OUT-OF-PLANE SEISMIC RESPONSE OF UNREINFORCED MASONRY WALLS: AN OVERVIEW OF RESEARCH IN AUSTRALIA

J. VACULIK[1], E. LUMANTARNA[2], M.C. GRIFFITH[1], N.T.K. LAM[2]
and J. WILSON[3]

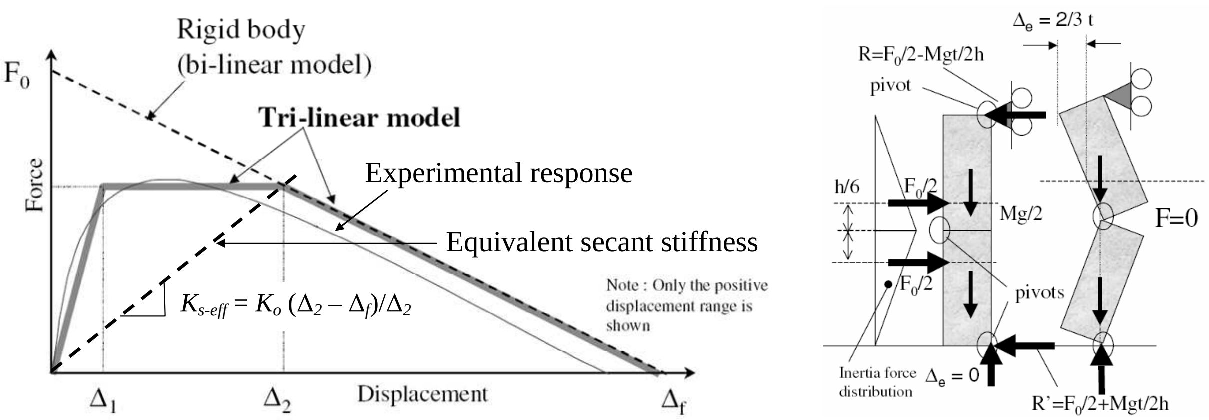
1. Department of Civil and Environmental Engineering, The University of Adelaide, Australia.
2. Department of Civil and Environmental Engineering, The University of Melbourne, Australia.
3. Faculty of Engineering and Industrial Science, Swinburne University of Technology, Australia.

SUMMARY

This paper presents the progress of collaborative research undertaken jointly by the Universities of Adelaide, Melbourne and Swinburne, as part of a long-term effort to develop state-of-the-art methodology for the seismic assessment and design of unreinforced masonry (URM) structures. The current phase of research is aimed at the problem of out-of-plane failure of two-way panels and can be broadly categorised into several component studies incorporating experimental and analytical work, as follows:

1) *Experimental quasi-static cyclic tests* on full-scale URM walls, aimed to study the nonlinear load-displacement response of walls subjected to two-way bending (Adelaide).
2) *Development of a hysteresis model* to provide a numerical representation of the experimentally observed out-of-plane load-displacement response, to be used as part of a nonlinear time history analysis (Adelaide and Melbourne).
3) *Dynamic shaketable tests* on half-scale URM walls, intended to verify the results of the quasi-static experimental tests under true dynamic loading and also to provide dynamic response data for validating the accuracy of a nonlinear time-history analysis (Adelaide).
4) *Analytical modelling of seismic response of the out-of-plane walls at the component level* using time-history analyses for a range of wall configurations and earthquake ground motions representative of the typical design space (Melbourne and Adelaide).
5) *Modelling the seismic response of overall multistorey* URM *buildings at the system level*, to provide representative floor accelerograms to be used as excitation input for individual component walls (Melbourne).
6) *Development of a displacement-based methodology* based on a simplified equivalent linear system method for predicting the out-of-plane seismic displacement demand of two-way masonry walls, to be used for engineering design and assessment of such walls (Melbourne and Adelaide).

This paper presents an overview of parts 1-4 above.



(a) Load-displacement model (b) Rigid body model

Figure 1. Idealised model for vertically spanning one-way walls (Doherty *et al*., 2002)

BACKGROUND

Research into the seismic response of URM buildings (Bruneau, 1994; Brunsdon, 1994; Calvi, 1999; Maffei *et al*., 2000; Abrams, 2001) has highlighted the need for improvements in our understanding the response of URM buildings under earthquake loading and in the corresponding procedures for earthquake resistant design. Significant improvements have been made in Australia in recent years in the design methodology used to predict the out-of-plane static strength of URM walls, with the development of a virtual work method (Lawrence and Marshall, 2000) applicable to one-way and two-way spanning wall panels with a range of boundary support conditions. The method, which has been adopted by the current version of the Australian Masonry Code AS-3700 (Standards Australia, 2001) provides the ultimate load bearing capacity which is used in the design of URM walls for lateral loading due to both wind and earthquake. Whilst a forced-based design approach is appropriate in the design of walls for wind loading, it has been shown to be vastly conservative for the ultimate limit state design of URM walls under seismic loading (Priestley, 1985; Magenes and Calvi, 1997). The force-based procedure effectively ensures that the deformation response of the wall does not exceed the displacement at which ultimate strength is reached (typically 5-15 mm), although collapse of a wall has been demonstrated not to occur until the deformation exceeds the ultimate displacement capacity (typically in the order of the wall thickness which is equal to 110 mm for standard Australian URM construction).

Displacement-based methods have gained popularity in recent years for the seismic design and assessment of ductile structural systems including multi-storey buildings (Medhekar and Kennedy, 2000), continuous concrete bridges (Kowalsky, 2002) and in-plane masonry walls (Magenes and Calvi, 1997). Recent joint research by the University of Adelaide and University of Melbourne into the out-of-plane seismic response of has led to the development of a simplified displacement-based design procedure for vertically spanning URM walls (Doherty *et al*., 2002). The procedure was based on approximating the nonlinear load-displacement behaviour using an idealised tri-linear relationship (Figure 1a), defined by parameters Δ_1, Δ_2 , Δ_f and F_o as shown. The accuracy of the tri-linear hysteresis model was validated by extensive shaketable testing (Doherty *et al*., 2002; Lam *et al*., 2003), which demonstrated that vertically spanning walls respond with good displacement capacity relative to their cracking displacement, but with minimal hysteretic energy dissipation. The ultimate displacement capacity of the wall (Δ_f) was

shown to be equal to the wall's thickness, whilst the ultimate load capacity (F_o) was determined using simple rigid-body theory (Figure 1b) and formulated as a function of the wall geometry, self-weight and vertical pre-compression. The displacements Δ_1 and Δ_2 were empirically derived parameters based on the assumed quality and state of degradation of the masonry. Analytical studies involving time history analyses with earthquake ground motions showed that reasonably accurate predictions of the maximum nonlinear displacement response could be obtained by replacing the tri-linear hysteresis model using an equivalent linear system with the effective secant stiffness $K_{s\text{-}eff}$ as shown by Figure 1a. This accuracy of this method was confirmed for a range of typical wall configurations and realistic earthquake inputs (Doherty *et al*., 2002). The present phase of research aims to expand this seismic assessment procedure to incorporate two-way walls, which include any class of panels supported by a combination of horizontal and vertical edges.

EXPERIMENTAL PROGRAMME

Since displacement-based seismic assessment methodology is inherently based on the load-displacement behaviour of a structural system it is essential that this behaviour is understood. For this purpose, two complimentary experimental studies were performed on two-way URM panels subjected to out-of-plane loading: firstly, quasi-static cyclic tests on eight full-scale masonry walls (published as Griffith *et al*., 2006); and secondly, dynamic shaketable tests performed on three half-scale masonry walls (published as Vaculik, *et al*., 2007). These studies will now be discussed in greater detail.

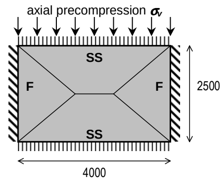
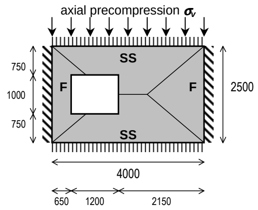
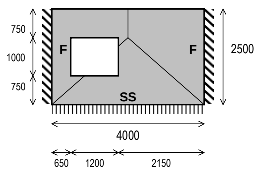
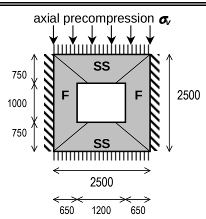
Quasi-Static Cyclic Tests

Eight full-scale URM walls comprising three different geometries (as illustrated in Table 1) were cyclically tested in displacement control using airbags positioned on both sides of the wall. Wall configurations were chosen to be representative of geometries and boundary conditions typically found in practice, comprising: two long walls without openings (s1-s2); four long walls with an eccentrically positioned 1200 × 1000 mm window opening (s3-s6); and two short walls with a symmetrically positioned 1200 × 1000 mm window opening (s7-s8). In addition, four of the walls were tested under the effects of vertical pre-compression of either 0.05 or 0.1 MPa, which remained constant for the duration of each test. Each wall was supported by 480 mm long return walls along its vertical edges, whereby full-moment restraint was provided. Simple-support was provided at the base of the walls and all walls were also provided with simple support along their top edge, except for wall s6 which was free along its top edge.

The walls were loaded using airbags located between each face of the wall and a stiff reaction frame. Face pressure was applied by slowly inflating the airbags, with the load acting on the wall being recorded using load cells. The imposed deformations were sequentially increased at increments of 10 mm, with typically two complete cycles performed at each displacement magnitude . The cyclic load-displacement response is shown by Figure 2, for walls s3 and s5, which can be considered typical for the eight walls tested. The main trends in behaviour are discussed in the remainder of this section.

The test walls exhibited substantial displacement capacity as most specimens were subjected to out-of-plane deformations approximately equal to the wall thickness of 110 mm. These results suggest that walls undergoing two-way action possess a large level of displacement capacity, believed by the authors to exceed that of vertically spanning one-way walls (Doherty *et al*., 2002)

Table 1. Test wall geometry and support conditions

Wall Configuration*	Pre-compression (MPa)	Quasi-static test wall label	Dynamic test wall label
	0.10	s1	d1
	0	s2	d2
	0.10	s3	d3
	0.05	s4	d4
	0	s5	d5
	N/A Top edge unsupported.	s6	-
	0.10	s7	-
	0	s8	-

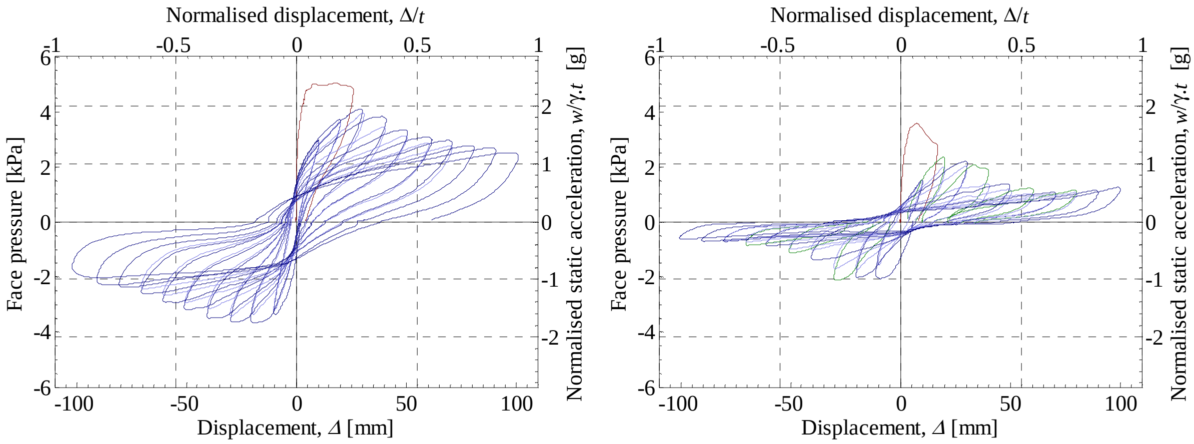
* Note that dimensions are shown (in mm) for full-scale walls in quasi-static tests. Walls used in dynamic shaketable tests were half-scale size, with dimensions provided in the text.

due to the additional frictional mechanisms present in two-way walls. Considering that conventional force-based design assumes that a wall is failed when its strength is exceeded which in these tests occurred typically at displacements between 5 and 15 mm there is a substantial reserve displacement capacity that is not being recognised in force-based seismic design.

Not surprisingly, walls with vertical pre-compression significantly outperformed walls without pre-compression with regard to post-peak strength capacity. This improvement in the post-peak strength was caused by the increased flexural and frictional resistance of the bed joints in their post-cracked state resulting from higher axial stress.

In general the walls exhibited poor self-centering characteristics upon unloading and typically dissipated a significant amount of energy through hysteresis loops. This is likely to have been caused by the frictional resistance mechanisms present in two-way walls, resulting in highly nonlinear and inelastic behaviour. Importantly, good energy dissipation characteristics under cyclic loading are highly beneficial to the seismic performance of the structural system.

Each wall underwent moderate degradation in both strength and stiffness, which was symptomatic of the damage incurred as a result of being subjected to progressively increasing displacements and repeated cyclic deformation during the test. The overall degradation of the wall specimens is



(a) Wall s3 (b) Wall s5

Figure 2. Typical quasi-static cyclic response of two-way walls

believed to have resulted from several irreversible types of damage, including progressive tensile and shear cracking of the brick-mortar bonds, line failure through the units in horizontal bending, crushing of the bed mortar joint at large crack rotations and sliding between successive courses of adjacent panels.

Dynamic Tests

Dynamic tests were performed on a set of five half-scale URM walls using a shaketable. These tests were intended to serve two key aims. The first aim was to verify the accuracy of the load-displacement data obtained in the previous quasi-static test study under true dynamic loading. The second aim was to aid the development and validate the accuracy of a nonlinear time history simulation model which will be discussed in the following section. It is emphasized that these tests were not aimed at investigating the seismic resistance or code compliance of similar full scale walls to any particular 'design' earthquake, but rather at providing data for validation of the numerical model to be used for simulating the dynamic response of such walls to arbitrary seismic motions. It will then be the role of the subsequent analytical model to generate data that can be used to make predictions regarding the seismic adequacy of particular masonry walls and to draw any recommendations regarding future code provisions for seismic assessment and design.

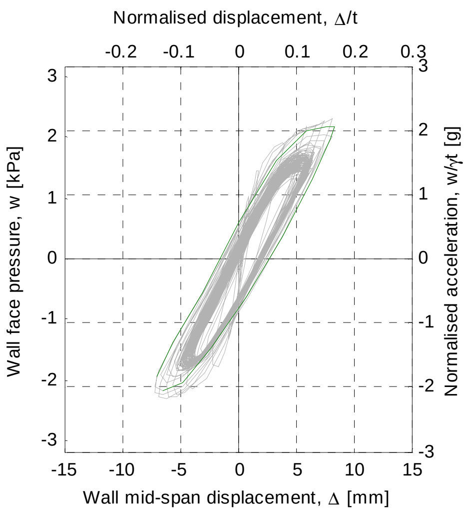
Five walls were tested (d1-d5 in Table 1) with configurations chosen to provide half-scale versions of walls s1-s5 in the quasi-static test study. The walls spanned 1840 × 1232 mm, with three of the walls containing an asymmetrically positioned 575 × 528 mm window opening. The boundary support conditions, including the vertical pre-compression levels provided were kept identical to those in the quasi-static tests, with simple support at the horizontal edges and full moment restraint at the verticals edges.

Each wall was instrumented using an array of accelerometers along its face and displacement transducers at the central position where the highest displacements were expected to occur. Testing was conducted in two phases. In the first phase, the natural frequency of the test wall (typically 13-14 Hz) was determined using a free-vibration impulse test and the wall was cracked by subjecting it to harmonic sinusoidal acceleration at its resonance frequency. In the second phase, the wall was subjected to a realistic earthquake inputs, including the Kern County 1952

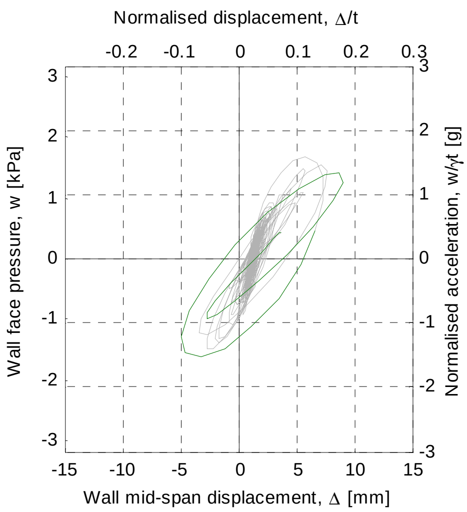
Figure 3. Shaketable test arrangement

(Taft) earthquake, modified to account for scaling effects of the model masonry, with the peak ground displacement of the record sequentially increased in each test run. Free-vibration impulse tests were conducted throughout testing to quantify changes in the natural frequency of the wall as a result of damage.

Typical load-displacement plots generated are shown on Figure 4 in response to sinusoidal input

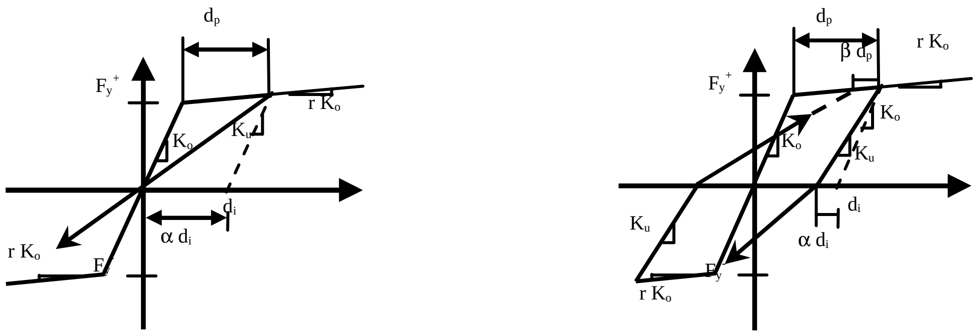


(a) Harmonic sinusoidal input



(b) Realistic earthquake input

Figure 4. Typical dynamic response of two-way walls (shown for wall d1)



(a) Origin-centered rule (b) modified Takeda rule

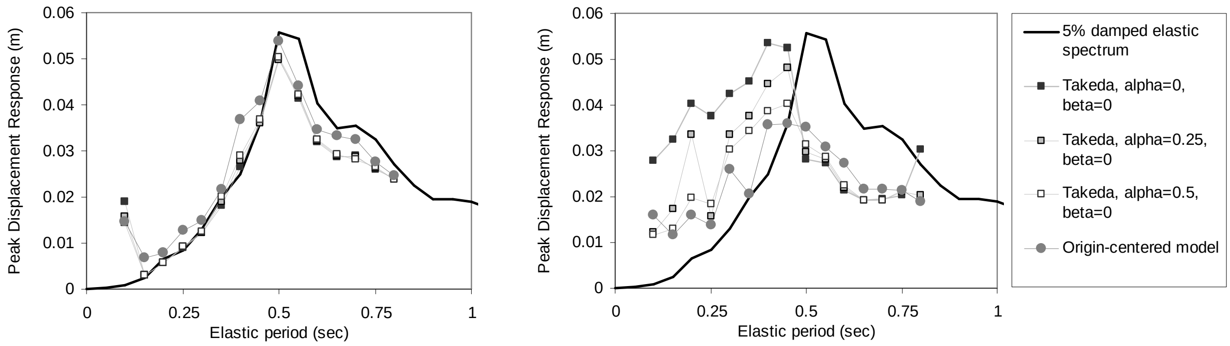
Figure 5. Hysteresis models used to investigate parameter influence on displacement response

whereby the loops were symmetrical (Figure 4a) and realistic earthquake input whereby the loops were rugged and asymmetrical (Figure 4b). The observed dynamic behaviour was comparable to the quasi-static behaviour in the main trends: high degree of nonlinearity; significant hysteretic energy dissipation; and strength and stiffness degradation. The measured time trace of the wall deformation in response to earthquake input was also subsequently used for comparisons with a nonlinear time-history analysis as discussed in the following section (see Figure 7).

ANALYICAL SIMULATION OF SESIMIC RESPONSE

It is generally accepted that the dynamic response of nonlinear systems can be modelled by numerical step-by-step time-history analysis with reasonable accuracy, provided that the model incorporates a good representation of the system's hysteretic behaviour, effective mass and effective viscous damping. Numerous studies were performed as part of this research using the well known time-history analysis software *Ruaumoko* (Carr, 1996) developed at the University of Canterbury, which provides a range of hysteresis rules to account for nonlinear structural load-displacement behaviour. The purpose of the studies conducted thus far has been twofold: firstly, to investigate the sensitivity of the peak dynamic displacement response to hysteresis modelling parameters (Lumantarna *et al.*, 2006), and secondly, to determine system properties that provide good agreement with the experimental dynamic response observed in the shaketable tests (Lumantarna *et al.,* 2007).

An investigation was conducted using a handful of commonly available hysteresis rules including the bilinear rule, origin-centered rule (Figure 5a) and modified Takeda rule (Figure 5b), to assess the sensitivity of the peak displacement response to system parameters such as hysteretic energy dissipation, self-centering ability and stiffness degradation. Furthermore, the influence of strength degradation which was highly prominent in the quasi-static tests was also investigated using damage representation models. The study found that when the displacement response of a degradable system is small, as shown by the low ductility response (R_μ = 1.5) in Figure 6a, the displacement demand was not sensitive to the level of self-centering ability. In general, good self-centering capability resulted in a slightly larger displacement response due to a lower degree of hysteretic energy dissipation, however this influence was small when compared to systems with poor self-centering and therefore greater hysteretic energy dissipation. By contrast, for a high ductility response (R_μ = 3.0) as shown by Figure 6b, the displacement demand of degradable systems became fairly sensitive to the self-centering capability, with a significant rise in the displacement demand as the self-centering capability was reduced. The authors believe this to be



(a) Low ductility response (R_μ = 1.5) (b) High ductility response (R_μ = 3.0)

(Note that the ductility response ratio R_μ is defined as the ratio of the maximum displacement response and the yield displacement)

Figure 6. Maximum displacement of degradable systems subject to synthetic earthquake record

a result of the accumulation of residual displacement for a system with poor self-centering capability during the course of the excitation, despite such a system having a greater capacity for hysteretic energy dissipation. Consequently, since this research is ultimately concerned with the collapse limit state, modelling of the wall as a system with poor self-centering ability is expected to provide conservative prediction of the displacement response.

Of the simple hysteresis rules considered in the course of these studies, the modified Takeda rule (Figure 5b) provided the best representation of the behavioural trends observed in experimental testing, explicitly accounting for the system's self-centering capability (through parameter α) and stiffness degradation (through parameter β). Consequently this rule was selected for a subsequent parametric study that aimed to determine values of modelling parameters to provide good agreement with the walls' response in the shaketable test study. Good agreement with the experimental response was found when the wall was modelled as a system with poor self-centering and high degree of stiffness degradation, as shown by Figure 7. These results, whilst being encouraging on their own, also agree well with the behaviour observed in the quasi-static experimental tests.

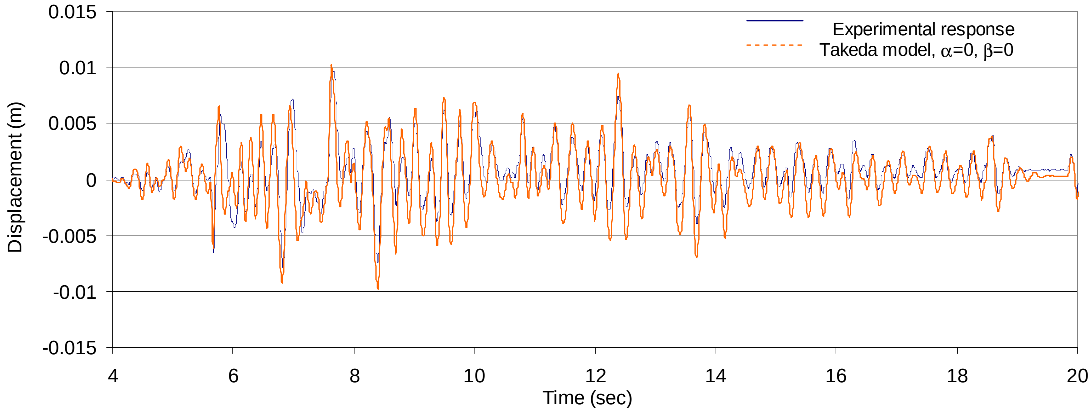


Figure 7. Comparison of experimental response with time-history simulation (wall d5)

CONCLUDING REMARKS AND FUTURE RESEARCH

Experimental and analytical studies into the seismic response of URM walls in two-way bending have been conducted as part of a collaborative research project between the Universities of Adelaide, Melbourne and Swinburne. The experimental work, consisting of quasi-static cyclic tests on full-scale specimens walls and dynamic shaketable tests on half-scale specimens, has generated promising results, demonstrating that URM walls in two-way bending possess good post-cracking strength, displacement capacity and energy dissipation potential - characteristics which are all beneficial to seismic performance. Analytical studies using time-history simulations with commonly available hysteresis rules have produced good correlation with the dynamic wall response observed in shaketable testing.

The next phase of the current research effort will be focused on developing analytical methods that can be used to calculate the hysteresis rule input parameters such as the post-cracked wall strength and displacement capacity as a function of the walls' physical parameters, *i.e.* wall dimensions, material properties, boundary support conditions and degree of vertical pre-compression. Extensive parametric studies will be subsequently undertaken to model the seismic response of two-way URM walls for a range of wall configurations and earthquake ground motions typical of the design space. System effects of URM buildings, including variations in the seismic vibrations between the different floor levels in multi-storey buildings and the behaviour of floor diaphragms and wall connections will also be taken into account. It is expected that this work will ultimately lead to the development of a simplified displacement-based procedure for the seismic design and assessment of URM walls subjected to either one-way or two-way bending.

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REFERENCES

Abrams, D. P., "Performance-based engineering concepts for unreinforced masonry building structures." *Progress in Structural Engineering and Materials,* Vol. 3, No. 1, 2001, pp. 48-56.

Bruneau, M., "State-of-the-Art Report on Seismic Performance of Unreinforced Masonry Buildings." *Journal of Structural Engineering*, Vol. 120, No. 1, 1994, pp. 230-251.

Brunsdon, D., "Study Group on Earthquake Risk Buildings 1993/94 Report." *Technical Conference of the New Zealand National Society for Earthquake Engineering*, 1994, pp. 1-6.

Carr, A., Ruaumoko User's Manual, University of Canterbury, Christchurch, New Zealand, 1996.

Calvi, G. M., "A displacement-based approach for vulnerability evaluation of classes of buildings." *Journal of Earthquake Engineering*, Vol. 3, No. 3, 1999, pp. 411-438.

Doherty, K., M. C. Griffith, N. Lam, and J. Wilson, "Displacement-based seismic analysis for out-of-plane bending of unreinforced masonry walls." *Earthquake Engineering and Structural Dynamics*, Vol. 31, No. 4, 2002, pp. 833-850.

Griffith, M. C., J. Vaculik, N. T. K. Lam, J. Wilson, and E. Lumantarna, "Cyclic Testing of Unreinforced masonry walls in two-way bending." *Earthquake Engineering and Structural Dynamics*, Vol. 36, No. 6, 2007, pp. 801-821.

Kowalsky, M. J., "Deformation limit states for circular reinforced concrete bridge columns." *Journal of Structural Engineering*, Vol. 126, No. 8, 2000, pp. 869-878.

Lam, N. T. K., M. Griffith, J. Wilson, and K. Doherty, "Time-history analysis of URM walls in out-of-plane flexure." *Engineering Structures*, Vol. 25, No. 6, 2003, pp. 743-754.

Lawrence, S., and R. Marshall, "Virtual Work Design Method for Masonry Panels Under Lateral Load." *12th International Brick/Block Masonry Conference*, Madrid, Spain, 2000, pp. 1063-1072.

Lumantarna, E., N. T. K. Lam, J. Wilson, M. Griffith, and J. Vaculik, "The Dynamic Out-of-Plane Behaviour of Unreinforced Masonry Walls." *19th Australasian Conf. on the Mechanics of Structures and Materials*, Christchurch, New Zealand, 2006.

Lumantarna, E., J. Vaculik, M. Griffith, N. Lam, and J. Wilson, "Dynamic response behaviour of unreinforced masonry walls subject to out of plane loading." *Australian Earthquake Engineering Society Conference*, Wollongong, NSW, Australia, 2007.

Maffei, J., C. D. Comartin, B. Kehoe, G. R. Kingsley, and B. Lizundia, "Evaluation of earthquake damaged concrete and masonry wall buildings." *Earthquake Spectra*, Vol. 16, No. 1, 2000, pp. 263-283.

Magenes, G., and G. M. Calvi, "In-plane seismic response of brick masonry walls." *Earthquake Engineering and Structural Dynamics*, Vol. 26, No. 11, 1997, pp. 1091-1112.

Medhekar, M. S., and D. J. L. Kennedy, "Displacement-based seismic design of buildings - application." *Engineering Structures*, Vol. 22, No. 3, 2000, pp. 210-221.

Priestley, M. J. N., "Seismic behaviour of unreinforced masonry walls." *Bulletin of the New Zealand National Society for Earthquake Engineering*, Vol. 18, No. 2, 1985, pp. 191-205.

Standards Australia, AS 3700-2001: Masonry Structures, Standards Association of Australia, Homebush, NSW, 2001.

Vaculik, J., and M. C. Griffith, "Shaketable Tests on Masonry Walls in Two-Way Bending." *Australian Earthquake Engineering Society Conference*, Wollongong, NSW, Australia, 2007.