# OUT-OF-PLANE SEISMIC PERFORMANCE AND FRAGILITY ANALYSIS OF RESIDENTIAL BRICK VENEER WALL CONSTRUCTION

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## ABSTRACT :

Wood-frame structures with anchored brick masonry veneer are a common type of residential construction throughout the United States, Canada, Australia, and other regions of the world. A study has been undertaken to investigate the out-of-plane seismic performance of brick veneer wall systems over wood framing, representing typical modern U.S. construction practice. Finite element (FE) models of brick veneer wall systems have been developed based on the results from tie connection and veneer wall experimental studies. These models have been used to carry out parametric studies, evaluating the effects on the out-of-plane seismic performance of brick veneer walls due to geometric variations in their construction, as well as from different brick veneer tie connection details. These studies have been used to establish the framework for seismic fragility analysis of this form of construction.

**KEYWORDS:** Brick masonry veneer, wood framing, metal tie connections, shake table tests, dynamic analysis

## 1. INTRODUCTION

Wood-frame structures with anchored brick masonry veneer are a common type of residential construction throughout the United States, Canada, Australia, and a number of other regions of the world. In general, brick veneer construction is valued for its pleasant appearance, excellent thermal performance, and ability to accommodate water penetration. This type of construction typically comprises an interior wood-frame backup structure with an exterior masonry wall (separated by an air cavity), with regularly spaced corrugated sheet metal ties used to connect the brick masonry to the backup through the cavity. In the U.S., prescriptive design and construction requirements for brick veneer wall systems are specified in the Masonry Standards Joint Committee (MSJC) Code (MSJC 2005), the International Residential Code (IRC) for One- and Two-Family Dwellings (ICC 2003), and the Brick Industry Association (BIA) Technical Notes 28 (BIA 2002) and 44B (BIA 2003).

Brick veneer wall damage (including cracking, relative movement, and collapse under out-of-plane loading) has been observed in recent years resulting from moderate earthquakes, as well as severe wind storms (LaFave and Reneckis 2005). In recent years, a study has been undertaken at the University of Illinois to evaluate the structural behavior of brick veneer on wood frame wall systems by addressing current widespread residential construction practice. One phase of the study involved laboratory testing of brick-tie-wood connection subassemblies comprising two bricks with a corrugated sheet metal tie either nail- or screw-attached to a wood stud. The subassemblies were subjected to monotonic and cyclic in-plane and out-of-plane loads (tension, compression, and shear), permitting an evaluation of the stiffness, strength, and failure modes for a local portion of a veneer wall system, rather than just of a single tie by itself (Choi and LaFave 2004; LaFave and Reneckis 2005). Another phase of the study included laboratory shake table testing and development of detailed finite element (FE) models for relatively simple full-scale solid single story rectangular brick veneer wall panel specimens, as well as a one-and-a-half story wall with a window opening and gable region (representing a gable-end wall of a typical residential structure). The wall tests and FE analyses captured the overall performance of brick veneer wall systems, including interaction and load-sharing between the brick veneer, corrugated sheet metal ties, and wood frame backup. Parameter studies were conducted to evaluate the effects on wall performance due to geometric changes in wall construction, as well as from tie connection types and layouts. The progression of system damage was noted up until partial collapse of the veneer walls; the tie connection properties and layouts were found to significantly affect wall performance at all stages of behavior (Reneckis et al. 2004; Reneckis and LaFave 2005; Reneckis and LaFave 2008a,b). FE wall model development and parameter studies are described in this paper, along with the framework for seismic fragility analysis of brick veneer walls.

## 2. OVERVIEW OF WALL TEST STRUCTURE AND FINITE ELEMENT MODEL DEVELOPMENT

An FE model of a brick veneer wall panel with a window opening and gable was developed based on the shake table experiments and results. Design and construction of the wall test structure, as well as the related FE wall modeling program, are summarized herein (described in greater detail elsewhere by Reneckis and LaFave 2008a,b).

### *2.1. Design and Construction of Brick Veneer Wall Test Structure*

The brick veneer with 2x4 wood stud backup wall panel, detailed in Fig. 1, was set up to be excited in the out-of-plane direction on a uniaxial shake table. A reinforced concrete foundation pad, representing the upper portion of a typical home foundation wall, was constructed for support of the wood frame and brick veneer wall panel. In residential construction, exterior wood frame walls are generally attached to perpendicular structural walls or partitions at their edges, and to ceiling or roof framing across the top; therefore, the wood frame backup was constructed containing partial floor, sidewall, ceiling, and roof components, to provide representative boundary conditions for the 2x4 stud wall panel being tested. Due to the limitations of shake table size and loading capacity, a steel reaction frame was utilized to represent the "rest of the house", providing gravity and lateral load support along the rear of the partial wood frame backup components. The mass, stiffness, and dynamic response of an entire house were not represented in this test setup; the accelerations along the bottom of the wall panel and at the top backup corners were expected to be nearly equal (to each other and to the table input), with perhaps some modest amplification across the ceiling and roof framing at the top.

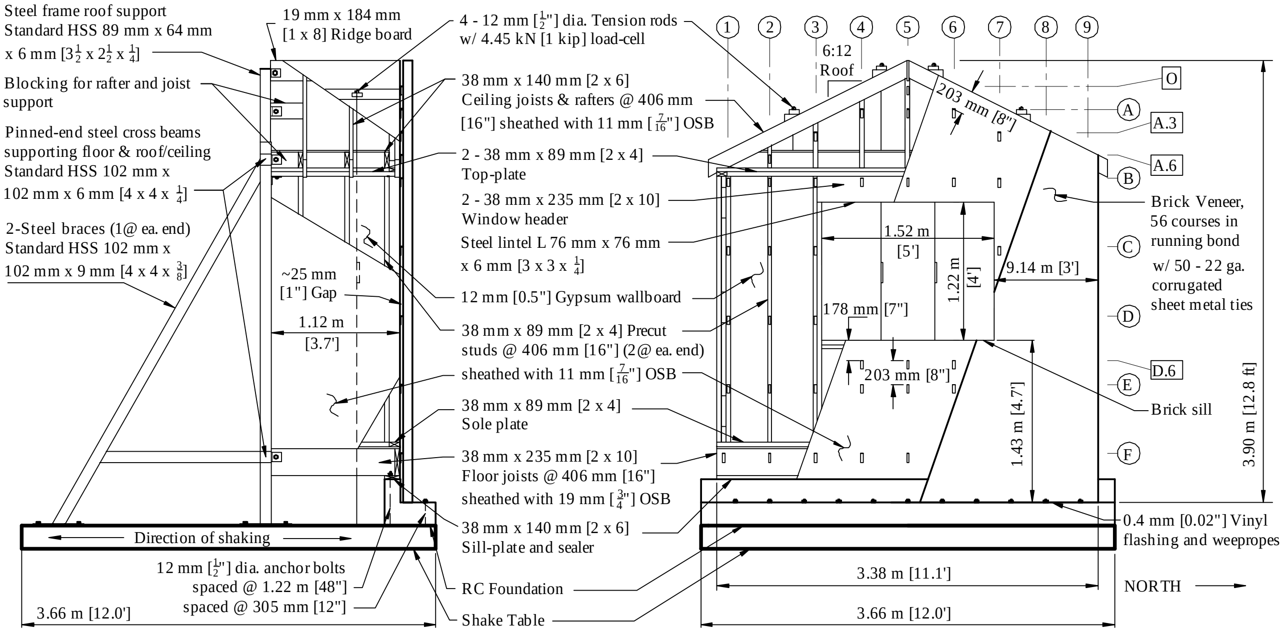

Figure 1 – Elevation views of brick veneer wall test structure.

The wood framing in the test structure comprised Standard Grade Spruce-Pine-Fir lumber, assembled in conformance with IRC (ICC 2003) requirements for nail size and spacing. The outside face of the wood frame wall was covered with oriented strand board (OSB) sheathing panels, and the interior face was covered with gypsum wallboard (Fig. 1). A simple pre-compression system was installed onto the wood frame backup, by means of four tension rods, to capture the overall effects of attic and roof dead loads on the wood wall panel and backup framing. A brick masonry veneer wall was constructed (by professional masons) in front of the wood frame wall panel, with free edges (open ends) similar to those found in residential construction with “front face” veneer walls only, where the masonry is terminated at a corner and some other siding material is used on the perpendicular return walls. (In brick veneer construction, it is also common to have veneer wall terminations at vertical expansion joints and openings, which permit individual sections of veneer to move independently of one another.) The bricks used in the veneer wall were 89 mm x 194 mm x 57 mm standard modular “Colonial Reds” with three holes, joined by type N mortar (cement : lime : sand = 1 : 1 : 6) in running bond.

As part of masonry installation, the brick veneer was attached to the wood frame wall panel using corrugated sheet metal ties, in general conformance with the prescriptive requirements for tie installation per BIA (2003), IRC (ICC 2003), and MSJC (2005). As shown in Fig. 2a, the 22 ga. ties (0.79 mm thick by 22 mm wide) in the wall specimen were fastened to the wood backup studs with 64 mm long smooth-shank (roofing) nails. The ties were bent as close as possible to the nail head, resulting in a small bend eccentricity of approximately 6 mm. (The maximum allowable bend eccentricity is 12.7 mm, as specified by MSJC (2005) and BIA (2002).) During construction of the veneer, an air space of approximately 25 mm was maintained between the outside face of the wood frame sheathing and the inside face of the brick veneer, though at some locations the air space narrowed a bit as a result of the wood wall being slightly out-of-plumb. At a few locations, excess mortar seeped out into the air space, landing on the corrugated sheet metal ties and locally filling the space. A general tie grid spacing of 406 mm horizontally and 610 mm vertically was employed (Fig. 1), with additional ties provided within 203 mm of open edges, such as below the window opening and along the roof edge, as recommended by BIA (2003). The tie layout also satisfied the IRC maximum tie spacing limit of 914 mm around the window opening perimeter. The average tensile force-displacement behavior of these tie connections, as determined from subassembly testing, are shown in Fig. 2b.

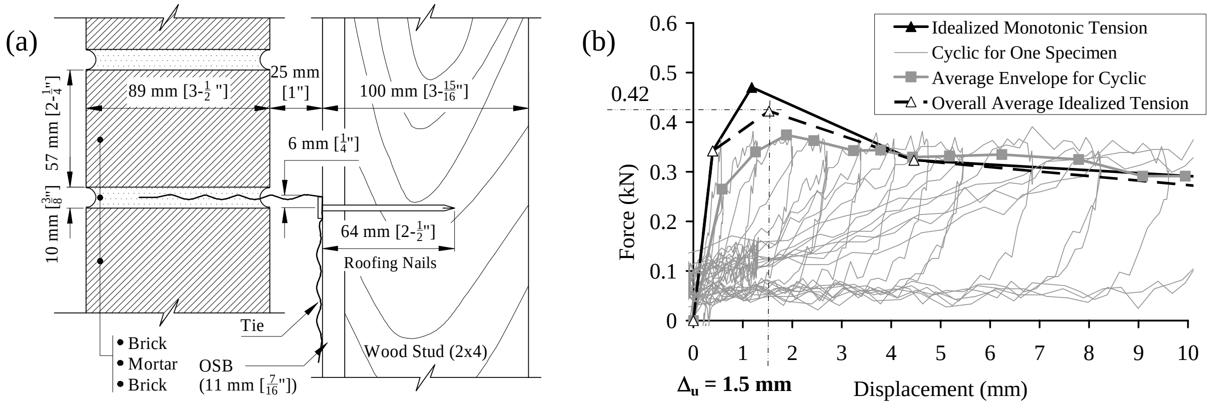

Figure 2 – Tie connection details: (a) section view of installation and (b) force-displacement behavior in tension.

### *2.2. Development and Validation of FE Wall Panel Models*

The analysis software *ABAQUS* (Abaqus Inc. 2006) and the pre- / post-processor software *MSC.Patran* (MSC 2005) were used to develop the FE brick veneer wall panel models. The models consisted of the wood frame wall panel, the brick veneer, and the corrugated sheet metal tie connections, representing the experimental wall panel geometry (Fig. 1); the surrounding “boundary” components of the experimental test structure were implemented as spring support conditions. In the FE models, the wood frame backup and brick veneer masonry material properties were assumed to be linear elastic (primarily based on the observed experimental behavior). The spring supports along the wood backup were also assumed to be linear elastic (and were calibrated per experimental static and dynamic test results), whereas the supports at the base of the brick veneer were represented by a nonlinear elastic rocking behavior model. A viscous damping ratio of 4% (evaluated from experimental test results) was assigned in terms of Rayleigh damping coefficients, in the first and second elastic modes of vibration.

Dynamic veneer wall tests showed that different levels of wall specimen response were closely related to certain key tie connection deformation limits in tension. At the onset of tie damage during veneer wall testing, tie connection deformations were typically similar to the opening displacements at ultimate tensile loading determined from the tie subassembly (monotonic tension and cyclic) tests. Therefore, the tie connection FE model was assigned nonlinear inelastic "material" properties in tension (based on subassembly test results) and linear elastic in compression (based on both subassembly and wall test results), to combine the effects of the ties and the excess mortar within the wall cavity, which helped transmit compressive forces and reduce the compression demand on the ties. The tie connections in the FE wall model of the test specimen configuration were assigned the average idealized force-displacement behavior, shown in Fig. 2b, as the backbone of their hysteresis rule in tension. During the parameter studies, described below, key features of the absolute and relative performance of different types of ties and tie installation methods were represented with the nonlinear inelastic tie material models.

The FE wall model was calibrated per experimental static and dynamic load test results. The model was then verified to capture different levels of the experimental specimen behavior, which corresponded to three levels of response and damage: *elastic* (no visible damage), *intermediate* (onset of tie and veneer damage), and *ultimate* (accumulation of tie and veneer damage sufficient to lead to collapse).

From shake table testing, displacement measurements were used to evaluate the different levels of wall specimen behavior. The displacements were measured at key tie locations throughout the wall specimen and on the shake table, thereby providing veneer and backup displacements relative to the shake table and also differential displacements between the veneer and backup (tie deformations). The experimental peak displacement response of the wall specimens was noted in the positive (outward – veneer deflecting away from the backup) and negative (inward) directions; likewise, peak experimental tie deformations were measured in both directions for each particular test. (The maximum positive displacements of the brick veneer and of the wood backup, as well as the peak positive tie deformations, were of particular interest because these results were closely related to different levels of experimental specimen response and damage.) Similarly, for the FE wall models, computed displacements (at the same tie locations as in the experimental specimens) were used to first verify and then further identify the model response when subjected to out-of-plane loading (i.e., peak brick veneer and wood backup model displacements relative to the supports, as well as peak relative tie displacements between the veneer and the backup models).

During wall panel testing, ties anchored to or near stiffer regions of the wood backup and those at the upper region of the wall panel experienced the highest loads and therefore showed first signs of damage (nail pullout for these particular tie connections); at higher load levels, tie damage spread out to more flexible (backup) and lower regions of the wall panel. The following damage limit states were then identified for this wall panel, based on onset of tie failures at key locations, as well as accumulation of tie failures throughout particular regions of the wall:

*(i)* End of *elastic* -to- start of *intermediate* range (first tie failure at top corners, at grids B/1 & B/9),
*(ii)* End of *intermediate* -to- *ultimate* range (tie failures in entire gable region, across rows O through B),
*(iii)* End of *ultimate* range – collapse (tie failures in entire gable region and down to across row D).

Tie connection damage in the FE model was determined from the maximum computed tie elongations, at a stage when these elongations exceeded the opening displacements at ultimate tensile load capacity found from the tie subassembly tests (equal to 1.5 mm for the ties used in the test specimen, as indicated in Fig. 2b). Scaled earthquake PGAs vs. analytical and experimental displacement response results (for key tie locations) are summarized below in Fig. 3. (The dominant earthquake record, labeled as M10, that was applied during testing was also used later during the FE parametric studies.) The FE wall model was calibrated and validated to within approximately 10% of the overall experimental wall behavior. Some disparities in the FE results were present, however, primarily because masonry cracking and wood-frame backup softening were not explicitly represented analytically. Finally, the criteria established here for evaluating different damage limit states of brick veneer walls, as a function of tie failure, are the basis for subsequent seismic fragility analyses of this form of construction.

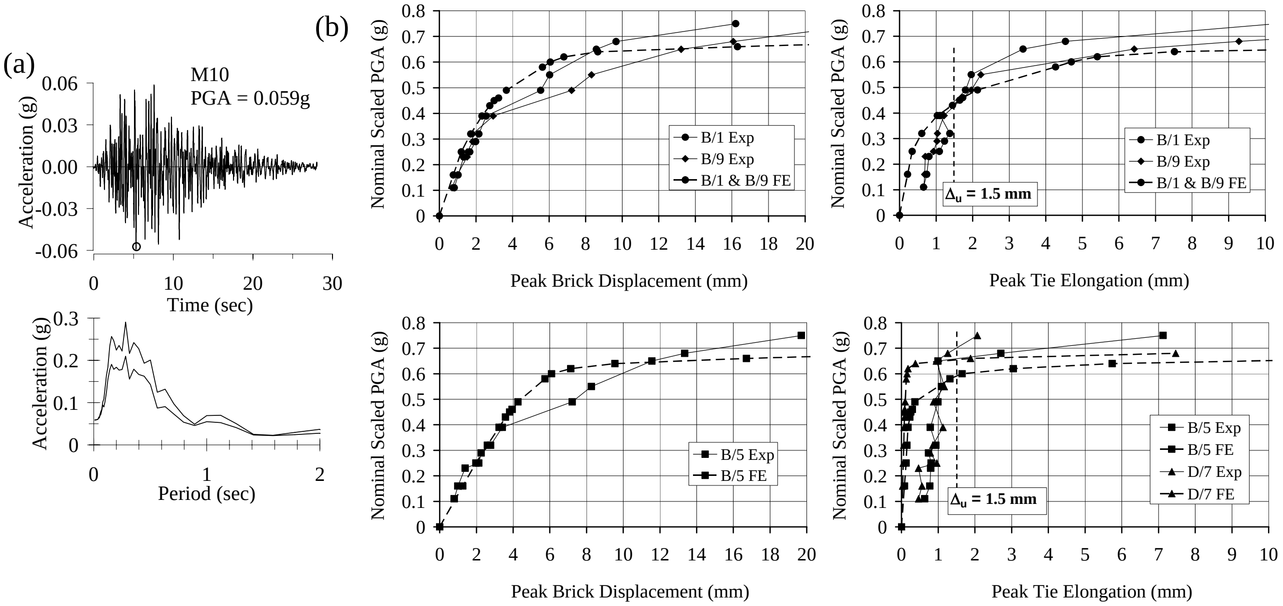

Figure 3 – (a) M10 earthquake record time history trace and response spectra at 3% and 6% damping; (b) example set of FE dynamic analysis validation results at key tie grid locations.

## 3. FINITE ELEMENT PARAMETRIC STUDIES

### *3.1. Wall Panel and Tie Connection Parameters*

As mentioned above, prescriptive requirements for residential brick veneer wall construction are specified in the MSJC (2005), the IRC (ICC 2003), and the BIA Technical Notes (2002, 2003). The minimum tie thickness is specified as 22 ga., installed with a maximum bend eccentricity of 12.7 mm (with the exception of IRC, which does not specify tie bend eccentricity limits), and attached to the wood backup studs with at least 8d nails. Furthermore, the maximum wall area to be supported by the ties is limited to 0.25 $m^2$ for construction in seismic design categories C and below, and reduced to a wall area of 0.19 $m^2$ in higher seismic design categories (among several other requirements for those higher design categories); respectively, these wall areas correspond to tie grid spacings of 610 mm x 406 mm, and 406 mm x 406 mm, in actual construction. Furthermore, MSJC (2005) and IRC (ICC 2003) require that ties be provided within 305 mm of wall edges near openings; this dimension is reduced to 203 mm in BIA (2003), and this maximum edge distance is recommended for tie placement near openings, as well as at other discontinuities in brick veneer walls (such as at wall edges, expansion joints, or shelf angles).

In actual construction practice, however, tie installation in brick veneer walls frequently deviates from these requirements; 28 ga. ties and/or shorter roofing nails are commonly used as substitutes, with a variety of tie layouts. Therefore, combinations of wall panel geometries and tie connection layouts, identified per Fig. 4, were investigated analytically to evaluate current design standards as well as common construction methods of brick veneer walls. The various tie connection properties implemented in these models are summarized in Fig. 5. The wall panel models were labeled as “Wall Type – Tie Layout / Tie Properties”, per the following (Fig. 4): Wall Type identified as I through IV, including Case (b) where the gable masonry edge dimension was increased from 203 mm to 305 mm; Tie Layout identified as grid A through D, where Y = with and N = without minimum required ties at wall gable and opening edges, and in some cases including (3) or (6) extra ties in the gable region; and, Tie Properties were identified by tie thickness, bend eccentricity, and attachment type (per Fig. 5b). For example, the experimental wall configuration is labeled as "I-AY/N(2.5)22min"; then, a wall labeled as "I-AY(3)/N(2.5)22min" would have the same properties as the test configuration, with 3 extra ties added in the gable region, and so on.

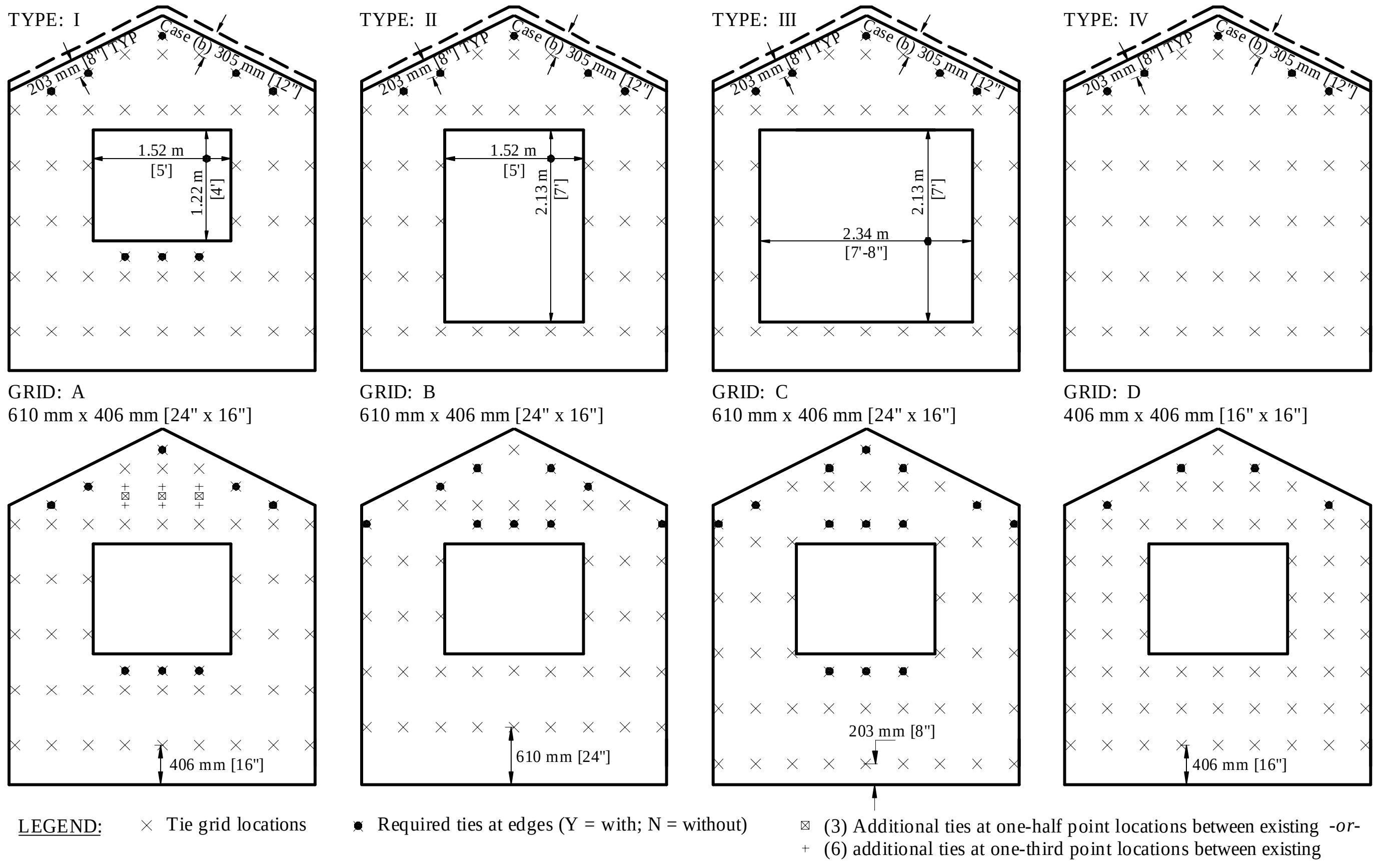

Figure 4 – FE wall panel model parameters and IDs.

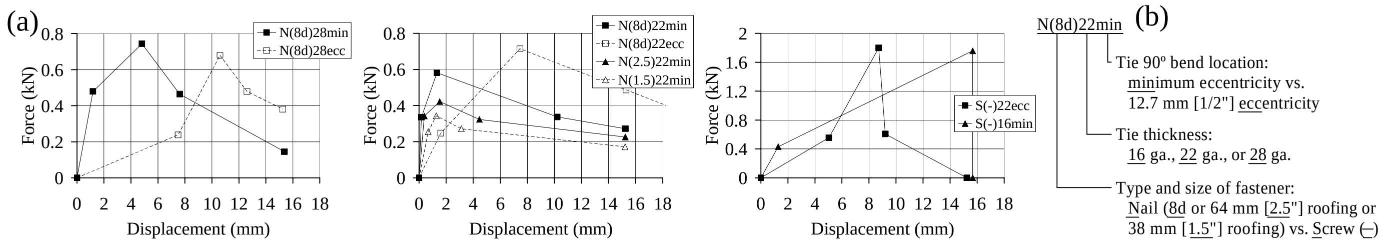

Figure 5 – (a) Average idealized tensile force-displacement behaviors of various tie connections and (b) outline of tie connection IDs.

### *3.2. Parametric Study Analysis Procedure and Results*

Parameter studies were conducted to evaluate the effects on the out-of-plane seismic performance of brick veneer walls due to various combinations of tie connection types and layouts, as well as geometric changes in veneer wall construction. The earthquake record, labeled as M10 (used during the experimental study, as well as for FE model development and validation), was utilized during the parametric studies (Fig. 3a). The earthquake record was normalized with respect to PGA, and then scaled up at PGA increments of 0.10g to 0.20g for loading in the elastic range of wall behavior, and then at reduced increments of 0.05g when estimating the wall panel damage limit states.

The dynamic FE analysis results (in the form of dynamic pushover plots) are summarized in Fig. 6, showing the M10 PGAs vs. overall brick displacements evaluated at the middle of the wall panels, directly above the window opening (at grid location B/5 per Fig. 1). The plots in Fig. 6 have been grouped to show the effects on wall performance due to variations of the following parameters: (a) tie connection properties; (b) overall tie grids, as well as tie placement at wall edges and in gable region; (c) brick masonry and overall wall panel geometries; and, (d) tie connection properties and layouts in a wall panel with large opening (wall type III).

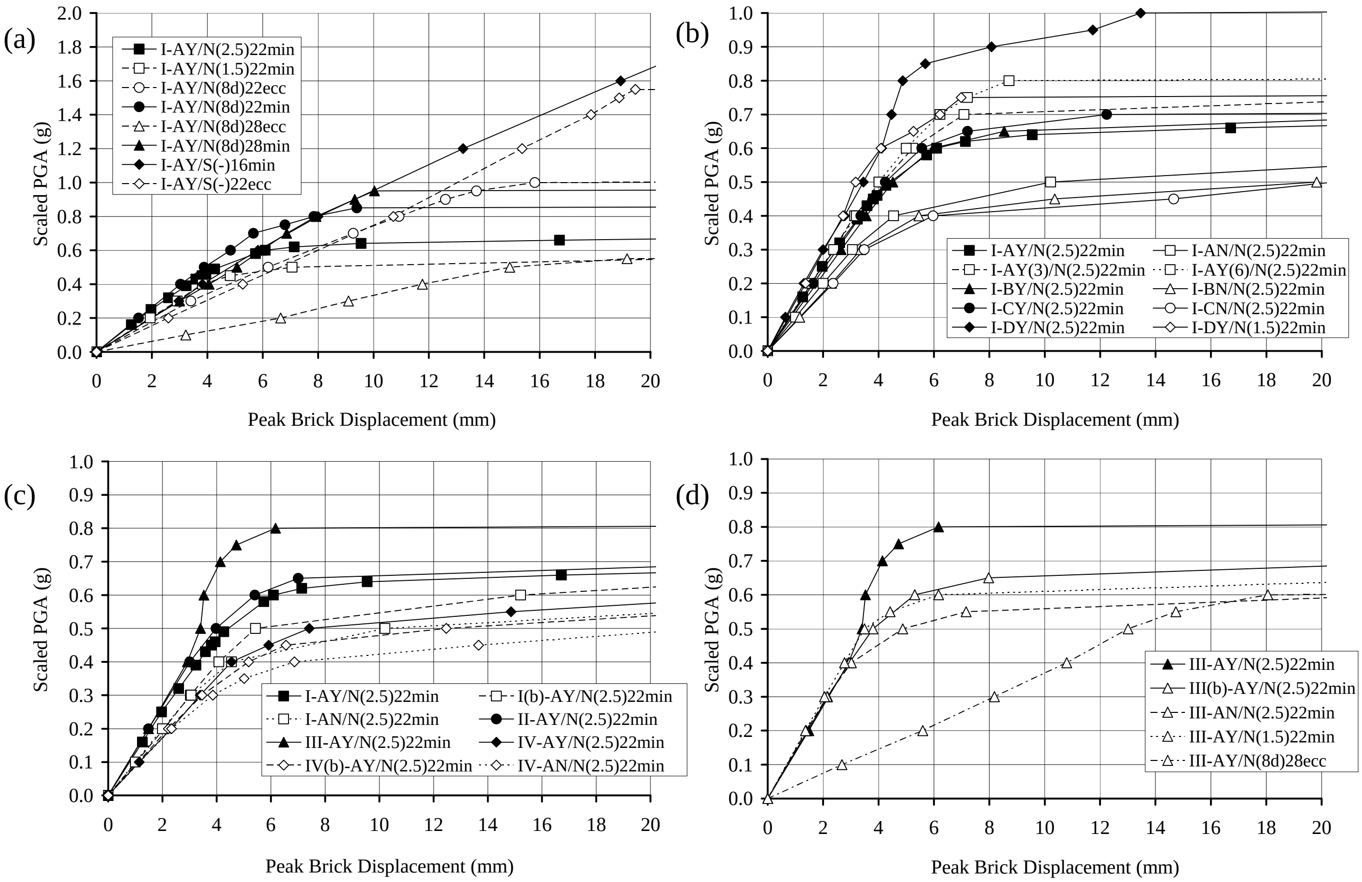

Figure 6 – FE dynamic pushover results (displacements evaluated at tie grid B/5), for various wall panel and tie connection parameters (identified as: Wall Type - Tie Layout / Tie Properties).

## 4. SUMMARY AND CONCLUSIONS

FE models of brick veneer wall panels were developed based on shake table experiments and results. Parameter studies were then conducted to evaluate the effects on the out-of-plane seismic performance of brick veneer walls due to various combinations of tie connection types and layouts, as well as geometric changes in wall construction. The most important results and observations may be summarized as follows:

- Tie connection strength and stiffness properties had a major influence on the out-of-plane seismic performance of brick veneer walls (Fig. 6a).
- The behavior of brick veneer walls was controlled by the overall grid spacing of the tie connections, and particularly by tie installation along the edges and in the upper regions of the walls (Fig. 6b). Three wall panels

comprising tie grids of 610 mm x 406 mm, with the minimum required ties along wall edges, exhibited similar overall behavior; the ultimate strength of those walls shifted noticeably after adding extra ties to the gable region, or after removing ties from wall edges. The out-of-plane strength of brick veneer walls improved significantly when a reduced tie spacing of 406 mm x 406 mm was employed.

- The total area of brick masonry veneer wall panels determined their overall inertial response, and the resulting forces that were then transferred through the tie connections onto the wood-frame backup (Fig. 6c). Brick veneer walls without openings, and those with slightly larger wall edges at the gable, sustained significantly lower dynamic loads, when compared to walls with larger window openings and less masonry at the gable.
- The behavior of wall panels with a relatively large opening was mainly governed by the brick veneer mass and by the tie connections within the gable region (Fig. 6d).

Finally, as a result of all the experimental and analytical studies, the framework for seismic fragility analysis of brick veneer walls has been established. Damage limit states of brick veneer walls have been identified as a function of tie failure. As part of the fragility analysis, variability in tie connection properties, as well as masonry wall cracking, are being considered. Furthermore, the FE wall models are being developed to include wood-frame home structure response (amplification) and its effects on the out-of-plane performance of brick veneer walls.

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