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NUMERICAL ANALYSIS OF UNREINFORCED MASONRY WALLS RETROFITTED BY CABLE SYSTEM

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Abstract

The purpose of this research is to develop a new and high strength seismic retrofitting technique for masonry structures. An innovative retrofitting technique is developed by using cable system. In this paper, a nonlinear finite element model has been developed for unreinforced masonry walls retrofitted by cable system to validate the experimental results. The model takes into account material nonlinearities as well as damage due to progressive cracking. Behaviour of the masonry is modelled using the theory of plasticity and cracking is modelled using smear crack approach. The model is generated using ABAQUS program. Reasonably good agreement has been found between the analytical and experimental results.

Key Words

Unreinforced masonry walls, seismic retrofitting, finite element model

1 Introduction

Traditionally Australian civil engineers have not paid a great deal of attention to earthquake resistant design. However, the Newcastle earthquake in 1989 led to the creation of a new set of guidelines for earthquake resistance. This new code has resulted in the need to systematically retrofit structures that no longer comply with the new guidelines. Masonry structures are one of the most common construction types in Australia. Although the history of past earthquakes has shown that masonry buildings have suffered the maximum damage and also accounted for the maximum loss of life, they continue to be popular. Most of the historical or existing buildings throughout Australia are unreinforced masonry, highlighting the need to improve their performance by retrofitting and strengthening to resist potential earthquake damages.

In the last two decades, several seismic retrofitting techniques for masonry structures have been developed and practiced, but rarely validated with experiments and numerical modelling. The purpose of this research is to develop a new and high strength seismic retrofitting technique for masonry structures. An innovative retrofitting

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technique has been presented in the companion paper using cable system. In that companion paper (Chuang et al.2003), the experimental results of three unreinforced masonry walls retrofitted with cable system were reported. All walls were tested under combined constant gravity load and incrementally increased in-plane lateral displacement reversals. The results showed that both the strength and ductility of tested specimens were significantly enhanced with this technique. Seismic retrofitting of unreinforced masonry walls with cable system proved to be an effective and reliable strengthening alternative.

In this paper, a nonlinear finite element model has been developed to validate the experimental results from unreinforced masonry walls retrofitted by cable system. Reasonably good agreement has been found between the analytical and experimental results. The model takes into account material nonlinearities as well as damage due to progressive cracking. Behaviour of the masonry is modelled using the theory of plasticity and cracking is modelled using smear cracking approach. The model is generated using ABAQUS finite element program. The details of the numerical modelling are also discussed in this paper. The validity of the model is established by comparison with experimental results. It is shown that the numerical model is capable of predicting the load carrying capacity of the URM wall and the retrofitted walls.

2 Finite element model

2.1 Modelling techniques for unreinforced masonry wall

Masonry is a composite material that consists of units and mortar joints. In general, the approach towards its numerical representation can focus on the micro-modeling of masonry as a components, such as unit (brick, block, etc.) and mortar, or the macro-modeling of masonry as a composite, see Rots (1991). Depending on the level of accuracy and the simplicity desired, it is possible to use the following modeling strategies, see Figure 1.

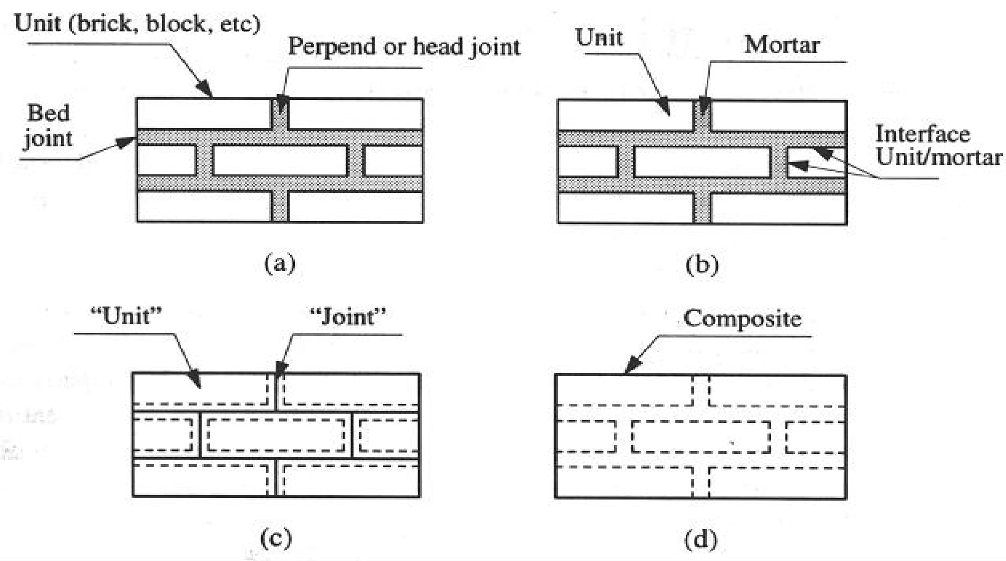

Figure 1 Modeling strategies for masonry structures: (a) masonry sample;(b) detail micro-modeling;(c) simplified micro-modeling;(d) macro-modeling (Lourenco, 1996)

- Detailed micro-modeling – units and mortar in the joints are represented by continuum elements whereas the unit-mortar interface is represented by discontinuous elements;

- Simplified micro-modeling - expanded units are represented by continuum elements whereas the behavior of the mortar joints and unit-mortar interface is lumped in discontinuous elements;
- Macro-modeling – unit, mortar and unit-mortar interface are smeared out in the continuum.

The macro-modeling is more practice oriented due to the reduced time and memory requirements as well as a user-friendly mesh generation. This type of modeling is most valuable when a compromise between accuracy and efficiency is needed. In this paper, the macro-modelling is adopted to model the unreinforced wall retrofitted by cable system. Masonry is a composite material. It consists bricks and mortar joints. The macro-modeling does not make a distinction between individual units and joints but treats masonry as a homogeneous anisotropic continuum. Masonry can be assumed to be a homogeneous material if a relation between average stresses and strains in the composite material is established. For the numerical analysis, bilinear plane stress continuum elements with full gauss integration are utilized.

2.2 Selection of element type

For macro-modeling, the four-node bilinear two-Dimensional plane stress element, CPS4R, was used to model the masonry. A more sophisticated element, such as the eight-node isoparametric element, was not used because it has been shown from previous research (Bazant and Cedolin, 1980; Ali, 1987) that the use of higher order elements was not warranted for the analysis of brick masonry (where nonlinearity is mainly due to progressive cracking and not non-linear material characteristics), provided a relatively fine element mesh was adopted.
The four-node bilinear two-Dimensional plane stress element, CPS4R, was also used to model the steel plates that used to connect between the cable and masonry wall.
The two-Dimensional truss element, T2D2, was used to model the cable. The 2-node straight truss element uses linear interpolation for position and displacement and has a constant stress. The truss element as long, slender structural members that can transmit only axial force. No Compressive option was used to make sure the cable only take tension. The element has two degrees of freedom at each node and translations in the nodal x and y directions.
The connector elements, connection type BEAM, were used to model connection between the steel plate and masonry wall and to model connection between the steel plate and cable.. This connector element, BEAM, provides a rigid beam connection between two nodes.

2.3 Constitutive law of Masonry

A constitutive model is a mathematical description of material behaviour. There are two major aspects to develop an accurate analytical model. One is to understand the behavior of masonry which is the constitutive relations of the material. And the other is the failure criteria of the material because the major nonlinear effect of URM under in-plane lateral load is due to progressive cracking. (Zhuge, 1995)
Development of a model for the behavior of masonry is challenging task. Masonry is a quasibrittle material and has different behavior in compression and tension. Figure 2 shows a typical stress-strain curve for clay-brick masonry.

Figure 2   A typical stress-strain curve for clay-brick masonry (ABAQUS, 2002)

Most masonry walls subjected to in-plane loads are in a state of biaxial stress. Since most masonry structures are in a biaxial stress state, it is necessary to consider a biaxial stress-strain model for masonry subject to in-plane loading.
The failure model is capable of predicting failure for masonry materials. Both cracking and crushing failure modes are accounted for. The two input strength parameters-i.e., ultimate uniaxial tensile and compressive strengths- are needed to define a failure surface for the masonry. Consequently, a criterion for failure of the masonry due to a multiaxial stress state can be calculated. A two-dimensional failure surface for masonry is shown in Figure 3. In masonry, cracking occurs when the principal tensile stress in any direction lies outside the failure surface. After cracking, the elastic modulus of the masonry element is set to zero in the direction parallel to the principal tensile stress direction. Crushing occurs when all principal stresses are compressive and lies outside the failure surface; subsequently, the elastic modulus is set to zero in all directions (ABAQUS, 2002), and the element effectively disappears.

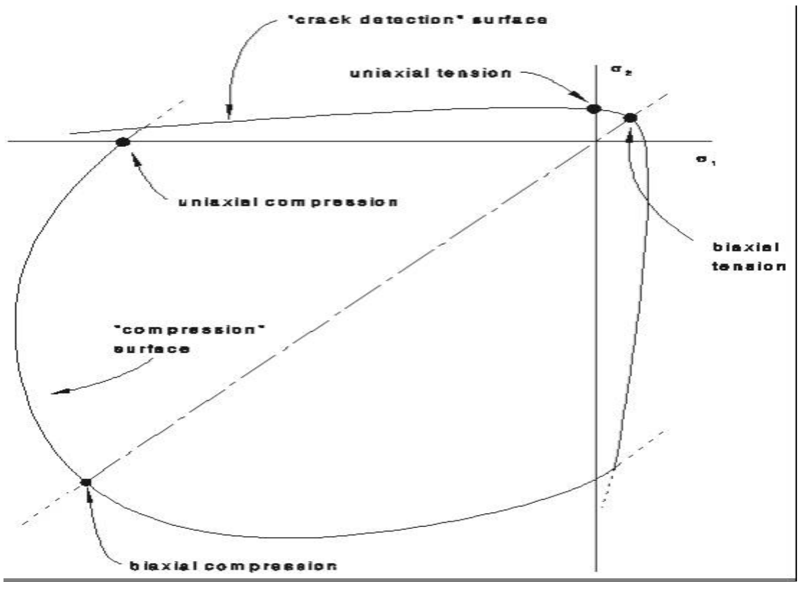

Figure 3 A two-dimensional failure surface for masonry (ABAQUS, 2002)

2.4 Finite element discretization

As an initial step, a finite element analysis requires meshing of the model. In other words, the model is divided into a number of small elements, and after loading, stress and strain are calculated at integration points of these small elements (*Bathe 1996*). An important step in finite element modelling is the selection of the mesh density. A

convergence of results is obtained when an adequate number of elements is used in a model. This is practically achieved when an increase in the mesh density has a negligible effect on the results (*Adams and Askenazi 1998*). Figure 4 shows meshing for the retrofitted wall model.

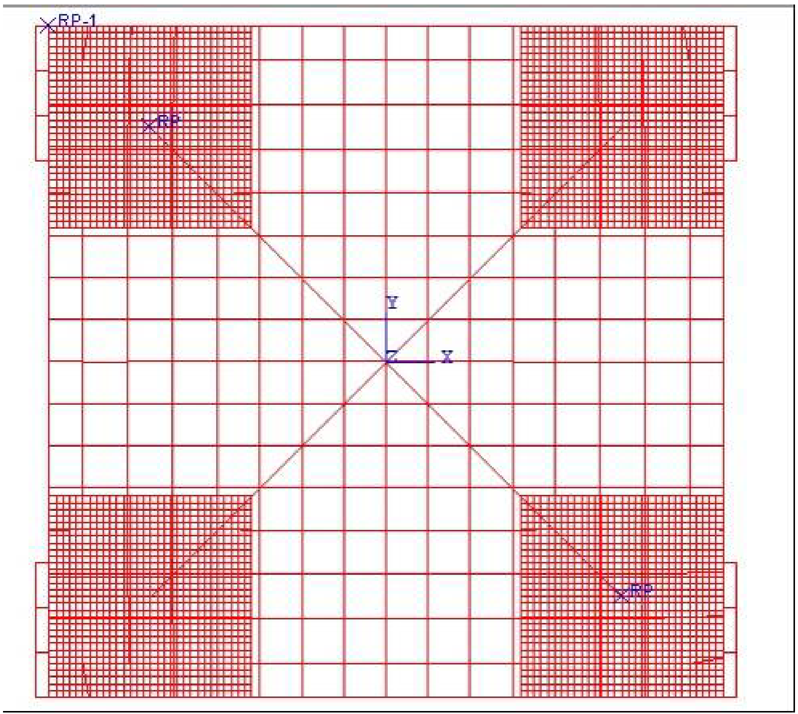

Figure 4 The mesh for the retrofitted wall model

3 Validation of the numerical modelling results with the test results

This section compares the results from ABAQUS finite element analyses with experimental results of four masonry walls. The following comparisons are made: load-deflection plots; cracking loads; loads at failure; and the forces carried by cable. The data from the finite element analyses were collected at the same locations as the experimental tests for the masonry wall.

3.1 Load-deflection plots

Force-displacement diagram from finite element models described in this paper have been compared with experimentally obtained envelopes of the lateral force-horizontal displacement relationships of retrofitted walls and unreinforced wall. These results are presented in Figs 5 and 6 for URM wall and retrofitted wall, respectively. The models provide good correlations with test data and can be considered as effective analytical tools.

Figure 5 shows that the load-deflection plot from the finite element analysis agrees well with the experimental data for the URM wall. The load-deflection plot from the finite element analysis is slightly stiffer than that from the experimental results. This is possibly due to the relative homogeneity of the finite element models when compared to the relative non-homogeneity of the actual walls that contain two different materials and neglect the weaker mortar effect. The first cracking load for the finite element analysis is 15.2 KN, which is higher than the load of 14.7 KN from the experimental

results by only 4%. Lastly, the ultimate load of 24.4 KN predicted by the model is higher than the ultimate load of 22.49 KN from the experimental data by only 8 %.

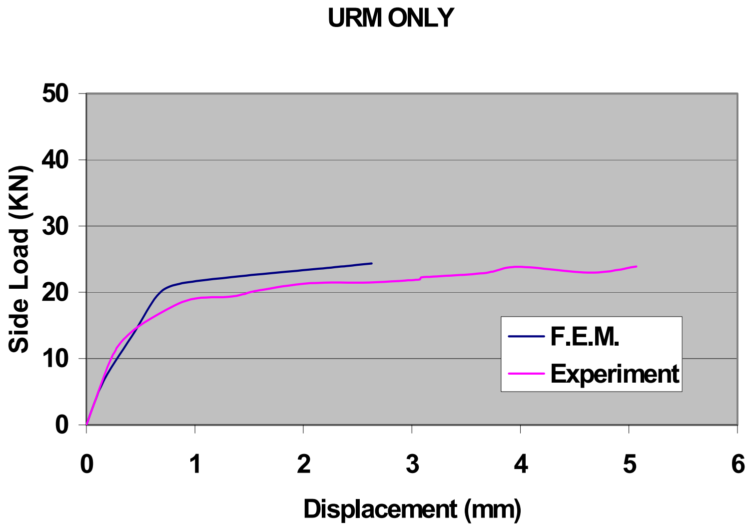

Figure 5 Load-deflection plot for URM wall

Figure 6 shows that the load-deflection plot from the finite element analysis agrees well with the experimental data for the wall retrofitted with cable. The load-deflection plot from the finite element analysis is stiffer than that from the experimental results. This is possibly due to the fatigue of the material. The result from the finite element model was under monotonic loading, but the results from experiment was under cyclic loading. The first cracking load for the finite element analysis is 17.5 KN, which is higher than the load of 15.2 KN from the experimental results by 15%. Lastly, the ultimate load of 49.15KN from the model is higher than the ultimate load of 46.4 KN from the experimental data by 6 %.

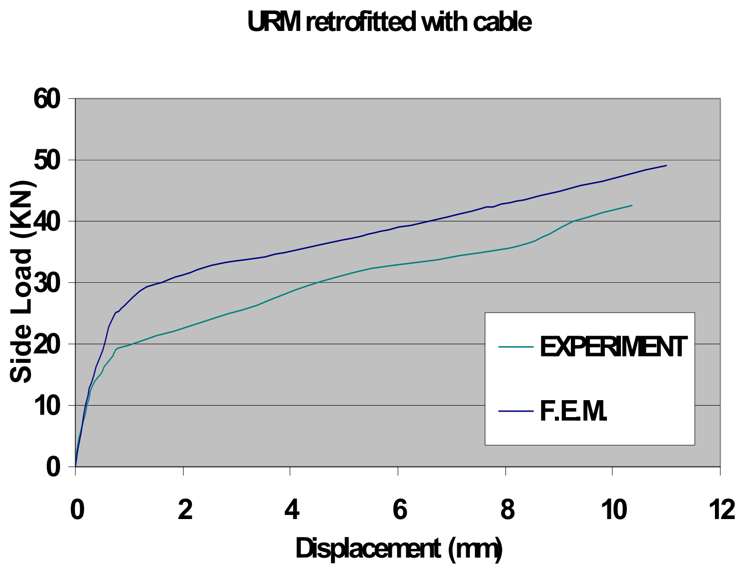

Figure 6 Load-deflection plot for URM wall retrofitted with cable

Figure 7 shows that the load-deflection curve for the wall before and after retrofitting with cable from the finite element analysis. The load-deflection curve for retrofitted wall is much stiffer than the load-deflection curve for unretrofitted wall. In this figure, it also shows that the retrofitted wall significantly increases the strength and ductility of the wall. These results are similar to the experimental results. The improvement of the ultimate lateral load resistance of the retrofitted walls with cables is 2 times the capacity of unreinforced wall. The improvement of the ductility of the retrofitted walls with cables is about 6 times the capacity of unreinforced wall.

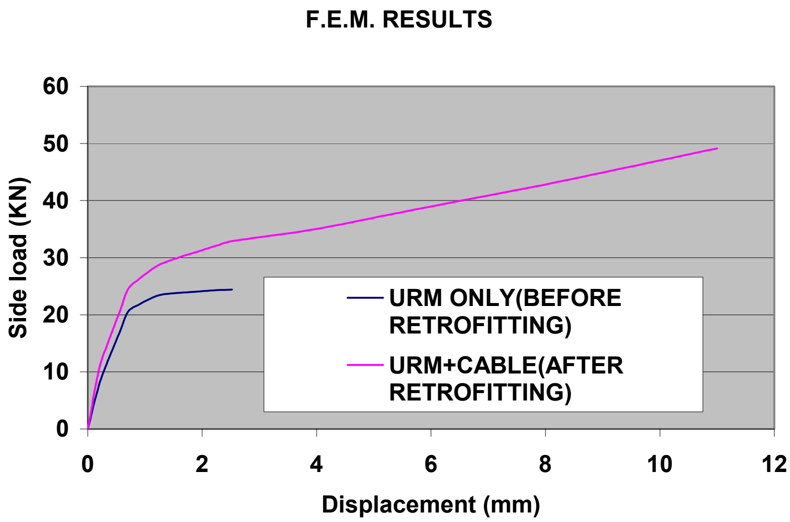

Figure 7 Comparison of Load-deflection behaviour before and after retrofitting

3.2 First cracking loads

The first cracking load from the finite element analysis is the load step where the first signs of cracking occur for masonry in the model. Loads at first cracking from the model and the experimental results are compared in Table 1.

Table 1 Comparisons between experimental and ABAQUS first cracking loads

Retrofitting	Experiment	F.E.M.	% Difference
URM	14.7KN	15.2KN	4%
CABLE	15.2KN	17.5KN	15%

The first cracking loads from the finite element analyses and the experimental data are within 15% for URM wall and retrofitted walls. In all cases, the first cracking load from ABAQUS is higher than that from the experimental data. This is possibly due to the relative homogeneity of the finite element models when compared to the relative heterogeneity of the actual walls that contain a number of microcracks.

3.3 Ultimate loads

Table 2 compares the ultimate loads for URM wall and retrofitted walls from experiments to the ultimate loads from the finite element simulations. The material properties assumed in this study may be imperfect. The stress-strain curve for the cable used for the finite element models should be obtained directly from material testing. The actual cable has a different stress-strain curve when compared to the

idealized cable used for the finite element modelling, as shown in Figure 8. Therefore, this may help to produce the higher ultimate load in the finite element results.

Table 2 Comparisons between experimental and ABAQUS loads at failure

Retrofitting	Experiment	F.E.M.	% Difference
URM	22.49KN	24.4KN	8%
CABLE	46.4KN	49.15KN	6%

3.4 Forces carried by cable

For the actual retrofitted walls, there was no evidence that the cable failed before overall failure of the walls. This is confirmed by the finite element analyses. In the figure 8, forces carried by the cable from ABAQUS are compared to the tensile strengths of the cable measured from experimental tests.

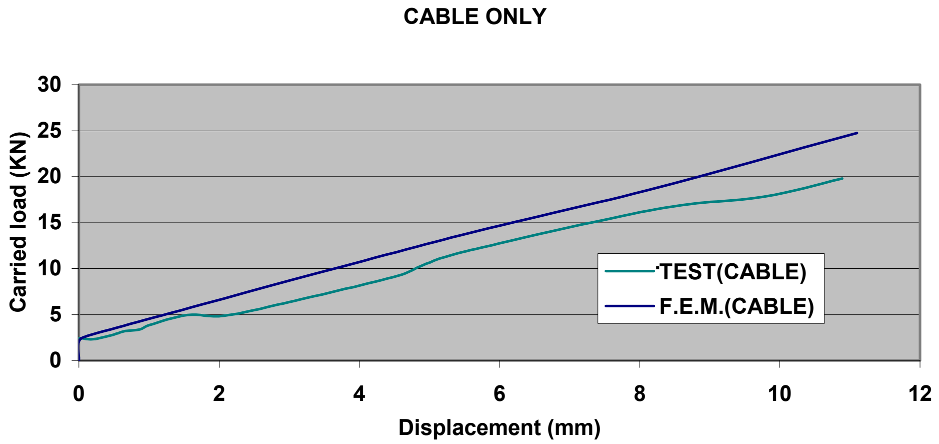

Figure 8 Comparison between experimental and ABAQUS for force carried by cable

4 Conclusion

A non-linear finite element models was developed to predict strength and ductility of URM wall and URM walls retrofitted with cable system. The experimental results obtained from URM masonry walls retrofitted with cable system are compared with respect to those obtained from analytical solutions. The analytical results was obtained using finite element program ABAQUS. These models have the ability to track the behaviour of URM wall and URM wall retrofitted with cable from the first cracking almost to final failure. The results from these models also show good agreement with the experimental results.

5 Acknowledgements

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