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Dynamic Response Behaviour of Unreinforced Masonry Walls Subject to Out of Plane Loading

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Abstract

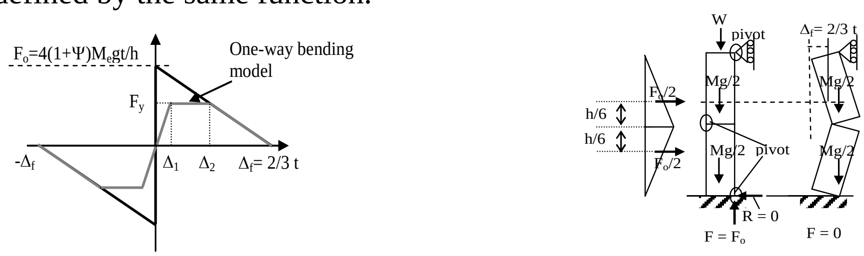
Unreinforced masonry (URM) walls have been traditionally considered to possess very limited ductility and hence designed to behave in a linear elastic manner when subject to out of plane loading. This notion contradicts recent findings which have found significant displacement capacity of URM walls beyond their linear elastic limit. This paper presents an overview of recent research progress on URM walls subject to out of plane two-way bending. Parametric studies based on non-linear time history analyses have been undertaken to identify the displacement demand behaviour of URM walls. Hysteretic models used in the studies were representative of hysteretic behaviour observed from cyclic testings. Analytical simulations of URM walls using the representative hysteretic models have then been evaluated by comparison with the dynamic response of the walls recorded from shaking-table testings. The materials presented in this paper represent an important part of the research outcomes from a joint ARC Discovery research project undertaken between the University of Adelaide and the University of Melbourne.

Keywords: unreinforced masonry; walls; earthquake; out of plane loading

1. Introduction

Unreinforced masonry (URM) walls have been widely perceived as a brittle form of construction and are expected to behave in a linear elastic manner when subject to out-of-plane loading. Current seismic design guidelines recommend failures of the walls as soon as the linear elastic limit has been exceeded. This notion contradicts recent research findings which have identified significant displacement capacity of URM walls in the post-cracked state (Priestley, 1985; Doherty et al., 2002). Consequently, walls are able to withstand earthquake loading well past their elastic strength capacity.

Recent research has led to the development of displacement-based seismic assessment method for URM walls spanning in the vertical direction (Doherty et al., 2002). The force-displacement behaviour of a URM wall when normalised to the effective mass is presented in Figure 1. The notional yield strength (F_y) was derived from simple statics assuming that the wall has cracked. Similarly, the displacement at the threshold of overturning (Δ_f) can be obtained from a simple kinematic model assuming rigid-body behaviour of the wall. Although highly non-linear, the loading and unloading behaviour of the walls can be defined by the same function.



(a) force displacement relationship (b) rigid body assumption

Figure 1 Force-displacement behaviour of URM wall subject to one-way bending (Doherty et al., 2002)

In this paper, the modelling of the displacement behaviour of URM walls is extended to URM walls subject to two-way bending. Recent cyclic testings undertaken at the University of Adelaide has shown that the force-displacement relationship of URM walls subject to two-way bending is characterised by unique loading and unloading behaviour (Griffith et al., 2007). The modelling of such behaviour is presented in Section 2. Parametric studies have been undertaken to quantify the effects of the modelling parameters on the displacement demand behaviour of the walls (Section 3) and analytical simulations of URM walls using hysteretic models were evaluated by comparisons with results recorded from shaking-table testings (Section 4). The objective of the comparison and parametric studies was to identify a robust relationship for modelling the maximum displacement demand of the walls in an earthquake (Section 5).

2. Hysteretic modelling for time-history analyses

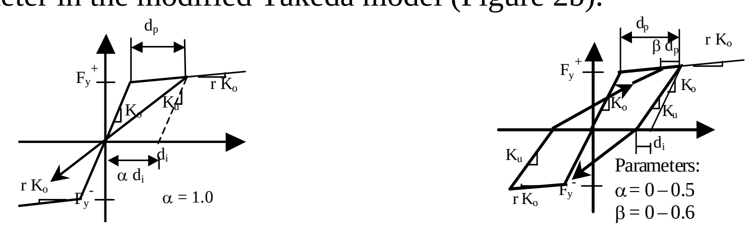
An experimental program has been conducted at which cyclic load testings were performed on eight full-scale URM walls to investigate their hysteretic behaviour (Griffith et al., 2007). The specimens tested include four long walls (of 4m wide and 2.5m high) and two short walls (of 2.5m wide and 2.5m high).

The resistance of the wall specimens in the cracked state (defined herein as the notional "yield" resistance) was recorded at around 2 kPa to 4 kPa. This is translated to about 1.5 – 3g in terms of accelerations (resistance divided by the effective mass of the wall). The yield resistance can be compared to the acceleration demand according to the new Australian Standard (AS1170.4, 2005). The acceleration demand was estimated by applying an amplification factor of 2.5 from the peak ground acceleration (PGA) for rock sites and a factor of 3.1 (=2.5 x 1.25) for soft-soil sites. Dynamic analyses of a six-storey building indicated that walls located at the top of the building can be subject to a peak acceleration of 2g due to the filtering effects of the multi-storey building. Therefore, it was found that URM walls can be subject to a maximum acceleration demand of between 0.15 – 2g based on a seismic zone factor of 0.06 - 0.12g and a return period of 500 years according to the Australian Standard (AS1170.4, 2005). It was indicated from the comparison that most of the tested walls are expected to be typically responding within the elastic limit. However, as the aspect ratio (length : height ratio) of a wall is increased, the (notional yield) resistance will decrease. It can be inferred from test results that the resistance of a single-leaf wall subject to two-way bending can be exceeded by a factor in the range 1 – 3 (ie R_{μ} = 1 – 3) depending on the geometry and boundary conditions of the wall, the dynamic properties of the buildings and the conditions of the site.

The initial natural period of the single leaf wall specimens in the cracked stated was recorded at 0.15 – 0.35 seconds (Griffith et al., 2007) with the initial period of a wall increasing with increasing aspect ratio. In an earlier study by Griffith et al. (2004), the initial natural period of single leaf walls with high aspect ratio was observed to be in the range 0.1 – 0.7 seconds.

The displacement response behaviour of walls in the dynamic condition of an earthquake can be simulated by time history analyses which have incorporated hysteretic models representative of experimental observations including: i) un-loading and re-loading behaviour and ii) strength degradation behaviour.

The maximum displacement demand imposed on URM walls is significantly affected by their un-loading behaviour in particular. The origin-centered model presented in Figure 2a represents walls with perfect self-centering capability (walls reverted to zero displacement when unloaded). The self-centering capability of the walls can be controlled by the α parameter in the modified Takeda model (Figure 2b). The re-loading behaviour characterises stiffness degradation in the re-loading phase and can be controlled by the β parameter in the modified Takeda model (Figure 2b).

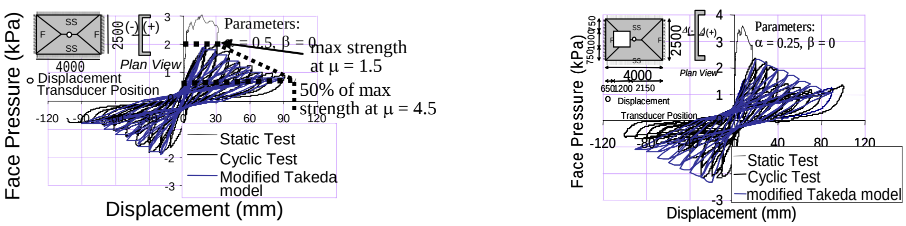


(a) Origin-Centered Model (b) Modified Takeda Model (Otani, 1974)

Figure 2 Hysteretic models

The values of parameters defining the hysteretic models were defined by curve-fitting the models to the hysteretic loops recorded from cyclic testings. It has been found that a reasonable match can be observed using: i) the modified Takeda model with values of α parameter varying from 0 to 0.5 and β parameter fixed at 0, ii) the origin-centered model (α = 1.0). Examples of calibrations of the hysteretic models to the cyclic test results are presented in Figure 3.

The degradation in strength during the cyclic excursion also affects the displacement response of the walls. From the cyclic testings, the strength of the walls was shown to degrade with increasing number of cycles. A small reduction of 5-10% in resistance between the 1st and 2nd cycle of loading was observed in the cyclic tests when the maximum displacement was held constant. However, the reduction in strength was more pronounced as the maximum displacement (ductility) was increased. Significant degradation in strength (about 50-60%) was observed when the ductility ratio μ reaches 3 – 4 (Figure 3a).



(a) Wall 1 (b) Wall 3

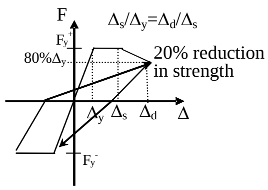
Figure 3 Examples of hysteretic modelling of walls

3. Sensitivity of displacement response of URM walls

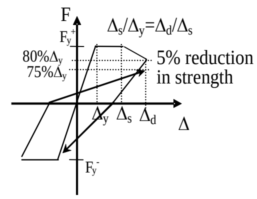
Parametric studies undertaken by the authors involving non-linear time history analyses (THA) were aimed at quantifying the effects of the modelling parameters on the displacement demand behaviour of the walls. The hysteretic models presented in Section 2 were used to represent the hysteretic behaviour of URM walls when subject to two-way bending. The yield resistances of the single-degree-of-freedom (SDOF) systems were calibrated with a ductility reduction factor R_μ of 1.5 - 3. The initial stiffnesses (in the cracked state) were also calibrated to an initial natural period of 0.1 - 0.8 seconds.

The SDOF systems were subject to synthetic accelerograms simulating earthquake scenarios on class C and D site according to the new Australian Standard (AS 1170.4, 2005). The earthquake excitations were generated using stochastic simulations using program GENQKE (Lam et al., 2000 & 2005) and soil response analyses using program SHAKE (Idriss & Sun, 1992) based on earthquake scenarios consistent with a peak ground velocity (PGV) of 60 mm/sec on rock sites. Filtered excitations at the top of a six-storey building (Griffith et al., 2004) have also been included.

Significant strength degradation was observed following the attainment of the maximum resistance of the wall. The displacement demands are shown in Figure 5a to be insensitive to strength degradation of the systems when their yield resistance has only been exceeded by the elastic strength demand (SDOF systems with R_μ of 1.5). The SDOF systems with strength modelled to degrade with increasing displacement (refer Figure 4a) were generally shown to be conservative for systems with highly inelastic response (Figure 5b). The addition of degradation in strength according to increasing number of cycles (refer Figure 4b) seems to have negligible effects on the displacement demands of the SDOF systems (Figure 5b). Due to the insensitivity of the displacement response to the strength degradation parameter, the strength is modelled to degrade with increasing displacement demand (or ductility demand) in the parametric studies.

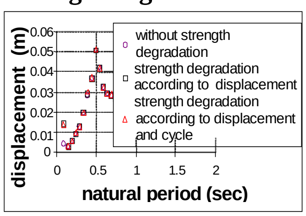


(a) strength degrading with displacement

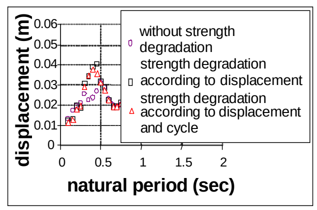


(b) strength degrading with increasing displacement and cycle

Figure 4 Strength degradation of walls



(a) $R_\mu = 1.5$



(b) $R_\mu = 3$

Figure 5 SDOF systems subject to class C site earthquake, M = 6.5 R = 40 km

The maximum displacement of a wall can be significantly affected by the unloading behaviour of the wall (ie. the self-centering capability of the wall). Non-linear time history analyses were performed on SDOF systems using the modified Takeda model and the origin-centered model to represent the systems hysteretic behaviour. The value of the α parameter in the modified Takeda model was varied from 0 to 0.5 in order to quantify the effects of the unloading behaviour on the displacement demands of the walls.

When the SDOF systems were excited well into inelastic range (SDOF systems with R_μ=3), higher displacement demands were observed on SDOF systems which have poor displacement recovery on unloading (represented by the Takeda model with α=0). The higher displacement is caused by the accumulation of residual (un-recovered) inelastic displacement as illustrated in Figure 6.

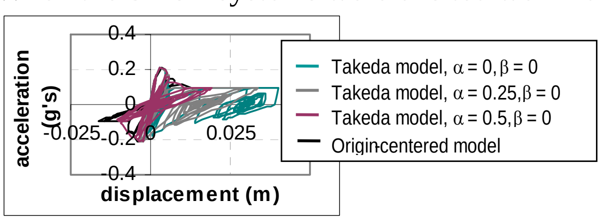
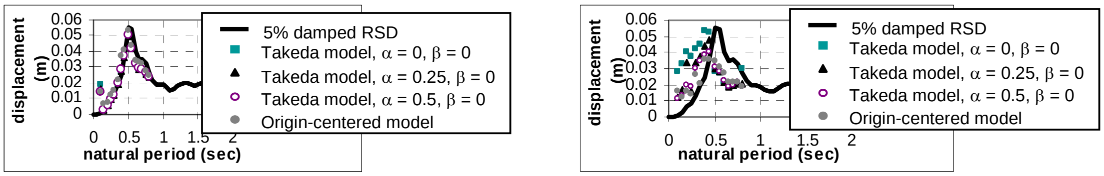


Figure 6 Hysteresis loops of SDOF systems with initial period of 0.2sec and R_μ=3 subject to class C site earthquake, M = 6.5 R = 40 km

Consequently, systems with poor self-centering capability (α = 0) were shown to generally provide conservative predictions of the displacement demands (Figures 7b). In contrast, when the systems have only been subject to limited ductility demand (eg. SDOF systems with R_μ = 1.5) and hence have only undergone limited strength degradation, the displacement of the systems was rather insensitive to the unloading behaviour (as controlled by α in the Takeda model) (Figure 7a). This finding is supported by an earlier sensitive study undertaken on SDOF systems with non-degradable strength which have concluded that the origin-centered model would provide conservative estimate of the displacement demands (Lumantarna et al., 2006).



(a) $R_\mu = 1.5$ (b) $R_\mu = 3$

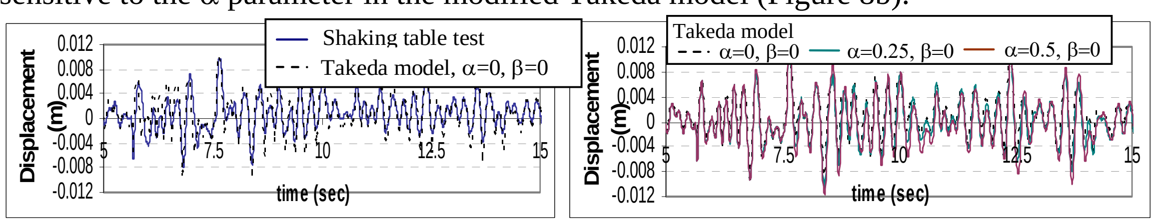
Figure 7 Maximum displacement of SDOF systems subject to class C site earthquake, M = 6.5, R = 40 km

4. Comparison with shaking table test

The parametric studies using hysteretic models representative of the hysteretic behaviour of the URM walls have been presented in the earlier section. The effects of parameters defining the hysteretic behaviour on the displacement demand of the URM walls have been determined. In this section, the response of wall no. 3 (from cyclic testing loadings) to a historical earthquake was simulated using the representative hysteretic models. These numerical simulations were then compared with results recorded from shaking table testings to evaluate the modelling parameters.

A series of dynamic tests were undertaken in which the URM wall specimens were subjected to shaking table tests (Vaculik et al., 2007). The wall specimens were half-scaled replica of the wall specimens subject to cyclic loading testings. Each wall specimens were 1840 mm wide and 1232 mm high. The walls were simply supported at the top and bottom edges and fully restrained against rotation at the vertical edges.

The SDOF systems were subject to the 1956 Taft ground motion scaled to achieve a level of intensity which produces a maximum ground displacement (PGD) of about 120 mm. The values of α and β parameter defining the hysteretic model were obtained by calibrating the model to the cyclic test results as shown in Figure 3c. The displacement of the SDOF systems with an initial natural period of 0.2 seconds has been shown to be in agreement with recordings from the shaking table testings (Figure 8a). The effective displacement was taken as 0.5 of the displacement measured at mid-height position in order that direct comparisons can be made with results from analyses of SDOF systems. For the intensity level of excitation considered, the displacement demand was shown not to be particularly sensitive to the α parameter in the modified Takeda model (Figure 8b).



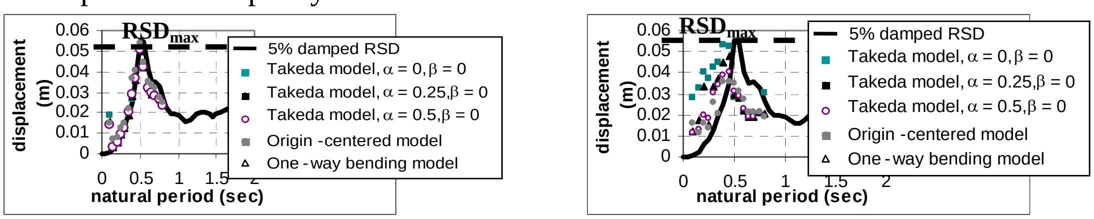
(a) shaking table test results (b) analytical results

Figure 8 Comparison with shaking table test results, wall 3 subject to Taft motion (PGD=120mm)

5. The prediction of maximum displacement demand

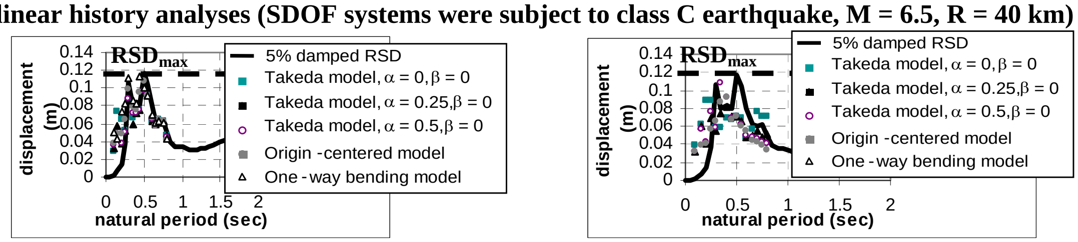
The results obtained from non-linear THA performed on SDOF systems with varying initial natural period have been used to develop simple rules for practical applications. The SDOF systems with hysteretic models representing the hysteretic behaviour of URM walls subject to one-way bending (Figure 1a) have also been included in the analyses to obtain generic predictions of the displacement demand.

The maximum displacement demands obtained from the inelastic THA can vary significantly from elastic displacement response spectrum. Significantly, the maximum displacement demands have been shown to never exceed the maximum level in the elastic displacement response spectrum (referred herein as the peak displacement demand RSD_{max}) in Figures 9 & 10. Thus, the peak displacement demands can be used as a conservative estimate of the maximum displacement demands imposed on URM walls. Consequently, the seismic performance of URM walls can be assessed by comparing the RSD_{max} against the displacement capacity of the walls.



(a) $R_\mu = 1.5$ (b) $R_\mu = 3$

Figure 9 Comparison of maximum displacement demands from 5% damped RSD and non-linear time linear history analyses (SDOF systems were subject to class C earthquake, M = 6.5, R = 40 km)



(a) $R_\mu = 1.5$ (b) $R_\mu = 3$

Figure 10 Comparison of maximum displacement demands from 5% damped RSD and non-linear time linear history analyses (SDOF systems were subject to class C earthquake at the top of multi-storey buildings, M = 6.5, R = 40 km)

The predictions of the RSD_{max} (the maximum point on displacement response spectrum) according to the Australian Standard (AS 1170.4, 2005) are presented in Table 1 based on site category B, C and D which is representative of rock, shallow and deep soil site respectively. A wall can be deemed seismically safe from collapsing when the maximum displacement demand is within the displacement capacity of the wall. For example, the displacement capacity of 55 mm* was observed in walls 3 and 4 from cyclic testings (Griffith et al., 2007). With the exception of the most onerous soil conditions, these walls have been demonstrated to possess a displacement capacity exceeding the maximum displacement demands stipulated by the standard (and hence deemed safe).

* The displacement capacity is equal to half the wall thickness to be comparable to the RSD_{max} from the displacement response spectra

Table1 Prediction of PDD as stipulated by AS 1170.4 (2005)

PGA in g's	RSD_{max} in mm		
	Class B	**Class C**	**Class D**
0.06	20	30	50
0.08	25	40	65
0.1	32	50	80
0.12	38	58	95

6. Concluding Remarks

This paper presents recent progress of the research undertaken by the University of Adelaide in collaboration with the University of Melbourne on the seismic performance of URM walls subject to out-of-plane two-way bending. Parametric studies have been undertaken based on non-linear time history analyses using standard hysteretic models which are representative of observations from cyclic testings. The sensitivity of the displacement demand behaviour of the walls to various parameters of the hysteretic model has been studied. Importantly, the displacement demand of the walls as shown by the THA has been shown to be in agreement with observations from shaking table testings. Simple displacement based rules for assessing the seismic safety of URM walls for practical applications have been proposed.

7. References

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