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Application of a recently proposed displacement-based assessment procedure for asymmetric-plan RC wall buildings

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Abstract

Architectural layouts of reinforced concrete buildings often require structural walls, with varying dimensions, to be placed in an asymmetric plan configuration. During seismic excitation the asymmetry induces a torsional component of response, which can impact negatively on the performance of the building by increasing demands on both structural and non-structural elements. Furthermore, the torsional response can render existing assessment procedures less effective at providing an accurate estimate of engineering demand parameters. In this paper a recently proposed displacement-based assessment procedure, developed specifically for asymmetric-plan RC wall buildings, is applied to a case study structure.

The method is based on a combination of two existing approaches, with the first being used to predict displacement demands in symmetric reinforced concrete wall buildings, and the second being used to account for torsional response in 2D asymmetric-plan systems. One of the key aspects of the procedure is the concept of assigning effective stiffness properties to the walls. In doing so the method is able to account for the influence of not only stiffness eccentricities but also strength eccentricities, which have been shown to play the more important role during inelastic response. Higher-mode effects, which can have a strong influence on a number of engineering demand parameters, are accounted for using existing simplified expressions.

The case study structure under consideration is an eight storey RC wall building designed in accordance with Eurocode 8. It is modelled using a lumped plasticity approach and then assessed using nonlinear response-history analysis over a range of increasing intensity levels to establish benchmark estimates of several relevant engineering demand parameters. The new displacement-based assessment procedure is then used to assess the building in an equivalent incremental framework. The analyses are then repeated with Modal Pushover Analysis to provide another point of reference for evaluating the new approach. Comparison of the results shows that the newly proposed procedure performs to a satisfactory level in predicting displacement demands and wall shear forces in the case study building.

Discussion is given on the relative merits and drawbacks of the new approach. One of the most significant advantages is that it can deal with what is arguably a highly complex analysis problem without the need of a numerical model. Its major disadvantages are that it is iterative and in its current form cannot account for bidirectional eccentricities of bidirectional excitation. However, it is deemed that the good results obtained in reference to the case study building and its appealing theoretical basis warrant its further development.

Keywords: RC walls, displacement-based assessment, irregular structures, torsional response, higher-mode effects.

1. Introduction

Reinforced concrete (RC) walls are a common lateral load resisting system used to withstand wind and seismic actions in buildings. Typically a number of walls will be located across the building plan; however, it is also common to find structural walls integrated into service cores. In either case it is not unusual that due to architectural constraints the walls will be arranged in an asymmetric configuration with respect to the building plan. During seismic excitation the asymmetry induces a torsional component of response, which can impact negatively on the performance of the building by increasing demands on both structural and non-structural elements. Furthermore, the torsional response can render existing assessment procedures less effective at providing an accurate estimate of engineering demand parameters (EDPs).

This paper examines the use of a newly proposed method for the displacement-based assessment of asymmetric-plan RC wall buildings. In Section 2 the key features of asymmetric-plan buildings are discussed along with a brief review of the some of the past studies on this category of buildings. Following this, Section 3 describes the proposed assessment procedure and details step-by-step the necessary calculations. In Section 4 the method is applied to a case study building and the response predictions compared to benchmark results obtained from nonlinear response-history analysis (NLRHA). This is followed, in Section 5, by a discussion of some of the benefits and drawbacks of the new approach.

2. Asymmetric-plan buildings

2.1 Key features of asymmetric-plan buildings

Fig. 1a shows the plan view of a simple RC wall building. In the *x* direction, lateral loads are resisted by walls 3 and 4, which are identical to each other. In the *z* direction, lateral loads are resisted by walls 1 and 2, with wall 1 assumed to be stiffer and stronger than wall 2. This results in the centre-of-stiffness (CR) and the centre-of-strength (CV) being located to the left of the centre-of-mass (CM). The distance in-plan from CM to CR is referred to as the stiffness eccentricity (e_r), which can be calculated using Eq. 1. Similarly, the distance from CM to CV is the strength eccentricity (e_v), which can be obtained from Eq. 2.

$$e_{rx} = \frac{\sum k_{zi} x_i}{\sum k_{zi}} \tag{1}$$

$$e_{vx} = \frac{\sum V_{zi} x_i}{\sum V_{zi}} \tag{2}$$

As shown in Fig. 1b, the building can be approximately represented by a simple 2D numerical model in which nonlinear springs are used to represent the walls. The floor is assumed to act as a rigid diaphragm and the mass, *m*, and rotational inertia, I_{rot}, are lumped at the centre of the floor area. I_{rot} can be calculated from Eq. 3 for a rectangular floor plan with uniformly distributed mass:

$$I_{rot} = \frac{m}{12}\left(b_x^2 + b_z^2\right) \tag{3}$$

For a symmetric building I_{rot} does not enter into the equations of motion; however, for asymmetric-plan buildings it can play a significant role. The reasons for approximating the building as a 2D system will become apparent in Section 3.

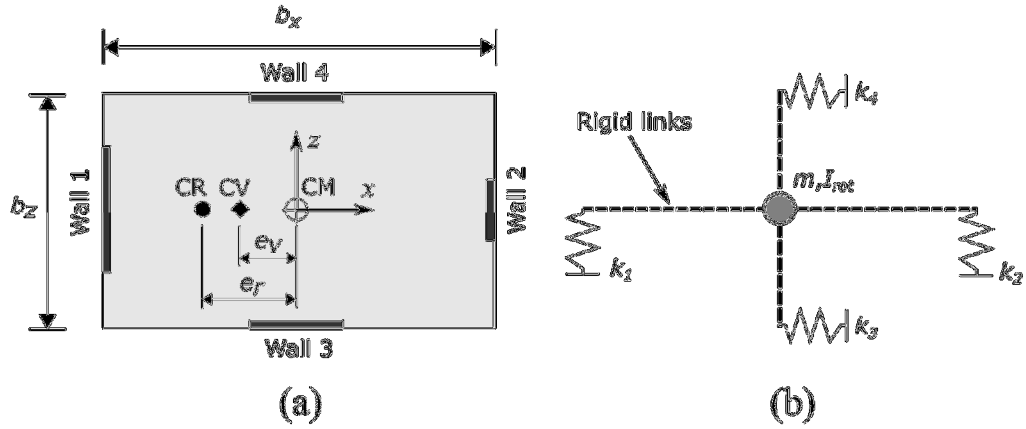


Fig. 1 – (a) Plan view of a RC wall building with an asymmetric configuration. (b) Numerical model of the building represented by an equivalent 2D system (adapted from [1]).

2.2 Previous studies on asymmetric-plan buildings

As summarised by Anagnostopoulos *et al.* [2], the torsional seismic response of structures has been studied extensively in the past. Here the discussion is limited to only the most relevant studies with respect to the current work.

Paulay [3, 4, 5] carried out a number of investigations into the torsional response of asymmetric ductile buildings. It was demonstrated that traditional codified techniques, based on the evaluation of torsional effects in elastic systems, are largely irrelevant during inelastic response. As a result, it was emphasised that the distribution of strength to the structural elements (which was argued to be the designer's choice) is of critical importance. A focus was also placed on controlling the ductility demand on critical structural elements, rather than the consideration of limiting the rotation of the system.

To come to such conclusions, Paulay often considered ductile systems under a static lateral load. Although this is useful for elucidating some of the phenomena relating to torsional response, it must be kept in mind that it is the response under dynamic earthquake excitation that is of interest, which is significantly more complex than the consideration of a static lateral load only.

Following the work by Paulay, Castillo [6] analysed both torsionally restrained (i.e. as per Fig. 1a) and torsionally unrestrained (as per Fig. 1a but with walls 3 and 4 removed) single-storey systems under unidirectional excitation using a set of three ground motions. The most significant findings were:

- The strong wall in torsionally unrestrained systems can yield, but only if the rotational inertia is greater than zero. This is in contrast to the behaviour of such systems under an equivalent static horizontal force, in which the strong wall will never yield. It is therefore essential to include the rotational inertia in such studies.
- The displacement demand on the CM can be predicted by an equivalent single-degree-of-freedom (SDOF) system that has been assigned the effective translational mass of the system and the total lateral stiffness.
- Stiffness eccentricity plays a relatively minor role in the response of ductile systems and if strength eccentricity is zero then the displacement demand on the CM, stiff edge and flexible edge will be similar. It should be kept in mind though that this finding was made considering only systems with large ductility demands in the order of five.
- For the design of structures, strength eccentricity is acceptable as long as it results from an excess of strength above that required for zero strength eccentricity. This finding was the basis of the design method developed by Castillo.

Based on the existing findings of Castillo [6] and the results of additional parametric studies, Beyer *et al.* [7] developed a displacement-based design approach for asymmetric-plan RC wall buildings. An important finding from work of Beyer *et al*. [7] was that both strength and stiffness eccentricity influence the torsional response of ductile asymmetric-plan systems.

Another relevant piece of work meriting discussion is the Modal Pushover Analysis of Chopra and Goel [8], which has been extended to include also the consideration of asymmetric-plan buildings [9]. In brief, the approach consists of conducting a pushover analysis for each mode of vibration using loading vectors that are based on the elastic mode shape. The responses due to the separate modal pushovers are combined using an appropriate modal combination rule. This approach was shown to provide accurate predictions of demands in an asymmetric-plan multi-storey frame building [9].

3. Details of the proposed method

The proposed methodology is a combination of two existing approaches. The first is Displacement-Based Assessment in accordance with Priestley *et al*. [10], which has been shown to provide accurate predictions of the response of regular (i.e. symmetric) RC wall buildings. The second is the recently developed approach of Fox *et al.* [1], which can provide accurate predictions of the torsional response of 2D (or equivalently single-storey) asymmetric-plan systems. The new methodology is herein described in three distinct parts. In part one the centre-of-mass displacement of the building is determined, in part two the torsional response is accounted for, and in part three the effects of higher modes are considered.

3.1 Part 1: Centre-of-mass displacement

As mentioned previously, the studies of Castillo [6] showed that the centre-of-mass displacement, Δ_{CM}, of an asymmetric-plan system can be determined with reasonable accuracy by assuming the structure is fully torsionally restrained (i.e. not rotation about the vertical axis). To this end, the displacement-based assessment procedure of [10] is used to determine the displacement demand on an equivalent single-degree-of-freedom (SDOF) system as follows:

1) The moment capacity and yield curvatures at the base of each wall are determined. This can be achieved using a sectional analysis computer program or alternatively by means of simplified equations (e.g. as included in [10]).
2) The yield displacement of each wall is then calculated. First Eq. 4 is used to determine the displacement at each floor level, *i*, at the onset of yielding by setting the plastic rotation at the base of the wall, θ_p, to zero. Eq. 5 is then used to determine the yield displacement of each wall in reference to an equivalent SDOF system.

$$\Delta_i = \frac{\phi_{Wy}}{2} h_i^2 \left(1 - \frac{h_i}{3H_n}\right) + \theta_p h_i \tag{4}$$

$$\Delta_d = \frac{\sum_{i=1}^{n} \left(m_i \Delta_i^2\right)}{\sum_{i=1}^{n} \left(m_i \Delta_i\right)} \tag{5}$$

3) The effective mass, m_e, and effective height, H_e, of the equivalent SDOF system are then calculated using Eq. 6 and Eq. 7, respectively. For the simple case of a structure with one stiff and one flexible wall, as shown in Fig. 1a, the Δ_i should be those corresponding to the displacement profile of the stiff wall, which will dominate the overall displaced shape of the building (recalling that in part 1 zero twist is assumed). In more complex configurations some judgement will need to be exercised by the engineer. It is also noted that in accordance with [10] the displacements used in Eq. 6 and Eq. 7 should correspond to the displaced shape of the building at the expected level of displacement demand; however, using the displacement profile at yield was found to be sufficiently accurate in the context of the current study.

$$m_e = \frac{\left[\sum_{i=1}^{n}(m_i \Delta_i)\right]^2}{\sum_{i=1}^{n}(m_i \Delta_i^2)} \tag{6}$$

$$H_e = \frac{\sum_{i=1}^{n}(m_i \Delta_i h_i)}{\sum_{i=1}^{n}(m_i \Delta_i)} \tag{7}$$

4) An initial estimate of the displacement demand is then made and the base shear calculated using Eq. 8:

$$V_b = \sum M_{Wj} / H_e \tag{8}$$

where M_{Wj} is the moment at the base of wall j, taking into account the possibility that it may or may not have exceeded its yield strength. With an estimate of the displacement demand and base shear, the effective (i.e. secant) stiffness and corresponding effective period of the equivalent SDOF can be determined using Eq. 9 and Eq. 10, respectively.

$$K_e = V_b / \Delta_{d,CM} \tag{9}$$

$$T_e = 2\pi \sqrt{\frac{m_e}{K_e}} \tag{10}$$

5) It is then necessary to calculate an equivalent viscous damping (EVD) ratio. For RC wall buildings Eq. 11, which is based on a 'thin' Takeda hysteresis rule, is appropriate. Because different walls may be subjected to different ductility demands it is necessary to use in Eq. 11 an equivalent system ductility demand, which can be calculated from Eq. 12.

$$\xi_{eq} = 0.05 + 0.444\left(\frac{\mu_{sys} - 1}{\mu_{sys}\pi}\right) \tag{11}$$

$$\mu_{sys} = \sum M_{Wj} \mu_j \tag{12}$$

where μ_j is the ductility demand on wall j. Because at this stage the system is assumed to be fully torsionally restrained the ductility demand on a given wall (in the direction of loading) can be calculated as:

$$\mu_j = \max\left(1; \frac{\Delta_{d,CM}}{\Delta_{yj}}\right) \tag{13}$$

6) Having calculated an EVD ratio it is then possible to calculate a damping reduction factor, η, as per Eq. 14. The 5 % damped spectral displacement demand at the effective period is then multiplied by η and one obtains a revised estimate of the centre-of-mass displacement demand (Eq. 15). If the revised value does not match the original guess then it is necessary to iterate, repeating steps 4, 5 and 6 until convergence. It

is noted here that the approach of [10] is 'direct' when used for design and iterative only in the assessment case.

$$\eta = \sqrt{\frac{0.07}{0.02 + \xi_{eq}}} \tag{14}$$

$$\Delta_{d,CM} = \eta . Sd(T_e) \tag{15}$$

3.2 Part 2: Accounting for torsional response

Having obtained the displacement demand at the centre-of-mass of an equivalent SDOF system it is now necessary to account for the torsional response. This is achieved by treating the structure as an equivalent 2DOF system, i.e. with a translational and a rotational degree-of-freedom. All necessary properties required to define the equivalent 2DOF system have been determined previously, with the exception of an equivalent rotational inertia, $I_{rot,e}$, which is calculated using Eq. 16:

$$I_{rot,e} = m_e \frac{\sum m_i}{\sum I_{rot,i}} \tag{16}$$

where $I_{rot,i}$ is the rotation inertia of floor i (e.g. Eqn. 3 for a rectangular floor plan).

From herein the procedure used to determine the rotation of the 2DOF system is identical to that presented in Fox *et al.* [1].

1) The effective (secant) stiffness of each wall (which can now be considered as equivalent springs, as per Fig. 1b) is determined from Eq. 17. For the first iteration the equivalent SDOF wall displacement, Δ_j, is assumed to be equal to the centre-of-mass displacement found previously.

$$k_{e,j} = \min\left[k_j, \frac{M_{Wj}}{H_e \Delta_j}\right] \tag{17}$$

2) The effective wall stiffnesses are then used to calculate an effective stiffness eccentricity and subsequently an effective rotational stiffness (about the effective centre-of-stiffness), using Eq. 18 and Eq. 19, respectively.

$$e_{r,eff} = \frac{\sum k_{j,eff} x_j}{\sum k_{j,eff}} \tag{18}$$

$$K_{rot_{eff},CR_{eff}} = \sum k_{zj,eff}\left(x_j - e_{r,eff}\right)^2 + \sum k_{xj} z_j^2 \tag{19}$$

3) A standard eigenvalue analysis, but with effective wall stiffnesses, is then carried out and the results used to calculate a torque, T, to apply to the system (Eq. 20).

$$T = V_b \frac{I_{rot,e}}{m_e} \frac{\phi_{21}}{\phi_{11}} \tag{20}$$

where ϕ_{11} and ϕ_{21} are the two terms in the first mode eigenvector, corresponding to translation in the direction of earthquake excitation and rotation about the vertical axis, respectively.

Although typically an eigenvalue analysis requires specialised software, it is near trivial in the case of a 2DOF system and can be undertaken by hand. The mass and stiffness matrices are given by Eqn. 21 and 22 (z and x directions correspond to those shown in Fig. 1a, assuming loading in the z direction).

$$\mathbf{M} = \begin{bmatrix} m & 0 \\ 0 & I_{rot} \end{bmatrix} \qquad \mathbf{K} = \begin{bmatrix} \sum k_{zj,eff} & \sum k_{zj,eff} x_j^2 + \sum k_{xj,eff} z_j^2 \\ \sum k_{zj,eff} x_j^2 + \sum k_{xj,eff} z_j^2 & \sum k_{zj,eff} x_j \end{bmatrix} \qquad (21, 22)$$

The first mode eigenvalue can by calculated from Eqn. 23 and if ϕ_{11} is set equal to one then the second term of the first mode eigenvector can be found from Eqn. 24:

$$\omega_1^2 = \frac{(k_{11}m_{22} + k_{22}m_{11}) - \sqrt{(k_{11}m_{22} + k_{22}m_{11})^2 - 4m_{11}m_{22}(k_{11}k_{22} - k_{22}^2)}}{2m_{11}m_{22}} \qquad (23)$$

$$\phi_{21} = \frac{\omega_1^2 m_{11} - k_{11}}{k_{12}} \qquad (24)$$

where the m_{ij} and k_{ij} correspond to the terms in the mass and stiffness matrices (Eqn. 21 and 22).

4) The rotation of the system can now be obtained using Eq. 25 and the wall (or strictly equivalent spring) displacements found using Eq. 26 and Eq. 27. Note that in Eq. 25 the sign of the $e_{r,eff}$ term must be respected.

$$\theta = \frac{T - e_{r,eff} V}{K_{rot_{eff},CR_{eff}}} \qquad (25)$$

$$\Delta_{zi} = \Delta_{CM} + x_i \theta \qquad (26)$$

$$\Delta_{xi} = z_i \theta \qquad (27)$$

5) At this point the influence of the second mode of vibration, which is predominantly torsional, is accounted for. The displacements due to the second mode of vibration can be obtained from Eq. 28, which uses the results of the modal analysis conducted in step 3. The second mode displacements can then be combined with those of the first mode using the square-root-sum-of the-squares (SRSS) rule. Note that in reference to mode numbers the purely translational modes in the direction orthogonal to loading have not been considered.

$$\begin{Bmatrix} \Delta_{CM} \\ \theta \end{Bmatrix} = \frac{\phi_{12} m_e}{\phi_{12}^2 m_e + \phi_{22}^2 I_{rot,e}} Sd(T_{2,e}) \begin{Bmatrix} \phi_{12} \\ \phi_{22} \end{Bmatrix} \qquad (28)$$

where $T_{2,e}$ is the second mode of vibration of the building with effective stiffness properties.

6) Having obtained the centre-of-mass displacement and rotation of the equivalent 2DOF system it is then necessary to determine the corresponding displaced shapes of the walls. This is done by increasing the plastic rotation term, θ_p, in Eq. 4 until the target displacement is reached. Alternatively, for walls that do not yield, the plastic rotation term is set to zero and the curvature term reduced.

3.3 Part 3: Accounting for higher-effects

Parts 1 and 2, described above, will in general be sufficient for predicting the displacement demands on structural elements. However, to accurately determine a number of other EDPs, such as shear forces, bending moment and floor accelerations, the influence of higher modes of vibration (in addition in the second, torsional, mode) must be considered. A detailed investigation into higher-mode effects is beyond the scope of this paper and so it is limited instead to the consideration of higher-mode effects on the shear force at the base of walls. To this end, the approach of Fox *et al.* [11] is used, which consists of Eqn. 29 to 31.

$$V_{w,base} = \sqrt{V_1^2 + C_2\left(m.Sa(T_c)\right)^2} \tag{29}$$

$$C_2 = \min\begin{cases} 0.048 - 0.008\mu \\ (0.56 - 0.125\mu)(C_1 + 0.01) \end{cases} \tag{30}$$

$$C_1 = \frac{2T_C^2 EI}{mH_n^3} \tag{31}$$

where V_1 is the first mode shear force in a given wall, T_C is the corner period of the design response spectrum between the regions of contact acceleration and constant velocity, and *EI* is the flexural rigidity. Note that the mass should be the tributary mass of the specific wall being considered and similarly the ductility should correspond to the specific wall under consideration.

4. Case study application

To investigate the accuracy of the proposed method a case study building is assessed and the results, in terms of key EDPs, are compared to those obtained from benchmark NLRHA results. In addition, the Modal Pushover Analysis (MPA) method of Chopra and Goel [8, 9] is also included to provide a further comparison.

4.1 Case study building and numerical modelling

The case study building under consideration, which was investigated previously by Fox *et al.* [12], is shown in Fig. 2. To amplify the torsional response, the walls in the NS direction have each been moved in 3 m towards the centre-of-mass. The building has eight stories and a total height of 27.2 m. The fundamental period of the building is 2.76 s when calculated using cracked section properties and the total strength and stiffness of the

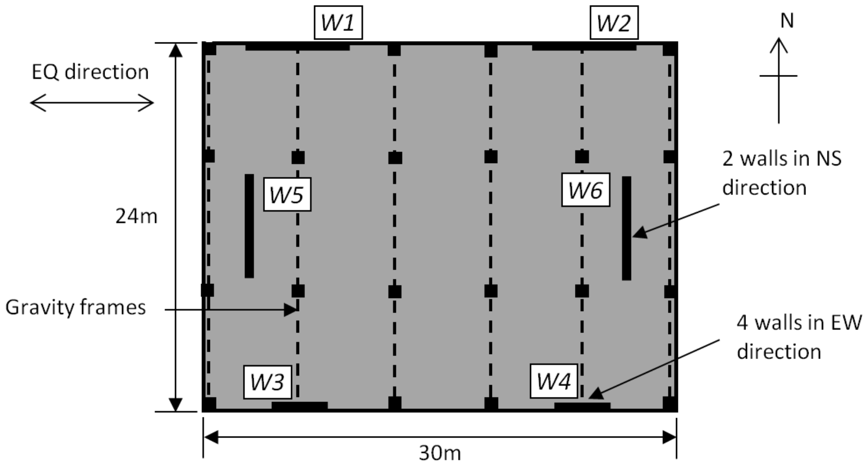


Fig. 2 – Eight storey case study building (adapted from [6]).

building is similar in both the EW and NS directions. In the EW direction four walls resist lateral loads. Walls W1 and W2 are 6.5 m long and have a longitudinal reinforcing ratio of $\rho_v = 0.59$ %. Walls W3 and W4 on the other hand are only 3.5 m long with $\rho_v = 0.68$ %. This results in a building that is asymmetric in plan when considering loading in the EW direction.

For both NLRHA and MPA the building is modelled using Ruaumoko3D [13] with a lumped plasticity approach. The floor diaphragms are modelled as rigid in plane and it is assumed that there is no foundation flexibility. The plastic hinge regions at the bases of the walls are modelled using a 'thin' Takeda hysteresis rule (with $\alpha = 0.5$ and $\beta = 0.0$, see [14]) and the plastic hinge length is calculated in accordance with [10]. Above the plastic hinge region the walls are assumed to remain elastic. A Rayleigh damping modelled is employed in which the stiffness matrix used is the tangent stiffness matrix, based on recommendations made by Priestley and Grant [15] and Petrini *et al.* [16]. For elastic response a damping ratio of 5 % is specified at the first and fourth modes of vibration. For inelastic response the first mode damping ratio is reduced based on the expected ductility demand, as recommended in [10].

4.2 Analyses

The building is analysed in an incremental fashion using the newly proposed method, MPA and NLRHA. The seismicity is represented by the Eurocode 8 [17] type 1 spectrum for ground type C; however, the corner period of the displacement spectrum, T_D, is increased from 2 s to 4 s, as shown in Fig. 3. For the NLRHA a set of 10 ground motions selected by Maley *et al.* [18] are used. The ground motions were selected to have a median response spectrum that is compatible with the aforementioned EC8 spectrum, as shown in Fig. 3. The reference ground acceleration, a_g, is scaled from 0.0 to 0.5 g in steps of 0.05 g. The purpose of conducting analyses in this incremental fashion is to provide a comparison of the different methods over a range of ductility demands. It is important to note that the building is analysed considering excitation in the EW direction only.

4.3 Results

Fig. 4 shows the roof displacements of walls 1 and 3 and the centre-of-mass in the EW direction and the wall 5 roof displacements in the NS direction. Comparing the displacements of wall 1 at the stiffer and stronger edge of the building with those of wall 3, one can see that the building is undergoing a significant level of rotation. Fig. 4c shows the roof level displacements at the centre-of-mass, which are predicted by the proposed method (and MPA) to a sufficient degree of accuracy. This is import considering that the proposed method is based around first determining the centre-of-mass displacements (Section 3.1). The roof level displacements of walls 1 and 3 are also predicted with good accuracy; however, it will be noted that both MPA and the proposed method tend to overestimate displacements for wall 1 and underestimate displacements for wall 3, which is indicative of the rotation of the system being underestimated. This is also reflected in the underestimation of the transverse wall

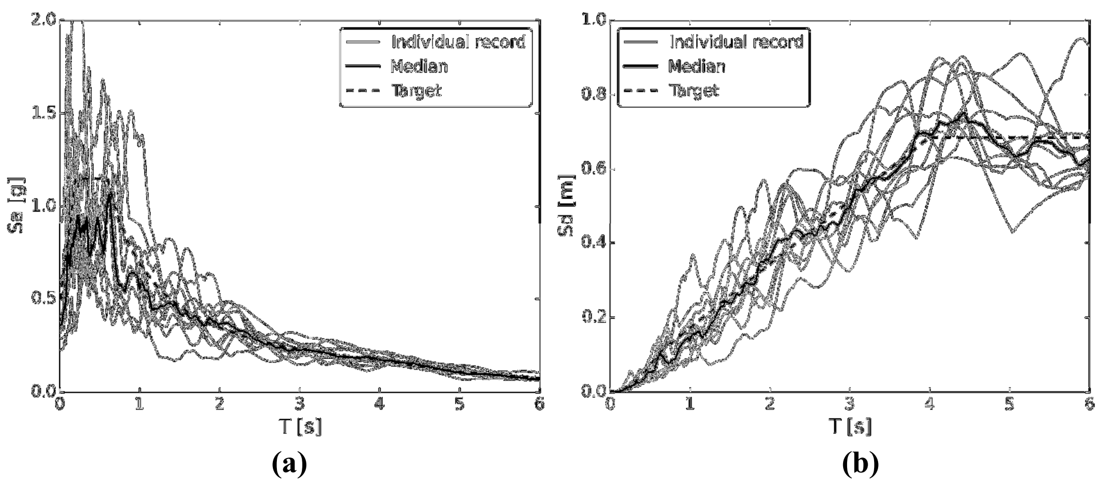


Fig. 3 – Design response spectrum used for analyses at $a_g = 0.4$ g and response spectra of selected ground motions from [18].

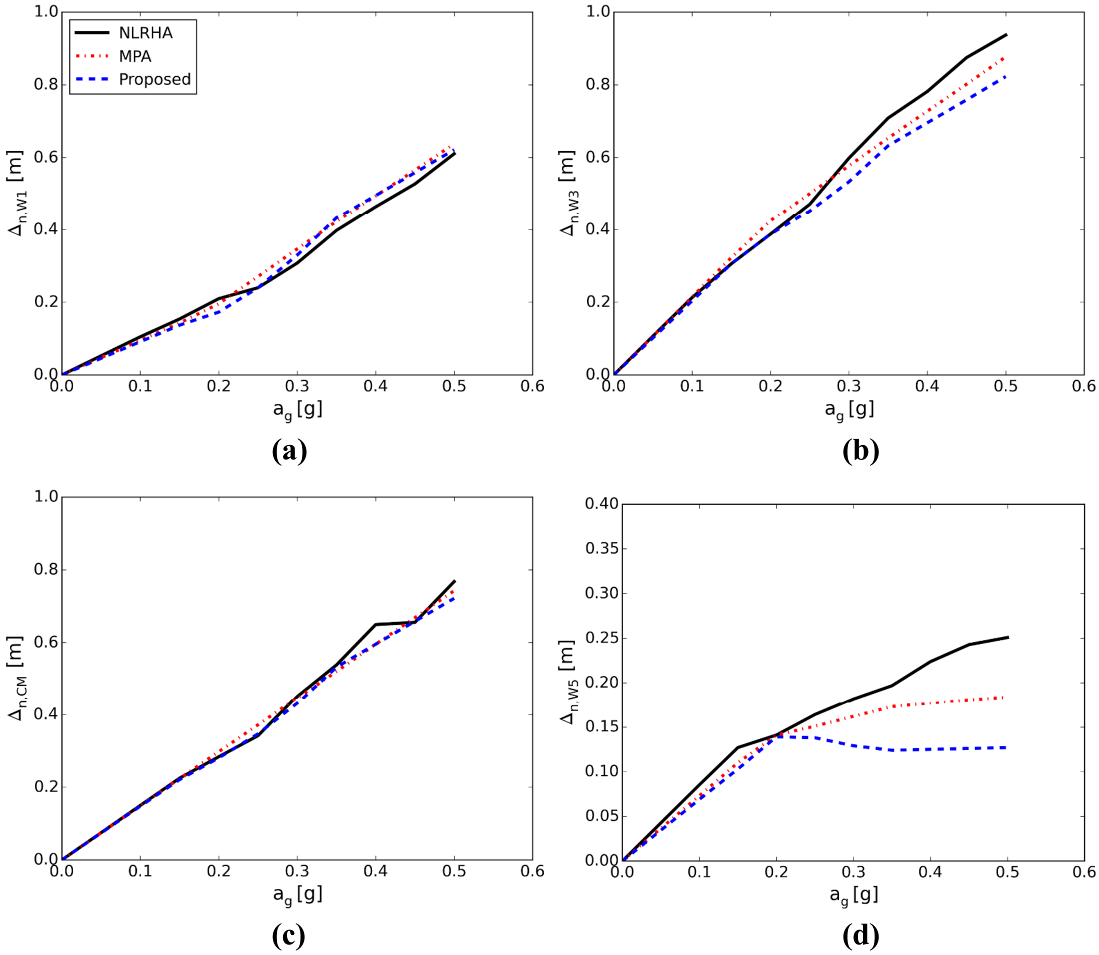
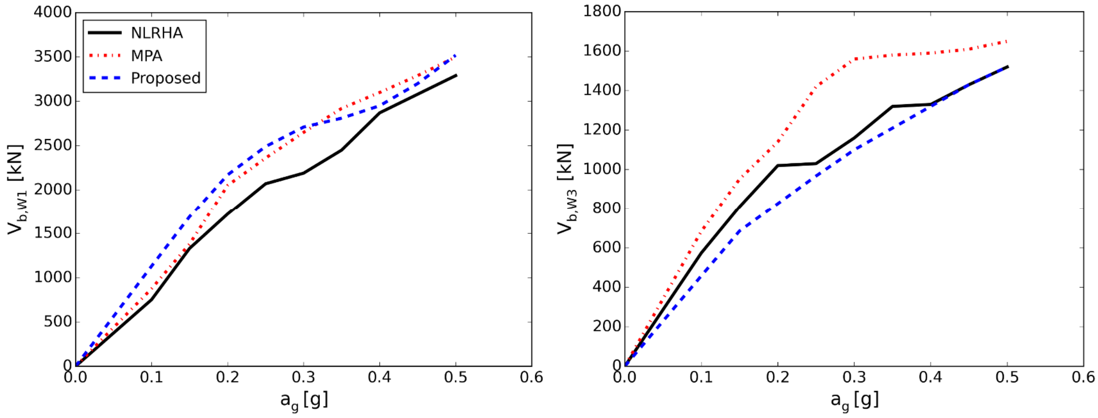


Fig. 4 – Roof displacements obtained using the three different methods for: (a) Wall 1; (b) Wall 3; (c) centre-of-mass; and (d) Wall 5 (NS direction).

(wall 5) displacements, shown in Fig.4, which are directly proportional to the rotation of the system when loading is in the EW direction only.

Inspection of Fig. 4c and Fig. 4d reveals an interesting feature of the response of this type of building which is that the ratio of displacements to rotation (using wall 5 displacements as a proxy) does not remain constant. Once the structures yields, between a_g = 0.15 and 0.2 g, the centre-of-mass roof displacement continues to increase approximately linearly (i.e. the equal displacement rule) while the rotation increases less rapidly. This phenomenon is captured by both the proposed method and MPA, but it is in fact significantly overestimated by both, with the wall 5 displacements remaining relatively constant after yield.

Fig. 5 shows the predicted shear forces estimated at the bases of walls 1 and 3. In wall 1, both the newly proposed method and MPA overestimate the expected shear force. In wall 3 the proposed method fractionally underestimates shear forces whereas they are significantly overestimated by MPA. Overall it could be argued that the predictions are reasonably good given the complexity of predicting shear forces in such a building. The success of the Fox *et al.* [11] approach appears to be a result of the torsional modes of vibration having only a minor influence on shear forces when compared to the predominantly translational modes of vibration. It should also be noted that the use of walls with different lengths connected by rigid diaphragms can induce large compatibility shear forces, as explained by Beyer *et al.* [19]. Although compatibility forces are unlikely to be severe in this case, due to the different length walls be located on opposite sides of the building plan, they may still play some role in the shear forces observed in Fig. 5 and are inherently difficult to account for using simplified analysis techniques.



(a) **(b)**

Fig. 5 – Shear forces obtained using the three different methods for: (a) Wall 1; and (b) Wall 3.

5. Discussion

When applied to the case study building the newly proposed methodology yielded generally satisfactory predictions of roof displacements and shear forces. In general the accuracy was comparable to that of Modal Pushover Analysis; however, a notable difference between the approaches is that the proposed procedure does not require the use of a numerical model or software capable of nonlinear analyses. Instead the new procedure can be undertaken by hand and with the use of a spreadsheet is very rapid. Clearly though the benefit of not requiring a numerical model is dependent on the scenario at hand and the particular expertise of the engineer.

Whilst it is important to consider the accuracy of the results obtained using the new approach, one should also consider the theory behind it. As mentioned earlier, both stiffness and strength eccentricities affect the response of asymmetric-plan structures. By considering the effective stiffness of the walls it is possible to capture the influence of both, for example, in the case study structure the effective stiffness eccentricity tends to decrease with ductility demand as the strength eccentricity begins to play a more important role. It is noted that this effect is not accounted for in MPA. Consider the case of a structure with a moderate strength eccentricity but zero stiffness eccentricity. In this instance the load vectors for MPA, which are based on the elastic modal response, would not include rotational loads about the vertical axis. This implies that rotational inertia forces play no role in the response, which is clearly not realistic.

The case study scenario considered in this work is rather simplistic in that the building was asymmetric in one direction only and was subjected to unidirectional excitation. It is likely that in practice one would encounter buildings that have stiffness and/or strength eccentricities in both their principle directions. Furthermore, the idea of unidirectional excitation is useful for simplifying analyses, but in reality such ground motions do not exist and therefore the effects of bidirectional excitation should always be considered. The use of an effective stiffness based approach, as has been presented, may be useful in considering the case of bidirectional eccentricities and excitation. The rationale behind this argument can be explained with reference to the case study building. If loading is considered in also the NS direction then at high intensities it is expected that walls 5 and 6 would yield. This would consequently reduce their ability to resist torsion, i.e. there is an effective reduction in stiffness.

6. Conclusions

A proposed approach for the seismic assessment of asymmetric-plan RC wall buildings has been presented. The method is based on the existing displacement-based assessment approach of Priestley *et al.* [10] for symmetric wall buildings and then incorporates the procedure develop by Fox *et al.* [1] to account for the torsional response. The new approach was applied to an eight storey case study building to assess roof displacements and wall shear forces. Comparison with benchmark NLRHA results showed the method to be sufficiently accurate and in fact it achieved results that were comparable to Modal Pushover Analysis.

Although the examination of the proposed approach was rather limited in this study, it was argued that it has a number of theoretically appealing aspects. It therefore serves as a solid platform for future development. In particular, future development could include extension to more complex cases involving bidirectional eccentricities and bidirectional excitation.

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