Out-of-Plane testing of an unreinforced masonry wall subjected to one-way bending

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Abstract

In order to investigate the seismic behaviour of typical New Zealand unreinforced masonry (URM) walls when subjected to out-of-plane loading, a research project was undertaken which included international collaboration between The University of Auckland, University of Adelaide and University of British Columbia in Canada. Aspects of this research project are discussed, beginning with details of the characterisation of typical New Zealand URM walls that are vulnerable to out-of-plane loading. Results of out-of-plane testing performed at the University of Auckland are presented. The testing included out-of-plane uniform static loading on a full-scale URM wall with a slenderness ratio (h/t) of 16 that had several different levels of pre-compression applied. The wall, with a height and width of 3500 mm and 1200 mm respectively, was simply supported at top and bottom and free at both ends, and behaved in an ideal one-way bending condition.

Keywords: unreinforced masonry (URM) walls, out-of-plane, airbag testing, one-way bending, force-displacement curve

1. INTRODUCTION

Although improvement of wall-diaphragm connections has often been assumed to be a viable alternative for out-of-plane strengthening of URM buildings, further investigation of out-of-plane behaviour is still necessary for buildings in New Zealand because of several reasons. One important factor is that many of these buildings have flexible diaphragms, which impose large displacements on the out-of-plane walls, no matter how adequately the walls are connected. A second reason that necessitates a detailed out-of-plane assessment and improvement is that retrofitting of the wall-diaphragm connections within an existing building may not always be aesthetically acceptable or even physically possible. Finally, for the case of heritage or other important buildings, it should be ensured that every element, specifically an out-of-plane wall, behaves within its elastic limits, and that strong non-linear behaviour is avoided. The latter demands for a pre-cracked study of out-of-plane walls, and should be separately investigated assuming both poor and good qualities of wall-diaphragm connections.

The New Zealand Building Act (DBH, 2004) requires buildings to be assessed based on the damage that they are likely to incur to the people in the property or to the people in any other property, and also for damage to other properties in a moderate seismic event. Although the threshold of life loss must be investigated and correlated with various damage states in an out-of-plane wall, several researchers have shown that the initiation of the first cracks in such walls does not mean a direct threat to human life. Research shows that these walls have substantial post-cracking capacity, which serves as an energy-absorbing feature unique to rocking systems and prevents the wall from collapse. ABK (1981) studied the subject for buildings in the United States. The requirements set in the current version of ASCE standards, Seismic Rehabilitation of Existing Buildings, ASCE/SEI 41-06 (ASCE, 2007), for allowable h/t ratio of out-of-plane walls are based on this research. Priestley (1985) proposed analytical relationships between the instability displacement and the mechanical properties of a URM wall. Based on a rigid diaphragm assumption, the inertial load applied to the surface of the wall was approximated by a uniform pressure, which increased up the height of the building. Finally, an energy method was proposed for calculation of maximum acceleration that could be sustained by a cracked out-of-plane wall. Zoutenbier (1986) used a program to model multi-storey walls according to the method suggested by Priestley (1985). Blaikie and Spurr (1992) developed a computer model for prediction of the stability of cracked walls subjected to out-of-plane seismic loading. The properties of the model were selected so that it matched the properties of one of the walls tested by ABK in 1981. A methodology was proposed based on the results of several numerical analyses. The method involved using displacement response spectra (RS) for a given earthquake and the period of the cracked wall. In addition, as one of the results of a survey done on damaged URM buildings in New Zealand and California, it was suggested that the New Zealand study should be concentrated on buildings with three or less stories. Doherty et al. (2002) studied the behaviour of one-leaf, one-way URM walls, and proposed a formulae for derivation of force-displacement curves that were used in subsequent time history analyses (THA). The “substitute structure” concept was then utilised to approximate the complex behaviour of cracked walls with a single-degree-of-freedom (SDOF) system, with a “substitute structure” defined as an elastic oscillator having an ultimate displacement equal to that of the real structure. The substitution made it possible to use the RS method, instead of THA, for evaluation of one-way walls. The study did not consider buildings with flexible diaphragms. Blaikie (1999, 2002) presented the results from non-linear multi-degree-of-freedom (MDOF) modelling of cracked walls. In the study, the effects of diaphragm flexibility were investigated numerically, and amplification factors were proposed based on the results from computer modelling. These results verified the procedure proposed by the New Zealand Society for Earthquake Engineering (NZSEE, 2006) for evaluation of out-of-plane walls in one-way bending. Although both Blaikie (1999, 2002) and Doherty et al. (2002) used a RS method, the proposed procedure for each of the studies was different. Blaikie (1999, 2002) predicted the behaviour of a cracked wall by assuming that the overall period of the wall was equal to its period at a specific displacement (60 percent of the instability displacement). In a different way, Doherty et al. (2002) assumed a dominant period for the vibration of the wall, which was found by performing several free vibration pulse tests and identifying a resonant situation.

Griffith et al. (2003) extended the results of Doherty et al. (2002) to a range of walls with different aspect ratios and axial loads. The new research investigated the "substitute structure" method for out-of-plane URM walls in more detail. As an alternative to the effective secant stiffness proposed in Doherty et al. (2002), Griffith et al. (2003) defined a new effective secant stiffness, which, in the average displacement range, led to a better linear approximation of the nonlinear wall behaviour. Simsir (2004) presented the results of an experimental study performed on a laboratory single-storey house model with a flexible roof. Although out-of-plane walls were reinforced and were made of concrete blocks, tests performed assuming different roof flexibility levels revealed the amplifying effects of flexible diaphragms on the behaviour of out-of-plane walls. The results of the study showed that the overall response of the out-of-plane walls was governed by the frequency of the flexible diaphragm, and in some cases, the out-of-plane vibration amplitude was amplified by as much as five times. Sharif et al. (2007) used a rigid body motion method to model the behaviour of cracked URM walls supported by rigid floors. They assumed that a crack had pre-formed at the wall mid-height, and calibrated their model based on a series of shaking table tests performed by Meisl et al. (2007). Fragility curves were presented for the collapse of walls with different h/t ratios located on different sites. There are a number of other studies, e.g. Griffith et al. (2007) and Vaculik et al. (2007), which consider two-way modelling of walls. These studies are still preliminary, and the subject is outside the scope of this study.

2. NEW ZEALAND SEISMIC ASSESSMENT

The NZ Building Act (DBH, 2004) requires all buildings to be assessed for earthquake movements, which are at least one-third as strong as the earthquake shaking used for design of new buildings. Any building not complying with this legislation is termed "*Earthquake Prone Building*". The NZSEE (2006) recommends to select a stronger earthquake level (two-thirds) for assessment. The NZSEE view is that any building below this level should be regarded as a questionable earthquake risk and the building is termed as "*Earthquake Risk Building*" in the guidelines. The proposed procedure for out-of-plane assessment in NZSEE (2006) includes both "one-way" and "two-way" evaluation. One-way walls are assessed based on a "dynamic stability" concept. The guidelines are easy to use in this section, as the problem is reduced from a complex analysis of a rocking wall to a RS method. The latter can readily be used in engineering offices without carrying out rigorous THA. In these guidelines, diaphragm flexibility effects are not considered.

It is concluded from the literature review in the previous section that the models for predicting out-of-plane behaviour are well developed for one-way walls connected to rigid floors, but are still in their initial stages for walls supported by flexible diaphragms. The latter forms one of the objectives of the current research. A rigid-body modelling computer program will be used in collaboration with the University of British Columbia (UBC) to investigate the effects of flexible diaphragms. In this respect, real data that account for the diaphragm flexibility effects will be obtained from existing or lab-built structures. Then, the rocking behaviour of cracked walls will be simulated by the computer program. In addition, SDOF modelling developed by researchers in Australia is a promising tool for out-of-plane assessment, which has not yet been evaluated for use in New Zealand. It is believed that using this method will generate additional data, which can be used to verify the RS method used in Blaikie (1999, 2002) and in the NZSEE guidelines. Bi-directional loading is another subject, which has not been studied for URM walls in New Zealand. It may be included as part of the present research.

3. NEW ZEALAND MASONRY

URM construction practice in New Zealand used similar details to those encountered on the West Coast of the US or in Victorian UK construction (Hare, 2007). Load-bearing brick walls would typically step at every second level, at which point the joist may simply seat onto the step, and often, a continuous timber plate was placed underneath to spread the load acting on the wall (Hare, 2007). Joists anchored to walls of uniform thickness were often seated in pockets (Oliver, 2007). It is obvious that in both cases there is no positive connection between wall and diaphragm. This lack of continuity in the seismic load path requires these connections to be looked at as the first retrofit targets. Accordingly, some recent retrofit work has been accomplished to enhance the as-built wall-diaphragm connection detail (Wilkinson, 2005). At the wall parallel to the joist span, the situation is even worse as there is no practical connection between the floor and the wall. The edge joist is placed hard against the wall (Hare, 2007), which only serves to push the wall outward, and does not provide a continuous support for the wall vibrating out-of-plane. The thicknesses of walls given in the Architects' and Builders' Pocket Book published in 1916, especially those recommended for California, are believed to have been commonly used by practitioners in New Zealand (Oliver, 2007). Wall thicknesses for two-storey buildings are either two or three leaves up to the first level and usually two leaves for the top storey of the two-storey buildings. The thickness of the walls in single-storey buildings is usually 2-leaf. Although most New Zealand buildings may comply with the mentioned book, there are always exceptions. The thickness for interior walls of a multi-storey building occasionally were less than the thickness of the exterior walls and even a two-leaf wall may have been used in interiors in all stories of a building. Figure 1 shows an example of these walls.

While URM buildings with a height of up to five stories can be found in New Zealand, the most prevalent forms are 2-storey and single-storey buildings respectively (Russell, 2008). The configuration of the building suggested in Russell's study in conjunction with the thickness range discussed above gives h/t ratios up to 27 for a wall in a given storey. Parapets and gables are among masonry components that are frequently found in New Zealand masonry buildings. These elements were found to be vulnerable in Gisbourne, September 2007 earthquake. Numerous failures of these elements were also reported in all of the seven earthquakes surveyed by Blaikie and Spurr (1992).

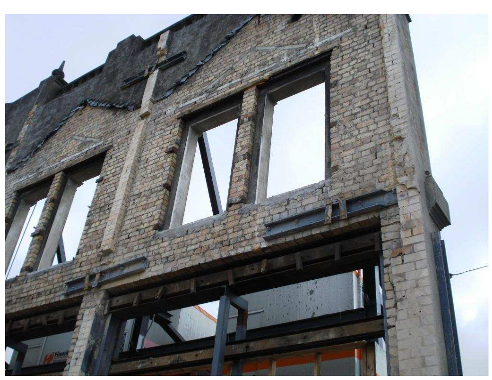

Figure 1: A section of a three-storey demolished building; stepped exterior walls and two-leaf uniform-thickness interior walls are visible

4. AIRBAG TESTING

Solid bricks and ASTM type “O” mortar with a cement-lime-sand ratio of 1:2:9 were used to build a two-leaf wall having height (h), width (w), and thickness (t) of 3500 mm, 1200 mm, and 220 mm, respectively. The above dimensions give a slenderness ratio of 16 for the wall. Bricks were used in a “common bond” pattern, with headers every fourth course. Material testing was performed on 3 mortar cubes and 7 masonry prisms to acquire data given in Table 1. Figure 2 shows the setup used for the testing. The specimen was tested at simply supported conditions, and with and without pre-compression according to specification given in Table 2. Two Bigfoot vinyl airbags with a thickness of 0.25 mm were used in the testing. A very thin layer of low-strength, highly flexible polyurethane foam (1 mm thickness) was used between the airbag and the masonry surface to prevent airbags damage. The load was transferred from the backing frame to the reaction frame by means of four S-type 10 kN load cells. Steel rollers were used underneath the plywood backing frame to minimize the friction between the frame and the ground. The displacements were measured by a linear variable displacement transducer (LVDT) placed at wall center at 1750 mm elevation. A data acquisition system with 24 channels (Figure 1(b)) was used, and data with frequency of more than 4 Hz were filtered from the results. First, the uncracked wall was tested without axial load. Two more tests were then performed on the cracked wall with differing levels of pre-compression.

Table 1: Mean mortar strength

Test	Compressive strength, (MPa)	Flexural strength of bond wrench, (MPa)
Test Method	ASTM C 780 – 02	ASTM C 1072 – 00a
Mean	3.95	0.44
CoV	0.13	0.19

Table 2: Pre-compression load

Test	Axial stress, (kPa)	Corresponding walls in real buildings
1	0	Non-load-bearing top-storey or single-storey wall
2	20	Load-bearing top-storey or single-storey wall
3	40	Non-load-bearing ground storey of a two-storey wall

Figure 2: (a) Test Setup (b) Data Acquisition System and Pneumatic Unit

5. TEST PROCEDURE AND RESULTS

In Test 1, the airbag pressure was slowly increased from zero to the maximum value of 1.15 kPa. At about the maximum load, a horizontal crack opened 350 mm above the wall mid-height (0.6h) in a fashion suggesting that either it had previously existed or it had initiated with little energy being released. The displacement of the wall at the crack was allowed to reach about 135 mm (0.61t). The same procedure was then repeated for Test 2 and 3. The hysteresis curve obtained from Test 3 (Figure 3) suggests that the actual behaviour of the wall was not elastic, and that significant energy was dissipated by hysteretic behaviour. Figure 4 reports the response envelopes from all tests. Figure 5 illustrates that the tri-linear model developed by Doherty et al. (2002) can be employed to represent the actual behaviour measured for two of the walls. A tri-linear model can be constructed for a one-way out-of-plane URM wall with known mass, boundary conditions, overburden and dimensions. Two values ($\Delta_{1/}\,\Delta_f$ and $\Delta_2/\,\Delta_f$ ratios) are used in conjunction with the bi-linear rigid body model of the wall to construct the tri-linear model. Δ_f is the maximum stable displacement which can be obtained from static equilibrium of the cracked wall at the point of incipient instability. Doherty et. al (2002) defined three stages of degradation of the mortar at the cracked bedjoint, which were the sole criteria for determining the ratio of $\Delta_{1/}\,\Delta_f$ and $\Delta_2/\,\Delta_{f.}$ The results of the current research suggest that the level of overburden has also a significant effect on these ratios.

For the tested wall, the ratios of $\Delta_{1/}\,\Delta_f$ and $\Delta_2/\,\Delta_f$ (Table 3) vary greatly from the values suggested by Doherty et al. (2002). The observed condition of the wall during three of the tests suggested that an average (moderate) state of degradation should be assumed for all of the tests when extracting the values suggested in Doherty et al. (2002). Accordingly, constant ratios were expected throughout the test program. In contrast, the plotted results (Figure 4 and Figure 5) show that the values varied from one test to another. Given the uniqueness of the test specimen and procedure, this difference can only be associated with the varying levels of overburden. According to Figure 4, initial stiffness of the wall was considerably higher for higher levels of pre-compression. As the wall had cracked before the start of Test 2 and Test 3, this increased stiffness, which corresponds to a significantly less $\Delta_{1/}\,\Delta_f$ ratio, can only be attributed to the presence of higher levels of pre-compression. The results of THA can be highly inaccurate, if this effect is not considered in the hysteresis model used. Additional testing with pre-compression on different walls is required to establish parameters which can be used for THA across a wide range of walls in New Zealand. The program must also include dynamic testing and must be followed by THA to confirm the models obtained by static testing.

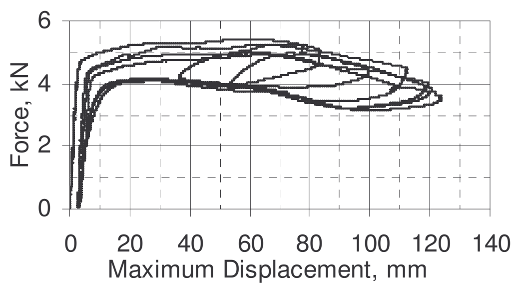

Figure 3: Test 3

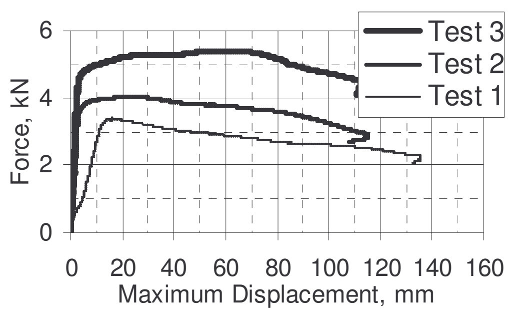

Figure 4: Force-displacement curve

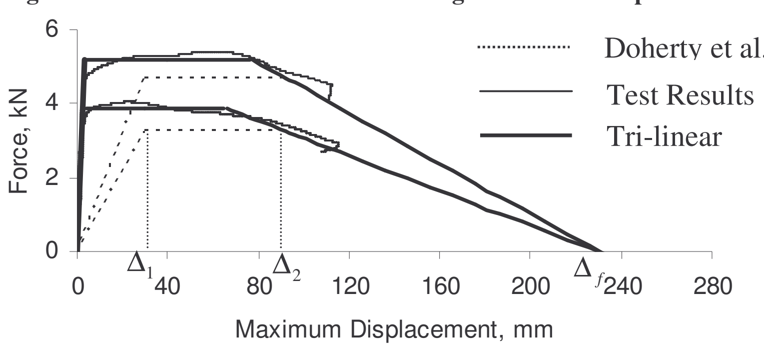

Figure 5: Obtained force-displacement curves, tri-linear representation

Table 3: Tri-linear model parameters

Parameters	Δ_1/Δ_f		Δ_2/Δ_f	
Test	Test wall	Doherty et al.	Test wall	Doherty et al.
1	9%	13%	20%	40%
2	2%		60%	
3	1%		70%	

6. CONCLUSION

The importance of out-of-plane evaluation was emphasized with a particular reference to the characteristics of URM buildings in New Zealand. A brief summary of the available literature on post-cracking behaviour of URM out-of-plane walls was presented with a discussion on the areas of scarce research. General aspects of this study and the correlation with research done in UBC and Australia were outlined. Basic characteristics of URM buildings in New Zealand with respect to how they affect the out-of-plane behaviour were discussed. The results of the airbag testing performed at The University of Auckland were presented. Tri-linear hysteresis model previously developed by researchers in Australia was successfully fitted to the test results. It was found that the differing levels of overburden significantly changed the shape of the tri-linear model. It is concluded that new values for parameters required for construction of the tri-linear model need to be established for walls in New Zealand through additional experimentation. These parameters should reflect directly the effects of overburden on the shape of the hysteresis model. The results of this study need to be confirmed by time-history analysis of the wall models and by comparing the results of the analysis with dynamic testing.

7. ACKNOWLEDGEMENTS

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