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New Behavioural Trends of Plan Asymmetric Limited Ductile Buildings Revealed by Incremental Dynamic Analysis

Yao Hu[a], Elisa Lumantarna[a], Nelson Lam[a], and Hing-Ho Tsang[b]

[a]Department of Infrastructure Engineering, The University of Melbourne, Melbourne, Australia; [b]School of Engineering, Swinburne University of Technology, Melbourne, Australia

ABSTRACT

The drift demand of plan-asymmetric buildings in low seismicity regions was studied by employing Incremental Dynamic Analysis to track the influence of torsion. A stepped increase in the (3D/2D) drift demand ratio was observed as the limit of yield was surpassed. This amplification phenomenon, which is typically muted with high, or moderate, ductility demand has not been reported in research literature on building responses in high seismic conditions. However, the undesirable torsion-induced amplification cannot be ignored as limited ductile buildings are particularly vulnerable depending on the disposition, number, size and orientation of the structural walls.

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KEYWORDS
Plan-asymmetric buildings; incremental dynamic analysis; drift demand ratio; torsional behaviour; post yield conditions

1. Introduction

Torsional behaviour of buildings in an earthquake has been a topic of research in past decades (e.g. Anagnostopoulos, Kyrkos, and Stathopoulos 2015; Chandler and Duan 1990; De Stefano and Pintucchi 2008; Fajfar and Krawinkler 1992; Mccrum and Broderick 2013). Buildings featuring plan asymmetry have been found to experience more damage in earthquakes than their symmetric counterparts (Kewalramani and Syed 2018; Sritharan et al. 2014). Torsional effects based on elastic and inelastic analyses have been well investigated for a wide range of system parameters (Goel and Chopra 1990, 1991a, 1991b). Two key controlling parameters at the structural system level have been identified: (i) eccentricity, which is the offset of the centre of resistance (CR) from the centre of mass (CM) of the building, and (ii) the ratio of the uncoupled torsional to lateral frequency Ω, which is referred as the torsional stiffness parameter (Cosenza, Manfredi, and Realfonzo 2000; Kim and Bang 2002; Tabatabaei and Saffari 2010). Large eccentricity has been found to have undesirable effects on torsional amplification (Chandler and Hutchinson 1986; Nagarajaiah, Reinhorn, and Constantinou 1993; Tena-Colunga and Escamilla-Cruz 2007; Tso and Sadek 1985). Torsional amplification in buildings with higher torsional stiffness (i.e. $\Omega > 1$) was found to be better controlled as the extent of torsional coupling becomes more suppressed (Humar and Kumar 1999; Jiang and Kuang 2016; Peruš and Fajfar 2005). A minimum value of $\Omega = 1.4$ was recommended to be adopted in the seismic design of a building which has a normalised eccentricity of up to 0.2. For buildings with a higher eccentricity, the limiting value of Ω was recommended to be increased to 1.6 (Kuang and Liu 2022).

The limits for the eccentricity and Ω parameters have been incorporated in some codes of practices for the seismic design of asymmetric buildings based on linear elastic behaviour (e.g. CEN 2005). In a design employing elastic analysis of the building structure, the ductility reduction factor (forming part of what is described in design standards as the "behaviour factor" or "structural response factor") is totally based on considering the post-yield behaviour of the building responding purely in

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CONTACT Yao Hu ✉ yaoh4@student.unimelb.edu.au Department of Infrastructure Engineering, The University of Melbourne, Parkville, Victoria 3010, Australia

translation. Thus, the implicit assumption is that the additional drift demand on the lateral load resisting elements caused by torsion (with the maximum value experienced at an edge of the building) would not worsen significantly as the yield limit of the structure is surpassed. Making this erroneous assumption may understate the actual torsional action in the building when excited beyond the limit of yield. Nonlinear static analysis (also known as "pushover analysis") methods stipulated by major design codes of practices (ASCE 2007; CEN 2005) have been found to give overly conservative estimates of the effects of torsional actions in an irregular building because of limitations with the use of statics to emulate dynamic response behaviour taking into account the effects of coupling between the vibrational modes (Bhatt and Bento 2011; Harasimowicz and Goel 1998). Other modified nonlinear static analysis procedures such as multi-mode pushover (MMP) analysis (Sasaki, Freeman, and Paret 1998), modal pushover analysis (Chopra and Goel 2004) and modified pushover analysis (D'Ambrisi, De Stefano, and Tanganelli 2009) have been developed to account for the effects of the higher modes, which have been shown to correlate reasonably well with results from inelastic dynamic analysis. Nonlinear static analysis incorporating the lumped plasticity model has demonstrated its efficacy and reliability for assessing the seismic vulnerability of the building featuring asymmetry in plan (Mazza 2014). Despite these advancements, the modified methods that have been developed can have limited uptake by design engineers operating in regions of low to moderate seismicity.

Torsional actions in the inelastic range have been found from research to be dependent mainly on strength eccentricity and the plan configurations of the lateral load resisting elements, and not so much on the stiffness parameters (Bhasker and Menon 2020, 2022; De La Llera and Chopra 1996). Torsional studies of buildings in the inelastic range have highlighted the importance of balanced distribution of stiffness and strength to minimise the undesirable effects of torsion (Aminnia and Hosseini 2015; Bhasker and Menon 2020; Myslimaj and Tso 2002, 2004; Tso and Myslimaj 2003). The benefits of the additional torsional stiffness provided by orthogonal walls has been widely reported (De La Llera and Chopra 1996; Goel and Chopra 1990). Lateral load resisting elements (like structural walls) that are orientated in the direction orthogonal to the direction of major ground excitations were found to be the main contributors to resistance against torsional actions (Goel and Chopra 1990). Interestingly, the response of asymmetric systems with high ductility was found to be less affected by plan asymmetry than that predicted by elastic analysis (De Stefano, Faella, and Ramasco 1998; Goel and Chopra 1991a, 1991b). More recently, torsional actions have been found to be muted by high, or moderate, ductility demand (Ha et al. 2019; Kosmopoulos and Fardis 2007; Peruš and Fajfar 2005).

Much of the research into torsional actions in buildings, as reviewed in the foregoing, was based on conditions in high seismic regions. Limited attention has been devoted to torsional behaviour in (code compliant) limited ductile buildings which are commonly found in regions of low seismicity, like Australia. Buildings are currently designed to resist torsional actions as predicted by elastic analysis even though the limit of yield is expected to be surpassed in severe conditions. Significantly, incidences of a building encountering higher torsional actions in the inelastic range than that predicted by elastic analyses have been reported (De Stefano and Pintucchi 2008; Stathopoulos and Anagnostopoulos 2005). Thus, the actual torsional behaviour in a code compliant designed building may be underestimated as the limit of yield is surpassed. Currently, there is a lack of knowledge on the extent of the under-design and the controlling factors.

This study deals with the behaviour of reinforced concrete buildings that are laterally supported by limited ductile reinforced concrete walls. This type of building is prevalent in regions of low to moderate seismicity. Initially, a parametric study was conducted to present the elastic torsional response behaviour of simple building models to establish a frame of reference. Incremental Dynamic Analysis (IDA) was employed to track the trend of torsional actions of limited ductile buildings transitioning from the pre-yield, and post-yield behaviour. Uncertainties as to whether elastic analysis can be relied upon for modelling torsional actions as the building responds into the inelastic range were resolved by systematically studying the behaviour of building models possessing a wide range of eccentricity and stiffness properties. Importantly, the influences of the disposition of structural walls (including core walls), their size, number and orientation on the torsionally induced drift demand of the building were studied. Results from incremental dynamic analyses are expressed in terms of the drift demand ratio $(\Delta_{3D}/\Delta_{2D})$ which is defined as the maximum drift demand on either edge of the building as obtained from 3D analyses in the direction of ground shaking, divided by the drift demand from the 2D analyses of the same building.

The scope of this study is to reveal the trend of torsional actions of limited ductile buildings transitioning from the elastic to inelastic range. Incremental dynamic analysis (IDA) was employed to scale seismic excitations up to 0.5 g (which is only relevant to areas where structures are typically of high ductility). The purpose of varying the intensity to this large extent was to track the sensitivity of the amplification anomaly to changes in intensity, and ductility. The emergence of the anomaly which is of particular concern in the low seismicity contexts, has not been documented in the literature. These results underscore the vulnerability of limited ductile buildings subjected to earthquakes, depending on the disposition, number, size and orientation of the structural walls. The newly revealed torsional behaviour highlights a critical aspect of building response that warrants further study and consideration of limited ductile buildings in seismic design practices.

2. Parameters Controlling Elastic Response Behaviour

The first phase of the study dealt with elastic analyses of simple single-storey frame-pair models (Fig. 1) which is in alignment with findings from previous investigations undertaken by the authors (Lam, Wilson, and Lumantarna 2016; Lumantarna et al. 2017, 2018). The reason for presenting known behaviour of simple models (of linear elastic properties) is to provide a frame of reference to be used in the later part of the article which deals with the more complex post-yield behaviour and is also for the benefits of those readers who are not familiar with the parameters introduced herein. One of two controlling parameters of the simple models is the elastic radius ratio (b_r), which is referred as Ω in previous publications (Humar and Kumar 1999; Kuang and Liu 2022). Ω is defined as the square root of the ratio of torsional stiffness (k_θ) to translational stiffness of the lateral load resisting elements in the building, normalised with respect to the mass radius of gyration (r). The values of b_r and r can be calculated using Eq. (1). Another parameter of interest is the eccentricity ratio (e_r) which is defined as the offset of the CR from the CM of the building (represented by e_x) normalised with respect to r. In the following, the parameter B_r is defined as the furthest distance of the edge element from CM (B_x) normalised with respect to r, as expressed in Eq. (2); k_{y1} and k_{y2} are the stiffness of lateral load resisting elements along the y direction, respectively; k_θ is the rotational stiffness, which is defined by Eq. (3). x_1 and x_2 are distances from each lateral load resisting element to CM; a and b indicate the width and length for a regular floor plan; $\Delta_{flexible}$, Δ_{stiff}, and Δ_{2D} represent the maximum drift demand derived from three dimensional (3D) models at the flexible and stiff edges, and two dimensional (2D) models, respectively.

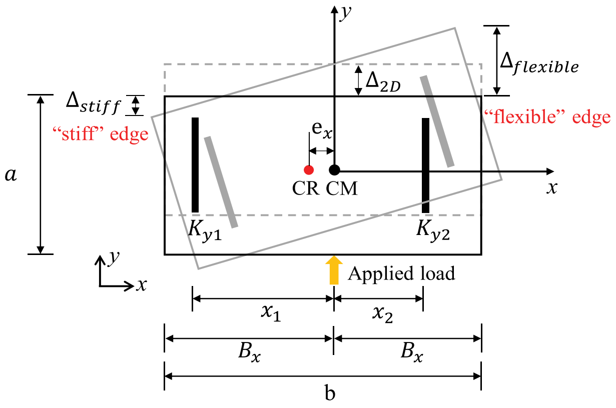
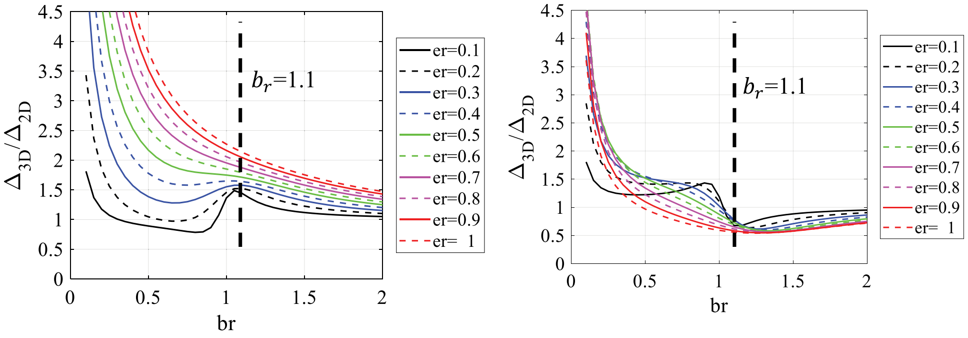


Figure 1. Single "frame-pair" model associated with torsion.



(a) B_r = 1.5 for flexible edge

(b) B_r = 1.5 for stiff edge

Figure 2. Maximum drift demand ratio from 3D analysis to 2D model.

$$b_r = \frac{1}{r}\sqrt{\frac{K_\theta}{K_{y1} + K_{y2}}}, r = \sqrt{\frac{a^2 + b^2}{12}} \tag{1}$$

$$e_r = \frac{e_x}{r}, B_r = \frac{B_x}{r} \tag{2}$$

$$K_\theta = K_{y1}(x_1 - e_x)^2 + K_{y2}(x_2 + e_x)^2 \tag{3}$$

The drift demand ratio (Δ_{3D}/Δ_{2D}) for the velocity-controlled condition with $B_r = 1.5$ based on response spectrum analyses is presented in Fig. 2 to illustrate the effect of the torsional parameters on the drift demand of plan asymmetric buildings of linear elastic properties. It is shown in Fig. 2 that the drift demand ratio is sensitive to low b_r values in the range of 0.5–1.1, especially for the flexible edge. The drift demand ratio becomes insensitive to e_r and b_r values when the values of b_r are higher than 1.1. The insensitivity of seismic demand to the torsional parameters for systems with high b_r has also been reported in the literature (Khatiwada and Lumantarna 2021; Khatiwada et al. 2020), which demonstrates a similar trend for a wider range of torsional parameters and different conditions controlled by acceleration, velocity and displacement. Thus, a high b_r is favoured in view of the effective suppression of additional drift demand which is caused by torsion. In Eurocode, a building that is categorised as being regular in plan shall satisfy the conditions that the value of b_r is equal to, or exceed, unity (CEN 2005).

3. Ground Motion Selection for Nonlinear Time-History Analyses

Having introduced parameters controlling torsional behaviour in the elastic range, the rest of this article presents findings from non-linear time-history analyses of models experiencing inelastic behaviour. Ground motion selection for supporting this type of analyses was based on site-specific response spectra for flexible soil sites in earthquake scenarios consistent with a notional peak ground acceleration of 0.12 g that corresponds to a return period of 2500 years (Standards Australia 2018). Six bedrock ground motion ensembles recorded have been retrieved from the PEER database and then scaled to the conditional mean spectrum (CMS) with a reference period of 0.5s. The list of the ground motion records used is presented in Table 1.

Further details of the selection of accelerograms can be found in Hu et al. (2022). The average response spectral acceleration (RSA) of individual bedrock ground motion demonstrates good agreement with CMS, as shown in Fig. 3(a). These bedrock ground motions were input into site response analyses for generating accelerograms on the surface of the targeted soft soil site (class

Table 1. Details for the selected bedrock ground motion ensemble.

Ref. number	Earthquake name	Year	Station name	Magnitude	Mechanism	Rjb (km)	Rrup (km)	Vs30 (m/sec)
1	Whittier Narrows-01	1987	Brea Dam (L Abut)	6.0	Reverse Oblique	19.1	24.0	437.5
2	Chi-Chi_ Taiwan-02	1999	TCU071	5.9	Reverse	20.1	21.1	624.9
3	Whittier Narrows-01	1987	Beverly Hills – 12520 Mulhol	6.0	Reverse Oblique	25.9	29.9	545.7
4	N.Palm Springs	1986	San Jacinto – Sobob	6.1	Reverse Oblique	22.9	23.3	447.2
5	Coalinga-01	1983	Parkfield – Stone Corral 3E	6.4	Reverse	32.8	34.0	565.1
6	Loma Prieta	1989	Yerba Buena Island	6.9	Reverse Oblique	75.1	75.2	659.8

D site) with a site natural period of 0.68s. The corresponding soil accelerograms are shown in Figs. 3(b–g). In this study, building models with walls in the perpendicular direction was only excited by full intensity in one direction (i.e. 100% of acceleration), while the building models with the presence of orthogonal walls were subjected to bi-directional excitations based on full intensity in one direction and 30% in the orthogonal direction (Standards Australia 2018). The alternative method of combination is to apply 70.7% + 70.7% scaling of the excitations in the two orthogonal directions. Both methods would ensure a resultant intensity equal, or close, to a resultant intensity of 100%.

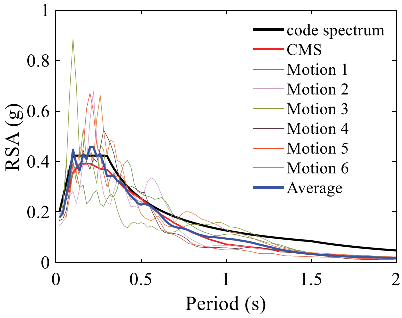
4. Parametric Studies of Single-Storey Building Models in the Inelastic Range

The study was aimed at detecting anomalies in inelastic torsional response behaviour of RC buildings that is not already known from any previous investigation. The influences of the following factors on the additional drift demand on the building generated by torsion were studied while holding eccentricity and torsional stiffness (e_r and b_r) constant: (1) disposition of the structural walls on the floor plan (2) number of structural walls (3) size of structural walls and (4) presence of orthogonal walls.

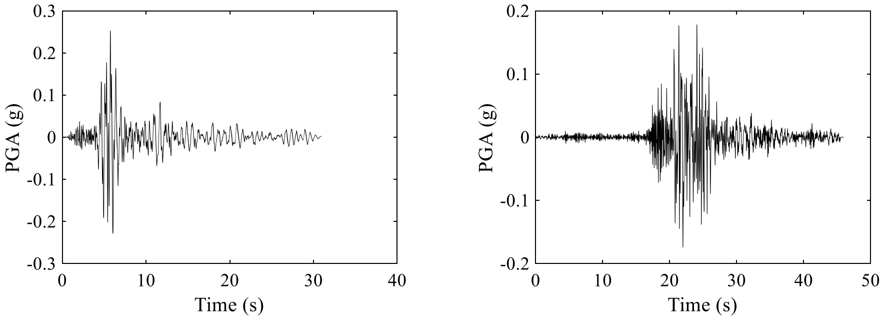
Parametric studies of single-storey building models will be conducted using Incremental Dynamic Analyses. There are equivalent static analysis provisions stipulated by design codes of practices (ASCE 2007; CEN 2005) or more advanced nonlinear static analysis such as multi-mode pushover (MMP) analysis (Sasaki, Freeman, and Paret 1998), modal pushover analysis (Chopra and Goel 2004), consecutive modal pushover (CMP) (Poursha, Khoshnoudian, and Moghadam 2009) that allow for estimating the effects of torsional actions in an irregular building. These conventional pushover analysis methods typically rely on defining a single target displacement, often at the mass centre, to approximate the response of the structure under seismic loading. However, in irregular buildings, the distribution of lateral displacements across the structural height and plan can vary significantly due to torsional effects and mode shapes. This non-uniformity makes it difficult for conventional methods to accurately capture the structural response, as they may not adequately represent the distribution of seismic forces throughout the building (D'Ambrisi, De Stefano, and Tanganelli 2009). As the objective of the study was to track the behavioural trend in the transition from the elastic to inelastic range, incremental non-linear dynamic analyses utilising scaled real earthquake records of gradual increase in intensity was preferred.

4.1. Building Models

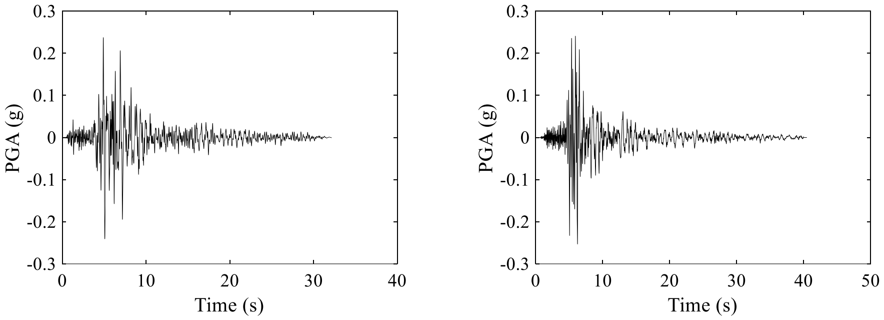
The single-storey building model, characterised by a rigid deck and lateral load resisting elements as shown in Fig. 4(a), was subject to parametric studies taking advantage of the appealing computational



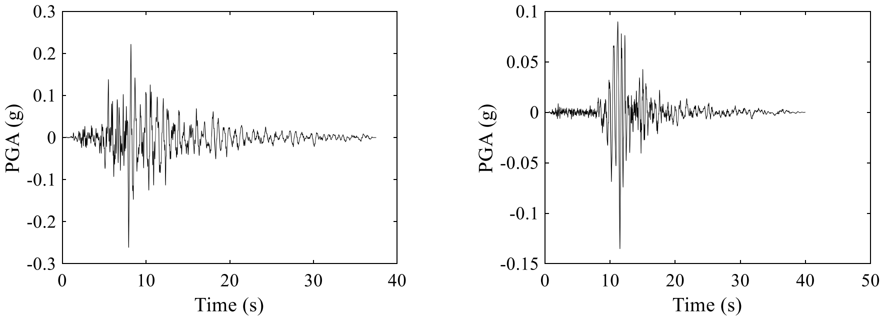
(a) RSA of bedrock ground motion ensemble, CMS and the class B code spectrum



(b) Accelerogram 1 (c) Accelerogram 2



(d) Accelerogram 3 (e) Accelerogram 4



(f) Accelerogram 5 (g) Accelerogram 6

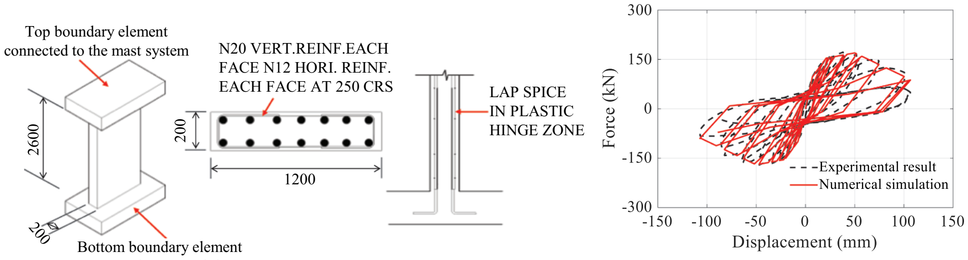
Figure 3. RSA of bedrock ground motion ensemble, the CMS and the class B code response spectrum and corresponding soil surface accelerograms of class D site.

efficiency (Anagnostopoulos, Kyrkos, and Stathopoulos 2015; Goel and Chopra 1990; Humar and Kumar 2004; Mccrum and Broderick 2013). The building model featured uni-directional eccentricity and the support of RC walls of limited ductility. Numerical modelling of the structural walls was developed by use of OpenSees software (Mckenna et al. 2000; Mitra 2012). The proper nonlinear modelling of the structural components pertinent on strength and stiffness degradation is critical to the inelastic seismic analysis of the structure (Do and Filippou 2018; Mazza 2019). In this study, the lateral force-displacement relationship of RC structural walls can be resolved into four stages of deformation: (i) onset of cracking, (ii) state of yield, (iii) development of peak resistance, and (iv) ultimate conditions as revealed by experimental testing (e.g. Menegon et al. 2017; Salonikios et al. 2000). The Pinching4 material as shown in Fig. 4(b) was used to define the hysteretic behaviour of the structural walls, which can effectively capture the pinching effect, stiffness degradation and strength deterioration (Amirsardari et al. 2020; Lowes, Mitra, and Altoontash 2003). Parameters for defining the backbone curve of the structural walls were determined using pushover analyses (Shen et al. 2013); cyclical behaviour of the wall in relation to pinching, stiffness and strength degradation were modelled by calibration to achieve good matches with experimental measurements of RC wall shown in Fig. 4(c). The test results were sourced from the study reported in Menegon et al. (2017) which was aimed at emulating contemporary Australian design and construction practices in the laboratory. The D500N reinforcing bars (AS/NZS: Standards Australia and Standards New Zealand 2001) used in the test specimen had yield stress, ultimate stress and ultimate strain of 532 MPa, 637 MPa, and 12.6%, respectively. The compressive strength of the wall specimen was 42 MPa. The experimental result was found to be in good agreement with results from numerical modelling as shown in Fig. 4(d).

The effect of varying position, number, size and orientation of structural walls on the torsional behaviour of plan-asymmetric buildings were investigated. Five different types of configurations of the lateral load resisting elements that were subject to analyses are presented in Figs. 5(a–e). To achieve a fair comparison across all the considered models, their translational stiffness in the direction of earthquake excitations was kept the same. The effect of plan asymmetry in a building was characterised by two parameters: (i) eccentricity e_r and (ii) torsional stiffness b_r, respectively. The different types of configurations were achieved by adjusting the position, number and size of walls that possessed

(a) Single-storey building

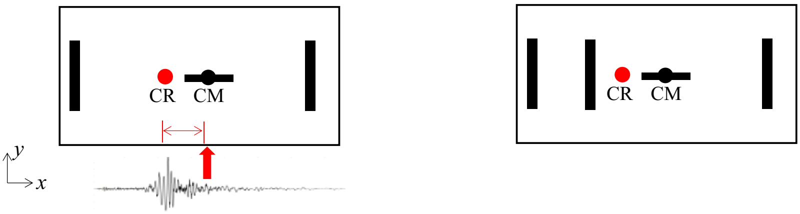
(b) Pinching4 material



(c) Detail of specimen wall (unit: mm)

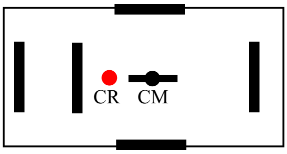
(d) Force-displacement of structural wall (Menegon et al. 2017)

Figure 4. The single-storey building model.



(a) Two walls (b) Three walls

(c) Four walls (d) Six walls



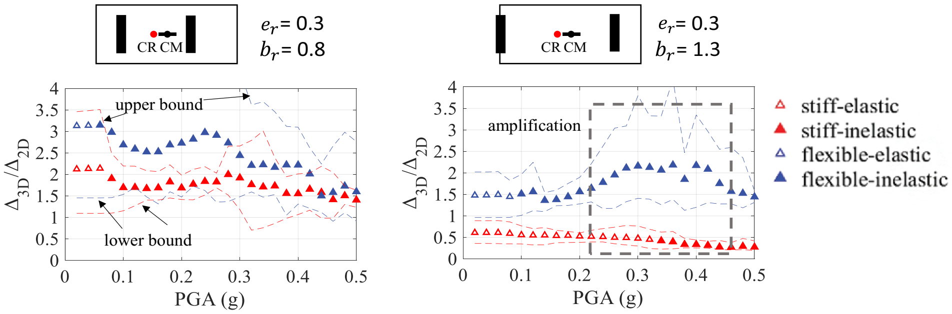
(e) Orthogonal walls

Figure 5. Single-storey building models with different types of configurations.

hysteretic properties shown in Fig. 4(d). Parametric studies involving Incremental Dynamic Analyses of the building models were conducted using soil surface accelerograms (shown in Fig. 3) which were progressively scaled in magnitude to result in varying intensity of shaking. Results of the analyses expressed in terms of the edge drift demand ratio (denoted as Δ_{3D}/Δ_{2D}) are of interests.

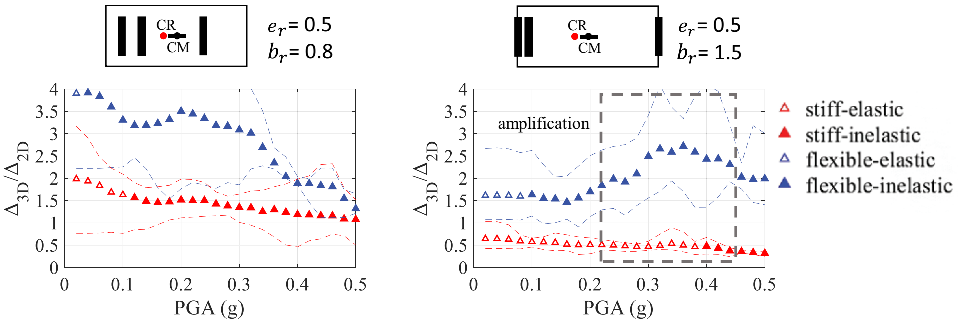
4.2. *Influences by the Disposition of Structural Walls*

Single-storey building models that were laterally supported by two, or three, RC structural walls of identical cross sections were studied. Walls with a closer spacing corresponded to a small b_r value (Figs. 6(a) and 7(a)) whereas walls that were spaced wider apart corresponded to a larger b_r value (Figs. 6(b) and 7(b)). Results from incremental dynamic analyses of the building models were presented in Figs. 6 and 7 (as for other figures presented in the same format in the rest of the paper), which show



(a) Lower b_r, closer wall spacing (b) Larger b_r, wider wall spacing

Figure 6. Single-storey building models with two walls.



(a) Lower b_r, closer wall spacing (b) Larger b_r, wider wall spacing

Figure 7. Single-storey building models with three walls.

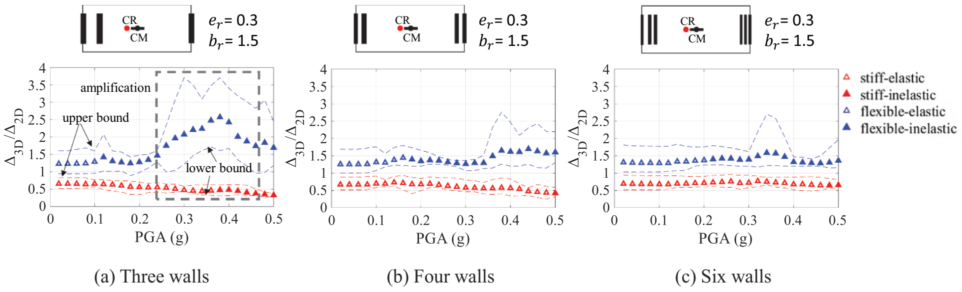
behaviour with intensity of up to PGA of 0.5 g. The purpose of reaching such a high intensity level in this study is to demonstrate that the anomaly presented herein is exclusive to limited ductile behaviour and would fade away in a ductile response to high-intensity ground shaking as typically experienced in high seismic regions.

The drift demand ratio Δ_{3D}/Δ_{2D} at the edges of the floor at each level of intensity (averaged from time-history analyses employing the six accelerograms of Fig. 3) were presented along with the upper and lower bounds shown by the dashed lines. Building models with a smaller b_r were seen to experience higher torsional amplifications in the elastic range which was consistent with well established trends as presented in Section 2 (refer hollow symbols in Figs. 6(a) and 7(a)). In contrasts, building models with a large b_r were seen to experience lower torsional amplifications (refer hollow symbols in Figs. 6(b) and 7(b)). Note that the yielding of the structural walls at the flexible edge commenced at an intensity of around 0.1 g. As this happened, other structural walls were still responding within the elastic limit. The asymmetric change in resistance of the structural walls on both sides of the building resulted in a stepped increase in the drift demand. This phenomenon was particularly evident with floor plans featuring widely spaced walls (as highlighted by the rectangular box in Figs. 6(b) and 7(b)) The amount of stepped increase of the averaged drift demand was about 30% – 60%. Similar phenomenon was not seen with the other floor plans featuring closely spaced walls.

The occurrence of the stepped increase phenomenon as demonstrated herein is in contradictions with the widely held notion of a high b_r value being generally desirable. It is demonstrated that building models exhibiting good behavioural trends in the elastic range might still exhibit undesirable behaviour as the limit of yield is surpassed depending on the number of walls and their disposition on the floor plan of the building. The risk of under-estimating the drift demand of a limited ductile building for the reasons described has not been addressed in the literature.

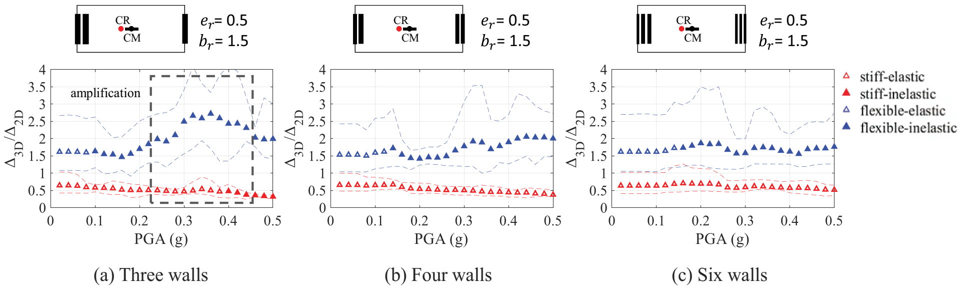
4.3. Influences of the Number of Structural Walls

Previous research demonstrated that the number of structural walls can have little influence on its performance in torsion provided that there were walls orientated in orthogonal directions (Fernández-Dávila and Cruz 2006; Goel and Chopra 1990). The finding was that a building which was supported by only two structural walls in the direction of excitation could be used as a representation of a building which was supported by a larger number of walls (Goel and Chopra 1990). In this study, the torsional behaviour of building models that were supported by three, four, or six structural walls without orthogonal walls featured very different post-yield response behaviour between the models, as shown in Figs. 8 and 9. Incremental dynamic analyses were conducted on the building models subject to the six soil surface accelerograms (as presented in Fig. 3) in the direction parallel to that of the



(a) Three walls (b) Four walls (c) Six walls

Figure 8. The effect of number of structural walls with e_r equal to 0.3.



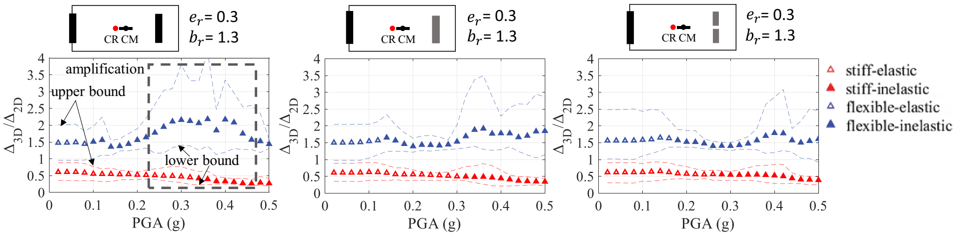
(a) Three walls (b) Four walls (c) Six walls

Figure 9. Figure 9 the effect of number of structural walls with e_r equal to 0.5.

structural walls. To ensure like-with-like comparison, the positioning of the walls in all the models were adjusted to have common system parameters (e_r and b_r). With buildings that were supported by only three walls (Figs. 8(a) and 9(a)) first yield of the wall was observed at the flexible edge (refer solid blue symbols). As this happened, the other structural walls was responding within the elastic limit (refer hollow red symbols). A significant stepped increase in the averaged drift demand (by some 50% – 60%) was observed as the limit of yield was surpassed. Importantly, with buildings that were supported by four, or six walls (Figs. 8(b–c) and 9(b–c)) the amount of stepped increase was only minor. It was found that a building which had a larger number of structural walls experienced only minor abrupt loss of resistance at the occurrence of first yield. The amount of stepped increase in the torsional amplification was significantly less even in the absence of orthogonal walls. Strength eccentricity of a building, and its torsional resistance, are well known to be most influential on the potential response behaviour of the building. It is demonstrated herein that the number of structural walls could also greatly influence the extent of the stepped increase phenomenon when the system parameters were kept unchanged.

4.4. Influence of Wall Size

The resizing of individual structural walls can also bring about considerable change in the torsional amplification behaviour when the eccentricity and stiffness parameters are kept unchanged. Note, the length of structural walls is known to be inversely proportional to the displacement at yield (Massone and Alfaro 2016; Priestley and Kowalsky 1998; Priestley, Calvi, and Kowalsky 2007; Wibowo et al. 2013). The systems with unequal length walls can represent analytical models that account for the influence of strength eccentricity in previous publications (Bhasker and Menon 2020, 2022; Rashidi et al. 2017). By allocating shorter walls, the Center of Strength (CV) tends to shift closer to the Center of Mass (CM) due to the altered yield displacement distribution. This adjustment in wall lengths directly affects the distribution of yield displacements within the structure, further reflecting changes

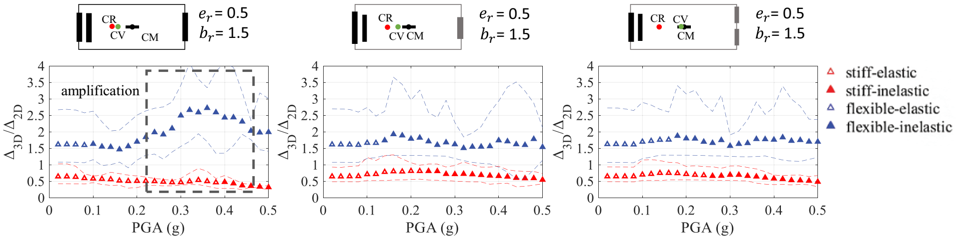


(a) Same walls at edges with e_v = 0.3

(b) One shorter wall at the flexible edge with e_v = 0.05

(c) Two shorter walls at the flexible edge e_v = -0.1

Figure 10. The effect of size of structural walls with e_r equal to 0.3.

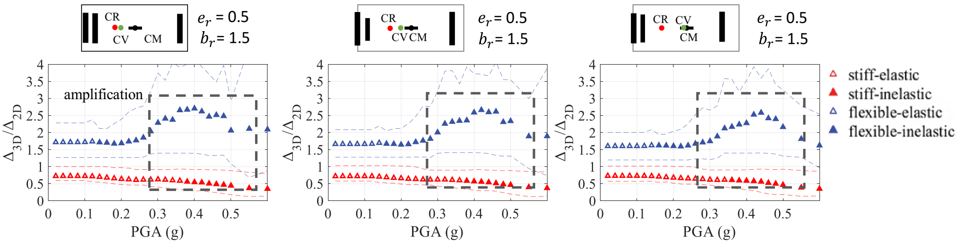


(a) Same walls at edges with e_v = 0.4

(b) One shorter wall at the flexible edge with e_v = 0.3

(c) Two shorter walls at the flexible edge e_v = 0.05

Figure 11. The effect of size of structural walls with e_r equal to 0.5.



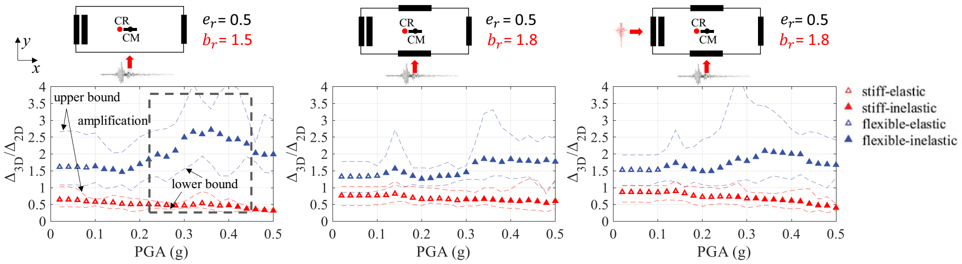
(a) Same walls at edges with e_v = 0.4

(b) Same walls at edges with e_v = 0.3

(c) Same walls at edges with e_v = 0.05

Figure 12. The effect of strength eccentricity with e_r equal to 0.5.

in the structural behaviour influenced by strength eccentricity. Thus, it was envisaged that the stepped increase in torsional amplifications caused by yielding of a structural wall would be mitigated by suitable sizing of the wall, as shown in Figs. 10 and 11. Models featuring structural walls of the same size were found to be subject to a prominent stepped increase in the additional drift demand caused by torsion (Figs. 10(a) and 11(a)). Designing a shorter wall (or a pair of shorter walls) closer to the flexible edge was found to have the benefits of delaying the occurrence of yielding thereby avoiding an abrupt asymmetric change in resistance in different parts of the building. If the strength eccentricity e_v was adjusted by changing the reinforcement ratio of structural walls at the flexible edge without altering the size of walls, the observed torsional amplification as observed in analytical models with similar walls at both edges did not show a significant sensitivity to changes in e_v, as shown in Fig. 12. This suggests that it is the distribution of yield displacements on both edges that primarily affects torsional amplification, rather than strength eccentricity alone. Therefore, the beneficial effects of resizing the



(a) Without orthogonal walls (b) Unidirectional excitations (c) Bidirectional excitations

Figure 13. Building models with orthogonal walls subjected to uni-directional and bi-directional excitations.

wall dimension as evident in Figs. 10(b–c) and 11(b–c) had not been well recognised in previous investigations on torsional behaviour in buildings.

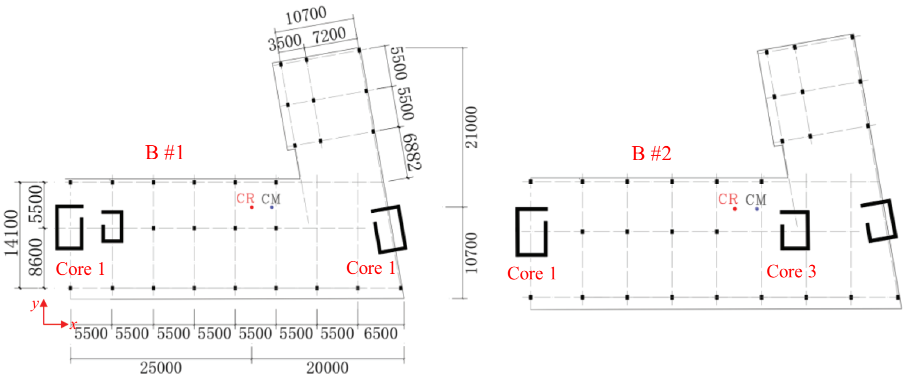
4.5. *Influence of Orthogonal Walls*

The benefit of the use of orthogonal walls in suppressing torsional actions is well recognised (De La Llera and Chopra 1996; Eivani, Tena-Colunga, and Moghadam 2022; Goel and Chopra 1990). Results from Incremental Dynamic Analyses as presented in Figs. 13(a–b) reaffirms this finding. However, the beneficial influences of the orthogonal walls can be overstated by analyses employing uni-directional excitations only. When a building was subject to bi-directional excitations that were generated from the bedrock ground motion ensembles as listed in Table 1, larger additional drift demand was observed as compared to a building that was subject to uni-directional excitations only (comparing Fig. 13(b) with Fig. 13(c)). This is because the effectiveness of orthogonal walls in suppressing torsional actions is contingent upon their state under seismic loading. When the orthogonal walls surpass the limit of yield, the torsional stiffness contributed by orthogonal walls is decreased as compared to the case of the building subjected to unidirectional excitations, where orthogonal walls always remain elastic. This highlights the importance of considering the yielding of orthogonal walls in seismic analysis and design, as it directly influences the structural responses to the seismic loading.

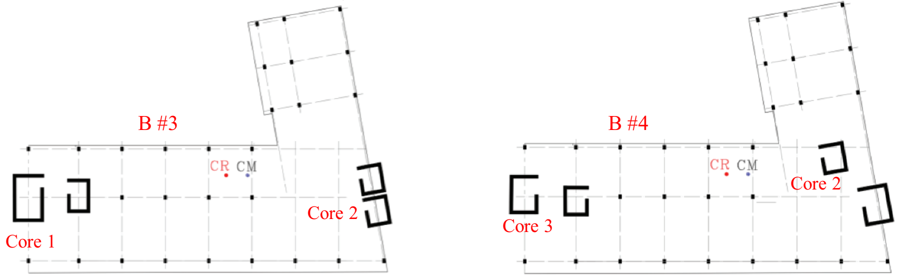
5. Case Study with Multi-Storey Buildings

5.1. *Building Design and Numerical Modeling*

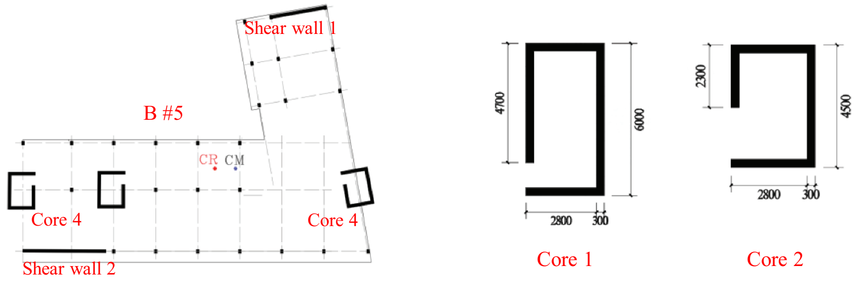
Previous studies have demonstrated that results from single-storey models could be used to infer the torsional behaviour of the corresponding multi-storey structural systems with the same stiffness asymmetry and distribution of lateral load resisting elements on the floor plan of the building (De La Llera and Chopra 1996; Hu et al. 2023; Peruš and Fajfar 2005). Further comparative studies involving analyses of multi-storey building models were undertaken to further verify this proposition, and to consolidate the findings presented in Section 4. Five case-study seven-storey reinforced concrete buildings of L-shaped floor plans and different configurations of structural walls (denoted herein as B#1-B#5) as shown in Fig. 14 were analysed using Incremental Dynamic Analyses. The design details for L-shaped floor plan were shown in Fig. 14(a). Information in relation to the geometry of the different core walls was also shown. The mass-radius of gyration (r) was 14.8 m, storey height was 3.3 m, and a designed imposed load of 2 kPa. The e_r and b_r values of the case study buildings were kept the same (by adjusting the position, size and number of structural walls while keeping their total translational stiffness in the direction of earthquake excitations the same). Building model B#1 had two identical core walls which were positioned close to the opposite edges of the building (Fig. 14(a)). Building model B#2 as shown in Fig. 14(b) had a smaller size core wall which was positioned close to the flexible edge of the building on the right, whereas building model B#3 as shown



(a) Walls of same size close to edges (b) Single short wall allocated to flexible edge



(c) Two short walls allocated to flexible edge (d) Four spaced out walls



(e) Orthogonal walls

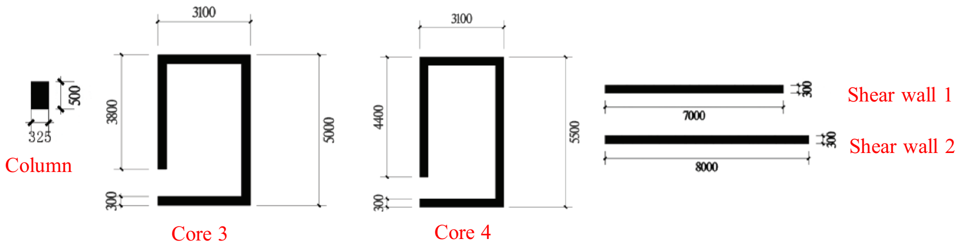


Figure 14. Plan configurations of the considered uni-directional asymmetric buildings.

in Fig. 14(c) had two short length core walls, both of which were positioned close to the flexible edge. Building model B#4 as shown in Fig. 14(d) had four spaced-out core walls which were disposed onto different parts of the floor plan. Building model B#5 as shown in Fig. 14(e) had the core walls and the rectangular shaped structural walls orientated in orthogonal directions. The e_r and b_r parameters for each of these models (consistent with the single-storey equivalences analysed in Section 4) along with the coupled natural period of vibration (T_1, T_2 and T_3) and uncoupled natural period of vibration (T_u) are listed in Table 2.

Table 2. Torsional parameters of uniaxial asymmetric buildings.

Structures	e_r	b_r	T_1 (sec)	T_2 (sec)	T_3 (sec)	T_u (sec)
B #1	0.5	1.5	0.59	0.39	0.25	0.36
B #2	0.5	1.5	0.70	0.39	0.28	0.36
B #3	0.5	1.5	0.69	0.39	0.23	0.36
B #4	0.5	1.5	0.61	0.39	0.24	0.36
B #5	0.5	1.5	0.40	0.39	0.22	0.36

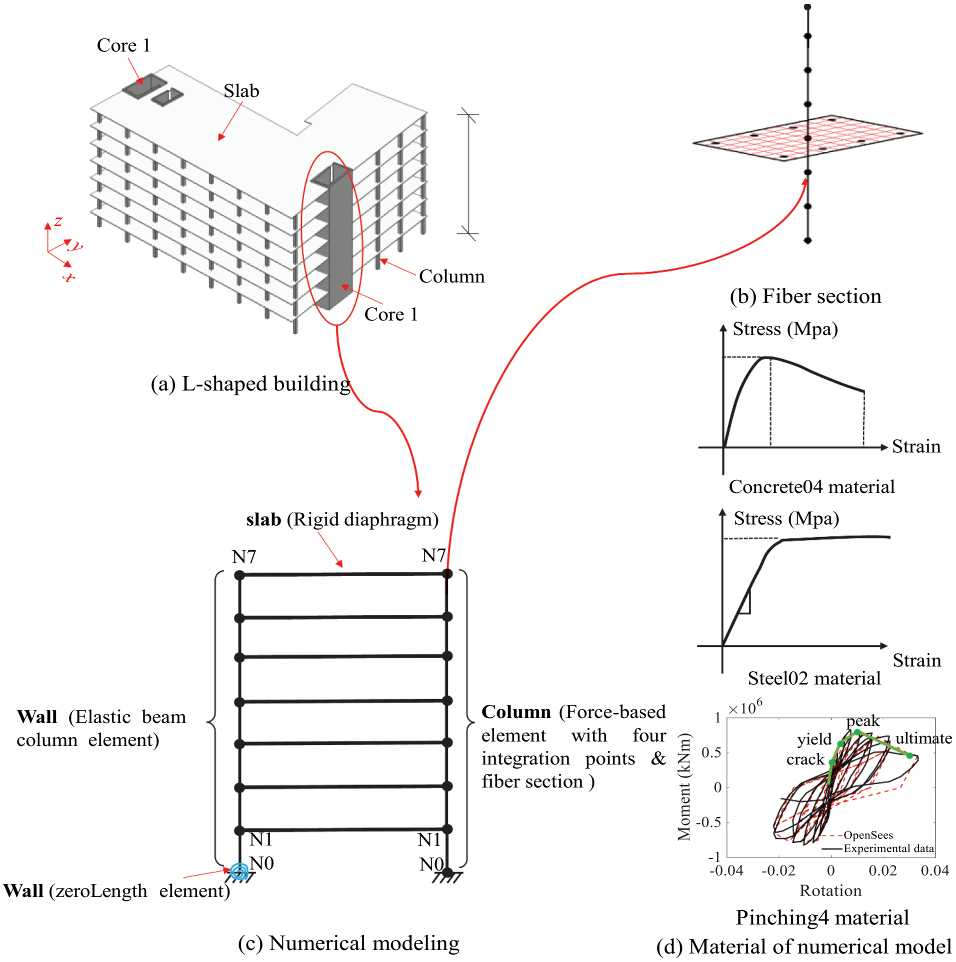
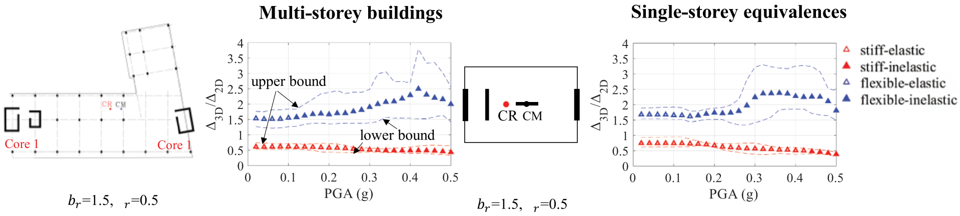


Figure 15. Schematic view of 3D building models.

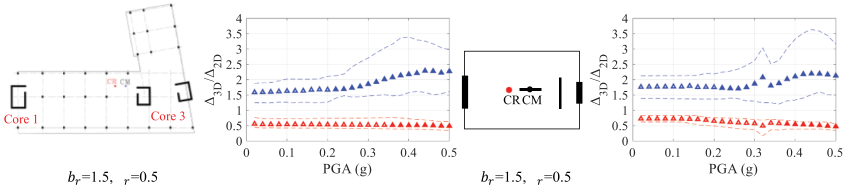
Three-dimensional (3D) finite element models of case study multi-storey buildings and their corresponding single-storey equivalence were constructed using the OpenSees software. The assumption of rigid floor diaphragms was made, and a lumped mass was assembled at the CM position on each floor (Fig. 15(a)). The nonlinear behaviour of RC columns was modelled by force-based beam-column element with fiber elements (Fig. 15(b–c)). Four points of integration along the element were applied with a view of balancing accuracy with computational expenses. The stress-strain behaviour of the reinforced concrete and that of the longitudinal reinforcement was simulated using the *Concrete04* and *Steel02* material models of *OpenSees*, respectively. The reinforced concrete (RC) had a nominal compressive strength (f_c) of 50 MPa and was reinforced by 16 mm diameter longitudinal reinforcing bars with a nominal tensile yield strength (f_y) of 460 MPa. Details of the material parameters can be found in Amirsardari et al. (2020). An elastic beam-column element was used to model the structural walls on the building floors, as shown in Fig. 15(c). The hysteretic characteristics of the structural walls that represented the dynamic behaviour under seismic loading were simulated using zeroLength element along with the Pinching4 material model in OpenSees. The Pinching4 material used for modelling the hysteretic behaviour of the core walls had been calibrated against results from experimental testing as illustrated in Fig. 15(d) (Menegon et al. 2017).

5.2. Comparisons of Multi-Storey Buildings and their Single-Storey Equivalence

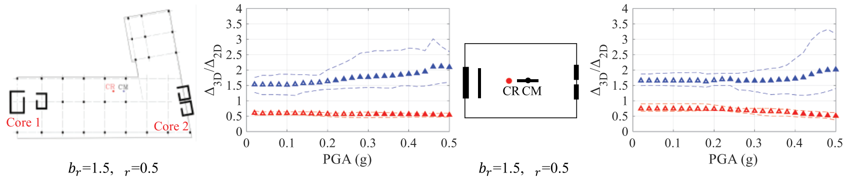
The averaged Δ_{3D}/Δ_{2D} drift demand ratio (along with the lower bound and upper bounds) drift demand ratio for both multi-storey buildings and their single-storey equivalences are compared in Fig. 16 to evaluate the accuracy of the use of representative single-storey building models to emulate torsional actions on multi-storey buildings. With walls positioned close to the flexible edge of the building, a significant stepped increase in the drift demand ratio was observed in B#1 (as well as its



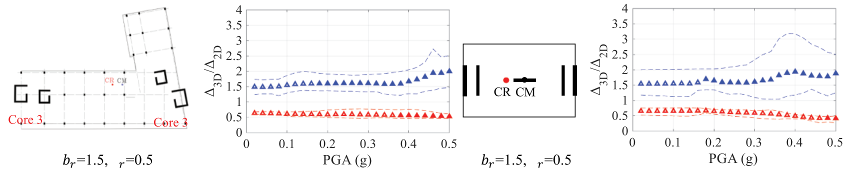
(a) B #1 with the multi-storey building and single-storey equivalence



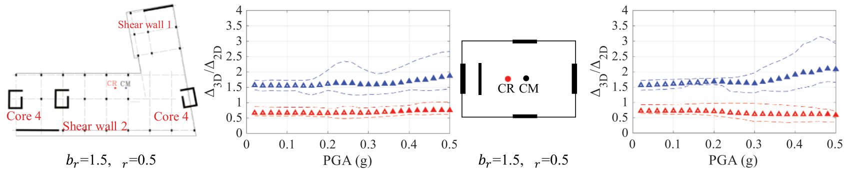
(b) B #2 with the multi-storey building and single-storey equivalence



(c) B #3 with the multi-storey building and single-storey equivalence



(d) B #4 with the multi-storey building and single-storey equivalence



(e) B #5 with the multi-storey building and single-storey equivalence

Figure 16. Comparisons of drift demand ratios between multi-storey buildings and their single-storey equivalences.

single-storey equivalence) when the yield limit of structural walls was surpassed at a ground motion intensity (PGA) of around 0.12 g (refer solid symbols in Fig. 16(a)). With the B#2 model, which had walls of reduced length positioned close to the flexible edge of the building, a delay in the occurrence of yield was observed at a higher PGA of 0.22 g for the averaged drift demand ratio. Such a delay effectively suppressed the amplification of the inelastic drift demand ratio to occur at an early stage. With the B#3 model, which had two shorter walls positioned close to the flexible edge of the building, the amount of stepped increase in the post-yield drift demand ratio was also shown to be suppressed. With the B#4 model (as for the single-storey equivalence), the use of four spaced out walls in the direction of ground motion resulted in a reduction in the amount of stepped increase in inelastic drift demand ratio. There was no significant amplification for the average seismic drift demand ratio in the B#5 model that featured orthogonal walls, as was consistent with findings from the analyses of the single-storey equivalences. The extent of the post-yield stepped increase in torsional amplification as revealed from analyses employing these two types of building models was found to be consistent. Therefore, the validity of extending the findings presented in Section 4 to multi-storey buildings was re-affirmed.

6. Discussions on Implications of Findings

Parametric studies conducted in this study revealed additional drift demand anomalies in the building at the transition from the elastic to inelastic range. The stepped increase in the drift demand caused by torsion would eventually fade away when the building is well excited into inelastic range (i.e. the ductility demand is increased to a high level). Thus, limited ductile structures are vulnerable in the translation from the elastic to inelastic range. From the perspective of seismic design, a low seismicity case is normally not recommended for PGA higher than 0.1 g (CEN 2005). The reason of extending the ground motion intensity to such a high level in this study is mainly to demonstrate the new trend of torsional behaviour of limited ductile buildings, which has not received adequate attention in mainstream research focused on well-studied regions with high seismicity. The uncovered phenomenon is dependent on the disposition of the lateral resisting elements in the building, their size and the number of such elements that are present. Buildings that are supported by only two or three lateral load resisting elements are particularly at risk. Increasing the number of resisting elements, or using shorter length walls, has been found to be effective in suppressing the undesirable phenomenon.

Clearly, factors governing the stepped increase phenomenon are not well represented by stiffness based, nor strength based, parameters for characterising the lateral resistant behaviour of the building at the system level. For example, the undesirable stepped increase in torsional amplification can be considerable even for buildings with high b_r values (which are widely believed to be desirable in terms of countering torsional actions at the system level). These are original findings that have not been reported in the literature. Thus, there are no code provisions to address this phenomenon. The drift capacity of structural elements, particularly those positioned close to the flexible edge of the building, needs to allow for up to about 50% stepped increase in the drift demand ratio above that calculated by elastic dynamic analysis of the building. Such a major increase in the additional drift demand can be alleviated by suitably disposing structural walls on the floor plan, designing sufficient number of structural walls to provide the bracing, and suitably sizing of the walls. The 50% stepped increased can then be lowered to 10%–20%.

7. Conclusion

This article deals with torsional actions amplifying the drift demand in a limited ductile building that translations from the elastic to inelastic range. Whilst acknowledging the proliferation of publications on this topic, there has been limited research to systematically track the trend of torsional actions of a limited ductile building revealed by incremental dynamic analyses. The main conclusions derived from the investigation of single-storey and multi-storey building models are summarised as follows:

- For systems with two or three lateral load resisting elements, a stepped increase in the drift demand ratio can occur even in buildings with large b_r value when the structural wall close to the flexible edge exceeds the limit of yield. A wider spacing between structural walls can increase the extent of the undesirable stepped change in torsional amplification up to about 50% in the averaged drift demand when the building transitions from the elastic to inelastic range.
- The stepped increase, as observed in the inelastic drift demand ratio in systems with two or three resisting elements, can be suppressed by having a larger number of lateral load resisting elements.
- Shortening the length of walls (i.e. increasing the yield displacement) that are susceptible to the premature yielding (flexible edge walls) can suppress the stepped increase in the inelastic drift demand ratio.
- The observed phenomenon reveals a new vulnerability element which is particular to limited ductile buildings featuring plan asymmetry in a rare earthquake, giving insights into the prioritization for future study concerning design practices in low to moderate seismic region. The undesirable torsional phenomenon is shown to be suppressed by designing walls in orthogonal directions, more structural walls in the direction of ground motion and shorter (more deformable) walls close to the flexible edge of the building. By employing these strategies, the amount of stepped increase in the averaged drift demand can be suppressed by about 10% to 20%.

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Disclosure Statement

No potential conflict of interest was reported by the author(s).

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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