

Finite Element Studies in the Out-Of-Plane Failure of Unreinforced Masonry

Kirk Martini

*Departments of Architecture and Civil Engineering, University of Virginia
Charlottesville Virginia, 22903, USA*

ABSTRACT

This paper describes finite element studies of one-way out-of-plane failure of unreinforced masonry walls under static loading. The studies are early steps in the development of a method that will be applicable to two-way out-of-plane failure of walls under dynamic loading. The approach is based on a discrete-crack approach, where mortar beds are modelled using contact-interface elements, and masonry blocks are represented as assemblies of elastic eight-node elements. Predictions of the method are compared with published theoretical and experimental results, showing very good agreement with theory and reasonable agreement with experiment, considering uncertainties in boundary conditions and other factors.

INTRODUCTION

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 modelling masonry behavior. As described by Rots (1991), there are three basic approaches to modelling 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, modelling 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 modelling 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 homogeneous 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, modelling stress distributions in the mortar, while a smeared joint approach gives a global view, appropriate for modelling 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 modelling 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 1994, Rots 1991), but there has been little application to out-of-plane effects.

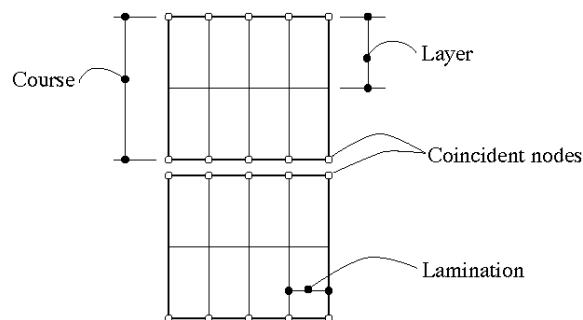


Fig. 1 Organization of finite element mesh.

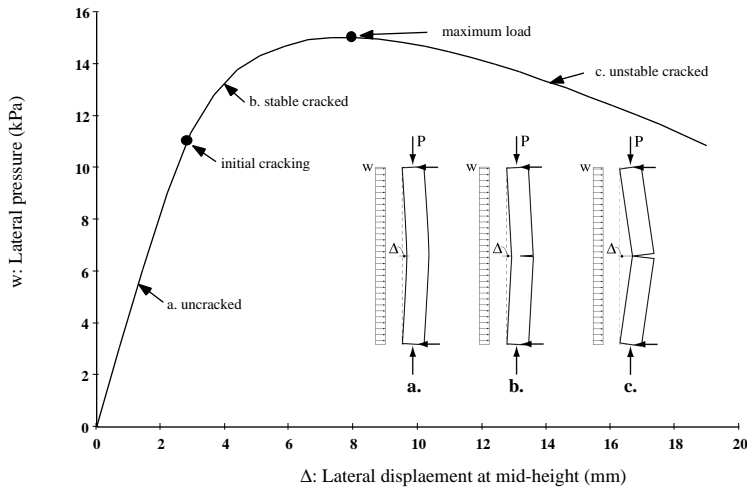


Fig 2. Load-deflection relationship for out-of-plane loading.

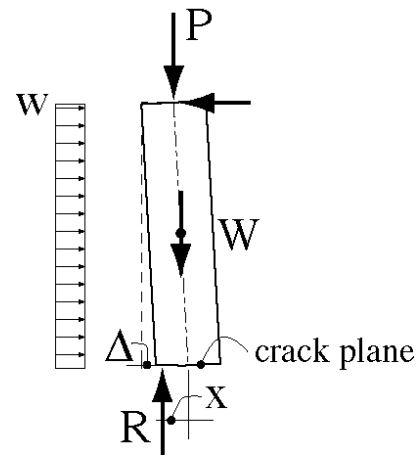


Fig 3. Free body diagram of upper portion of wall subjected to out-of-plane loading. (after Paulay 1992)

Figure 1 shows a close-up view of a typical finite element mesh, described using the following terms:

- **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

Figure 2 shows a load deflection curve which highlights key features of out-of-plane failure; the figure is based on an example panel discussed in detail below. 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 shown in figure 3, 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

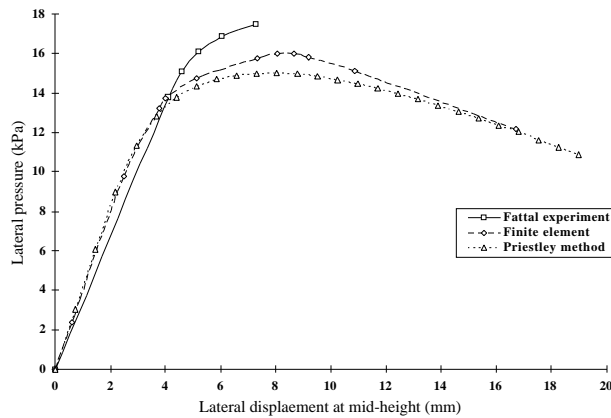


Fig 4. Comparison with Fattal's experiment and a method developed by Priestley.

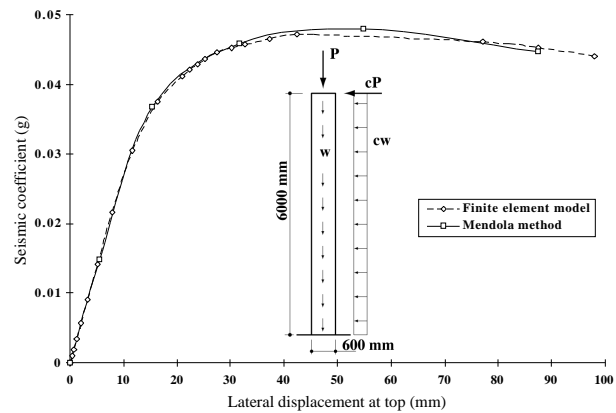


Fig 5. Comparison with a method developed by Mendola.

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 modelling 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

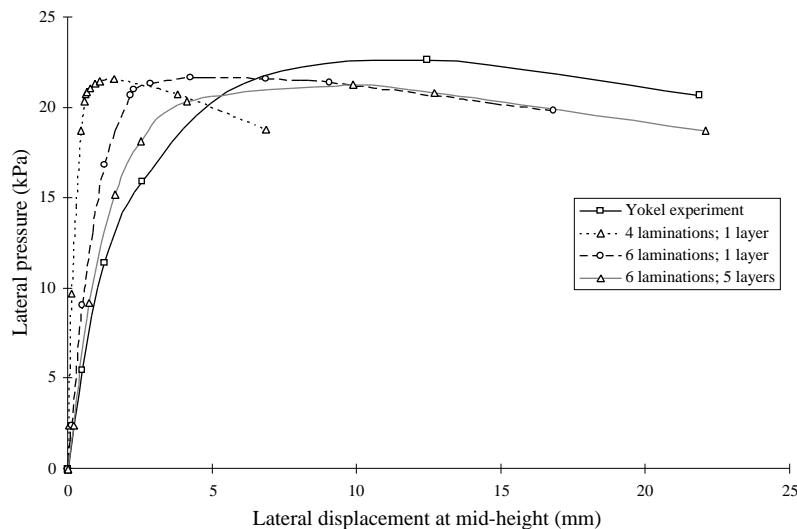


Fig 6. Finite element models compared to Yokel's experimental results.

1,140 MPa, vertical surcharge 68.4 kN. Figure 5 compares the curve predicted by the Mendola method with that of the finite element method. The agreement is very close.

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 overpredict the stiffness and underpredict 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. Figure 4 shows a comparison of load-deflection curves for one of Fattal's test panels with results predicted by Priestley's method and a block interface model. 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. Both these trends are visible in the curves of figure 4.

SUMMARY AND CONCLUSIONS

Modelling 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.

ACKNOWLEDGEMENTS

This work has been conducted as part of the Pompeii Forum Project, directed by John J. Dobbins, with support from the University of Virginia's School of Architecture Dean's Forum, and Center for Advanced Studies. This support is gratefully acknowledged.

REFERENCES

- ABK: A Joint Venture (1981), *Methodology for Mitigation of Seismic Hazards in Existing Unreinforced Masonry Buildings: Wall Testing, Out-of-Plane*, ABK-TR-04, El Segundo, CA.
- Boussabah, L. and Bruneau, M. (1992) "Review of the Seismic Performance of Unreinforced Masonry Walls," *Proc. of the 10th World Conf on Eq. Eng.*, 4537-4540.
- HKS: Hibbitt, Karlsson & Sorensen, Inc. (1997), *ABAQUS*, Pawtucket, Rhode Island, <http://www.abaqus.com/>
- Lam, N.T.K.; Wilson, J.L.; Hutchinson, G.L. (1995) "The Seismic Resistance of Unreinforced masonry Cantilever Walls in Low Seismicity Areas," *Bull. of the New Zealand National Society for Eq. Eng.*, Vol. 28 (3), 179-195.
- Lotfi, H.R. and Shing, P.B. (1994) "Interface model applied to fracture of masonry structures," *Journ. of Struct. Eng.*, ASCE, vol. 120 (1), 63-80.
- Mendola, L.L.; Papia, M.; Zingone, G. (1995) "Stability of Masonry Walls Subjected to Seismic Transverse Forces," *Journ. of Struct. Eng.*, ACSE. vol. 121(11), 1581-1587.
- Paulay, T. and Priestley, M.J.N. (1992), *Seismic Design of Reinforced Concrete and Masonry Buildings*, J. Wiley, New York.
- Priestley, M.J.N. (1985) "Seismic Behaviour of Unreinforced Masonry Walls," *Bull. of the New Zealand National Society for Eq. Eng.*, Vol 18(2), 191-205.
- Priestley, M.J.N. and Robinson, L.M (1986) "Discussion: Seismic Behavior of Unreinforced Masonry Walls," *Bull. of the New Zealand National Society for Eq. Eng.*, Vol 19(1), 65-75.
- Rots, J.G. (1991) "Numerical simulation of cracking in structural masonry" *Heron*, Vol. 36(2) 49-63.