Study On Behavior of Unreinforced Masonry Walls

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Abstract: *Masonry is one of the oldest construction materials. Masonry structures have been in existence since the earliest days of mankind. Clay units have been in use for over 10,000 years and Sun dried bricks were widely used. Unreinforced masonry structures are most vulnerable during an earthquake. Normally they are designed for vertical loads and since masonry has adequate compressive strength, the structure behaves well as long as the loads are vertical. When such a masonry structure is subjected to lateral inertial loads during an earthquake the walls develop shear and flexural stresses. The strength of masonry under these conditions often depends on the bond between brick and mortar (stone and mortar), which is quite poor. This bond is also often poor when lime mortars and mud mortars are used. A Masonry wall can also undergo plane (in-plane and out of plane) shear stresses if the inertial forces are in the plane of the wall. Shear failure in the form of diagonal cracks is observed due to this. However catastrophic collapses takes place when the wall experiences out-of-plane flexure. This can bring down a roof and cause more damage. Masonry buildings with light roofs such as tiled roofs are more vulnerable to out-of-plane vibrations since the top edge can undergo large deformations. It is always useful to investigate the behavior of masonry buildings after an earthquake, so as to identify any inadequacies in earthquake resistant design. Studying types of masonry construction, their performance and failure patterns helps in improving the design and detailing aspects.*

Introduction

Masonry is the oldest of all construction materials, dating back more than eight millennia to cultures around the globe. Early masonries consisted of stone units with no mortar. The structural action in this form of masonry is much different than that of modern-day clay-unit and concrete masonry, which is found in nearly all existing masonry buildings in the United States, with the exception of some historic buildings that predate the 1850s.

Although unreinforced masonry is an ancient building material, effective methods for modeling its structural behavior remains an active research issue. One particularly difficult aspect is the Out-of-plane response of unreinforced masonry walls to seismic loading, which Paulay and Priestley have described as “one of the most complex and ill-understood areas of seismic analysis” (Paulay 1992, p. 623). The complexity arises from the fact that the behavior is highly non-linear, governed primarily by cracking and instability rather than material failure.

Most studies of out-of-plane failure have emphasized analysis of one-way span conditions (e.g. Kariotis 1981, Lam 1995), and design procedures typically neglect the two-way spanning action that occurs near intersecting perpendicular walls, which provide support along a vertical line (Boussabah 1992). Neglecting the two-way action is conservative, but may significantly underestimate the strength of the wall. Towards the objective of developing a method appropriate for the two-way dynamic analysis of unreinforced masonry walls, this paper describes finite element studies of the one-way static condition. The study is motivated by an ongoing archaeological investigation concerning the reconstruction of the ancient city of Pompeii following an earthquake in 62 AD, seventeen years prior to the famous eruption of Mt. Vesuvius (Dobbins 1994), however the results have broader applications to the seismic assessment and renovation of unreinforced masonry structures.

Objectives and Approach

The project seeks to develop a method which can be used to assess the mode of failure in damaged buildings, so the analysis must not only reasonably predict whether a certain action will produce failure, but also indicate the pattern of failure. Another priority is that the method should employ commercially available finite element packages and libraries rather than developing and implementing new element types, since the primary objective is a structural investigation rather than theoretical development.

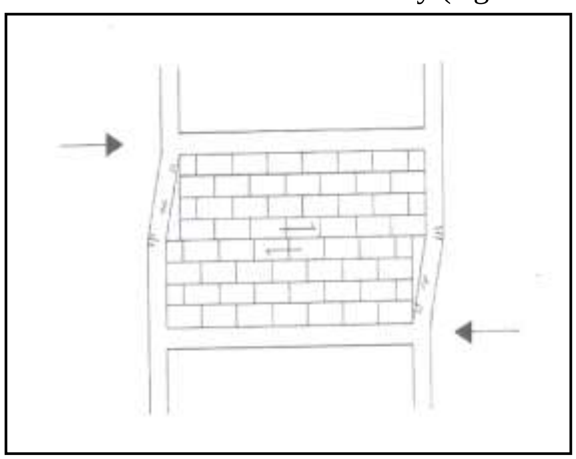
These factors influence the overall approach to modeling masonry behavior. As described by Rots (1991), there are three basic approaches to modeling the behavior of jointed masonry:

• **Joints are represented by continuum elements**: In this approach, the mortar material between the blocks is represented by continuum elements, modeling phenomena resulting from different elastic properties of block and mortar.

• **Joints are represented by discontinuum elements**: This approach neglects the elastic properties of the mortar and associated local effects at the block-mortar interface, instead modeling the mortar joints as potential lines of failure due to cracking.

• **Joints are smeared out**. In this approach, the block-mortar composite is treated as a homogenous solid whose mechanical properties average the effects of the two interacting materials.

These three approaches move upward in scale and abstraction, where representing joints as continuum elements provides a highly detailed view, modeling stress distributions in the mortar, while a smeared joint approach gives a global view, appropriate for modeling the overall behavior of a large building. Because the project investigation is concerned with the behavior of wall panels and assemblies, the middle-scale approach was chosen, representing joints as discontinuum elements. This approach also has the advantage that it can be implemented with commercial software packages (the ABAQUS program (HKS 1995) was used in this study) and is better suited to modeling seismic load reversals than the smeared crack approach. This approach will be termed the block-interface approach, several researchers have used it to study in-plane behavior of unreinforced masonry (e.g. Lotfi



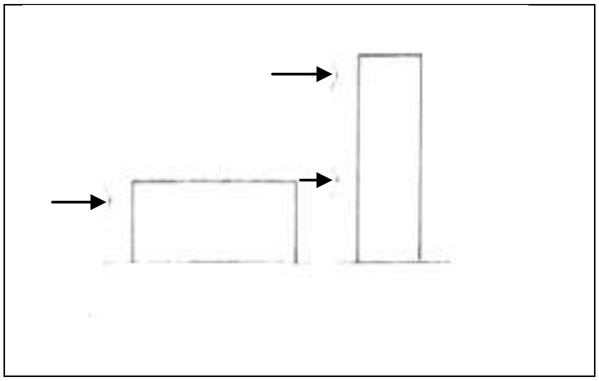


Figure1.Interaction between frame and horizontally sheared infill masonry.

1994, Rots 1991), but there has been little application to out-of-plane effects.

Figure 2.Overturning Effects of horizontal loads.

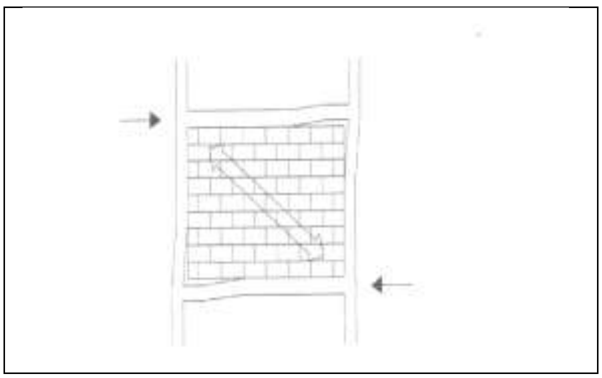


Figure 3. Interaction between frame and infill masonry

Figure 1 shows an Interaction between frame and horizontally sheared infill masonry

• **Course**: A course corresponds to a horizontal row of masonry units, separated from adjacent courses by arrays of 8-node contact-interface elements at coincident nodes.

• **Layer**: A layer is a horizontal subdivision of a course into continuous 8-node elastic finite elements.

• **Lamination**: A lamination is a vertical subdivision of a course into continuous finite elements.

Verification Studies

Although the ultimate objective is to model two-way dynamic behavior, the verification process began with static one-way behavior, since it is an appropriate starting point, and there is a greater body of literature for comparison. The following discussion presents fundamental aspects of behavior and theory followed by comparisons with other theoretical and experimental studies in the literature.

Fundamentals

Initially, the wall deflects as a linear elastic slab, which cracks when the moment creates enough tension to exceed the compressive prestress; the tension strength is assumed zero. The wall continues resisting load beyond initial cracking, but loses stiffness as the crack grows, eventually reaching a point of maximum load, beyond which the wall is unstable. The condition of stability can be understood in terms of the free body diagram, showing the upper half of a cracked wall. The resultant of the horizontal pressure and the horizontal reaction form a counter-clockwise disturbing moment with a restoring moment formed by the downward resultant of the applied load P plus the self weight of the wall portion W and the upward force R, which is the compressive stress resultant at the cracked

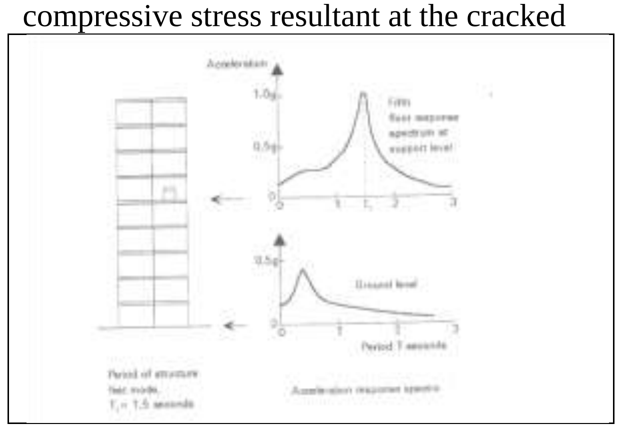


Figure 4. Secondary structure response to ground motion

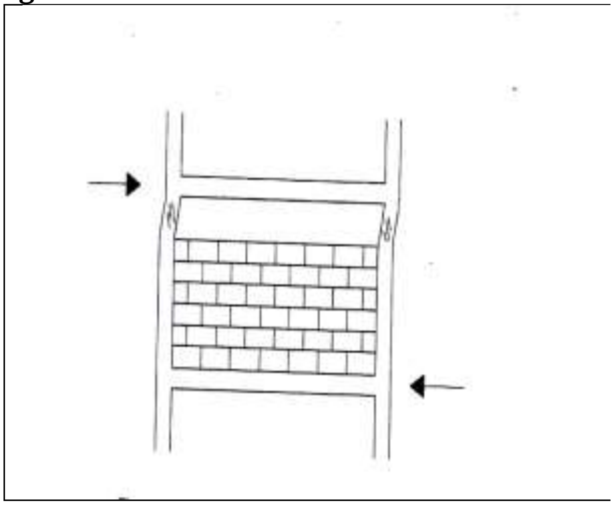


Figure 5. Interaction between frame and partial infill masonry.

plane. As the load w increases, the distance x from the centerline to the resultant R increases, increasing the lever arm of the restoring moment, however the lever arm eventually decreases with increasing deflection Δ. Instability occurs when the resultant R moves outside the resultant of the gravity loads (Paulay 1992). A wall can be defined as lightly loaded if the point of instability is reached before the masonry material reaches compressive crushing stress, meaning there is no material failure. This project is primarily concerned with lightly loaded walls which occur in one and two story masonry building with timber-frame floors and roofs, so the modeling method does not account for material crushing.

Theoretical studies

Two cases were used to compare results of the finite element model with other theoretical methods. The first uses a method first presented by Priestley in 1985 and 1986, and then published in slightly modified form in 1992 (Paulay 1992). The method is based on first principles of beam theory, assuming zero tension strength, and accounts for the P-delta effects of large displacements. Figure 4 shows a comparison of load-deflection curves for a wall panel with the following properties: vertical span 2095 mm, thickness 90 mm, width 802 mm, vertical surcharge 312 kN, elastic modulus 19.3 GPa, mass density 1850 kg/m3. The figure also includes experimental results for this case (Fattal 1976), discussed below. The curves from Priestley's method and the finite element model show very good agreement, particularly in the linear elastic range, and in the range well beyond the instability point. The finite element model predicts a maximum load that is approximately 6 percent higher, occurring at virtually the same displacement level. Another theoretical comparison involved a method developed by Mendola (1995). Like Priestley's method, it is also based on first principles of beam theory and accounts for P-delta effects, but uses a more complex and refined formulation. One of Mendola's examples was a cantilever vertical pier subjected to a constant vertical surcharge equal to the weight of the pier, plus lateral loads consisting of a percentage of the self weight plus a concentrated load at the top equal to the same percentage of the vertical surcharge (see figure 5). The pier had the following properties: height 6000 mm, depth 600 mm, width 1000 mm, weight density 19 kN/m3, elastic modulus

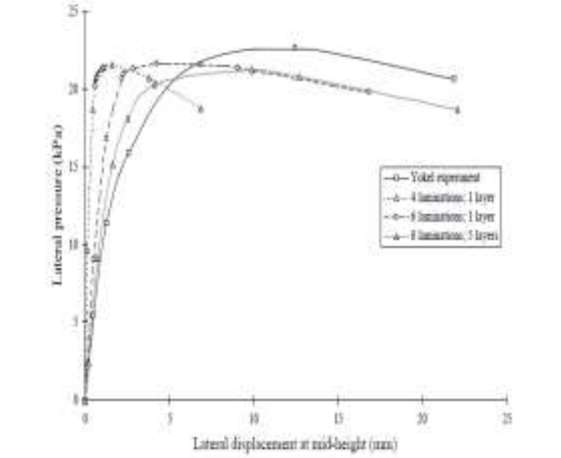


Fig 6. Finite element models compared to Yokel's experimental results.

1,140 MPa, vertical surcharge 68.4 kN.

Experimental Studies

In addition to comparisons with theory, the verification studies have also included comparisons with experiments, using studies conducted by Yokel (1971) and Fattal (1976). One of the panels in the Yokel study was a lightly loaded solid concrete block wall, a configuration well suited to the interests of the project. The panel had the following properties: thickness 194 mm, height 2095 mm, width 1210 mm, vertical surcharge 111 kPa, elastic modulus 6.20 GPa, mass density 1600 kg/m3. Figure 6 shows the load-deflection curve for the experiment along with corresponding curves for three finite element models with different mesh configurations. The comparison shows that the prediction of the finite element model is sensitive to the mesh configuration.

Although all three finite element models predict the same maximum strength within 2 percent, the coarser meshes significantly over predict the stiffness and under predict the displacement capacity. Although an accurate prediction of strength is adequate for many purposes, in non-linear seismic analysis, it is also important to model stiffness and displacement capacity with reasonable accuracy. One important source of discrepancy between the model results and the experiment is the uncertainty in the boundary conditions of the experiment, which used flexible fiberboard with unknown properties to allow rotation at the base of the test panel. The Fattal (1976) study was similar to that of Yokel, using slightly smaller panels and supporting them top and bottom on steel half-round bars, which created a more ideal boundary condition. Note that both the finite element model and Priestley's method overestimate the stiffness and underestimate the strength. This is probably due to round holes in the cross section of the brick which reduce the cross section area by 21 percent and the moment of inertia by approximately 3 percent; the analyses using finite elements and Priestley's method did not account for the holes, whose effect is to decrease elastic bending stiffness by about 3 percent and increase the load that initiates cracking by about 20 percent.

Summary and Conclusions

Modeling unreinforced masonry using a block-interface approach shows good agreement with theoretical predictions for one-way out-of-plane loading of both simple span and cantilever walls, as shown in the comparisons with the Priestley and Mendola methods. Comparisons with the experimental results of Yokel (1971) and Fattal (1976) showed more divergence, due partly to aspects of the experiment which were uncertain or difficult to model. The study also indicates that the strength predicted by a block-interface model is not highly sensitive to the refinement of the mesh, but the predictions of stiffness and displacement capacity are sensitive to the mesh. Although the block-interface approach gives good predictions for the one-way static case, it is not well suited to that purpose, since it is far more computationally intensive than the methods of Priestley and Mendola, which are equally accurate. The advantage of the block-interface model is that it can be extended to model a two-way span condition, an extension that is quite difficult for the Priestley and Mendola methods, since they are based in beam theory. The two-way case, plus dynamic loadings, is the next step for further research.

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