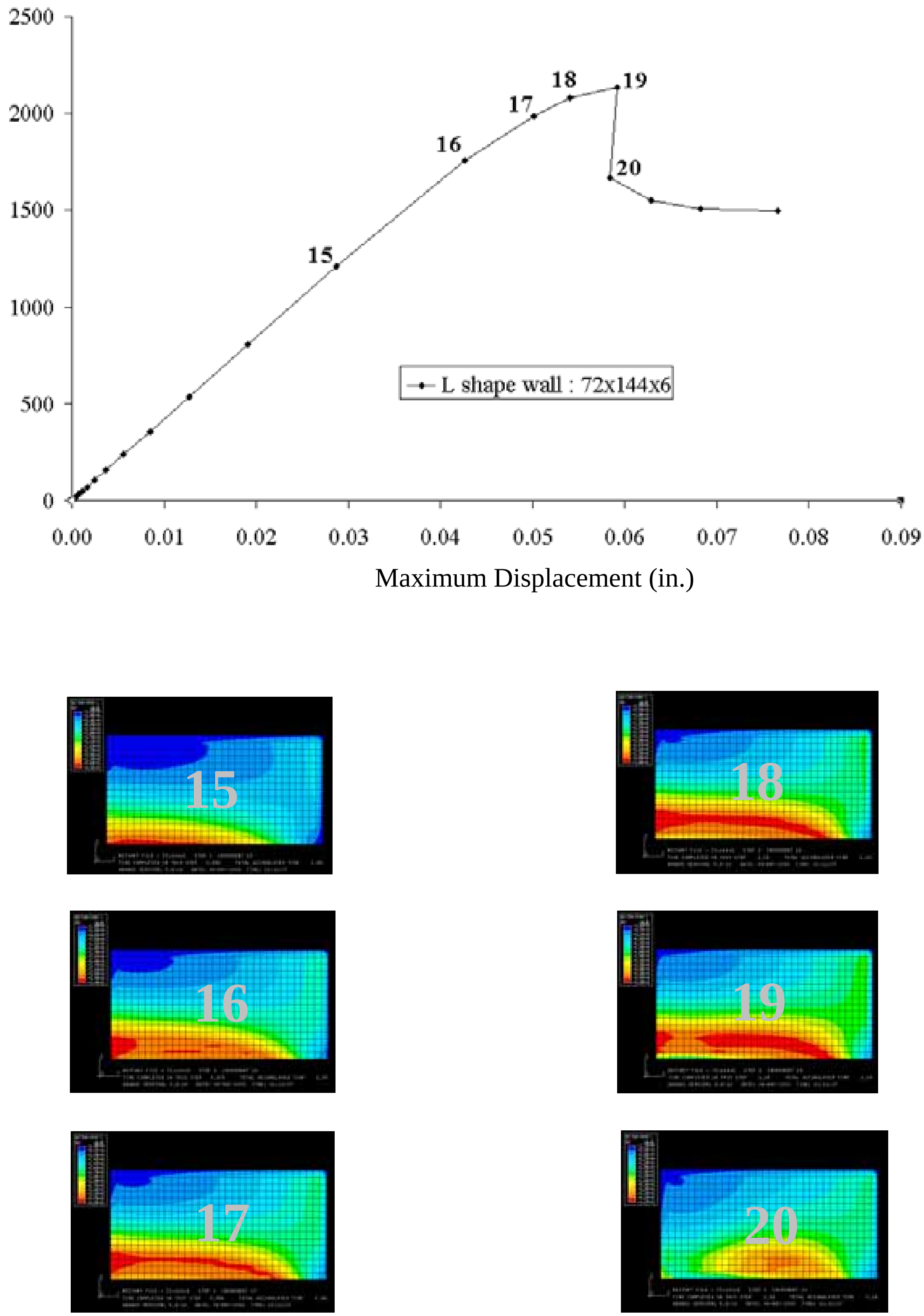


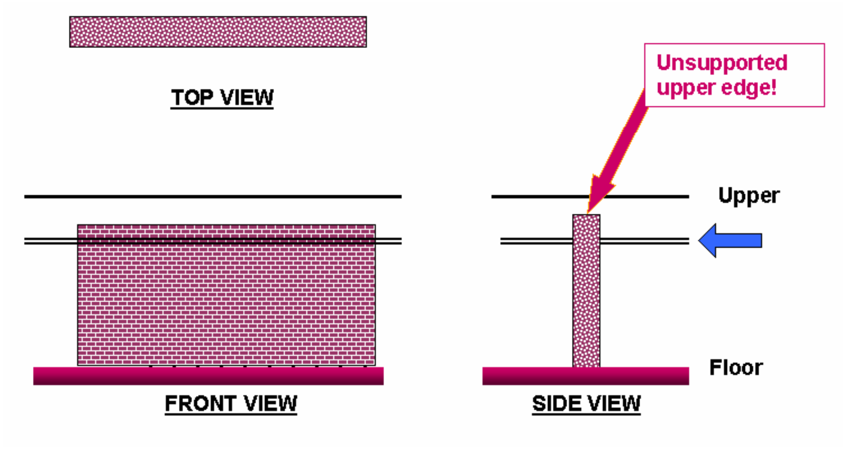
Figure 5.9 Sample Results from Nonlinear Static Pushover Analysis

The L-shape sample partition dimensions are 72:144:6 (height : width : thickness). The edge was assumed pinned along the right hand vertical edge as shown in Figure 5.8, typical of partitions divided into two pieces by a door opening as discussed in Chapter 2. Stress contours at various stages along the load path are shown in Figure 5.9. The number of the loading step is marked on the graph.

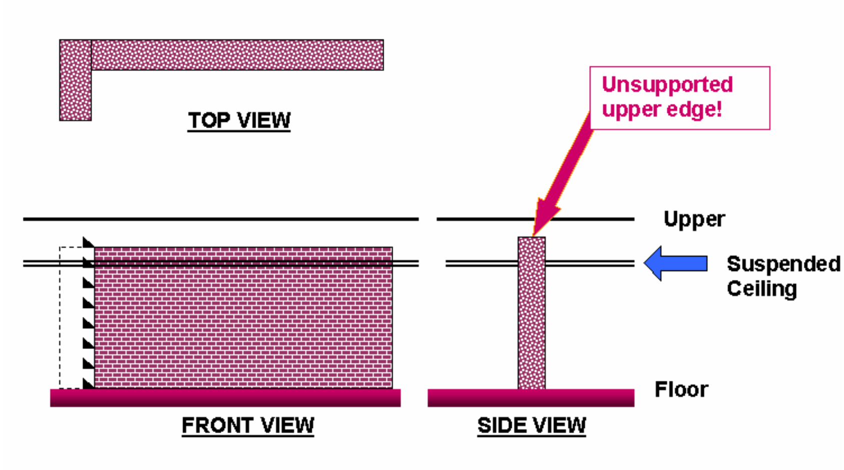
The results show that the stress-strain relationship is linear until load step 15. The maximum stress is along the fixed base and higher on the free edge. When the load is increased to step 16, the stress at the hot spot is reduced due to the damage in the wall. The damage is expanded as the wall is loaded. When the load reaches the capacity of the partition at load step19, the distributed stress pattern changes and overall is dramatically reduced.

5.7 Parameter Study

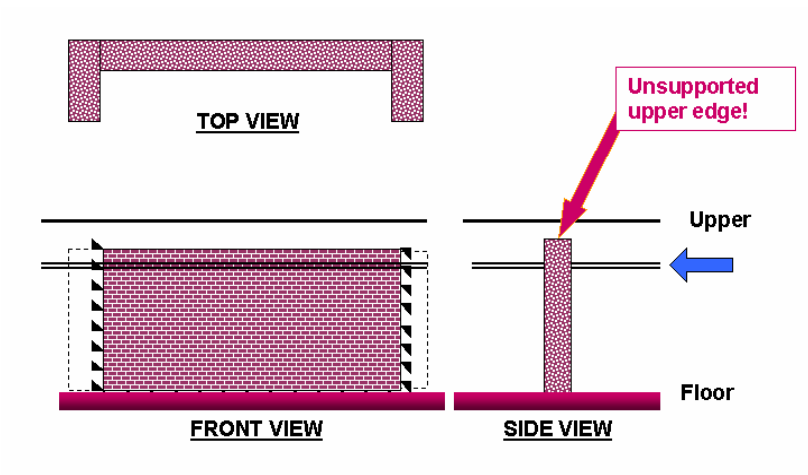
The procedure described in Section 5.6 was next applied to other partial height partition cases with varying aspect ratios and support conditions. Three different support conditions were used as shown in Figure 5.10 (sample ABAQUS input files for these cases are provided in Appendix A).



a) Free Standing URM Partial Height Partition



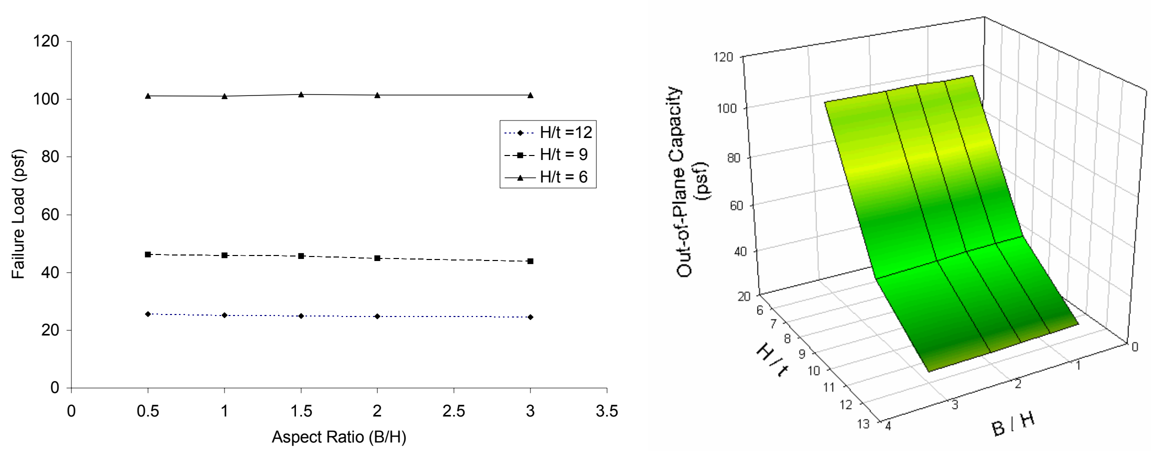
b) One-edge Supported URM Partial Height Partition



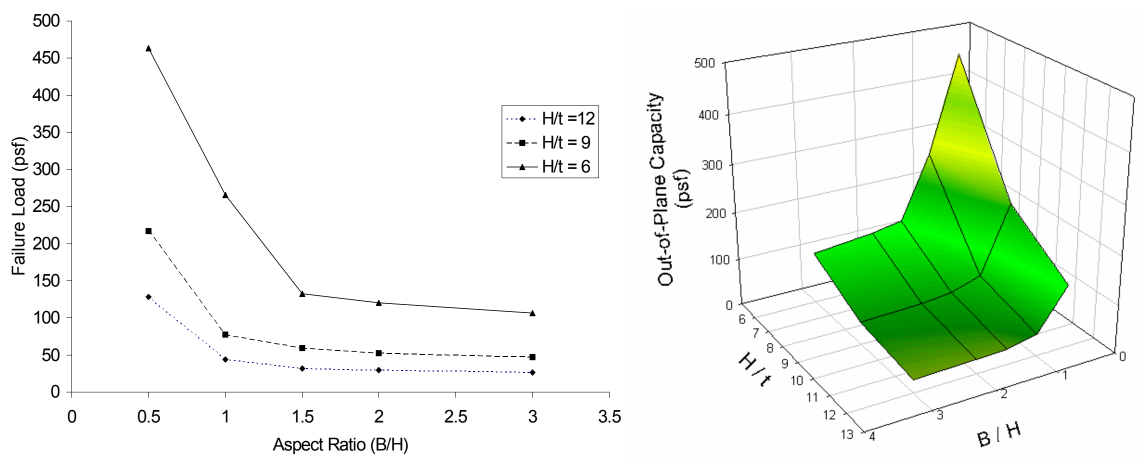
C) two-edge Supported URM Partial Height Partition

Figure 5.10 Different Wall Configurations for Parametric Study

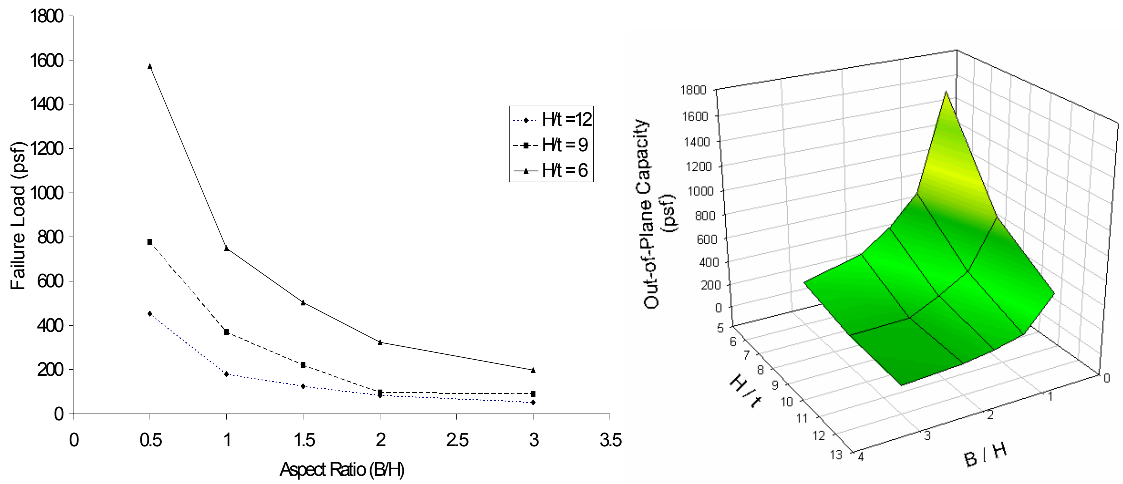
The analysis results for these three cases show that the capacity of the partial height partition will increase as the aspect ratio (B/H) decreases. As the aspect ratio of the wall increases, the wall capacity approaches that of the freestanding condition (Fig. 5.11).



a) Freestanding Partial Height Partition



b) One-edge Supported Partial Height Partition



c) Two-edge Supported Partial Height Partition

Figure 5.11 Failure Loads for URM Block Partial Height Partitions with different Aspect Ratio

5.8 Out-of-plane Capacity Equations

Parameter studies were performed to investigate the effect of wall geometry on the out-of-plane capacity of the partition. The width/height (B/H) ratio was varied from 0.5 to 3.0 and the height/thickness (H/t) ratio was varied from 6 to 12 on the basis of actual wall dimensions observed in the field investigations (Chapter 2). Material properties of the URM walls were held constant.

Analysis results confirm that the out-of-plane capacity of freestanding URM partial height partitions is not function of aspect ratio (B/H) but instead is proportional to $1/(H/t)^2$. The out-of-plane wall capacity increases as H/t decreases. This result is in agreement with previous studies (ABK 1981, 1984). The relationship between the out-of-plane capacity of freestanding partitions and the wall H/t ratio is presented in Eq. (5.1):

$$PF = \frac{14}{15}\frac{\sigma_t}{(H/t)^2} \tag{5.1}$$

where

PF = Out-of-plane capacity of URM partial height freestanding partition

σ_t = Failure tensile strength of URM

H = Height of the wall

t = Thickness of the wall

The out-of-plane capacity of freestanding partial height partitions is plotted in Figure 5.11(a). Since the H/t ratio is constant for each graph, the out-of-plane capacity is constant as B/H varies. However, for the one-edge and two-edge supported partial height partition, the out-of-plane capacity will be greater as B/H and H/t ratios decrease. The analysis results are shown in Figure 5.11(b) and 5.11(c). The out-of-plane capacity expressions are presented in Eqs. (5.2) and (5.3) below. Note that C1 and C2 are constants given in Table 5.2.

$$PL = \frac{14}{15}\frac{\sigma_t}{(H/t)^2} + \frac{C1}{(B/H)^{2.5}} \tag{5.2}$$

$$PH = \frac{14}{15}\frac{\sigma_t}{(H/t)^2} + \frac{C2}{(B/H)^{1.5}} \tag{5.3}$$

where

PL = Out-of-plane capacity of one-edge supported URM partial height partition

PH = Out-of-plane capacity of two-edge supported URM partial height partition

C1, C2 = Constants in Table 5.2

B = Width of the wall.

Table 5.2 Constants in Out-of-Plane Capacity Equations

	Height/Thickness (H/t)		
	12	9	6
C1	20	30	70
C2	170	300	550

The out-of-plane capacity of one-edge and two-edge supported partitions will no longer depend on the edge support condition when B/H ration exceeds a value of 2. This can be explained by the fact that the second term in Eqs. (5.2) and (5.3) is small compared to the first term.

6. Simplified Model Method

A simplified approach is needed to find the out-of-plane capacity of partial height partitions. The nonlinear analysis tools, models and results summarized in the previous chapter are too complex for everyday use by a practitioner concerned with rehabilitation of essential facilities. A simplified model and analysis approach is presented below to address this need.

6.1 Simple Way for User to Define Capacity of Partial Height Partitions

As indicated in Figure 6.1, the behavior of masonry and concrete may be considered as lying somewhere between the extremes of perfectly plastic and perfectly brittle. The stress first increases to a maximum then decreases gradually with increasing deformation. Plastic, softening, or brittle behavior then follows depending on the type of material used. This post-elastic behavior is caused by the gradual break down of the weakest links in the heterogeneous material, after which the micro cracks finally link up to form a macro crack.

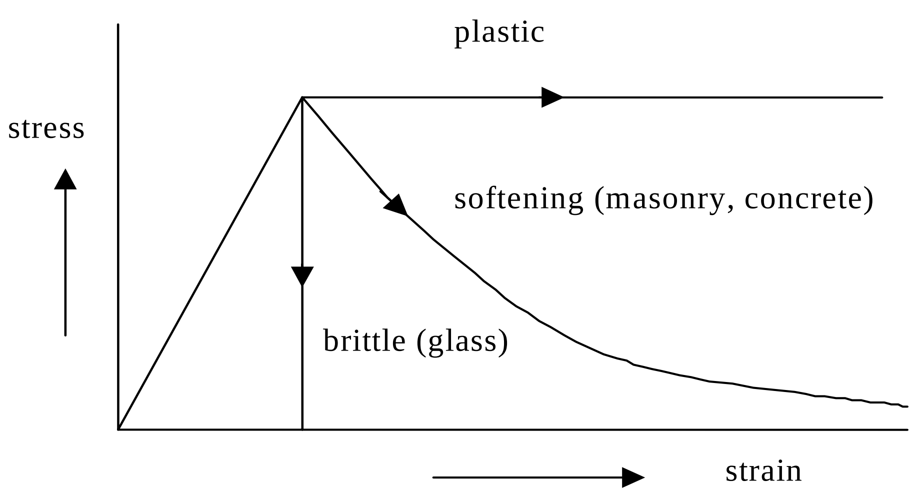


Figure 6.1 Stress-Deformation Behavior of Materials: Elastic-Plastic, Elastic Brittle and Elastic Softening Behavior

Free standing, one-edge supported and two-edge supported partial height partitions have similar force and displacement curves, such as that shown in Figure 6.2. The partition subjected to lateral uniform load will displace linearly until the partition experience the first crack. After that, the partition will lose stiffness as it softens and failure follows shortly thereafter.

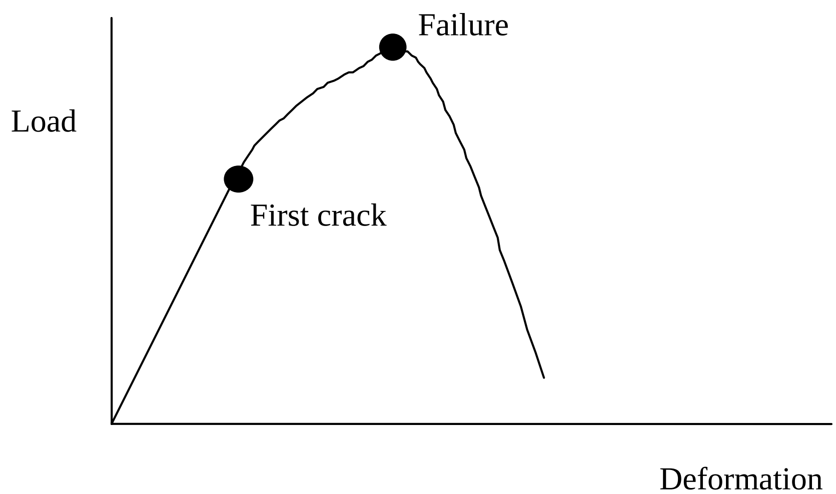


Figure 6.2 Typical Load-Deformation Relationship for Freestanding, One-Edge Supported and Two Edge Supported Partitions

A simplified nonlinear force-deflection relationship can be assumed using the two key points at the first crack and at the failure point as shown in Figure 6.3. The resulting load-deflection graph can be normalized by failure load (Q_{CE}) and the height (H) of the partition. For each partition support configuration (freestanding, one-edge supported and two-edge supported), idealized load-deflection relations can be established as shown in Figure 6.4 based on information given in Table 6.1.

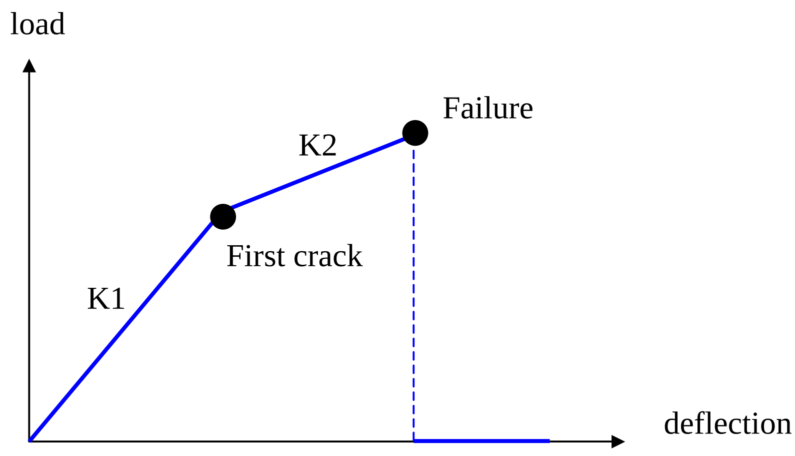
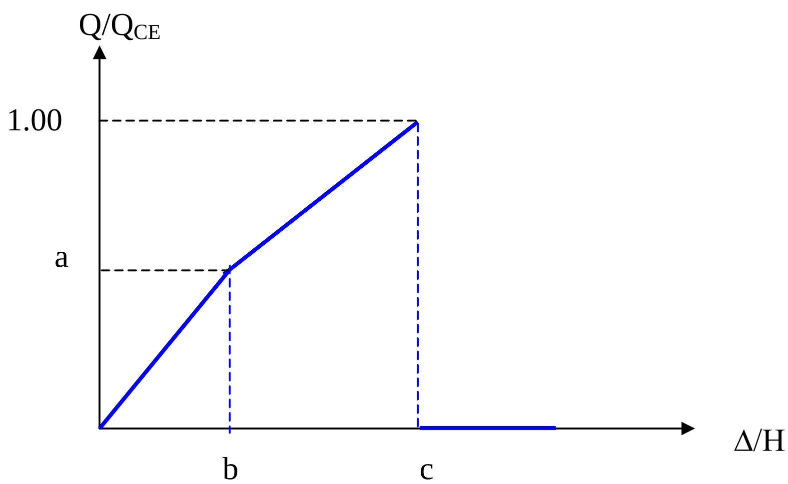


Figure 6.3 Simplified Nonlinear Force-Deflection Relationship



Where

Q = load applying on the partition

Q_{CE} = expected failure load of the partition

D = maximum deflection

H = height of the partition

Figure 6.4 Idealized Load-Deflection Relation for the Partial Height Partition

Table 6.1 Nonlinear Static Procedure (NSP) – Simplified Force-Deflection Relations for URM Out-of-Plane Partitions

	a	b %	c %	NOTES
Freestanding	0.52	0.04	0.1	at the middle-top
One-edge supported	$0.33\sqrt{B/H}$	0.04	0.1	at the top free corner
Two-edge supported	$0.52\sqrt{B/H}$	0.03	0.08	at the middle-top

6.2 Simplified Spring Model

Finally, a nonlinear spring type element can be used to represent the nonlinear characteristics of the partial height partition in the out-of-plane direction. The stiffness properties (K1, K2) of the nonlinear spring can be computed using appropriate tabulated values (Table 6.1) for the wall support conditions of interest.

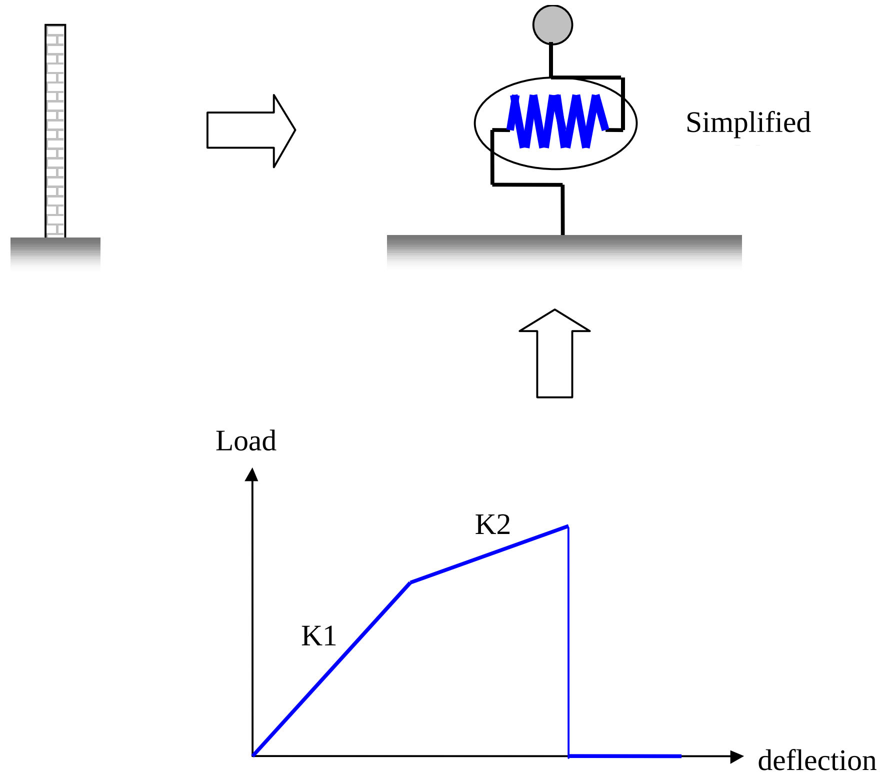


Figure 6.5 Out-of-Plane Wall Simplified Spring Model

7. Rehabilitation in Guidelines

The nonstructural systems within a building include architectural, electrical, and mechanical components, as well as the contents of the building. Common nonstructural components include ceilings, windows, office equipment, computers, inventory stored on shelves, file cabinets heating, ventilating and air conditioning (HVAC) equipment, electrical equipment, furnishings lights, etc. Typically, nonstructural items and their proper installation are not reviewed by engineers for resistance to seismic forces, and are usually specified by architects, mechanical and electrical engineers and/or interior designers. They may also be purchased and installed later, after construction of the building is complete, without the direct involvement and review of design professionals who are fully aware of the need for aseismic design.

7.1 Significance of Nonstructural Damage

There are three major types of risk associated with earthquake damage to nonstructural components: life safety, property loss and interruption or loss of essential functions. Damage to a particular nonstructural item may have differing degrees of risk in each of these three categories. In addition, this damage to the item may result in direct injury or loss, or indirect loss in which the injury or loss is a secondary effect or consequence of the failure of the item.

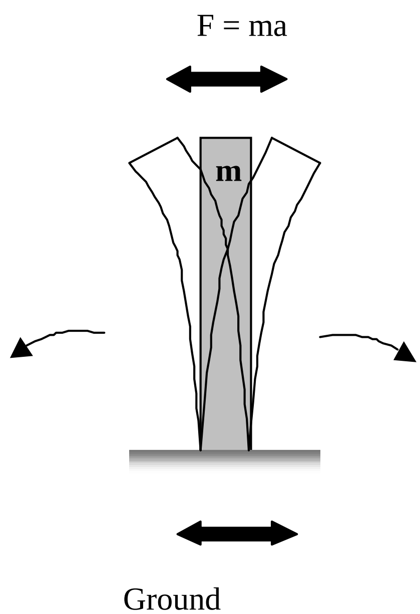
Life Safety is of primary concern because people could be injured or killed by damaged and falling nonstructural components. Examples of potentially hazard nonstructural damage that has occurred in past earthquakes include broken glass, overturned tall and heavy cabinets or shelves, falling ceiling or overhead light fixtures, ruptured gas lines and other such releases of hazardous materials, falling pieces of decorative brickwork or precast concrete panels, and collapse masonry walls or partitions.

Damage to nonstructural elements can also be costly to building owners, either in the form of direct or indirect losses. Property losses attributable to contents alone are often estimated to be one third of total earthquake losses.

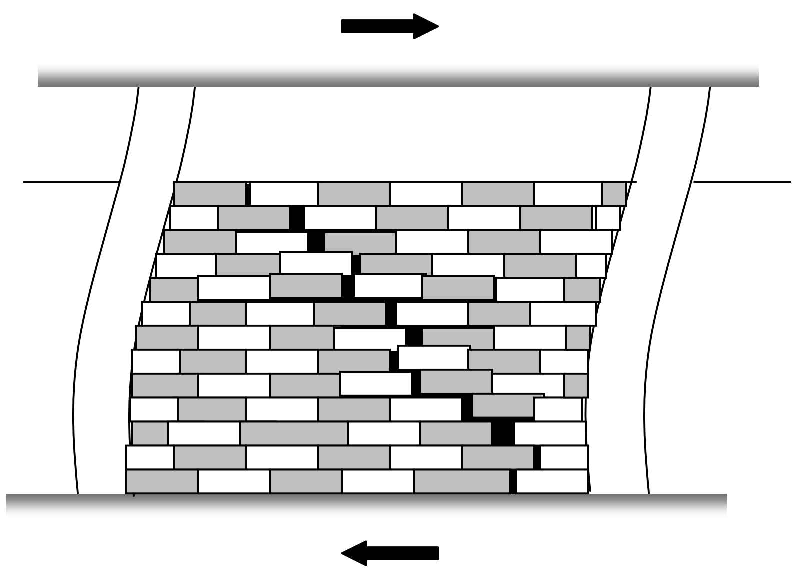
In addition to the life safety and property loss considerations noted above, nonstructural damage is also likely to make it difficult or impossible to carry out the functions normally accomplished in a facility. The potential for post earthquake downtime or reduced productivity is a serious risk that could lead to financial ruin for the building owners or occupants.

7.2 Causes of Nonstructural Damage

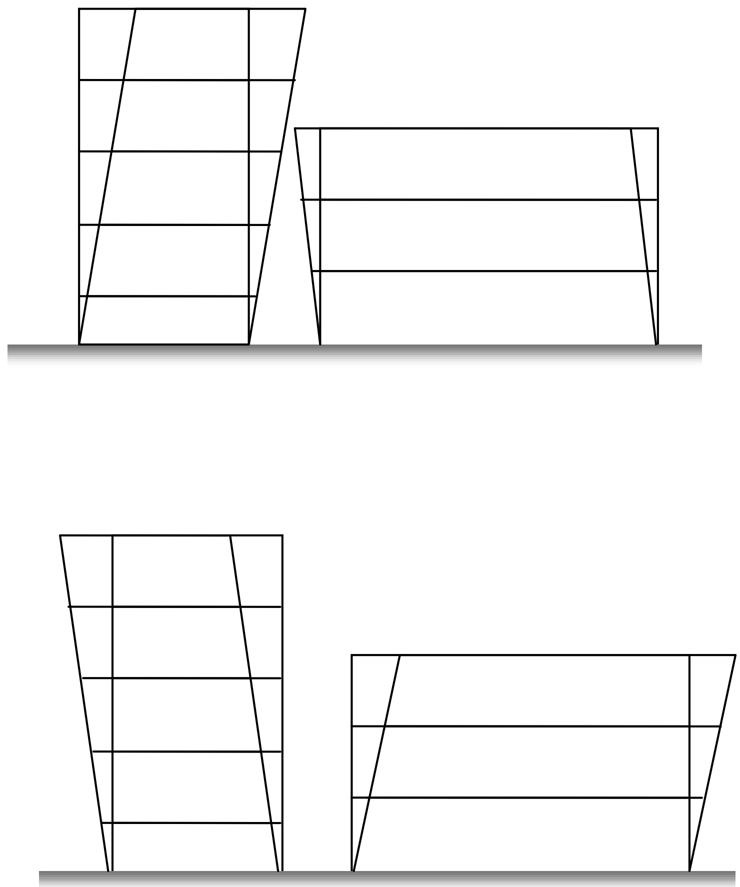
Three major effects from earthquake ground shaking can result in failure of nonstructural elements in the building: (1) inertial or shaking effects on the nonstructural elements themselves; (2) distortions imposed on nonstructural components due to building displacements; and (3) cladding and other localized damage (e.g., water penetration) associated with separation or pounding at the interface between adjacent structures. Each of these effects is illustrated in Fig. 7.1 below.



a) Inertial Forces



b) Building Distortion



c) Building Separation and Pounding

Figure 7.1 Causes of Nonstructural Damage

7.2.1 Inertial Forces

When a building is shaken during an earthquake, the base of the building moves with the ground, and the entire building and its contents develop inertial forces proportional to the acceleration at each location. The ground motion is filtered through the structure and amplified over the height of the structure. Localized response of the structure will result in a complex history of accelerations being applied to the nonstructural components; floor spectra are typically used to estimate forces applied to a nonstructural component at its specific location in the building.

7.2.2 Building Distortion

During an earthquake, flexible structures distort in response to the earthquake forces (Fig. 7.1(b)). The roof of a tall building may displace several feet in each direction relative to the base during ground shaking. The floor-to-floor distortion or story drift might range from a quarter of an inch to several inches depending on the dynamic characteristics of the building structure in relation to that of the ground motion. Interstory drift is limited by provisions of modern codes in part to control nonstructural damage. Partitions, windows and other items that span from floor to floor must be designed to accommodate this interstory drift. Providing gaps between a pane of glass and the surrounding mullions will protect glass panels from failure due to in-plane distortions. Brittle drywall partitions and glass and masonry infill elements cannot tolerate any significant distortion due to drift, either in-plane or out-of-plane, and must be protected by flexible joint separation materials or gaps to prevent their failure.

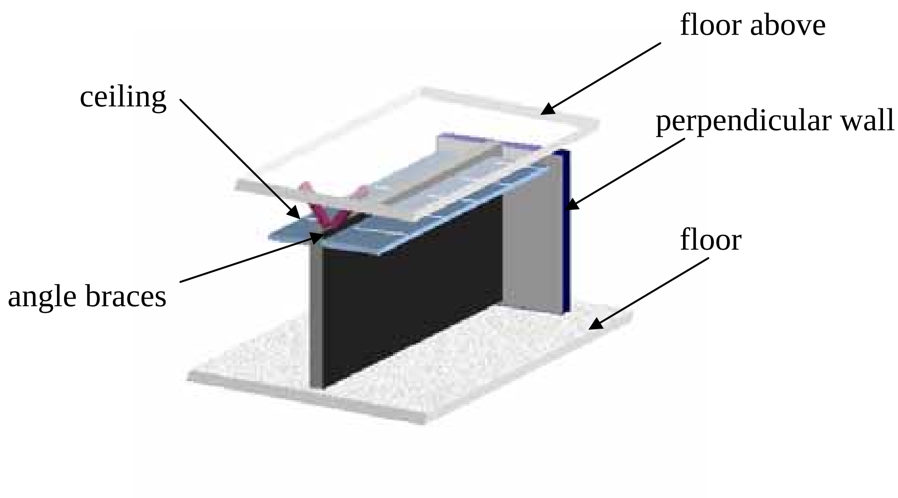
7.2.3 Building Separation

Another source of nonstructural damage is pounding of adjacent structures due to differences in response characteristics of the two structures and inadequate separation. The resulting damage to cladding, walls, and framing can be especially severe if contact does not occur at the floor levels. Damage can also occur across expansion joints in structures of irregular planform. Cladding and utilities that meet at these points must be designed appropriately to avoid localized failure due to contact or excessive response levels.

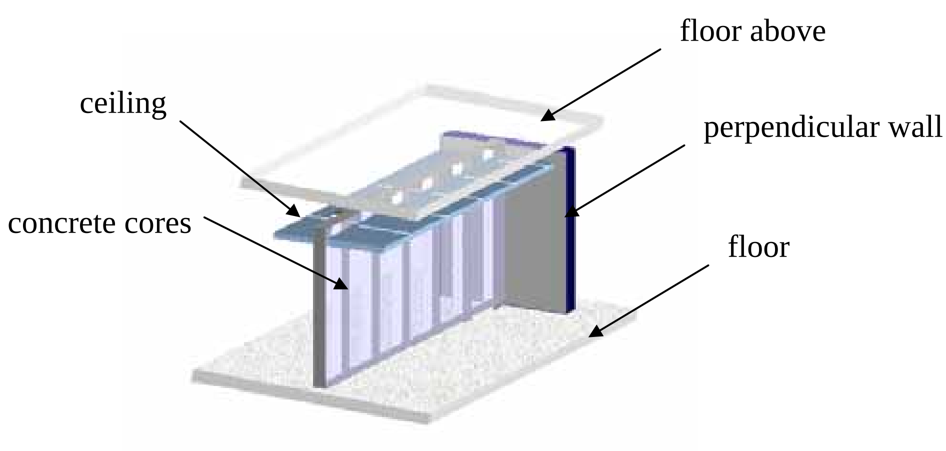
7.3 Rehabilitation Schemes for Partial Height Partitions

The primary concern of this investigation is the rehabilitation of heavy partial height partitions. These walls do not extend from floor to floor so are not susceptible to interstory drift distortions out of plane, but rather are mostly vulnerable to lateral inertial forces. (Care must be taken to detail these partitions in plane so that they do not create a short column effect which leads to excessive lateral shears in adjacent columns.) FEMA 74 provides a number of bracing solutions to stabilize and protect nonstructural systems and equipment. In the case of out-of-plane response of partial height partitions, this document recommends that angle braces attached to the underside of the floor above and to the top of the partial height partition to hold the partition in place (Fig. 7.2(a)). The approximate cost of this solution may be as high as $24-$40 per linear foot. In addition, this rehabilitation option changes the behavior of out of plane wall from acceleration-sensitive to both acceleration-sensitive and drift-sensitive.

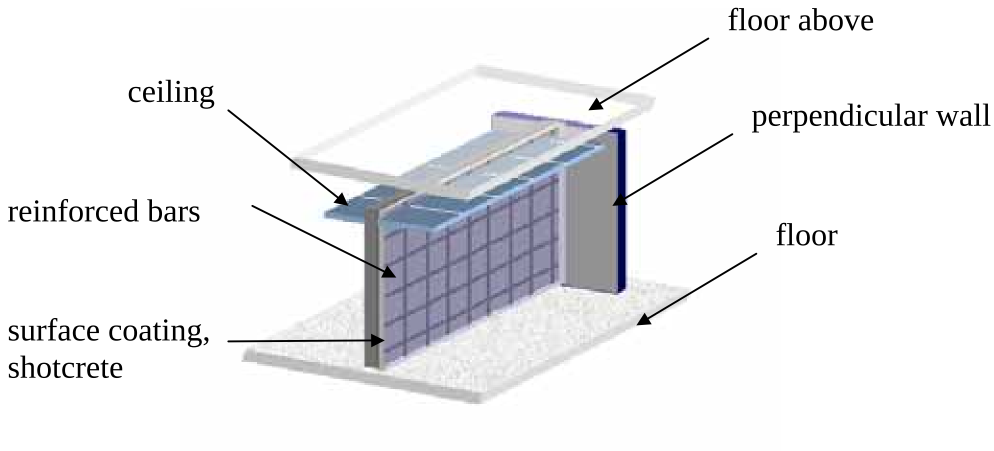
Two other methods that can be used to increase the out of plane capacity of the partition are shown in Figs. 7.2(b) and 7.2(c); both methods were evaluated in MAE Project ST-6. First is use of reinforced concrete cores in which voids in the partition are filled with concrete. A second method utilizes shotcrete as a surface coating, and requires adding two layers of concrete and one layer of reinforcing bars. Both rehabilitation approaches are expensive and will disrupt activities in the building as they are being applied.



a) Angle Braces



b) Reinforced Concrete Cores



c) Surface Coating

Figure 7.2 Rehabilitation Options for Partial Height Partitions

7.4 Proposed Rehabilitation Scheme: Compression Stud

A simple, less expensive and less invasive rehabilitation method is needed to stabilize partial height heavy partitions and to increase their capacity in the out-of-plane direction. In addition, this improved rehabilitation method should not make them more susceptible to building distortions by converting them from acceleration-sensitive-only to both acceleration-sensitive and drift-sensitive, as would happen in the use of the V-brace proposed in FEMA 74. To avoid some of these difficulties, a compression stud device (Fig. 7.3) is proposed for use in strengthening the partition by increasing the vertical compressive stress (Adham [1985] and Bariola [1990]). The stud is to be designed and proportioned by an engineer to apply a predetermined level of compressive stress to the partial height partition while, at the same time, limiting the transfer of interstory drift distortions in the out of plane direction of the panel from the floor above.

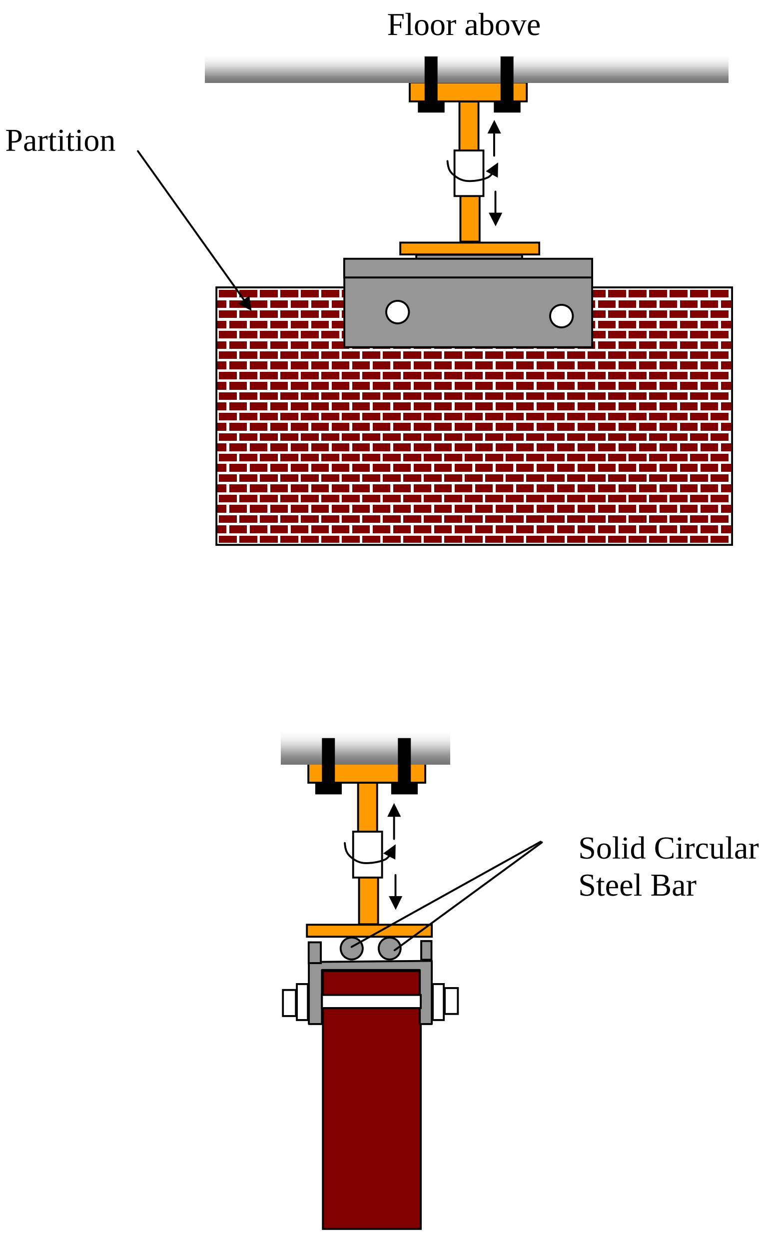
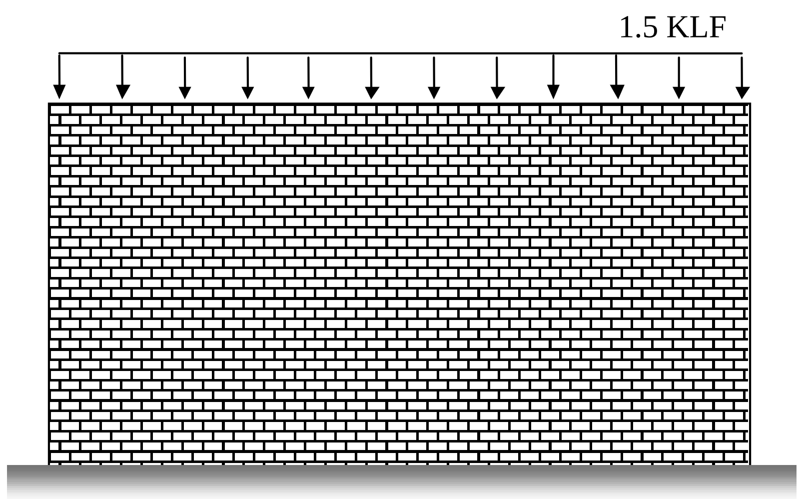


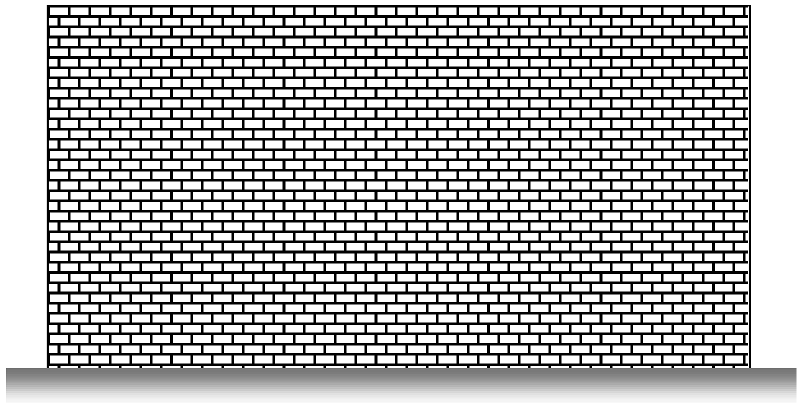
Figure 7.3 Proposed Compression Stud Device

Prescribed levels of vertical compressive stress can increase the capacity of a partial height URM partition (Meli [1973], Mendola [1995] and Velazquez [2000]). Compression stud devices can be used to create desired levels of initial vertical compressive stress in the URM partition resulting in an increase in capacity against out-of-plane forces. To confirm these assumptions, two sample freestanding partitions (Fig. 7.4) were analyzed using static pushover analysis. Partition dimensions are 72 inch high, 144 inch wide and 6 inch thick. One partition has 1.5 klf uniform compressive load applied along the top of the wall (Fig. 7.4(a)) while the other partition is free from applied vertical compressive stress (Fig. 7.4(b)). Their nonlinear out-of-plane load-displacement response under lateral load is compared below in Fig. 7.5.



H:B:t = 72x144x6

a) Partition with Vertical Compressive Stress (1.5 KLF) at the Top



H:B:t = 72x144x6

b) Partition Without Vertical Compressive Stress (0 KLF) at the Top.

Figure 7.4 Sample Partitions to Test Effect of Vertical Compressive Stress

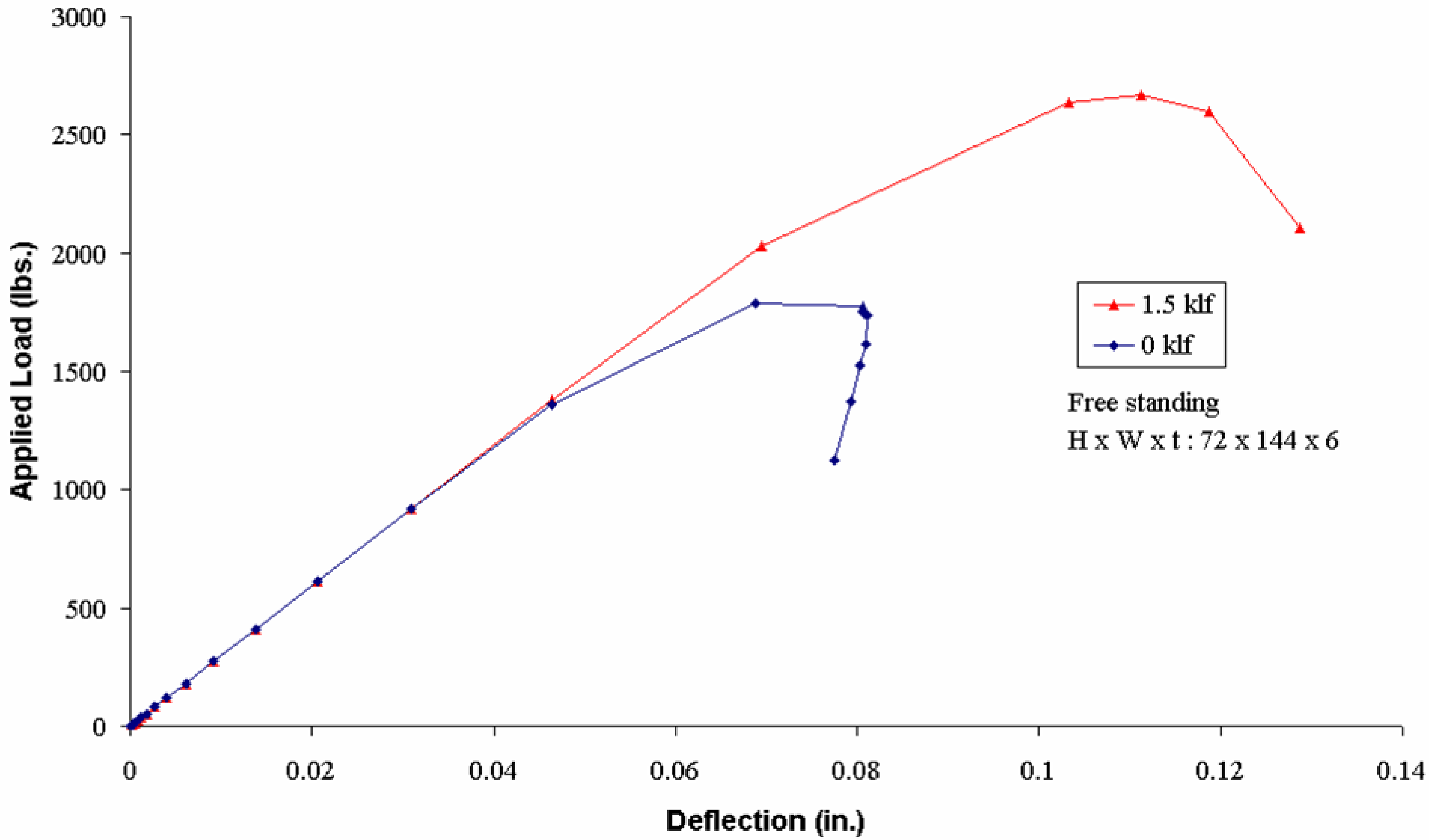
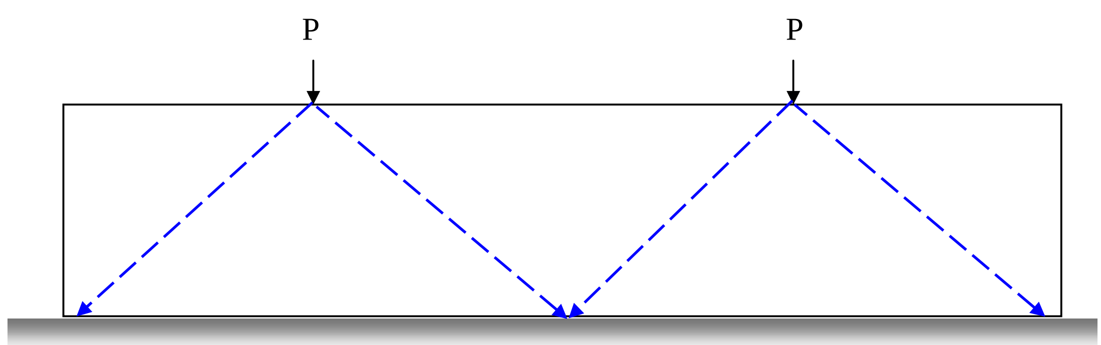


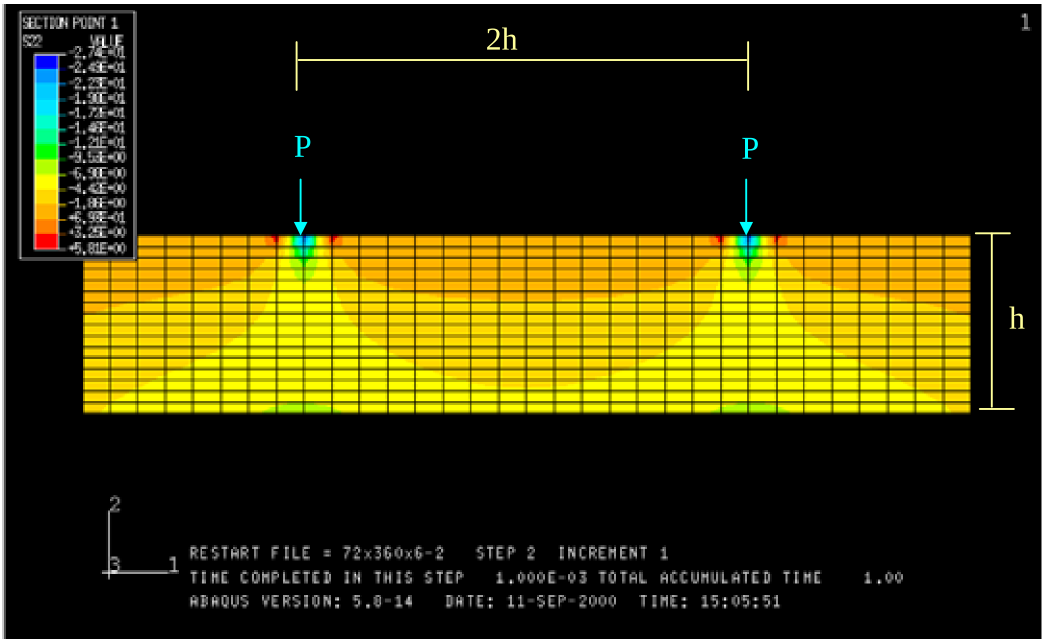
Figure 7.5 The Analysis Results from Pushover Static Analysis of Partition With and Without Vertical Compressive Stress

Figure 7.5 shows that precompression increases the out-of-plane resistance of the freestanding partial height partition by approximately 30%. The increased capacity is dependent upon the amount of compressive stress applied to the partition. However, as a practical matter, it will be difficult to apply such a uniform compressive stress as a means of rehabilitation of partial height partitions in existing structures. The level of compressive stress will also depend on the capacity of the floor system above to which the jacking forces from the compression stud device are applied. A more practical approach is illustrated in Fig. 7.6(a) and involves spacing the compression studs at appropriate intervals such that the compressive stress at the base of the partition (where initial cracks leading to eventual failure out of plane will form) is uniform. The vertical stress from the concentrated loads is distributed to the base at a 45 degree angle (Fig. 7.6(a)) and this sets the spacing of the compression studs along the top of the wall (hidden from view in the space above the drop ceiling) at twice the height (2h) of the partial height wall. The vertical compressive stress distribution was confirmed by finite element analysis (Fig. 7.6(b)).

Finally, the increase in out-of-plane capacity of the partial height partition is dependent upon the level of vertical compressive stress as noted above. Fig. 7.7 shows the amount of increase to be expected for a freestanding partition at various levels of applied vertical compressive stress.



a) Vertical Stress Distribution from Concentrated Loads Spaced at 2h



b) Vertical Stress from Concentrated Load

Figure 7.6 Vertical Stress Contour of Partial Height Partition due to 2 Concentrated Loads at the Top of the Partition (load spacing = 2h)

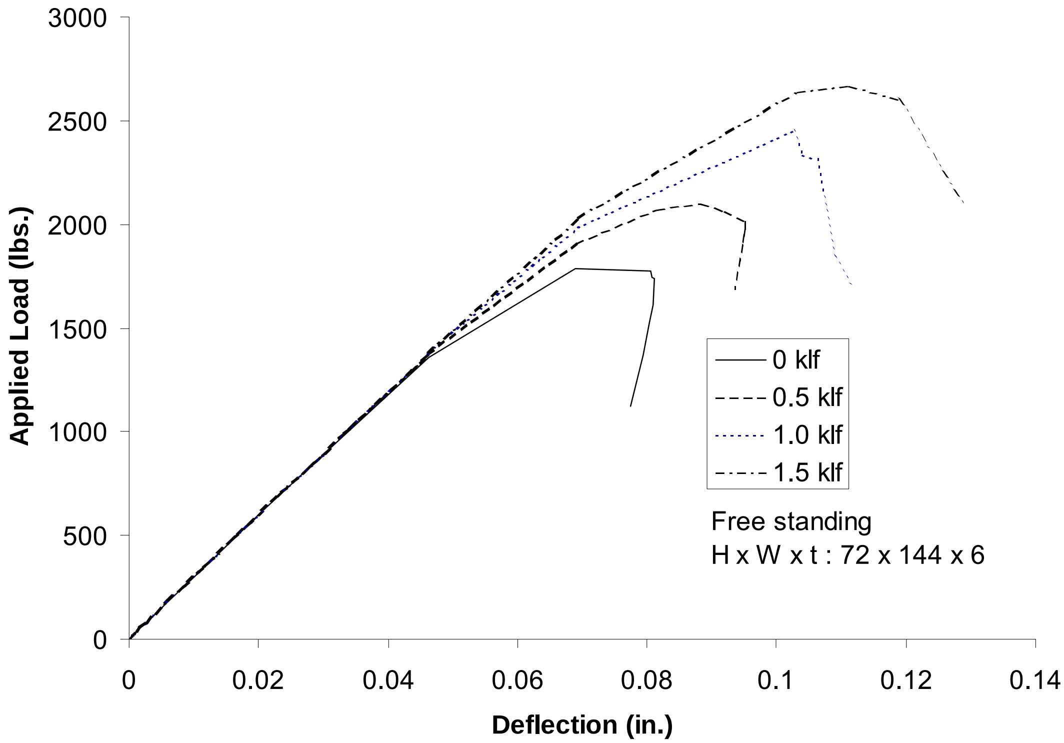


Figure 7.7 Effect of Pre-Compression on Lateral Strength of Free-Standing Partial Height Walls

8. SUMMARY AND RECOMMENDATIONS

8.1 Summary

URM partial height partitions can be found in many low-rise buildings throughout the Mid-America region. Their failure out of plane could pose a very serious risk to occupants and present a significant obstacle to those trying to exit a building following an earthquake. Vertical edge support conditions for these partitions vary depending on the location of the wall within the structural framing and on the presence of openings for doorways. Either one or both edges of the partial height partition can be laterally supported because of their attachment to adjacent framing members. However, analysis procedures for URM partial height partitions recommended in FEMA 273/356 are based only on freestanding support conditions so components are assumed to have no support along the top or along vertical edges.

The capacity of URM partial height partitions including the effect of lateral edge supports was examined using a FE model of a URM wall developed in ABAQUS. This model was also used in nonlinear static pushover analyses to estimate the out-of-plane capacity of a variety of walls. The model includes the effect of tension stiffening on the overall URM material behavior to properly simulate post cracking in the inelastic range. Analytical results show that for partial height partitions with the same height-to-thickness (H/t) and aspect ratios (B/H), walls with lateral support along two vertical edges have the greatest capacity and freestanding walls the least capacity to resist out-of-plane loads. The out-of-plane capacities of one-edge and two-edge supported partitions are significantly higher than the out-of-plane capacity of freestanding partitions. For walls with B/H ratios greater than 2, the out-of-plane capacity is close to that of freestanding walls regardless of the support conditions. FEMA recommendations for URM walls loaded out-of-plane are based on the assumption of freestanding support conditions. As a result, these recommendations may be overly conservative in the case of walls with different support conditions and aspect ratio B/H less than 2. A revised set of equations was developed for use in predicting the out-of-plane capacity of URM partial height partitions of varying geometries and support conditions.

The V-brace rehabilitation scheme recommended in FEMA 74 to stabilize partial height partitions changes the behavior of the wall in the out-of-plane direction from acceleration-sensitive to both acceleration and drift-sensitive. An alternative scheme was proposed in the form of a compression stud device which restricts the behavior of the rehabilitated wall to the acceleration sensitive region while providing additional lateral capacity through precompression of the wall. Analysis results show that the proposed method can increase the out-of-plane capacity of the wall by up to 30 percent.

8.2 Recommendations

The work described in this research report suggests that the out-of-plane capacity of partial height URM partitions should be given serious consideration in seismic zones. It is important to be able to predict the out-of-plane capacity of the partitions in order to assess their expected seismic performance. This report provides simple empirical formulas of the type presented in FEMA 273/356 to calculate the out-of-plane capacity of URM partial height partitions of varying geometries and support conditions, and also proposes a simple methodology for their rehabilitation. The general equations for base shear given in FEMA 356, Chapter 11, should be expanded to include the additional vertical edge support condition cases for partial height partitions which were the subject of this investigation. Moreover, the V-brace concept for partition rehabilitation introduced in FEMA 74 should be re-examined and the precompression scheme presented in Figure 7.3 of this report substituted in its place.

Since time and data were limited, there are many important aspects of the partial height partition problem that could not be thoroughly investigated in the limited set of parameter studies conducted as part of this research program. Partial height partitions are distributed throughout the structure and their performance should be evaluated for a variety of locations (such as around stairways and near exits) and at various levels above the base of the structure for ground motion inputs with differing spectral characteristics. Efforts to collect field data on performance of these and other nonstructural elements following major earthquakes should continue. This data should include collection and evaluation of direct and indirect losses associated with failure of nonstructural systems to aid in future loss assessments and decision making. Methods for cost effective rehabilitation of these and other nonstructural components should continue to be developed and refined. On-going efforts to incorporate nonstructural systems in Performance Based Earthquake Engineering (PBEE) methodologies through ATC 58 should continue. Finally, perhaps the most critical need is for additional experiments to confirm analysis results which predict the performance of a wide variety of nonstructural systems. Testing to determine out-of-plane capacities of partial height walls for a variety of geometries and support conditions would be especially beneficial for use in confirming the results predicted by FE analysis in this investigation.

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APPENDICES

A. ABAQUS Input Files

A.1 Freestanding Partition for NSP

```
*HEADING
 Freestanding Partial Height Partition - 72x144x6, supported at the bottom
 edge
*NODE
 101,0.
 165,144.
 3301,0.,72.
 3365,144.,72.
*NGEN, NSET = NL
   101,  3301, 100
*NGEN, NSET = NR
   165,  3365, 100
*NFILL, BIAS = 1.00, NSET = NWALL
 NL, NR, 64, 1
*ELEMENT,TYPE=S8R,ELSET=WALL
 101, 101,103,303,301,102,203,302,201
*ELGEN,ELSET=WALL
 101,32,2,1,16,200,100
*SHELL SECTION,ELSET=WALL,MATERIAL=A1
 6.0,9
*MATERIAL,NAME=A1
*ELASTIC, TYPE = ISOTROPIC
 515000, 0.25
*CONCRETE
 5000
 10000, 1.94E-2
*FAILURE RATIO
 1.16, 0.004
*TENSION STIFFENING
 1., 0.
 0., 1E-3
*NSET, NSET=SUPPF,GENERATE
 101,165,1
*NSET, NSET=SUPPL,GENERATE
 101,165,1
 165,3365,100
*NSET, NSET=SUPPH,GENERATE
 101,165,1
 165,3365,100
 101,3301,100
*BOUNDARY
 SUPPF, 2
 SUPPF, 3
 SUPPF, 4
 SUPPF, 5
*RESTART, WRITE
```

```
*STEP,INC=2000
*STATIC
.05,1.
*DLOAD
 WALL, BY, -0.0717
*END STEP
*STEP,INC=2000
*STATIC, RIKS
.0001 , 1.
*DLOAD
 WALL, P, 0.2
 WALL, BY, -0.0717
*NODE FILE,NSET=SUPPF
 U
 CF
 RF
*END STEP
```

A.2 One-Edge Supported Partition for NSP

```
*HEADING
 One-Edge Supported Partial Height Partition - 72x144x6, supported at the
 bottom and one vertical edge
*NODE
 101,0.
 165,144.
 3301,0.,72.
 3365,144.,72.
*NGEN, NSET = NL
   101,  3301, 100
*NGEN, NSET = NR
   165,  3365, 100
*NFILL, BIAS = 1.00, NSET = NWALL
 NL, NR, 64, 1
*ELEMENT,TYPE=S8R,ELSET=WALL
 101, 101,103,303,301,102,203,302,201
*ELGEN,ELSET=WALL
 101,32,2,1,16,200,100
*SHELL SECTION,ELSET=WALL,MATERIAL=A1
 6.0,9
*MATERIAL,NAME=A1
*ELASTIC, TYPE = ISOTROPIC
 515000, 0.25
*CONCRETE
 5000
 10000, 1.94E-2
*FAILURE RATIO
 1.16, 0.004
*TENSION STIFFENING
 1., 0.
 0., 1E-3
*NSET, NSET=SUPPF,GENERATE
 101,165,1
*NSET, NSET=SUPPL,GENERATE
 101,165,1
```

```
 165,3365,100
*NSET, NSET=SUPPH,GENERATE
 101,165,1
 165,3365,100
 101,3301,100
*BOUNDARY
 SUPPF, 2
 SUPPF, 3
 SUPPF, 4
 SUPPF, 5
 NR, 1
 NR, 3
*RESTART, WRITE
**
*STEP,INC=2000
*STATIC
 1,1.
*DLOAD
 WALL, BY, -0.0717
*END STEP
**
*STEP,INC=2000
*STATIC
 0.1,1
*DLOAD
WALL, P, 0.06
 WALL, BY, -0.0717
*END STEP
**
*STEP,INC=2000
*STATIC, DIRECT
 0.01,1
*DLOAD
WALL, P, 0.06
WALL, P, 0.02
 WALL, BY, -0.0717
*END STEP
**
*STEP,INC=2000
*STATIC, RIKS
.001 , 1.
*DLOAD
WALL, P, 0.06
WALL, P, 0.02
 WALL, P, 0.2
 WALL, BY, -0.0717
*NODE FILE,NSET=SUPPF
 U
 CF
 RF
*END STEP
```

A.3 Two-Edge Supported Partition for NSP

```
*HEADING
 Two-Edge Supported Partial Height Partition - 72x144x6, supported at the
bottom and two vertical edges
*NODE
 101,0.
 165,144.
 3301,0.,72.
 3365,144.,72.
*NGEN, NSET = NL
   101,  3301, 100
*NGEN, NSET = NR
   165,  3365, 100
*NFILL, BIAS = 1.00, NSET = NWALL
 NL, NR, 64, 1
*ELEMENT,TYPE=S8R,ELSET=WALL
 101, 101,103,303,301,102,203,302,201
*ELGEN,ELSET=WALL
 101,32,2,1,16,200,100
*SHELL SECTION,ELSET=WALL,MATERIAL=A1
 6.0,9
*MATERIAL,NAME=A1
*ELASTIC, TYPE = ISOTROPIC
 515000, 0.25
*CONCRETE
 5000
 10000, 1.94E-2
*FAILURE RATIO
 1.16, 0.004
*TENSION STIFFENING
 1., 0.
 0., 1E-3
*NSET, NSET=SUPPF,GENERATE
 101,165,1
*NSET, NSET=SUPPL,GENERATE
 101,165,1
 165,3365,100
*NSET, NSET=SUPPH,GENERATE
 101,165,1
 165,3365,100
 101,3301,100
*BOUNDARY
 SUPPF, 2
 SUPPF, 3
 SUPPF, 4
 SUPPF, 5
 NR, 1
 NR, 3
 NL, 1
 NL, 3
*RESTART, WRITE
*STEP,INC=2000
*STATIC
.5,1.
*DLOAD
 WALL, BY, -0.0717
*END STEP
*STATIC, RIKS
```

```
.001 , 1.
*DLOAD
 WALL, P, 0.2
 WALL, BY, -0.0717
*NODE FILE,NSET=SUPPF
 U
 CF
 RF
*END STEP
```

A.4 Freestanding Partition for LSP

```
** URM WALL FIXED AT THE BOTTOM
** 3D SHELL ELEMENT
** TO CALCULATE STRESS AND DISPLACEMENT IN THE FREE STANDING PLATE
** WALL DIMENSION : 144X72X6
** BC : BOTTOM IS FIXED. THE OTHERS ARE FREE.
** UNIFORM LOAD APPLYS NORMAL TO THE WALL'S SURFACE
** KIPS INCH
*HEADING
 PARTIAL HEIGHT PARTITION, 8 NODE SHELL ELEMENT, 90X42 MESH
*PREPRINT, ECHO = NO, HISTORY = NO, MODEL = YES
*RESTART, WRITE, FREQUENCY = 1
**
*NODE, SYSTEM = R
** FRONT PLANE
   10101,   0.0,   0.0,   0.0
   13701,   0.0,  72.0,   0.0
   10191, 144.0,   0.0,   0.0
   13791, 144.0,  72.0,   0.0
**
** NODE GENERATION
**
** GENERATE FRONT PLANE NODES
**
*NGEN, NSET = FL1
   10101,  13701, 100
*NGEN, NSET = FL2
   10191,  13791, 100
*NFILL, BIAS = 1.00, NSET = FP
 FL1, FL2, 90, 1
**
** ELEMENT GENERATION
**
*ELEMENT, TYPE = S4, ELSET = WALL
 10101,
 10101, 10102, 10202, 10201
** GENERATE THE REST ON THE PLANE
*ELGEN, ELSET = WALL
 10101, 90, 1, 1, 36, 100, 100
**
** MATERIAL PROPERTIES
**
*SHELL SECTION, ELSET = WALL, MATERIAL = URM
```

```
 6
*MATERIAL, NAME = URM
*ELASTIC, TYPE = ISOTROPIC
 515, 0.25
**
** BOUNDARY CONDITION
**
*NSET, NSET = SUPP-BOT, GENERATE
 10101, 10191, 1
*NSET, NSET = SUPP-LEFT, GENERATE
 10101, 13701, 100
*NSET, NSET = SUPP-RIGHT, GENERATE
 10191, 13791, 100
*BOUNDARY, OP = NEW
SUPP-BOT,  ENCASTRE
**
** LOAD CONDITION
**
*STEP
*STATIC
** TRIANGULAR PRESSURE LOAD
*DLOAD, OP = NEW
 WALL, P, 0.0009331
*EL PRINT, ELSET=WALL, POSITION=AVERAGED AT NODES
 S
 SF
 SP
*END STEP
```

A.5 One-Edge Supported Partition for LSP

```
** URM WALL FIXED ON RIGHT SIDE AND BOTTOM
** 3D SHELL ELEMENT
** TO CALCULATE STRESS AND DISPLACEMENT IN THE FREE STANDING PLATE
** WALL DIMENSION : 144X72X6
** UNIFORM LOAD APPLYS NORMAL TO THE WALL'S SURFACE
** KIPS INCH
*HEADING
 PARTIAL HEIGHT PARTITION, 8 NODE SHELL ELEMENT, 90X42 MESH
*PREPRINT, ECHO = NO, HISTORY = NO, MODEL = YES
*RESTART, WRITE, FREQUENCY = 1
**
*NODE, SYSTEM = R
** FRONT PLANE
   10101,   0.0,   0.0,   0.0
   13701,   0.0,  72.0,   0.0
   10191, 144.0,   0.0,   0.0
   13791, 144.0,  72.0,   0.0
**
** NODE GENERATION
**
** GENERATE FRONT PLANE NODES
**
*NGEN, NSET = FL1
```

```
   10101,  13701, 100
*NGEN, NSET = FL2
   10191,  13791, 100
*NFILL, BIAS = 1.00, NSET = FP
 FL1, FL2, 90, 1
**
** ELEMENT GENERATION
**
*ELEMENT, TYPE = S4, ELSET = WALL
 10101,
 10101, 10102, 10202, 10201
** GENERATE THE REST ON THE PLANE
*ELGEN, ELSET = WALL
 10101, 90, 1, 1, 36, 100, 100
**
** MATERIAL PROPERTIES
**
*SHELL SECTION, ELSET = WALL, MATERIAL = URM
 6
*MATERIAL, NAME = URM
*ELASTIC, TYPE = ISOTROPIC
 515, 0.25
**
** BOUNDARY CONDITION
**
*NSET, NSET = SUPP-BOT, GENERATE
 10101, 10191, 1
*NSET, NSET = SUPP-LEFT, GENERATE
 10101, 13701, 100
*NSET, NSET = SUPP-RIGHT, GENERATE
 10191, 13791, 100
*BOUNDARY, OP = NEW
SUPP-BOT,  ENCASTRE
SUPP-RIGHT, 1
SUPP-RIGHT, 2
SUPP-RIGHT, 3
**
** LOAD CONDITION
**
*STEP
*STATIC
** TRIANGULAR PRESSURE LOAD
*DLOAD, OP = NEW
 WALL, P, 0.0009331
*EL PRINT, ELSET=WALL, POSITION=AVERAGED AT NODES
 S
 SF
 SP
*END STEP
```

A.6 Two-Edge Supported Partition for LSP

```
** URM WALL FIXED ON BOTH EDGES AND BOTTOM
** 3D SHELL ELEMENT
** TO CALCULATE STRESS AND DISPLACEMENT IN THE FREE STANDING PLATE
```

```
** WALL DIMENSION : 144X72X6
** UNIFORM LOAD APPLYS NORMAL TO THE WALL'S SURFACE
** KIPS INCH
*HEADING
 PARTIAL HEIGHT PARTITION, 8 NODE SHELL ELEMENT, 90X42 MESH
*PREPRINT, ECHO = NO, HISTORY = NO, MODEL = YES
*RESTART, WRITE, FREQUENCY = 1
**
*NODE, SYSTEM = R
** FRONT PLANE
   10101,   0.0,   0.0,   0.0
   13701,   0.0,  72.0,   0.0
   10191, 144.0,   0.0,   0.0
   13791, 144.0,  72.0,   0.0
**
** NODE GENERATION
**
** GENERATE FRONT PLANE NODES
**
*NGEN, NSET = FL1
   10101,  13701, 100
*NGEN, NSET = FL2
   10191,  13791, 100
*NFILL, BIAS = 1.00, NSET = FP
 FL1, FL2, 90, 1
**
** ELEMENT GENERATION
**
*ELEMENT, TYPE = S4, ELSET = WALL
 10101,
 10101, 10102, 10202, 10201
** GENERATE THE REST ON THE PLANE
*ELGEN, ELSET = WALL
 10101, 90, 1, 1, 36, 100, 100
**
** MATERIAL PROPERTIES
**
*SHELL SECTION, ELSET = WALL, MATERIAL = URM
 6
*MATERIAL, NAME = URM
*ELASTIC, TYPE = ISOTROPIC
 515, 0.25
**
** BOUNDARY CONDITION
**
*NSET, NSET = SUPP-BOT, GENERATE
 10101, 10191, 1
*NSET, NSET = SUPP-LEFT, GENERATE
 10101, 13701, 100
*NSET, NSET = SUPP-RIGHT, GENERATE
 10191, 13791, 100
*BOUNDARY, OP = NEW
SUPP-BOT,  ENCASTRE
SUPP-LEFT, 1
SUPP-LEFT, 2
SUPP-LEFT, 3
SUPP-RIGHT, 1
```

```
SUPP-RIGHT, 2
SUPP-RIGHT, 3
**
** LOAD CONDITION
**
*STEP
*STATIC
** TRIANGULAR PRESSURE LOAD
*DLOAD, OP = NEW
 WALL, P, 0.0009331
*EL PRINT, ELSET=WALL, POSITION=AVERAGED AT NODES
 S
 SF
 SP
*END STEP
```

B. Tables from FEMA356

Chapter 11: Architectural, Mechanical, and Electrical Components

Table 11-1 Nonstructural Components: Applicability of Hazards Reduced, Life Safety and Immediate Occupancy Requirements and Methods of Analysis

		Performance Level					
			Seismicity				
			High & Moderate Seismicity		Low Seismicity		
	COMPONENT	IO	LS	HR	LS	HR	Evaluation Procedure
ARCHITECTURAL (Section 11.9)							
1.	Exterior Wall Elements						
	Adhered Veneer	Yes	Yes	Yes[15]	No	No	F/D
	Anchored Veneer	Yes	Yes	Yes[15]	No	No	F/D
	Glass Blocks	Yes	Yes	Yes[15]	No	No	F/D
	Prefabricated Panels	Yes	Yes	Yes[15]	Yes	Yes[15]	F/D
	Glazed Exterior Wall Systems	Yes	Yes	Yes[15]	Yes	Yes[15]	F/D/PR
2.	Partitions						
	Heavy	Yes	Yes	Yes[15]	No	No	F/D
	Light	Yes	No	No	No	No	F/D
	Glazed	Yes	Yes	Yes[15]	Yes	Yes[15]	F/D/PR
3.	Interior Veneers						
	Stone, Including Marble	Yes	Yes[18]	Yes[15]	No	No	F/D
4.	Ceilings						
	Directly Applied to Structure	Yes	No[13]	No[15]	No	No	F
	Dropped Furred Gypsum Board	Yes	No	No	No	No	F
	Suspended Lath and Plaster	Yes	Yes	Yes[15]	No	No	F
	Suspended Integrated Ceiling	Yes	No[11]	No	No[11]	No	PR
5.	Parapets and Appendages	Yes	Yes	Yes[15]	Yes	Yes	F[1]
6.	Canopies and Marquees	Yes	Yes	Yes[15]	Yes	Yes	F
7.	Chimneys and Stacks	Yes	Yes	Yes[15]	No	No	F[2]
8.	Stairs	Yes	Yes	No	Yes	No	*
MECHANICAL EQUIPMENT (Section 11.10)							
1.	Mechanical Equipment						
	Boilers, Furnaces, Pumps, and Chillers	Yes	Yes	No	Yes	No	F
	General Mfg. and Process Machinery	Yes	No[3]	No	No	No	F
	HVAC Equipment, Vibration-Isolated	Yes	No[3]	No	No	No	F
	HVAC Equipment, Non-Vibration-Isolated	Yes	No[3]	No	No	No	F
	HVAC Equipment, Mounted In-Line with Ductwork	Yes	No[3]	No	No	No	PR
2.	Storage Vessels and Water Heaters						
	Structurally Supported Vessels (Category 1)	Yes	No[3]	No	No	No	Note[4]
	Flat Bottom Vessels (Category 2)	Yes	No[3]	No	No	No	Note[5]
3.	Pressure Piping	Yes	Yes	No	No	No	Note[5]
4.	Fire Suppression Piping	Yes	Yes	No	No	No	PR

Table 11-1 Nonstructural Components: Applicability of Hazards Reduced, Life Safety and Immediate Occupancy Requirements and Methods of Analysis (continued)

	COMPONENT	Performance Level					Evaluation Procedure
			Seismicity				
			High & Moderate Seismicity		Low Seismicity		
		IO	LS	HR	LS	HR	
5.	Fluid Piping, not Fire Suppression						
	Hazardous Materials	Yes	Yes	Yes[12]	Yes	Yes[12]	PR/F/D
	Nonhazardous Materials	Yes[14]	No	No	No	No	PR/F/D
6.	Ductwork	Yes	No[6]	No	No	No	PR
ELECTRICAL AND COMMUNICATIONS (Section 11.11)							
1.	Electrical and Communications Equipment	Yes	No[7]	No	No	No	F
2.	Electrical and Communications Distribution Equipment	Yes	No[8]	No	No	No	PR
3.	Light Fixtures						
	Recessed	No	No	No	No	No	PR[17]
	Surface Mounted	No	No	No	No	No	PR[17]
	Integrated Ceiling	Yes	Yes	Yes[15]	No	No	PR
	Pendant	Yes	No[9]	No	No	No	F/PR
FURNISHINGS AND INTERIOR EQUIPMENT (Section 11.11)							
1.	Storage Racks	Yes	Yes[10]	Yes[16]	No	No	F
2.	Bookcases	Yes	Yes	No	No	No	F
3.	Computer Access Floors	Yes	No	No	No	No	PR/FD
4.	Hazardous Materials Storage	Yes	Yes	No[12]	No[12]	No[12]	PR
5.	Computer and Communication Racks	Yes	No	No	No	No	PR/F/D
6.	Elevators	Yes	Yes	No	No	No	F/D/PR
7.	Conveyors	Yes	No	No	No	No	F/D/PR

1. Rehabilitation of unreinforced masonry parapets not over 4 ft. in height by the Prescriptive Design Concept shall be permitted.
2. Rehabilitation of residential masonry chimneys by the Prescriptive Design Concept shall be permitted.
3. Equipment type A or B that is 6 ft. or more in height, equipment type C, equipment forming part of an emergency power system, and gas-fired equipment in occupied or unoccupied space shall be rehabilitated to the Life Safety Nonstructural Performance Level in areas of High Seismicity. In areas of Moderate Seismicity, this equipment need not be considered.
4. Rehabilitation of residential water heaters with capacity less than 100 gal. by the Prescriptive Procedure shall be permitted. Other vessels shall meet the force provisions of Sections 11.7.3 or 11.7.4.
5. Rehabilitation of vessels or piping systems according to Prescriptive Standards shall be permitted. Storage vessels shall meet the force provisions of Sections 11.7.3 or 11.7.4. Piping shall meet drift provisions of Section 11.7.5 and the force provisions of Sections 11.7.3 or 11.7.4.
6. Ductwork that conveys hazardous materials, exceeds 6 sq. ft. in cross-sectional area, or is suspended more than 12 in. from top of duct to supporting structure at any support point shall meet the requirements of the selected Rehabilitation Objective.
7. Equipment that is 6 ft. or more in height, weighs over 20 lbs., or forms part of an emergency power and/or communication system shall meet the Life Safety Nonstructural Performance Level.
8. Equipment that forms part of an emergency lighting, power, and/or communication system shall meet the Life Safety Nonstructural Performance Level.
9. Fixtures that exceed 20 lbs. per support shall meet the Life Safety Nonstructural Performance Level.

(continued)

Table 11-1 Nonstructural Components: Applicability of Hazards Reduced, Life Safety and Immediate Occupancy Requirements and Methods of Analysis (continued)

COMPONENT	Performance Level					Evaluation Procedure
		Seismicity				
		High & Moderate Seismicity		Low Seismicity		
	IO	LS	HR	LS	HR	

10. Rehabilitation shall not be required for storage racks in unoccupied spaces.
11. Panels that exceed 2 lbs./sq. ft., or for which Enhanced Rehabilitation Objectives have been selected, shall meet the Life Safety Nonstructural Performance Level.
12. Where material is in close proximity to occupancy such that leakage could cause an immediate life safety threat, the requirements of the selected Rehabilitation Objective shall be met.
13. Plaster ceilings on metal or wood lath over 10 sq. ft. in area shall meet the Life Safety Nonstructural Performance Level.
14. Unbraced pressure pipes with a 2-inch or larger diameter and suspended more than 12 inches from the top of the pipe to the supporting structure at any support point shall meet the requirements of the selected Rehabilitation Objective.
15. Where heavy nonstructural components are located in areas of public occupancy or egress, the components shall meet the Life Safety Nonstructural Performance Level.
16. Storage racks in areas of public assembly shall meet the requirements of the selected Rehabilitation Objective.
17. Evaluation for the presence of an adequate attachment shall be checked as described in Section 11.10.9.3.
18. In areas of Moderate Seismicity, interior veneers of ceramic tile need not be considered.

Key:

HR Hazards Reduced Nonstructural Performance Level

LS Life Safety Nonstructural Performance Level

IO Immediate Occupancy Nonstructural Performance Level

PR Use of the Prescriptive Procedure of Section 11.7.2 shall be permitted.

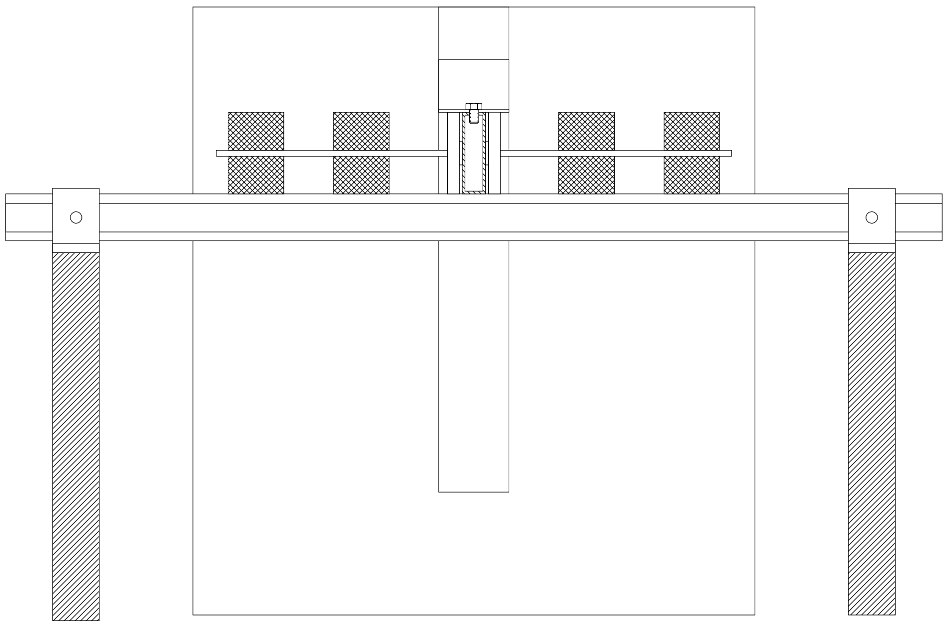
F The Analytical Procedure of Section 11.7.1 shall be implemented and a force analysis shall be performed in accordance with Sections 11.7.3 or 11.7.4.

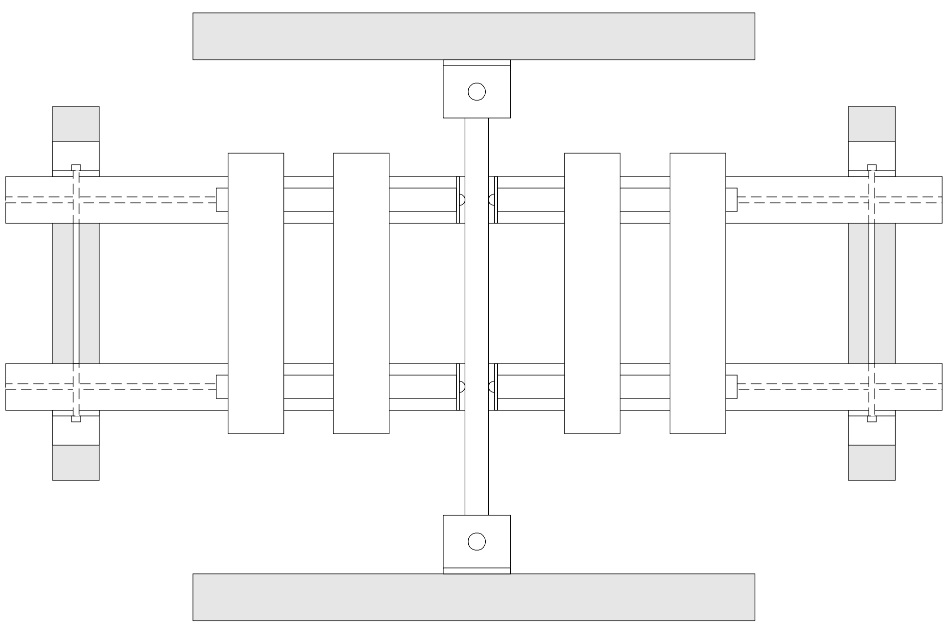
F/D The Analytical Procedure of Section 11.7.1 shall be implemented and a force and deformation analysis shall be performed in accordance with Sections 11.7.4 and 11.7.5, respectively.

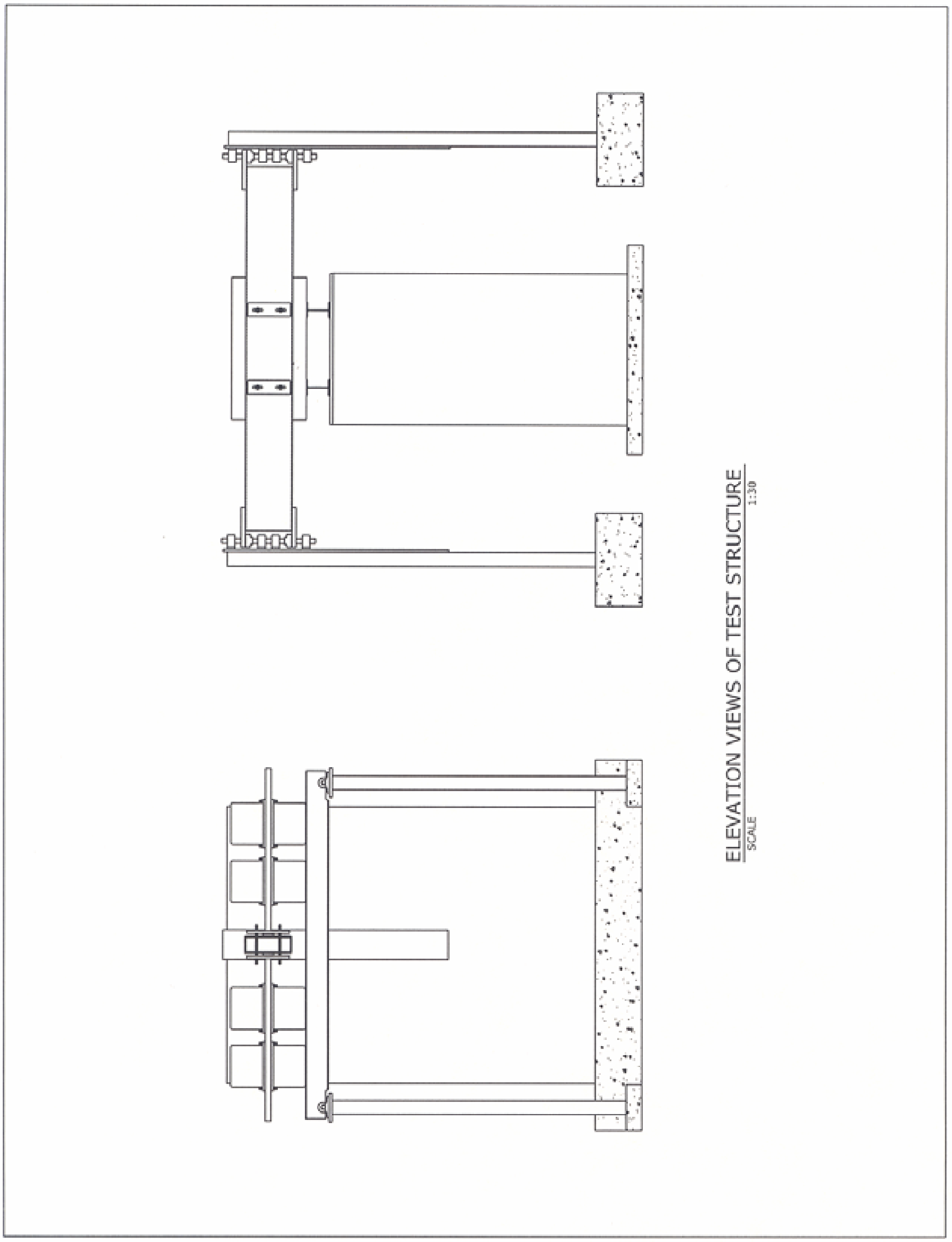
* Individual components shall be rehabilitated as required.

C. ST-10 Experiment Scheme

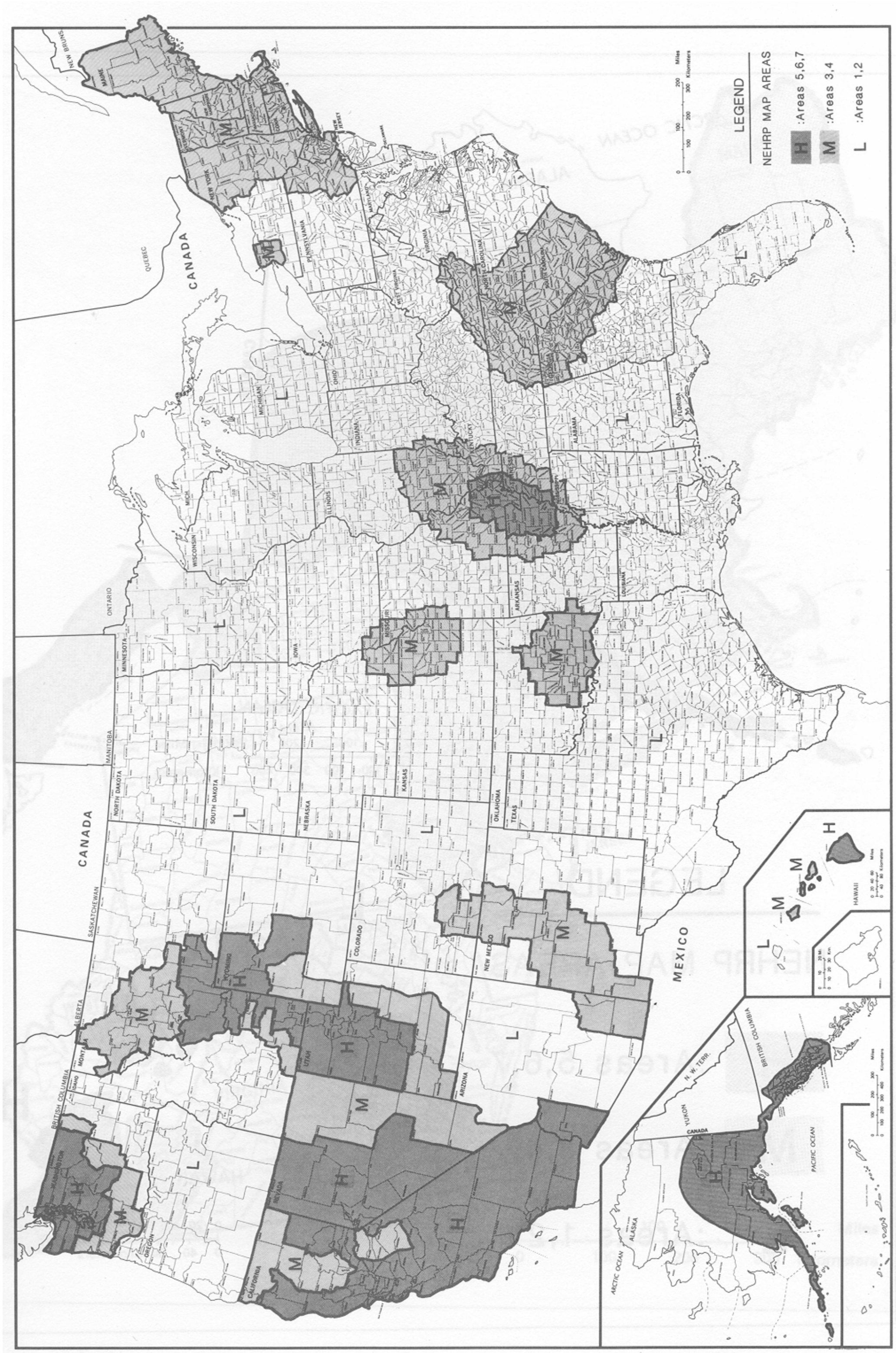
ST-10 Test Model Schematic
(drawn from email description by M. Aschheim 7-18-00)

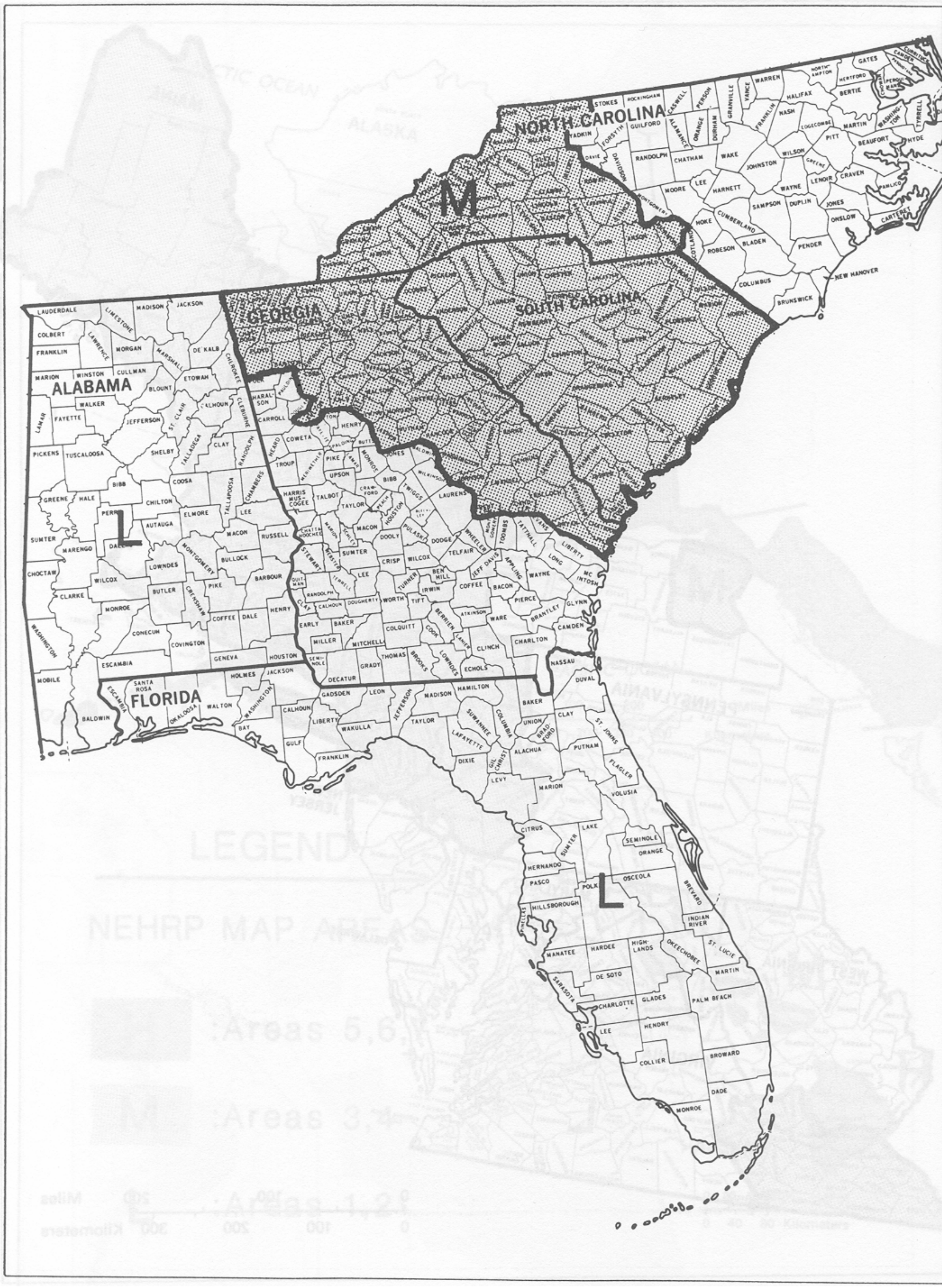





ELEVATION VIEWS OF TEST STRUCTURE
SCALE 1:30

D. ATC-21 Survey Form




NORTH CAROLINA
SOUTH CAROLINA
GEORGIA
ALABAMA
FLORIDA
M
L
L

ATC-21/ (NEHRP Map Areas 3,4, Moderate)

Rapid Visual Screening of Seismically Hazardous Buildings

Scale:

Address ____________________ Zip ______

Other Identifiers ____________________

No. Stories ____________ Year Built ________

Inspector ______________ Date ________

Total Floor Area (sq. ft) ____________________

Building Name ____________________

Use ____________________

(Peel-off label)

INSTANT PHOTO

OCCUPANCY

	No. Persons
Residential	
Commercial	
Office	0–10
Industrial	11–100
Pub. Assem.	100+
School	
Govt. Bldg.	
Emer. Serv.	
Historic Bldg.	

Non Structural Falling Hazard ☐

DATA CONFIDENCE

* = Estimated, Subjective, or Unreliable Data

DNK = Do Not Know

STRUCTURAL SCORES AND MODIFIERS

BUILDING TYPE	W	S1 (MRF)	S2 (BR)	S3 (LM)	S4 (RC SW)	C1 (MRF)	C2 (SW)	C3/S5 (URM INF)	PC1 (TU)	PC2	RM	URM
Basic Score	**6.0**	**4.0**	**3.0**	**6.0**	**4.0**	**3.0**	**3.5**	**2.0**	**3.5**	**2.0**	**3.5**	**2.0**
High Rise	N/A	-1.0	-0.5	N/A	-1.0	-0.5	-1.0	-1.0	N/A	0	-0.5	-0.5
Poor Condition	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
Vert. Irregularity	-0.5	-0.5	-0.5	-0.5	-1.0	-1.0	-0.5	-1.0	-1.0	-1.0	-0.5	-1.0
Soft Story	-1.0	-2.0	-2.0	-1.0	-2.0	-2.0	-2.0	-1.0	-1.0	-1.0	-2.0	-1.0
Torsion	-1.0	-2.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
Plan Irregularity	-1.0	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-1.0	-1.0	-1.0	-1.0
Pounding	N/A	-0.5	-0.5	N/A	-0.5	-0.5	N/A	N/A	N/A	-0.5	N/A	N/A
Large Heavy Cladding	N/A	-2.0	N/A	N/A	N/A	-1.0	N/A	N/A	N/A	-1.0	N/A	N/A
Short Columns	N/A	N/A	N/A	N/A	N/A	-1.0	-1.0	-1.0	N/A	-1.0	N/A	N/A
Post Benchmark Year	+2.0	+2.0	+2.0	+2.0	+2.0	+2.0	+2.0	N/A	+2.0	+2.0	+2.0	N/A
SL2	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3
SL3	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
SL3 & 8 to 20 stories	N/A	-0.8	-0.8	N/A	-0.8	-0.8	-0.8	-0.8	N/A	-0.8	-0.8	-0.8

FINAL SCORE

COMMENTS

Detailed Evaluation Required?

YES NO

ATC346MD
30032.01