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SEISMIC DISPLACEMENT RESPONSE ANALYSIS OF OUT-OF-PLANE LOADED URM WALLS: COMPARISON WITH SHAKE TABLE TESTS

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ABSTRACT: Damages to unreinforced masonry (URM) buildings from earthquake ground motion shaking are often caused by out-of-plane failure of walls, parapets, chimneys or brick veneers. This is particularly relevant to the majority of URM buildings in Eastern Canada constructed prior to the introduction of seismic design prescriptions. Seismic vulnerability assessment of this failure is therefore an essential step towards mitigation and retrofit planning. Past research on dynamic response of URM walls have shown that the out-of-plane collapse appears to be primarily associated with an increase in displacement demand. Therefore, realistic evaluation of the out-of-plane vulnerability requires a reliable prediction of the displacement demand. This paper presents a simplified nonlinear static based procedure for displacement demand prediction of out-of-plane URM walls. The procedure includes the development of an equivalent-single-degree-of-freedom (ESDOF) model of the wall with a characteristic force-deformation capacity curve based on the material and geometrical parameters. This curve is convolved with a displacement response spectrum to predict the displacement demand. The procedure is validated by comparing the displacement response predictions with observed results from shake table tests on URM walls of the literature. A sensitivity study is conducted to evaluate the influence of ESDOF model parameters on the displacement response estimates.

1. Introduction

In Eastern Canada, many buildings, whether residential, commercial or historical, are constructed of unreinforced masonry (URM). Majority of these buildings was built before the introduction of seismic design standards and codes and their response to future seismic events is a concern. Post-earthquake inspection reports showed that out-of-plane damages to URM buildings were very frequent in moderate seismicity zones (Ingham and Griffith 2011, EERI 2014). The most seismically vulnerable URM components are: parapets, chimneys, gables, brick veneers and unattached walls sensitive to out-of-plane failure. Thus, in recent years, the out-of-plane response and failure mechanism of URM walls became a subject of many research studies. It has been shown that the out-of-plane vulnerability was associated with the increase in displacement demand and simplified nonlinear static displacement based assessment procedures were developed to evaluate the seismic vulnerability of URM walls (e.g. Doherty et al. 2002, Griffith et al. 2003; Derakhshan et al. 2009, Derakhshan 2011, Derakhshan et al. 2013). The displacement capacity of an URM wall can be represented by a tri-linear capacity curve for an equivalent Single Degree of Freedom (SDOF) model. The displacement demand can be estimated using an equivalent linear SDOF model with an equivalent period and viscous damping ratio. Doherty et al. (2002) recommended the use of a single equivalent period and 5% viscous damping to estimate the displacement demand and compared it with the collapse displacement capacity. Griffith et al. (2003) evaluated different combinations of equivalent period and damping using dynamic time history analysis on SDOF models of URM walls. Griffith et al. (2003) recommendations were similar to Doherty et al. (2002) in using a single equivalent period and 5% damping to evaluate the collapse potential of URM walls. However, experimental validation of these recommendations is scarce in the literature.

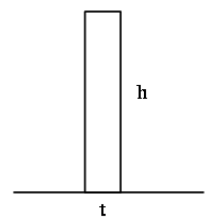
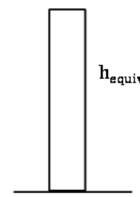
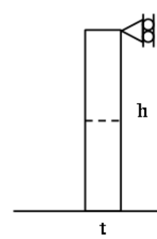
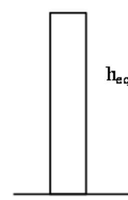
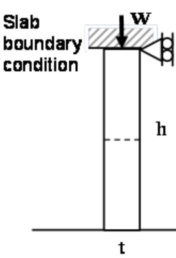
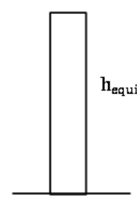
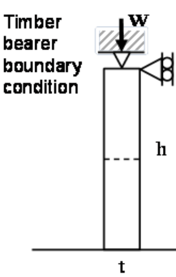
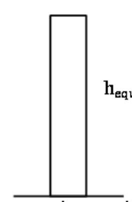
The objective of this paper is to provide an experimental validation example of the simplified equivalent linear procedure of seismic demand estimation using different combinations of equivalent period and damping. Three shake table investigations from the literature were selected for this validation. The tested wall panels represent different configurations of typical URM walls including: brick veneers with wood backing (Paquette et al. 2001), two wythes load bearing masonry wall (Meisl et al. 2007) and a concrete block masonry partition (Asselin 2014). Equivalent periods and damping are estimated using a characteristic force-deformation tri-linear capacity curve based on the material and geometrical characteristics of the tested specimen. Displacement demands are then predicted from the simplified procedure by increasing seismic intensity in terms of peak ground acceleration. The computed displacements are compared to the experimentally observed displacements and a discussion is presented for proper selection of the equivalent SDOF model parameters.

2. Simplified nonlinear static based procedure

2.1. Modelling with an Equivalent Single Degree of Freedom (ESDOF) system

According to a study of Doherty et al. (2002), the behaviour of URM walls subjected to horizontal movements can be modeled by rigid blocks separated by cracked section. Moreover, mechanisms of damages depend on several parameters such as geometric properties, boundary conditions, location of the element and characteristics of openings. Displacement capacity is influenced by the wall thickness t and its aspect ratio (h/t), while the constraint capacity depends on boundary conditions. To facilitate the evaluation of the out-of-plane vulnerability of URM walls, different configurations and boundary conditions can be simplified to a simple reference parapet model as illustrated in Table 1. The simplified equivalent parapet model is defined by equivalent thickness (t_{equiv}) and height (h_{equiv}) depending on its boundary conditions and the overburden ratio acting on the wall, ψ. This parapet wall can then be simplified into an equivalent single degree of freedom (ESDOF) model. Table 1 presents four configurations of URM walls with different boundary conditions. The two first cases are without overburden: (a) rigid parapet with cracking at the base, and (b) rigid non-load bearing simply supported wall with a slip joint at the top and cracking at the mid-height. The two other configurations are characterised by an overburden and cracking at mid-height: (c) rigid load bearing simply supported wall with slab boundary condition at the top, and (d) rigid load bearing simply supported wall with a timber bearer boundary condition so the top reaction is centered.

Table 1 - Configurations of URM walls and equivalent parapet model (adapted from Doherty et al. 2002)

Support type	Representation	Equivalent parapet model
a) Rigid parapet		 $h_{equiv} = h$, $t_{equiv} = t$
b) Rigid non-load bearing simply-supported wall with base reaction at the leeward face		 $h_{equiv} = \frac{h}{4}$, $t_{equiv} = t$
c) Rigid load bearing simply-supported wall with top and base reactions at the leeward face		 $h_{equiv} = \frac{h}{4(1+\psi)}$, $t_{equiv} = t$
d) Rigid load bearing simply-supported wall with top reaction at center line and base reaction at the leeward face		 $h_{equiv} = h\frac{(1+0{,}75\psi)}{4(1+\psi)^2}$, $t_{equiv} = t\frac{(1+0{,}75\psi)}{1+\psi}$
	ψ : overburden ratio	

2.2. Parameters of the tri-linear capacity model

Fig. 1 shows the tri-linear capacity model to predict the behaviour of cracked out-of-plane walls and the classical rigid body bilinear equilibrium model. Four parameters are used to draw the tri-linear capacity model: the displacement values Δ_1, and Δ_2, the wall instability displacement Δ_{ins} and the maximal force F_i. Several experimental studies were done to define displacements Δ_1 and Δ_2 as a ratio of Δ_{ins} (Doherty et al. 2002, Griffith et al. 2003, Derakhshan et al. 2009). Through a theoretical analysis and experimental investigation, Derakhshan et al. (2013) have shown that the wall instability displacement Δ_{ins} and displacement values Δ_1, and Δ_2 are sensible to the crack height ratio, the overburden ratio and the masonry compressive strength. Derakhshan's tri-linear model considers the influence of finite masonry compressive strength (f'_j) through an empirical parameter PMR, and is based on the hypothesis of an infinite stiffness at the top of the URM wall (Derakhshan 2011). In this study both Doherty's and Derakhshan's modelling approaches are combined. Configurations described in Table 1 are used to define the boundary conditions of the experimental test parameters and adapt the equations for the parameters of the tri-linear model. Doherty's model is used to define the displacement causing the instability of the wall Δ_{ins} (Eq. (1(1), the maximum force F_0 (Eq. (7) of the rigid body bilinear model and tri-linear maximum lateral force F_i (Eq. (8). Displacements Δ_1 (Eq. (2) and Δ_2 (Eq. (3) are then computed from Derakhshan's model considering masonry compressive strength (f'_j) and overburden ratio ψ. The following equations are expressed in terms of the equivalent thickness (t_{equiv}) and height (h_{equiv}) of the equivalent parapet model. The parameters are presented as follow:

- displacement causing the instability of wall Δ_{ins}

$$\Delta_{ins} = \frac{2}{3} t_{equiv} \tag{1}$$

- displacements Δ_1 and Δ_2

$$\Delta_1 = 0,04.\Delta_{ins} \tag{2}$$

$$\Delta_2 = (1 - 0,009 PMR_{emp})\Delta_{ins} \tag{3}$$

with,

PMR: Percentage of Maximum rigid Resistance

$$PMR_{emp} = 83\left[1 - \frac{\rho.g}{0,85.f'_j}\left(\frac{h_{equiv}}{t_{equiv}}\right)t_{equiv}\left(\psi + \frac{(1-\beta)(2\psi + 2 - \beta)}{2(1-\beta) + (2-\beta)\psi}\right)\right] \tag{4}$$

β = 0,5 for a simply-supported wall

$$PMR_{emp} = 83\left[1 - \frac{\rho.g}{0,85.f'_j}\left(\frac{h_{equiv}}{t_{equiv}}\right)t_{equiv}\left(\psi + \frac{0,5(2\psi + 1,5)}{1 + 1,5\psi}\right)\right] \tag{5}$$

ψ: overburden ratio

$$\psi = \frac{P_0}{W} \tag{6}$$

- rigid body bilinear maximum force F_0

$$F_0 = \frac{M_e.g.t_{equiv}}{h} = F_0 = \frac{3}{4}\frac{M.g.t_{equiv}}{h} \tag{7}$$

- tri-linear maximum lateral force F_i

$$F_i = F_0\left(1 - \frac{\Delta_2}{\Delta_{ins}}\right).\frac{\left(h/t\right)_{equiv}}{\left(h/t\right)} \tag{8}$$

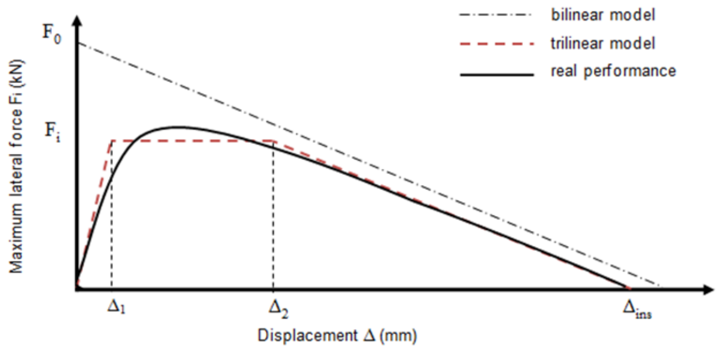


Fig. 1 - Representation of the tri-linear capacity model and those parameters (adapted from Derakhshan et al. 2013)

2.3. Equivalent period and damping

In order to evaluate the displacement demand using a simplified equivalent linear model, an equivalent period and damping need to be estimated. Different equivalent period and damping were proposed and investigated in the literature. Doherty et al. (2002) and Griffith et al. (2003) recommended the use of a single equivalent secant period T_2 (Fig. 2), instead of the elastic period T_1, and 5% viscous damping to estimate the displacement demand and compare it with the collapse displacement capacity. An intermediate T_s value for the equivalent period is suggested in this study. The objective of this study is to evaluate the sensitivity of the selection of the equivalent period and damping on the predicted displacement demand compared to shake table test results. In all cases, the equivalent fundamental period T_i of unreinforced masonry wall is defined as follows :

$$T_i = 2\pi\sqrt{\frac{Me}{Ke}} = 2\pi\sqrt{\frac{0{,}75M}{Ke}} = 2\pi\sqrt{\frac{0{,}75 \times \rho_m . h . t_{equiv} . L}{F_i/\Delta_i}} \tag{9}$$

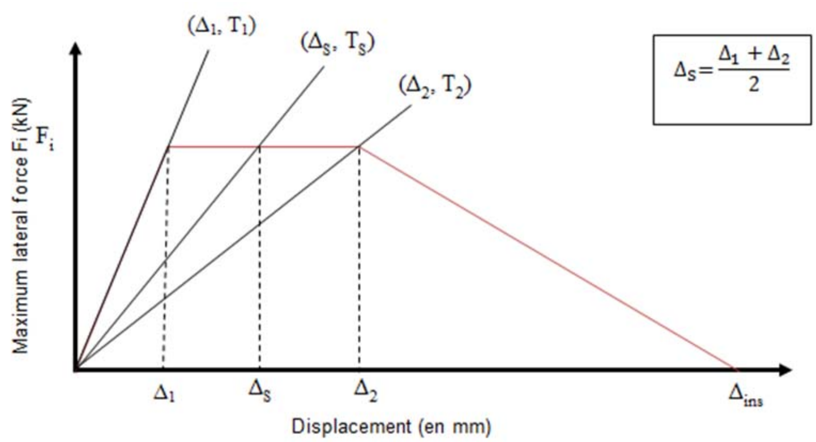


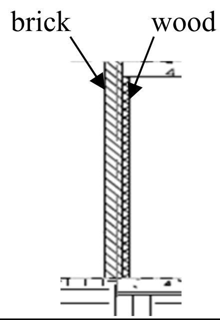
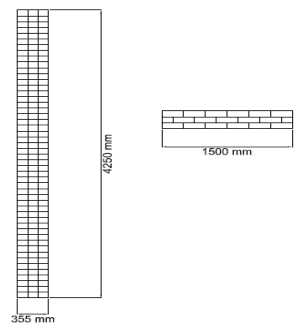
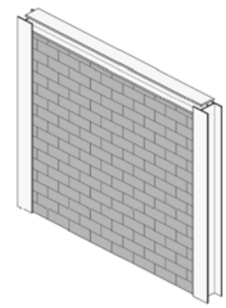
Fig. 2 - Definition of equivalent periods and associated displacements.

3. Shake table tests on URM walls

3.1. Modelling of tested wall and their characteristics

The three tested wall panels selected from the literature represent different configurations of typical URM walls: (i) brick veneers with wood backing (Paquette et al. 2001), (ii) two wythes load bearing masonry wall (Meisl et al. 2007), and (iii) concrete block masonry partition (Asselin 2014). The experimental data used to develop the theoretical model for each experimental specimen include the compressive strength of mortar f'_j; geometric characteristics of the wall: thickness t, wide L, high h; boundary conditions and overburden ψ; density of the masonry ρ_m; the response spectral shape corresponding the ground motion input applied during the tests.

Table 2 - Characteristics of the tested wall panels

	URM masonry wall with its wood (Paquette et al. 2001)	URM masonry wall with brick (Meisl et al. 2007)	URM masonry wall with concrete block (Asselin et al. 2014)
Drawing			
f'_j (MPa)	0,401 MPa	6,14 MPa	9,2 MPa
Location	Montreal	Vancouver	Sherbrooke
h (m)	1,50m	4,25m	2,40m
L (m)	1,20m	1,50m	2,40m
t (mm)	95mm	355mm	190mm
ρ_m (kg/m^3)	1800 kg/m^3	2615 kg/m^3	1800 kg/m^3
overburden ψ (kN)	0	0	0
Boundary conditions	URM walls are acting as a beam in bending mode, corresponding to configuration (b) in**Erreur ! Source du renvoi introuvable.**		

3.2. Tri-linear capacity model

The parameters of the tri-linear capacity model for each test are defined using the material and geometrical characteristics described in Table 2 and using equations presented in Section 2.2. They are summarized in Table 3 and the resulting tri-linear capacity curves are shown in Fig. 3. The corresponding equivalent periods (T_1, T_2 and T_s) are evaluated according to the tri-linear capacity model (Fig. 2) and Equation (9) and are presented in Table 3.

Table 3 - Parameters of the tri-linear capacity models for tested URM wall specimens.

	URM masonry wall with wood backing (Montreal)	URM masonry wall with two wythes brick (Vancouver)	URM masonry wall with concrete blocks (Sherbrooke)
Δ_1 (mm)	2,5mm	9,5mm	5,1mm
Δ_2 (mm)	16,7mm	60,3mm	32,2mm
Δ_{ins} (mm)	63,3mm	236,7mm	126,7mm
PMR_{emp} (%)	81,8%	82,8%	82,9%
F_i (N)	422N	7 464N	4 973N
T_1 (s)	0,23s	0,39s	0,29s
T_S (s)	0,46s	0,75s	0,56s
T_2 (s)	0,60s	0,99s	0,74s

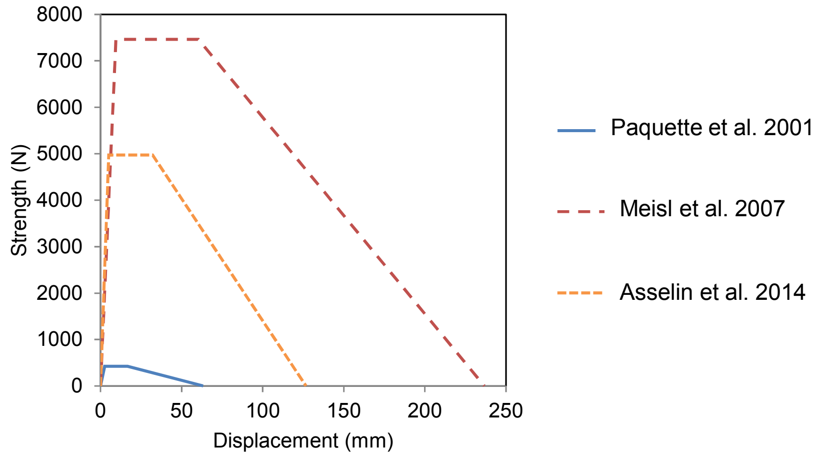


Fig. 3 – Tri-linear analytical capacity curves for the tested URM walls.

3.3. Displacement response

The peak displacement of each tested URM wall specimen given a specific seismic intensity is obtained using the ESDOF model through the following steps:

1. Define the tri-linear capacity model of each experimental wall specimen using its geometric characteristics and Equations (1 to (9 and compute the equivalent fundamental periods (T_1, T_S, T_2) of the ESDOF model;
2. Determine the spectral acceleration for different values of seismic intensity scaling (PGA) as applied in the experimental tests.
3. Determine the spectral acceleration $S_a(T_i)$ for each equivalent period (T_1, T_S, T_2); and calculate the corresponding spectral displacement $S_d(T_i)$ in accordance with:

$$S_d = \frac{S_a}{\omega} \text{ where } \omega = \frac{2\pi}{T} \tag{1}$$

4. Evaluate the peak displacement of URM wall for the different PGA and draw the displacement response as a function of the (PGA).

To evaluate sensitivity of the selection of the equivalent period and damping parameters on the analytical prediction of the peak displacement corresponding the experimental results, 5 different combinations of equivalent periods (T_1, T_S, T_2) and equivalent viscous damping at 5% and 10% were applied. A damping reduction factor (Eq. 11) was used to estimate the spectral ordinates for damping ratios larger than 5% (Priestley et al. 2007):

$$R_\xi = \left(\frac{0{,}10}{0{,}05 + \xi}\right)^{0.5} \tag{2}$$

3.4. Sensitivity Analysis

To study the sensitivity of the equivalent period and damping parameters on the displacement response estimates, the displacement response corresponding to increasing levels of seismic intensity (PGA) are calculated for the three tests for periods T_1, T_S and T_2 and two damping ratios (5% and 10%). Results are presented in Fig. 4 to Fig. 6. For low and moderate seismic demand, fundamental period T_S and an equivalent damping of 10% gave conservative prediction for the displacement demand. This observation can be made from Fig. 4 and Fig. 5 comparing results of the shake table tests conducted by (Paquette et al. 2001) and (Asselin 2014). It should be noted that these specimens demonstrated extensive cracking without collapse. This type of behavior is associated to displacement response less than the 50% of the ultimate displacement capacity Δ_{ins}. At higher seismic demand, as shown in Fig. 6 for the shake table tests (Meisl et al. 2007), the wall specimens reached near collapse state. In that case, the equivalent fundamental period T_2 and damping at 5% give a better estimation of the level of response of the wall for the displacement demand near the ultimate displacement capacity (more than 50% of Δ_{ins}). This is compatible with the recommendations made by Doherty et al. (2002) and Griffith et al. (2003) especially if the objective of the assessment is to estimate the collapse potential of walls.

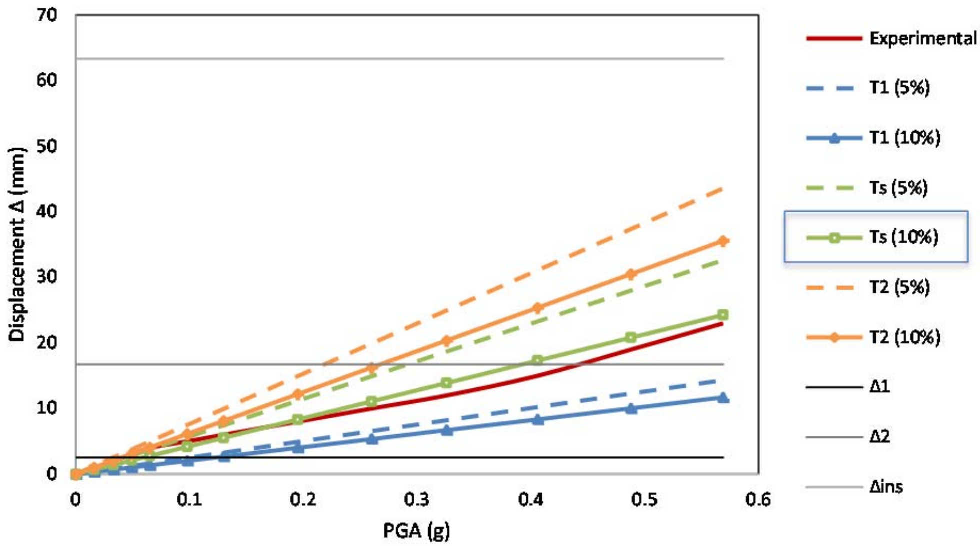


Fig. 4 - Analytical and experimental displacement response in terms of PGA for the URM walls tested by Paquette et al. (2001)

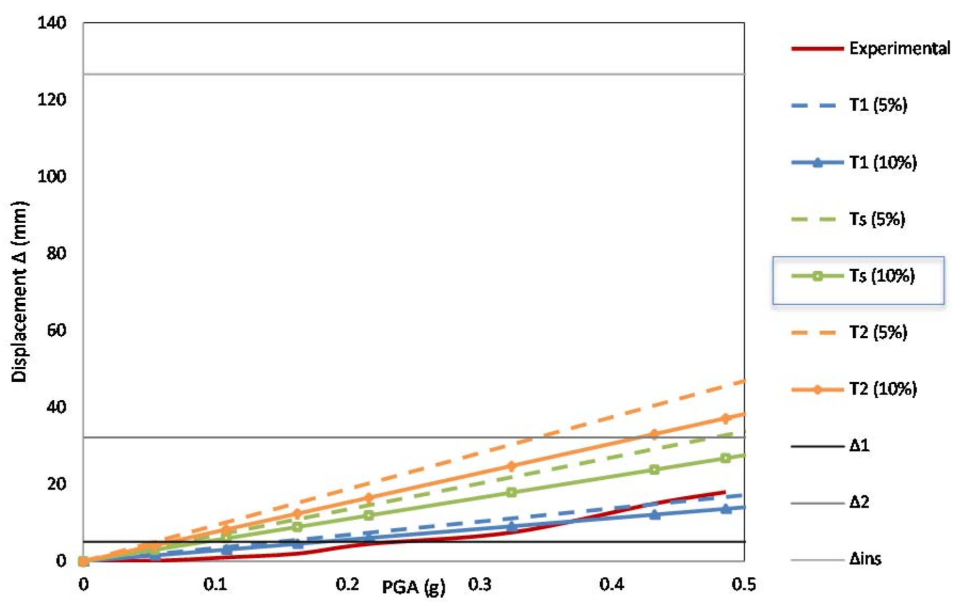


Fig. 5 - Analytical and experimental displacement response in terms of PGA for the URM walls tested by Asselin et al. (2014).

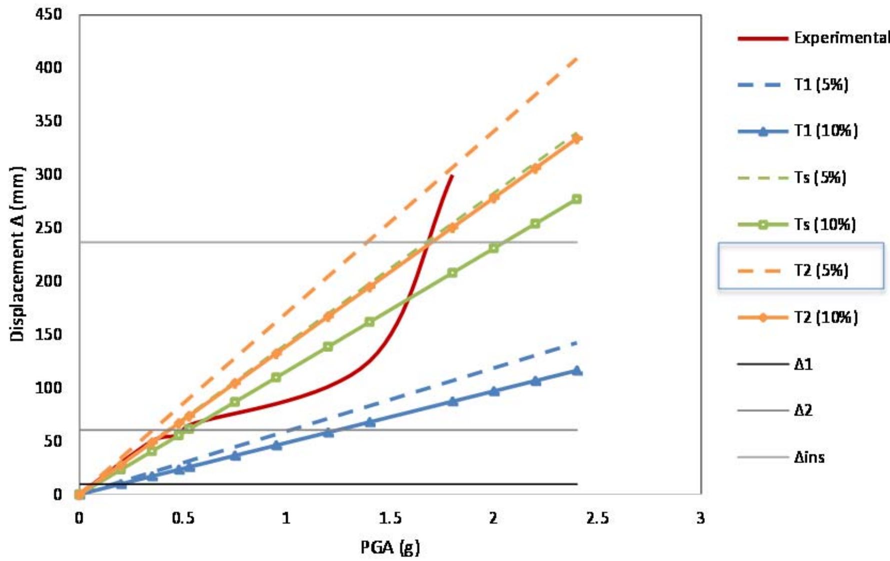


Fig. 6 – Analytical and experimental displacement response in terms of PGA for the URM walls tested by Meisl et al. (2007)

4. Conclusion

Damages to unreinforced masonry (URM) buildings from earthquake ground motion shaking are often caused by out-of-plane failure of walls, parapets, chimneys or brick veneers. This is particularly relevant to the majority of URM buildings in Eastern Canada that were constructed prior to the introduction of seismic design prescriptions. Seismic vulnerability assessment of this type of failure is therefore an essential step towards mitigation and retrofit planning. Past research on dynamic response of URM walls have shown that the out-of-plane collapse appears to be primarily associated with an increase in displacement demand. Therefore, realistic evaluation of the out-of-plane vulnerability requires a reliable prediction of the seismic induced displacement demand. This paper presents a validation example of a simplified nonlinear static based procedure for displacement demand prediction of URM walls subjected to out-of-plane seismic excitation. The procedure includes the development of an equivalent single degree of freedom (ESDOF) model of the wall with a characteristic force-deformation tri-linear capacity curve based on the material and geometrical characteristics. The capacity curve is then convolved with a displacement response spectrum to predict the displacement demand. The procedure is validated by comparing the displacement response predictions with observed results from shake table tests on URM walls available in the literature. A sensitivity study is conducted to evaluate the influence of ESDOF model parameters (equivalent period and damping) on the displacement response estimates. The results showed that the displacement demand prediction is more sensitive to the selection of the equivalent period than the damping ratio. In addition, the application of T_S with 10% damping provided the least conservative prediction of displacement demands less than 50% of the ultimate displacement capacity (where extensive cracking occurred without collapse). However, at higher seismic demand (near collapse or collapsed walls) where the displacement demand near the ultimate displacement capacity, the T_2 and 5% damping (as recommended by Doherty et al. 2002) provided good prediction of the collapse potential of the walls. Further validation and analysis with additional experimental results are required in order to provide recommendations for the selection of the equivalent linear parameters in seismic assessment of URM walls for cracking and collapse limit states. This is currently under investigation by the authors.

5. Acknowledgement

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