Shaketable Tests on Masonry Walls in Two-Way Bending

Jerry Vaculik [1] **and Mike Griffith** [2]

1. PhD student, Dept of Civil and Environmental Engineering, University of Adelaide, SA5005, Australia.

2. Corresponding author. Head, Associate Professor, Department of Civil & Environmental Engineering, University of Adelaide, SA5005, Australia.

Email: mcgrif@civeng.adelaide.edu.au

ABSTRACT

This paper presents the preliminary results of an experimental test program to investigate the dynamic response of unreinforced brick masonry walls subjected to out-of-plane loading. Five half-scale walls were tested, each spanning 1840 mm in length and 1232 mm in height, with three of the walls containing an asymmetrically positioned window opening. Three of the walls were subjected to vertical pre-compression of up to 0.1 MPa to simulate load bearing walls. This study was unique in that all walls were two-way spanning, with supports at all four edges and thus underwent two-way bending. The walls were loaded using their own inertial load by subjecting them to a series of accelerations on a shaketable and the walls' acceleration and displacement were recorded. The data obtained was used to generate hysteresis plots of the face pressure versus the mid-span displacement of each wall. A discussion of these results is presented with reference to the seismic response of such masonry walls and comparisons are made with cyclic tests previously conducted on full-scale versions of the test walls. The implications of these tests for the likely seismic response of masonry buildings will also be discussed.

Keywords: unreinforced masonry walls, out-of-plane, two-way bending, shaketable tests, dynamic tests, seismic response.

1. BACKGROUND

This paper presents the progress of collaborative research undertaken jointly by the University of Adelaide and University of Melbourne, as part of a long term effort to reduce the seismic risk posed by unreinforced masonry (*URM*) structures in Australia by developing state-of-the-art methodology for the seismic assessment and design. The current phase of research is aimed specifically at the out-of-plane seismic response of *URM* walls, which has been identified as one of the most widespread causes of structural collapse in the 1989 Newcastle earthquake (Page 1992). Whilst a considerable amount of effort has been conducted on one-way vertically spanning walls (Doherty et al. 2002), current understanding of the seismic response of two-way walls, which are any class of walls supported on at least one vertical and one horizontal edge, is still limited. One of the factors responsible for this lack in knowledge has been largely contributed to a serious lack in experimental research conducted in this area (Griffith et al. 2007).

Previous experimental work into the seismic response of two-way walls includes work by the authors (Griffith et al. 2007; Vaculik et al. 2005), where eight full-scale walls were subjected to quasi-static cyclic loading using airbags. A key advantage of quasi-static nature of these tests was that the slow rate of loading gave precise control of the applied displacements and thus enabled the load-displacement behaviour of the walls to be accurately characterised. It is important, however, to validate the results of the quasi-static tests using true dynamic testing, which generates inertial loading conditions that are representative of realistic earthquake motions.

A future aim in this research project is to develop a hysteresis model (a numerical representation of the load-displacement relationship) for two-way walls, which can be entered into a step-by-step time history analysis to simulate the dynamic nonlinear response of the walls to generic acceleration records. Promising progress has already been made in the analytical components of this project (Lumantarna et al. 2006a; Lumantarna et al. 2006b) whereby nonlinear time history analyses were used to generate seismic fragility curves for a range of earthquake scenarios, site conditions and building types using the empirical load-displacement behaviour observed in the quasi-static tests.

The remainder of this paper will report experimental study complementary to the quasi-static study already undertaken, involving shaketable testing of five half-scale masonry walls. The load-displacement data obtained in these tests under true dynamic loading conditions was intended to serve two key aims: Firstly, to verify the accuracy quasi-static test data obtained in the previous study (Griffith et al. 2007), and secondly, to aid the development and validate the accuracy of a nonlinear time history simulation model for *URM* walls. 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 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.

Table 1. Test wall configurations

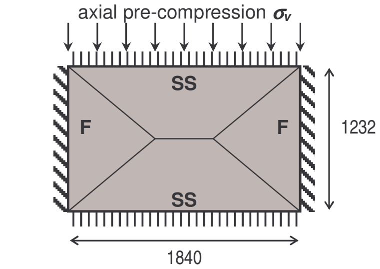
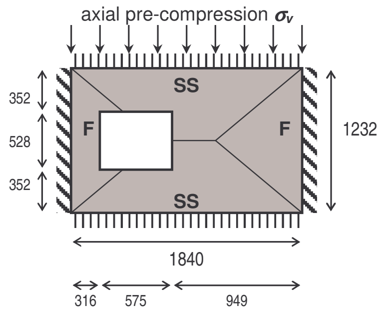
<table>
<tr><th>Wall Geometry and Support Conditions</th><th>Wall</th><th>Pre-compression, σ_v (MPa)</th></tr>
<tr><td rowspan="2">
</td><td>d1</td><td>0.10</td></tr>
<tr><td>d2</td><td>0</td></tr>
<tr><td rowspan="3">
</td><td>d3</td><td>0.10</td></tr>
<tr><td>d4</td><td>0.05</td></tr>
<tr><td>d5</td><td>0</td></tr>
</table>

Table 2. Summary of material properties of the masonry

Parameter	Mean value	CoV
Flexural tensile strength of masonry, f_{mt}	0.415 MPa	0.53
Coefficient of friction across masonry bond, μ	1.15	0.10
Compressive strength of masonry, f_{mc}	25.9 MPa	0.09
Young's modulus of elasticity of masonry, E_m	9,180 MPa	0.15
Young's modulus of elasticity of brick units, E_u	32,100 MPa	0.16

2. TEST METHODOLOGY

The experimental work reported herein was conducted at the Chapman Laboratories at The University of Adelaide. The test walls used in this study are summarised in Table 1. These configurations, including geometry, boundary conditions and axial loading were chosen to represent half-scale replicas of the first 5 walls used in the aforementioned quasi-static cyclic tests conducted by the authors. The walls were 1840 mm in length and 1232 mm in height, with two of the walls being solid and the other three containing an asymmetrically positioned window opening. As illustrated in Figure 1, walls were restrained with simple supports at the top and bottom edges and full moment restraint at the vertical edges, with boundary conditions representative of

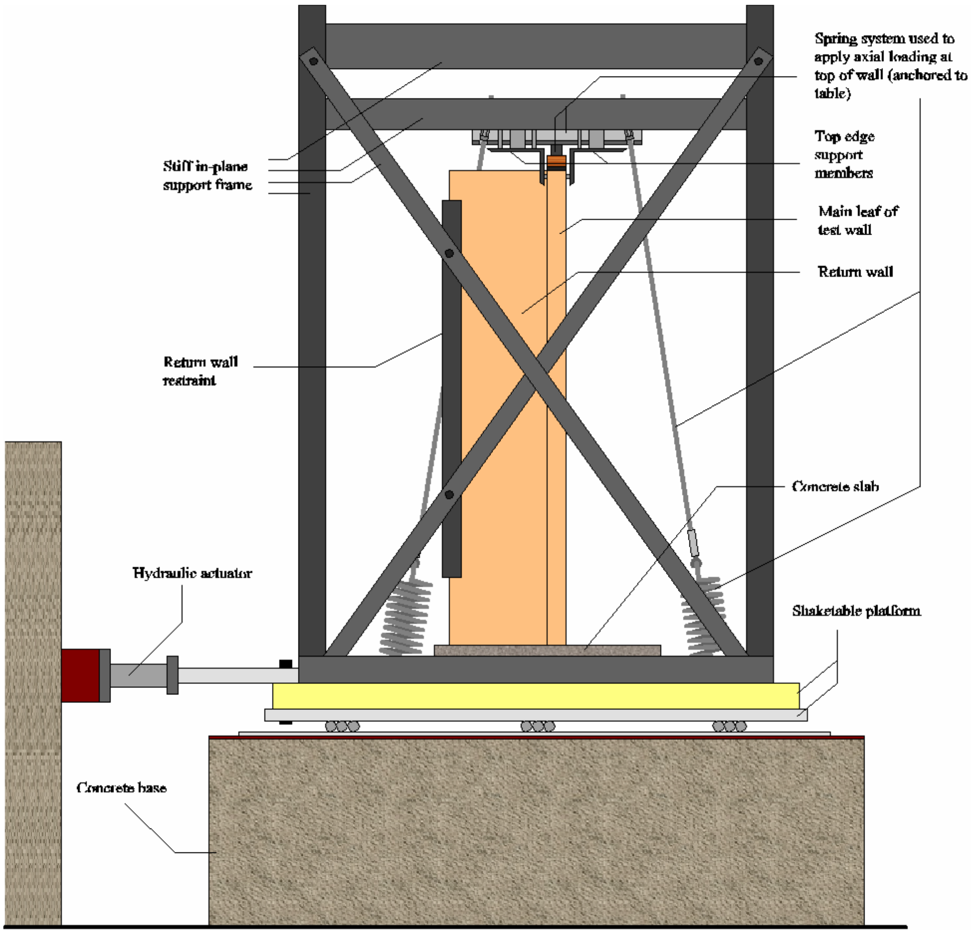


Figure 1. Shaketable test arrangement

those found in practice. In addition three of the walls were also loaded with vertical pre-compression of up to 0.1 MPa at the top edge to represent load bearing walls.

The brick units were cut from clay pavers, resulting in reduced-scale bricks with 110 × 50 × 39 mm dimensions (length × width × height) and mortar joints were constructed at 5 mm thickness using 1:2:9 mortar (cement, lime, sand). Material tests were conducted to quantify key material properties of the masonry, as summarised in Table 2, which are typical for the type of masonry used.

The walls were built on concrete slabs, which were lifted together onto the shaketable prior to testing. As shown by Figure 1, the test wall was restrained at the vertical edges by a stiff frame representative of the in-plane stiffness expected for a masonry wall acting in-plane to the seismic excitation. A horizontal cross bar attached to the stiff in-plane frame provided support to the wall at the top edge. Each wall was instrumented using an array of accelerometers along its face and displacement transducers at the mid-span position where the highest displacements were expected to occur.

The shaketable was driven in displacement control using a hydraulic actuator, with three basic types of input motion:

1. A displacement step function used to generate a quick impulse for the purpose of observing the free vibration response of the wall.

2. Harmonic sinusoidal input at a constant frequency, used primarily for generating symmetrical cyclic response.
3. Earthquake-like motions with a broad frequency content. The primarily used seismic motion was the well known Kern County 1952 (Taft) earthquake, chosen for its broad frequency content, which was scaled to account for the reduced scale of the masonry by speeding the record up by a factor of √2. Several synthetic earthquake motions were also used.

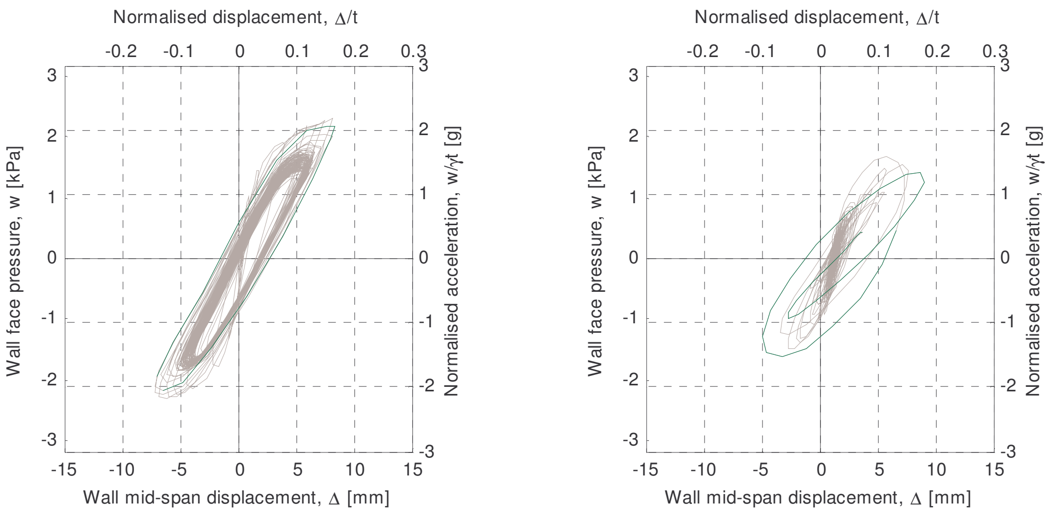
Testing was conducted in two phases. Firstly, the yet uncracked wall was subjected to a free vibration impulse test to determine its natural frequency, which was typically 13-14 Hz. The wall was then subjected to harmonic sinusoidal input at its resonance frequency, with increasing intensity until the wall cracked and developed a failure mechanism. In the second phase, the wall was subjected to earthquake-like motions, 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 cumulative damage.

3. RESULTS AND DISCUSSION

This section will present preliminary results from the dynamic tests and discuss their significance with regard to the seismic resistance of *URM* walls. As well as providing comparisons with the results of the previous quasi-static test study, the implications of the observed results for future development of a nonlinear time history analysis will also be discussed.

3.1. Load-displacement behaviour

In general the walls exhibited highly nonlinear and inelastic load-displacement



(a) Harmonic sinusoidal input (b) Taft earthquake input

Figure 2. Typical response of walls to dynamic loading (shown for wall d1)

Table 3. Hysteretic damping ratios for various levels of damage

Wall	Equivalent damping ratio, ξ_{hyst} for various damage states				Mean damping for equivalent wall in quasi-static test
	Uncracked	Lightly cracked	Fully cracked	Heavily damaged	
d1	0.23	-	0.12	-	0.13
d2	0.17	0.16	0.27	-	0.13
d3	0.11	0.11	0.27	-	0.14
d4	0.12	0.30	0.32	0.39	0.12
d5	0.06	0.15	0.29	-	0.17

behaviour as shown by the hysteresis curves on Figure 2 which were typical for the walls tested. These nonlinearities are caused by the frictional resistance mechanisms along crack lines as well as rigid-body rocking mechanisms which have been well established for vertically spanning one-way walls (Doherty et al. 2002). In addition the walls underwent significant strength and stiffness degradation during the course of testing due to cumulative cracking. These characteristics of the load-displacement behaviour were observed previously in the quasi-static cyclic tests conducted by the authors (Griffith et al. 2007).

Good hysteretic energy dissipation characteristics are highly favourable with regard to performance during seismic loading. Equivalent viscous damping ratios were calculated by the method of energy dissipated per cycle of loading, using hysteresis loops in the harmonic cyclic loading tests (e.g. Figure 2a). These damping ratios are summarised in Table 3 for various levels of damage as determined qualitatively by the authors. As a general trend the damping ratios increased as the walls accumulated damage. The reason for this is believed to be that as the walls developed a greater number of cracks with continued testing, the walls underwent a shift in their ability to resist the lateral loads imposed on them, from elastic deformation, to frictional sliding along the cracks and therefore exhibit more inelastic behaviour.

The mean equivalent damping ratios observed for the full scale walls in the quasi-static cyclic tests are also provided in Table 3. These values are generally lower than those observed in the dynamic tests for the half scale walls. This is believed to be due to the dominant modes of cracking observed in the respective test specimens, with frictional resistance being more prominent in the half scale walls (as will be discussed later).

3.2. Frequency of vibration

The peak displacement response of a structural system can be very sensitive on its initial elastic frequency when comparable in magnitude to the frequency content of the seismic excitation signal. Thus it is important that the initial frequency of the system is represented with sufficient accuracy in the time history analysis. As an additional study performed on wall d1, the wall was subjected to a series of simple pulse tests to determine its free vibration frequency under various levels of axial loading. These results are summarised in Table 4.

Table 4. Effect of axial loading on free vibration frequency for wall d1

Damage State	Axial pre-compression [MPa]	Dominant Frequency [Hz]	
		mean	1/2 power band
New (uncracked)	0	13.6	12.2 - 15.0
	0.05	13.0	12.5 - 13..4
	0.10	12.5	11.0 - 13.7
Damaged	0.10	14.3	11.6 - 17.0
	0	7.7	6.9 - 8.3

The frequency of the wall in prior uncracked state was fairly non-sensitive to the axial loading, but tended to reduce slightly with increased pre-compression from 13.6 Hz at 0 MPa to 12.5 Hz at 0.10 MPa. This low sensitivity is believed to be a result of the wall responding in the elastic range and thus its frequency being dependant on its material stiffness (modulus of elasticity) rather than the absolute value of axial stress. In the damaged state, however, the frequency of vibration became highly dependent on the level of axial loading, with a reduction in the frequency from 14.3 Hz to 7.7 Hz when the overburden axial stress of 0.10 MPa was removed. This result is likely to be due to the confining effect of the axial stress, which increases the restoring force acting to keep cracks closed thus causing the wall to have a larger lateral force resistance.

Recognising that in the case of the uncracked wall the lateral stiffness of the wall is governed by its material properties, whilst in the case of a cracked wall it is governed by its geometric (stability) properties is important to understanding the observed trends, which should be incorporated into the time history analysis in order to enhance its accuracy in simulating the dynamic response of such walls.

3.3. Crack patterns

Idealised versions of the crack patterns observed for the five walls are shown on the wall illustrations in Table 1. The significance of the crack pattern to the out-of-plane response of a masonry wall is that it determines a wall’s collapse mechanism which directly affects its load capacity as well as its displacement capacity. The crack patterns observed in these tests were similar in the overall shape to those observed in the quasi-static cyclic tests and are typical for two-way walls supported at all four edges.

One important difference between the observed crack patterns in the two test studies, however was that cracks were found to occur exclusively along the brick-mortar joints (stepped failure) in the half scale masonry used in the dynamic tests. By contrast the full scale masonry used in the quasi-static tests exhibited a large number of brick units cracking in tensile rupture (line failure). This observation was reflected by the relative tensile strengths of the brick units and the mortar joints in the respective studies. The critical difference between the two crack modes is that stepped cracks possess some degree of frictional resistance, whereas line cracks do not. Therefore stepped failure is more desirable with regard to seismic resistance since it is more beneficial to a wall’s lateral load resistance in the post cracked state. In fact, the improved energy dissipation in the half scale masonry used in the dynamic tests was likely to have been due to an increase in the frictional resistance resulting from this mode of cracking.

4. CONCLUDING REMARKS

Whilst the dynamic tests reported in this paper provide valuable data to complement that obtained in the quasi-static tests and they agree in the general trends observed, neither study should be disregarded when their results don't exactly match. In the author's opinion the results from the two studies can be best used to complement each other by using the results from the respective studies primarily in those areas where they are believed to provide the most reliable information. For instance, as previously discussed the primary advantage of the quasi-static cyclic loading tests over dynamic loading tests was that the former provided better control over the displacement history imposed on the walls. Therefore the general curve shape in the hysteresis model to be used in nonlinear time history analyses will be based primarily on the results of the quasi-static tests. Other aspects of the model, however, such as the initial vibration frequency of the wall and the influence that various factors such as the damage state of the wall and the levels of axial loading have on the vibration frequency can only be provided by the dynamic tests.

ACKNOWLEDGEMENTS

This research was conducted with the financial support of the Australian Research Council (Grant No. DP0450933) and the Universities of Adelaide and Melbourne. The technical assistance of the laboratory staff from the School of Civil and Environmental Engineering at the University of Adelaide is also gratefully acknowledged.

REFERENCES

Doherty, K., M. C. Griffith, N. Lam, and J. Wilson. (2002). "Displacement-based seismic analysis for out-of-plane bending of unreinforced masonry walls." Earthquake Engineering and Structural Dynamics, 31(4), 833-850.

Griffith, M. C., J. Vaculik, N. T. K. Lam, J. Wilson, and E. Lumantarna. (2007). "Cyclic testing of unreinforced masonry walls in two-way bending." Earthquake Engineering and Structural Dynamics, 36(6), 801-821.

Lumantarna, E., N. T. K. Lam, J. Wilson, M. Griffith, and J. Vaculik. (2006a). "The dynamic out-of-plane behaviour of unreinforced masonry walls." 19th Australasian Conference on the Mechanics of Structures and Materials, Christchurch, New Zealand.

Lumantarna, E., J. Vaculik, M. Griffith, N. Lam, and J. Wilson. (2006b). "Seismic fragility curves for unreinforced masonry walls." Australian Earthquake Engineering Society Conference, Canberra, Australia, 33-40.

Page, A. W. (1992). "The design, detailing and construction of masonry - the lessons from the {Newcastle} earthquake." Civil Engineering Transactions, Institution of Engineers Australia, CE34(4), 343-353.

Vaculik, J., M. Griffith, N. Lam, J. Wilson, and E. Lumantarna. (2005). "Cyclic response of unreinforced clay brick masonry walls." Australian Earthquake Engineering Society Conference, Albury, Victoria, Australia.