ACCOUNTING FOR INELASTIC RESPONSE OF URM BUILDINGS IN ACCELERATION DEMANDS ON FACE-LOADED WALLS

Arun Menon[1] and Guido Magenes[2]

[1] *Post-doctoral researcher, Department of Structural Mechanics, University of Pavia*
[2] *Assoc. Professor, Dept. of Structural Mechanics, University of Pavia, via Ferrata 1, 27100 (PV) Italy*
Email: guido.magenes@unipv.it

ABSTRACT :

Response of unreinforced masonry (URM) to out-of-plane excitation is a complex, yet inadequately addressed theme in seismic analysis. Seismic input expected on a face-loaded wall in an URM building is the ground excitation filtered by the in-plane response of the walls and the floor diaphragm response. The dynamic response, i.e., the superposition of vibration modes of the primary lateral load-resisting structure, and the non-linear structural response contribute to the filtering phenomenon. The current paper summarises an investigation aimed at developing a semi-analytical formulation to estimate the acceleration demand on a face-loaded URM wall or a generic secondary system, that explicitly takes into account the level of inelastic demand on the primary structure, in terms of the displacement ductility demand. The proposed formulation is based on statistical evaluation of several non-linear dynamic time-history analysis results treated within a parametric framework.

KEYWORDS: Seismic input on face-loaded walls; inelastic response of URM buildings

1. INTRODUCTION

Out-of-plane collapse of peripheral walls is a recurring failure mechanism in existing URM buildings, structures that were not built in conformity with any code but rather to a builder's rules of the art. Modern seismic codes for design of new masonry buildings, on the other hand, provide dimensioning and detailing rules that make out-of-plane failure almost unlikely even under severe seismic load (e.g. limits on slenderness ratio for walls). Lack of structural detailing (e.g. presence of efficient floor-wall ties, adequately rigid diaphragms) renders such building stock, ubiquitous in urban historical nuclei, highly susceptible to out-of-plane failure even under low intensities of ground motion.

Out-of-plane response to seismic excitation, especially under ultimate conditions, is associated with displacement demand rather than attainment of static out-of-plane strength capacity. This concept, originally purported by Priestley (1985), was ratified in recent years by theoretical and experimental research (e.g. Doherty *et al*., 2002, etc.). A first step towards looking at this complex problem needs to envisage evaluation of the actual seismic demand on walls by considering the dynamic filtering effect of the building and its diaphragms and the dynamic response of the walls. Non-linear behaviour of the primary lateral load-resisting structure can alter the response of the face-loaded wall either by significantly reducing or substantially amplifying its response compared to that under the linear regime. Interactions between the response of the primary structure and face-loaded walls can be fully investigated only by means of inelastic dynamic time-history analysis (THA).

In the current research, the effect of the inelastic response of the primary structure on the seismic input to face-loaded walls is investigated. The semi-analytical formulation proposed based on statistical evaluation of results of inelastic THA treated within a parametric framework, explicitly accounts for the inelastic response of the primary structure. Within the context of the dynamic filtering effect of buildings on the seismic input to face-loaded walls, a parallel can be drawn with seismic forces transmitted to secondary systems in a building. A secondary system could be a non-structural component (NSC) within, attached to, or supported by the structure but not included in the design of primary structure (e.g. face-loaded walls, parapets, equipment, etc.). Most procedures available to compute the seismic demand on face-loaded walls have to be derived from code-based methods to estimate seismic demand on NSCs (e.g. CEN-EN-1998, 2005), a fact rarely stated explicitly in codes.

Bulk of the research effort on response of secondary systems has essentially focussed on estimating elastic floor spectra from linear response of primary and secondary systems, based on random dynamics approaches. A limited number of studies in the literature explore the effects of non-linear structural response on secondary system response (e.g. Lin and Mahin, 1985; Sewell *et al.*, 1986; Miranda and Taghavi, 2005; Ray Chaudhuri and Villaverde, 2008; etc.) and far fewer have come up with recommendations incorporating the phenomenon in simple analytical or semi-empirical formulae to estimate the seismic demand on secondary systems (e.g. Villaverde, 1997; Rodriguez *et al.*, 2002; Ray Chaudhuri and Hutchinson, 2004, etc.). Current code-based approaches take into account the resonance effect, the height effect and ductility in the secondary system (e.g. CEN-EN-1998, 2005), and with the exception of the New Zealand Standard (NZS 1170.5, 2004), none of the others reviewed in the current research accounts for the inelastic behaviour in the primary structure.

2. METHODOLOGY ADOPTED

The parametric inelastic THA is carried out by means of uncoupled seismic analyses (neglecting feedback effect between the primary and secondary systems) of an elastic SDOF secondary system upon a non-linear SDOF primary system. As the focus here is on out-of-plane response of URM walls, neglecting coupling effects is acceptable given that the mass ratios (mass of the secondary system to the mass of the primary system) are generally less than one percent. The numerical analyses and the proposed formulation are based on SDOF idealisation of the primary system, implying that the non-linear response affects only the first mode of vibration of the structure represented. The assumption may be valid for 3-4 storied URM structures, however, due importance to higher mode effects on secondary system response has to be accorded in taller and more flexible structures. In URM walls, initiation of cracking can be related to an acceleration-sensitive limit state, whereas, the ultimate limit state is definitely displacement-sensitive. Therefore the seismic demand on face-loaded walls is investigated in the current study in terms accelerations as a first approach.

The seismic demand expected on a face-loaded wall is defined by means of a semi-analytical formulation that explicitly considers the inelastic response of the primary system in terms of displacement ductility demand, a quantify which can eventually be related to a structural behaviour factor (e.g. Fajfar, 1999). The following factors have been treated within the parametric inelastic THA:

1. Initial period of vibration of the primary lateral load-resisting structure (T_1)
2. Level of displacement ductility demand (μ_Δ) on the primary structure
3. Hysteretic model of the primary structure (modified-Takeda, elastic-perfectly-plastic (EPP), masonry shear-dominated hystereses)
4. Nature of excitation signal used for the THA (natural vs. synthetic records)
5. Spectral response shape of the seismic input (stiff soil vs. soft soil spectrum)

3. PARAMETRIC STUDY

The SDOF oscillator representing the primary structure is modelled as a frame element with strength, geometrical characteristics and axial loading calibrated to ensure a shear-controlled failure mode, and to represent the shear-dominated global response of URM buildings. The base shear capacity ratios (maximum base shear to weight ratio) ranged between 0.17-0.36 with an average of 0.25 for the 17 oscillators, broadly indicative of the global strengths of URM buildings with moderate to high seismic vulnerability. T_1 varied between 0.04-1.0s, representing an ample spectrum of elastic vibration periods of URM buildings. The target displacement ductility demands varied from 0.40 and 0.75 (elastic response) to 1.5, 2, 2.5, 3 and 4 (inelastic), with μ_Δ defined as the ratio of the maximum oscillator displacement to the yield displacement. The hysteretic laws modelling inelastic oscillator response (primary structure) were a modified-Takeda (Otani, 1974), a masonry shear-dominated (Lagomarsino *et al.*, 2006) and the EPP hystereses (see Figure 1). Inelastic THA analyses were executed using numerical codes RUAUMOKO (Carr, 2005) and TREMURI (Lagomarsino *et al.*, 2006).

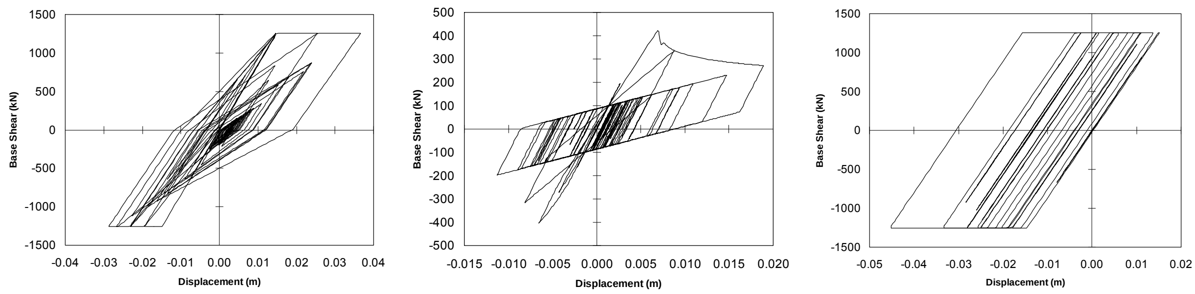

Figure 1:Hysteresis response of the SDOF oscillator representing the primary system using (left) modified-Takeda; (centre) masonry shear-dominated; (right) EPP hysteretic rules

The inelastic THA were carried out using a suite of 10 natural ground motion records compatible with a soil type-B ($V_{s,30}$ > 800m/s) elastic response spectrum (CEN-EN-1998, 2005). A suite of 10 artificial records compatible with the soil type-B response spectrum and a suite of 15 natural records compatible with a soil type-D ($V_{s,30}$ < 180m/s) elastic response spectrum (CEN-EN-1998, 2005) were used concurrently within the parametric study to evaluate the effects of characteristics of the natural records (used in the current study) and that of a different input spectral shape on the dynamic filtering. Acceleration records were individually scaled in amplitude so as to achieve target levels of μ_Δ. Existing relationships between μ_Δ and the ductility reduction factor (Fajfar, 1999) were used to estimate appropriate scale factors required to take the oscillators to preset levels of μ_Δ. Further details of the parametric study are discussed elsewhere (Menon and Magenes, 2008).

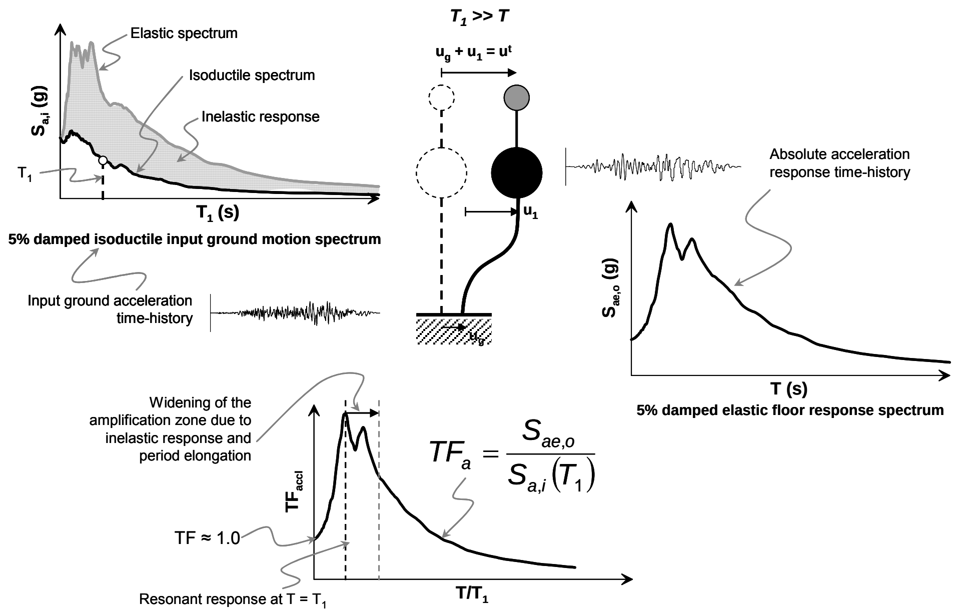

Figure 2: Acceleration transfer function for a flexible primary structure under inelastic response

Influence of the inelastic response of the primary system on the seismic input to face-loaded walls is evaluated in terms of "transfer functions". The transfer function is an analytical representation of the modification of secondary system response by the dynamic filtering effect, calculated as the ratio of the spectral acceleration on the secondary system (elastic response spectrum ordinates estimated from absolute floor acceleration response) to the spectral acceleration at the initial period of the oscillator (elastic or inelastic response spectrum ordinate from input ground acceleration).

In rigid primary structures, the floor acceleration response spectrum is almost identical to the ground acceleration response spectrum. Contrarily, the floor or secondary system response in flexible structures is severely affected by the primary system's response and the dynamic filtering effect. The floor spectrum is differently shaped from that of the ground response spectrum and shows response amplification confined to a narrow band of vibration periods centred on T_1 due to the resonance effect. Features of the acceleration transfer function for ductile response of a flexible primary structure are illustrated in Figure 2. Under inelastic structural response, the amplification of response is no longer confined to a narrow band around T_1 but extends rightwards beyond T_1, to longer periods. This is coherent with the concept of period elongation due to inelastic response of the primary structure.

The acceleration transfer functions for different oscillators for all levels of target μ_Δ (EL: elastic; IN-1: μ_Δ 1.5; IN-2: μ_Δ 2.0; IN-3: μ_Δ 2.5; IN-4: μ_Δ 3.0; IN-5: μ_Δ 4.0) are shown in Figure 3. Effect of the inelastic structural response in reducing the secondary system response with increasing μ_Δ is significant for moderately-rigid and flexible oscillators. Peak floor accelerations consistently reduce with increasing μ_Δ for all oscillators. Acceleration demands on out-of-plane walls tend to marginally increase with increasing μ_Δ for period ratios (T/T_1) beyond approximately 1.5.

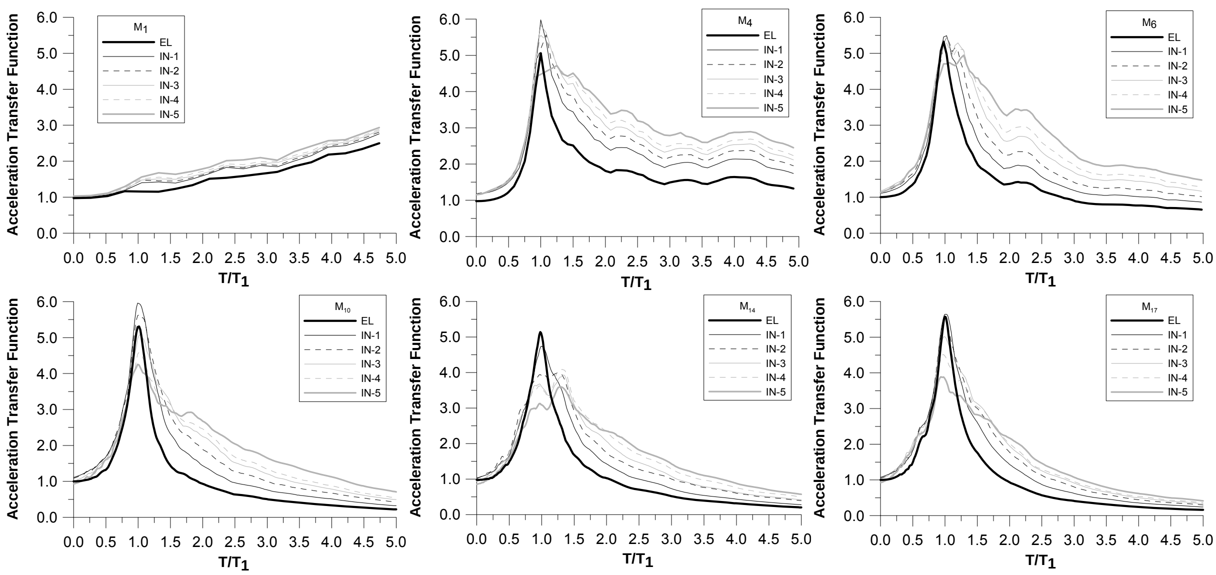

Figure 3: Acceleration transfer functions for all target μ_Δ for oscillators M_1 (T_1=0.04s), M_4 (T_1=0.12s), M_6 (T_1=0.23s), M_{10} (T_1=0.48s), M_{14} (T_1=0.72s) and M_{17} (T_1=0.95s).

Emergence of a second amplification zone, to the right of the main peak at resonance ($T=T_1$), was noticed in moderately-rigid and flexible oscillators with increasing μ_Δ and subsequent period elongation in the oscillator. Time-frequency analysis of response acceleration histories obtained from inelastic THA to identify an effective post-yield period of vibration for each oscillator and subsequent logarithmic regression have enabled development of a semi-empirical correlation between the effective inelastic period and μ_Δ (see Figure 4, Eqn. 3.1). For a generic idealised force-displacement relationship within a secant stiffness approach, at peak displacement, such an effective inelastic period is directly proportional to the square root of μ_Δ. Eqn. 3.1 is used within the proposed formulation to capture the phenomenon of the emergence of the second peak. k is a coefficient dependent on the logarithm of the displacement ductility demand.

$$T_{eff}/T_1 = k * \sqrt{\mu_\Delta} \text{ where } k = -0.192\ln(\mu_\Delta) + 1.00 \tag{3.1}$$

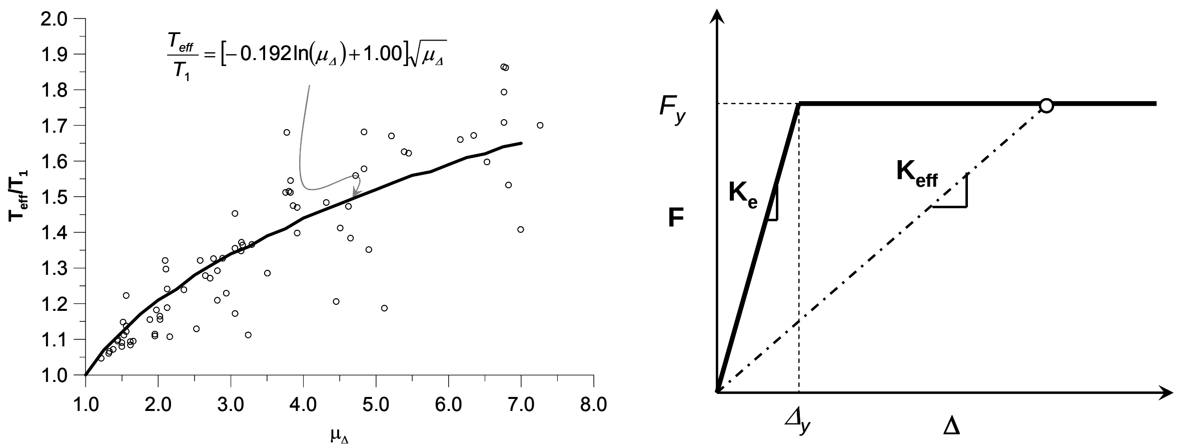

Figure 4: (L) Semi-empirical equation relating the period ratio (T_{eff}/T_1) to μ_Δ obtained by regression analysis of inelastic THA (each point represents average of 10 THA); (R) Secant stiffness approach

4. SEMI-ANALYTICAL FORMULATION

The seismic demand on the face-loaded wall (or a generic secondary element) is calculated in terms of spectral acceleration (Eqn. 4.1). The proposed expression is constituted by the ground motion component, the elastic dynamic filtering component and the inelastic dynamic filtering component, which are combined using the ductility dependent proportionality coefficients C, DT_1 and DT_{eff}, respectively. In Eqn. 4.1, $S_{ae,o}(T)$ is the spectral acceleration relative to wall period, T; $S_{ae,i}(T)$ is the ordinate of the input elastic response spectrum at the wall period; $S_{a,i}(T_1)$ is the ordinate of the input isoductile response spectrum at the initial structural period, T_1 and $S_{a,i}(T_{eff})$ is the ordinate of the input isoductile spectrum at the effective inelastic period, T_{eff}.

$$S_{ae,o}(T) = \{S_{ae,i}(T) * C\} + \{S_{a,i}(T_1) * TF_{har}(T/T_1) * D_{T_1}\} + \{S_{a,i}(T_{eff}) * TF_{har}(T/T_{eff}) * D_{T_{eff}}\} \tag{4.1}$$

Coefficient C, which varies exponentially with T_1, is defined by Eqn. 4.2 using the ductility-dependent coefficient A and constant x, the latter implying a residual contribution from the ground motion component to the floor or secondary system response under elastic and inelastic structural response.

$$C = x + (1-x) * e^{-AT_1^2} \quad x = 0.05 \text{ (elastic); } 0.10 \text{ (inelastic)} \tag{4.2}$$

The harmonic functions (TF_{har}) in Eqn. 4.1 are defined by Eqn. 4.3 (or 4.5) and Eqn. 4.4 (or 4.6) for elastic and inelastic structural responses, respectively. Coefficients α, a and β are also ductility-dependent, while ξ is the damping ratio (0.05).

$$TF_{har}(T/T_1) = 1 \Big/ \sqrt{\left(1-(T/T_1)^{\alpha}\right)^2 + (\beta\zeta\, T/T_1)^2} \quad \text{for } T/T_1 \leq 1.0 \tag{4.3}$$

$$TF_{har}(T/T_{eff}) = 1 \Big/ \sqrt{\left(1-(T/T_{eff})^{\alpha}\right)^2 + (\beta\zeta\, T/T_{eff})^2} \quad \text{for } T/T_{eff} \leq 1.0 \tag{4.4}$$

$$TF_{har}(T/T_1) = 1 \Big/ \sqrt{\left(1-(T/T_1)^{a}\right)^2 + (\beta\zeta\, T/T_1)^2} \quad \text{for } T/T_1 > 1.0 \tag{4.5}$$

$$TF_{har}(T/T_{eff}) = 1 \Big/ \sqrt{\left(1-(T/T_{eff})^{a}\right)^2 + (\beta\zeta\, T/T_{eff})^2} \quad \text{for } T/T_{eff} > 1.0 \tag{4.6}$$

Coefficients α, a and β together with the proportionality coefficients (A, DT_1, DT_{eff}) have been estimated by calibrating the analytical predictions to the average spectra of 10 THA using the set of stiff soil natural records for each oscillator represented by the modified-Takeda hysteresis and for each observed μ_Δ class. Values of these coefficients prescribed for different μ_Δ classes are reported in Table

1. For very rigid primary structures ($T_1 \leq 0.05$s) under inelastic response, DT_{eff}, may be ignored and DT_1 can be assumed as 0.05. For T_1 0.05-0.15s, DT_1 can be assumed to be varying linearly between 0.05 and the value reported in Table 1 for a given ductility class. Similarly, DT_{eff} may be assumed to vary from 0.05 to the corresponding value reported. For elastic structural response, DT_1, can be assumed to vary linearly from 0.05-0.95 for oscillator periods 0.05-0.15s.

Table 1: Prescribed values for coefficients A, DT_1, DT_{eff}, α, a, β

Ductility Class	Observed Ductility[1]	TF_{har} (T_1)			TF_{har} (T_{eff})			$DT_1{}^2$	$DT_{eff}{}^2$	A
		α	a	β	α	a	β			
Elastic	-	1.80	0.85	3.75	-	-	-	0.95	-	15
I. 1.00-1.50	1.40	1.50	0.65	3.70	1.00	0.50	2.00	0.90	0.05	25
II. 1.50-2.00	1.71	1.40	0.65	3.70	1.00	0.45	2.00	0.88	0.08	30
III. 2.00-2.50	2.13	1.30	0.50	3.70	1.00	0.40	2.00	0.85	0.10	35
IV. 2.50-3.00	2.74	1.30	0.45	3.70	1.00	0.40	2.00	0.78	0.12	40
V. 3.00-4.00	3.49	1.20	0.40	4.00	1.00	0.33	2.00	0.74	0.15	45

[1] average observed ductility demands from THA results for the ductility class
[2] values applicable to $T_1 > 0.15$s for inelastic cases

In comparison to numerical results, the formulation adequately estimates the spectral acceleration on the secondary system up to a secondary system period of 2.0s, with a margin of error consistently lower than 20% (see Fig. 5). It efficiently covers secondary systems attached to rigid and flexible structures, both under elastic and inelastic structural response. The expression tends to overestimate beyond a secondary system period of 2.0s, which however is beyond the practical range of interest.

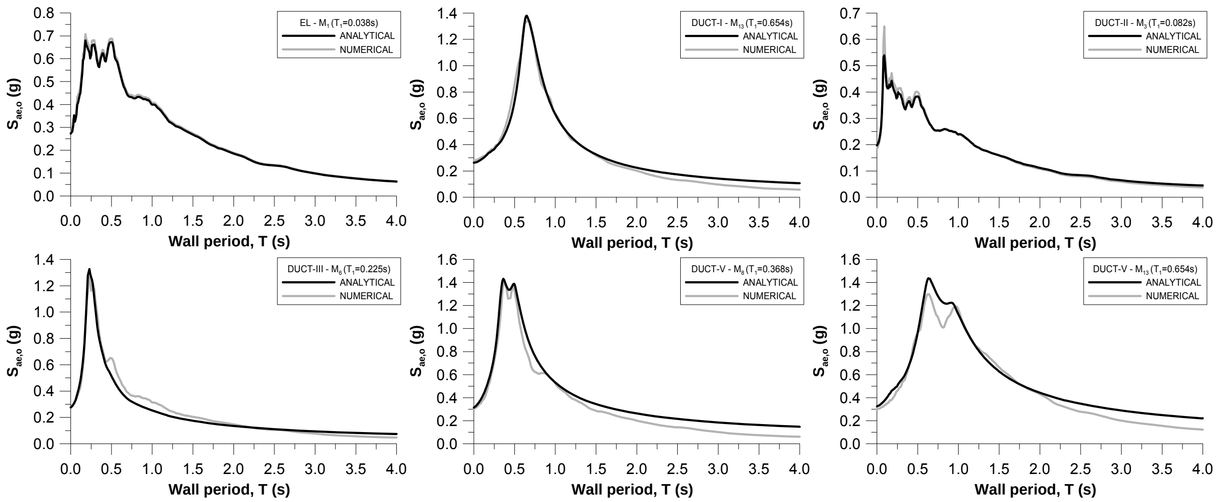

Figure 5: Comparison of acceleration demands computed using the proposed expression with THA results for different oscillators under elastic and ductile response (ductility classes – refer Table 1)

The simplicity of the expression lies in the number and type of parameters needed to calculate the seismic demand whilst the format makes it consistent with response spectrum definitions in current codes. Elastic and/or isoductile acceleration response spectra of the ground motion are required along with initial elastic structural period. Once the level of ductility demand on the structure is known, or chosen, T_{eff} is easily calculated (Eqn. 3.1), while rest of the coefficients are prescribed here. A generic floor spectrum can be derived, or alternatively, knowing the secondary system's vibration period (T), the corresponding spectral acceleration can be directly estimated.

The expression captures the physical sense of the filtering effect in URM buildings concisely. Seismic demand on a secondary system attached to a rigid structure comes mainly from the ground motion component, while the dynamic filtering component diminishes and the floor spectrum tends to that of the ground motion. Conversely, as the structure becomes more flexible, the role of the dynamic filtering component increases with a parallel reduction of the ground motion component. Under purely elastic structural response, the dynamic filtering component is constituted only by the elastic component and the inelastic counterpart is zero, whereas as the inelastic structural response increases, the proportion of the latter increases with a concurrent reduction in the former.

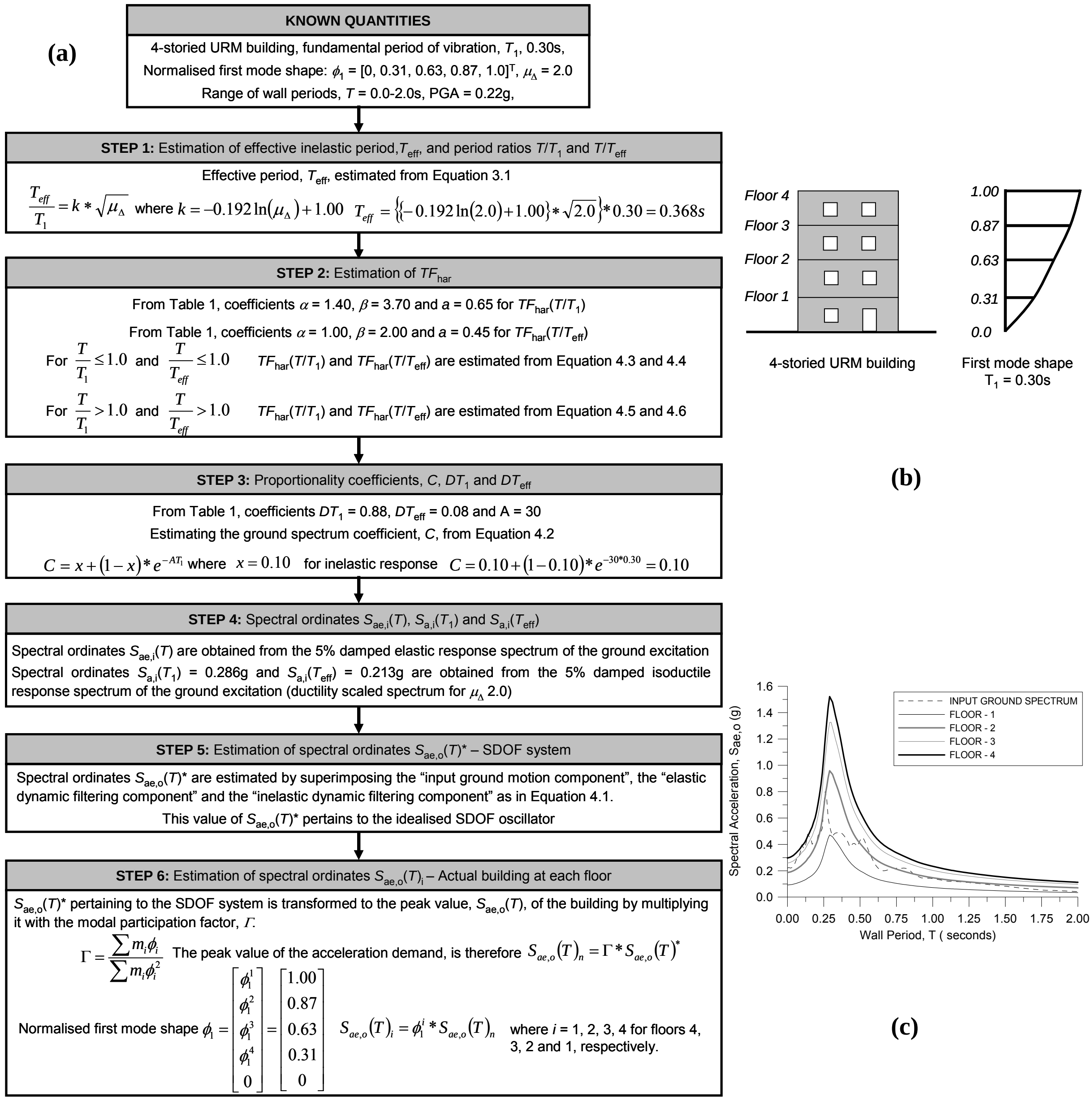

Figure 6: (a) Procedure for estimating floor acceleration demands in an example 4-storied URM building, shown in (b) and (c) floor acceleration spectra for floors 1-4 of the URM building

The seismic demand given by the proposed formulation pertains to an equivalent SDOF model of a URM building. A possible application of the formulation to estimate floor spectra of individual floors of an URM building, based on a generalised SDOF system approach, would involve the transformation of the floor demand relative to the SDOF system to the peak response of the building using the modal participation factor Γ (see Fig. 6). The peak response is then coupled with the normalised first mode shape of the structure to estimate the acceleration floor spectra pertaining to the respective floors. If the acceleration demand on walls, especially in the lower floors, is lower than the peak ground acceleration (PGA), a conservative approach would be to use the PGA directly as the demand on such walls. The procedure described here could be valid for 3-4 storied URM buildings, but neglecting higher mode contributions may not be acceptable for taller and more flexible structures.

5. CONCLUDING REMARKS

The current paper proposes a semi-analytical formulation to estimate acceleration demands on an out-of-plane URM wall (or a generic secondary system) by explicitly accounting for the inelastic response of the primary structure. The formulation is based on statistical evaluation of results of inelastic dynamic THA executed within a parametric framework on an SDOF-on-SDOF primary-secondary system, neglecting higher mode contributions. A possible application of the proposed expression in estimating the floor acceleration spectra of 3-4 storied URM buildings, up to a wall period of 2.0s is described. The proposed expression is applicable not only within assessment methods for existing URM buildings but also as a design check in new constructions.

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