Australian Earthquake Engineering Society
National Conference, 23-25 November 2023
Brisbane, Queensland, Australia

Investigation of torsional amplification of inelastic seismic demand in plan asymmetric buildings

Yao Hu[1,*], Elisa Lumantarna[1], Nelson Lam[1], and Hing-Ho Tsang[2]

1. Department of Infrastructure Engineering, The University of Melbourne, Melbourne, Australia;

2. School of Engineering, Swinburne University of Technology, Melbourne, Australia;

Abstract

Torsion-induced seismic response amplification is a major concern for the seismic safety of a plan-asymmetric building subjected to the earthquake. Particularly, the undesirable torsional behaviour of a building in the post yield condition is unpredictable as it is largely affected by the plan configurations of structural walls with varying number, position, size, and orientations. Nonlinear time history analysis is a rigorous method for the accurate assessment of torsional actions in a building that responds to the inelastic range. However, the development of a three-dimensional building model based on the finite element method makes the seismic analysis costly and time consuming. In this paper, extensive parametric studies were carried out to quantify the effect of system parameters such as eccentricity, the elastic radius ratio and yield ratio on the torsional amplification that may occur in a building transitioning from the elastic to inelastic range. The degree to which these factors affected the torsion was examined by performing incremental dynamic analyses to single-storey buildings with different plan configurations of structural walls. Considerable torsional amplification was observed in a building with large eccentricity and high elastic radius ratio. A larger yield ratio that indicates larger yield displacement of structural walls susceptible to the yielding can effectively suppress the torsional amplification.

Keywords: Torsional behaviour, incremental dynamic analyses, the yield displacement, plan asymmetric buildings

1 Introduction

Buildings featuring plan asymmetry generally experience high seismic demand owing to the complex coupling effect of translational and rotational vibration (Anagnostopoulos et al. 2015; De Stefano & Pintucchi 2008). Considerable torsional amplification can occur in the post-yield condition as the premature yielding of one of structural walls may lead to an increase in eccentricity and a reduction in torsional resistance due to the change of stiffness distribution. A larger eccentricity or lower torsional stiffness will in turn cause higher seismic demand of the building (Chandler & Hutchinson 1986). Therefore, the undesirable torsional effect can occur in the inelastic range, which can be one of major concerns for the seismic performance of plan-asymmetric buildings, especially for limited-ductile buildings in the regions of low to median seismicity (Hu et al. 2023; Lucchini et al. 2009; Sritharan et al.2014). However, the seismic design of plan-asymmetric buildings in current codes is based on the elastic analyses (CEN. 2005), which may understate the torsional behaviour of the building in the post-yield condition.

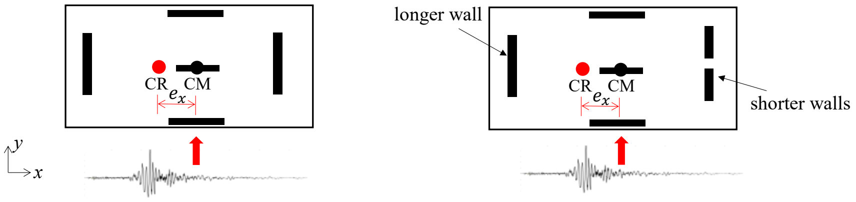
The torsional effect of buildings is mainly cased by the nonuniform distribution of mass or lateral load resisting elements in the floor plan. Eccentricity ratio (e_r) and the elastic radius ratio (b_r) are two important factors to reflect the torsional effect in the elastic state (Lam et al.2016; Humar & Kumar 1999). The eccentricity ratio (i.e. $e_r = \frac{e_x}{r}$) is the offset of the centre of rigidity (CR) from the centre of mass (CM) of the building (e_x) normalised with respect to the mass radius of gyration (*r*); the elastic radius ratio (i.e. $b_r = \frac{1}{r}\sqrt{\frac{K_\theta}{K_y}}$) is defined as the square root of the ratio of torsional stiffness (K_θ) to translational stiffness (K_y) of the lateral load resisting elements in the building, normalised with respect to *r*. Previous studies on the elastic torsional effect have shown that a higher b_r value is desirable to supress the torsion-induced seismic responses amplification in the linear domain, and the drift demand ratio becomes insensitive to e_r when the values of b_r are higher than 1.1 (Khatiwada et al. 2021). The limit of b_r is also advised to be equal to, or exceed, unity in a design requirement (CEN. 2005). However, when the same structure responds in nonlinear domain, there is no general agreement as what system parameters are the best to control the torsional effect of plan-asymmetric buildings (Eivani et al. 2022). The seismic behaviour is highly affected by plan configurations of lateral load resisting elements in the change of size, position and number (Bhasker & Menon 2020; De La Llera & Chopra, 1996). In this case, the potential torsional amplification can only be identified by performing nonlinear time history analyses to 3D building models. However, the development of a three-dimensional building model based on the finite element method makes the seismic analysis costly, which is unpractical for the day-to-day design. Therefore, there is a strong need to conduct extensive parametric studies to quantify how system parameters affect the torsional amplification of a building in the post-yield condition, so that the designers can be aware of the likely seismic risks of the building at the preliminary design stage.

In this paper, incremental dynamic analyses were conducted to investigate the influence of system parameters such as e_r and b_r on the torsional amplification of a building transitioning from the elastic to inelastic range. Torsional amplification factor that was represented by the ratio of inelastic drift demand ratio to elastic drift demand ratio was examined by use of single-storey buildings with different plan configurations of structural walls. The analysis results offered a thorough insight into the extent to which these factors influence the torsional effect.

2 Numerical modelling

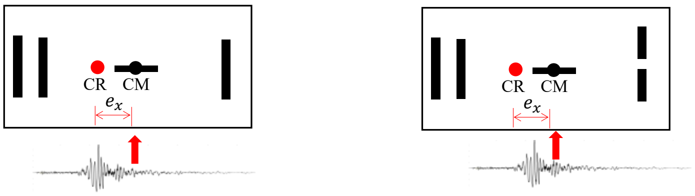
2.1 Single storey building models

To study the effect of system parameters on the torsional amplification of the buildings, the single-storey building model, which is characterised by a rigid deck and lateral load resisting elements, is employed for nonlinear time history analysis. Fig. 1 shows the analytical models adopted in the parametric studies, which includes a two-element models with orthogonal walls and three-element models without orthogonal walls. The adopted structural wall is a rectangular RC wall tested under low cyclic loading (Menegon et al. 2017), as shown in Fig. 2(a). The numerical model of structural walls was developed by use of OpenSees software (Mitra 2012; McKenna et al. 2000). The hysteretic behaviour of the structural walls was modelled by Pinching4 material in OpenSees, which was characterised by the onset of cracking, state of yield, development of peak resistance, and ultimate conditions, as shown in Fig. 2(b). The model accuracy of structural wall was calibrated to be in good agreement with the experimental data, as presented in Fig. 2(c). The torsional amplification of single storey building models was investigated by considering the influence of system parameters including b_r, e_r and yield ratio (i.e. $\frac{\Delta_{flex}}{\Delta_{Stif}}$ represents the ratio of yield displacement of structural walls at the flexible edge (Δ_{flex}) to yield displacement of structural walls at the stiff edge (Δ_{flex})). The change in system parameters was achieved by adjusting the position and size of structural walls in the direction of ground motion. Torsional amplification factor was employed to quantify how much the inelastic drift demand ratio was amplified as compared to the elastic drift demand ratio, which was expressed as $\frac{R_{inelastic}}{R_{elastic}}$ (i.e. inelastic drift demand ratio ($R_{inelastic}$) divided by elastic drift demand ratio ($R_{elastic}$))



(a) Two walls with same walls in direction of ground motion

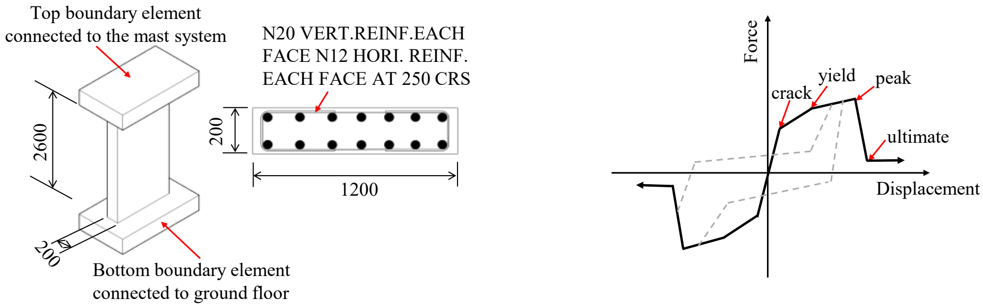
(b) Two walls with different walls in direction of ground motion



(c) Three walls with same walls in direction of ground motion

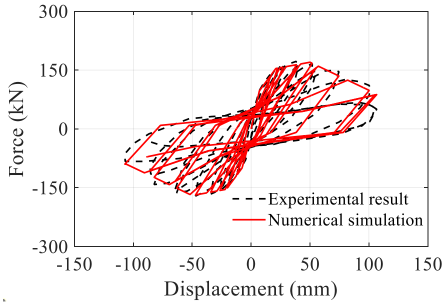
(d) Three walls with different walls in direction of ground motion

Figure 1. Single storey building models with different configurations of structural walls.



(a) Detail of structral wall (unit: mm)

(b) Pinching4 material



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

Figure 2. The dimension and numerical model of structural wall

2.2 Ground motion selection

A suite of six realistic seismic excitations were selected from the PEER database based on site-specific response spectra with a notional peak ground acceleration of 0.12g (Standards Australia 2018). The details of selected bedrock ground motion ensembles are listed in Table 1. Based on the conditional mean spectrum (CMS), soil surface accelerograms for the targeted soft soil site (class D site) were generated by inputting these bedrock accelerograms into site response analyses (Hu et al. 2022). The generated soil accelerograms were scaled to a variety of earthquake intensity to excite the building. Incremental dynamic analyses were performed to track the torsional amplification factor in the building transitioning from the elastic to inelastic range.

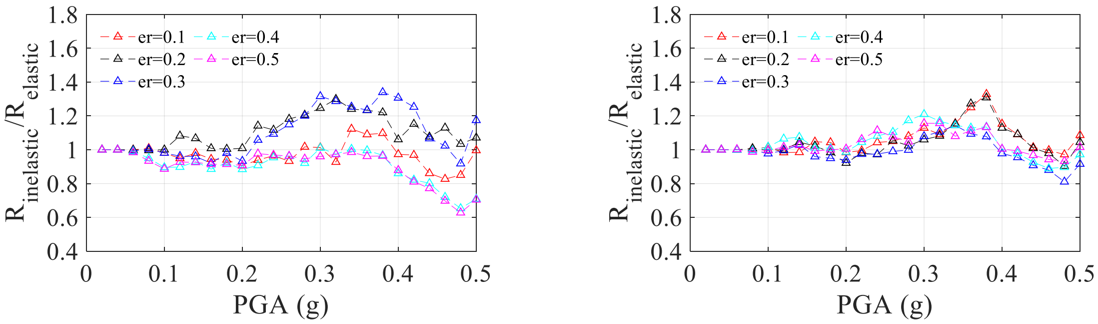
Table 1. Details for the selected bedrock ground motion ensemble

No.	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

3 Parametric studies on torsional amplification factor

3.1 *The influence of* e_r

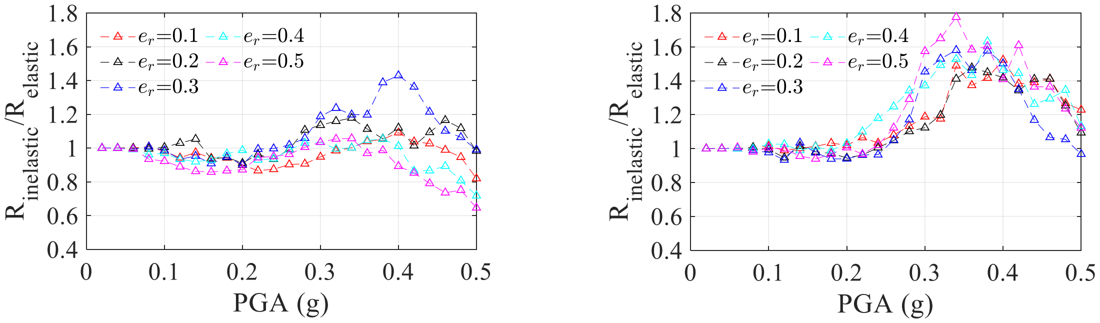
The influence of e_r on the torsional amplification factor of buildings with two and three elements is shown in Figs. (3-4). In the cases with low b_r of 1.1, a low e_r value less than 0.3 will experience larger torsional amplification in the post yield condition. The maximum torsional amplification factor can be up to 1.4, as shown in Fig. 3(a) and Fig. 4(a). As e_r increases to up 0.5, the torsional behaviour of the building is dominated by the elastic analysis due to the insufficient torsional resistance. With a higher b_r value of 1.5, the torsional amplification phenomenon is becoming more prominent as a large factor of 1.8 is observed in high e_r value when the structural wall supresses the limit of yield, see Fig. 4(b). In this case, the desirable effect of high b_r value that is supposed to suppress the elastic torsional behaviour can cause considerable torsional amplification in the inelastic range.



(a) b_r = 1.1, yield ratio = 1

(b) b_r = 1.5, yield ratio = 1

Figure 3. Torsional amplification factor of two-element models



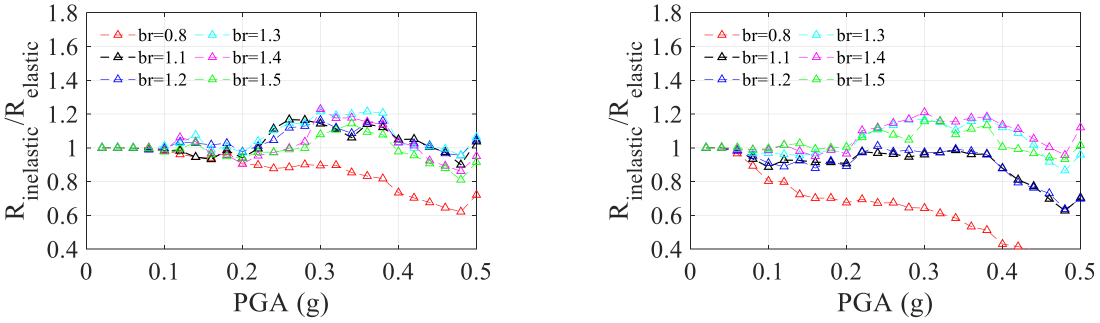
(a) b_r = 1.1, yield ratio = 1

(b) b_r = 1.5, yield ratio = 1

Figure 4. Torsional amplification factor of three-element models

3.2 *The influence of b_r*

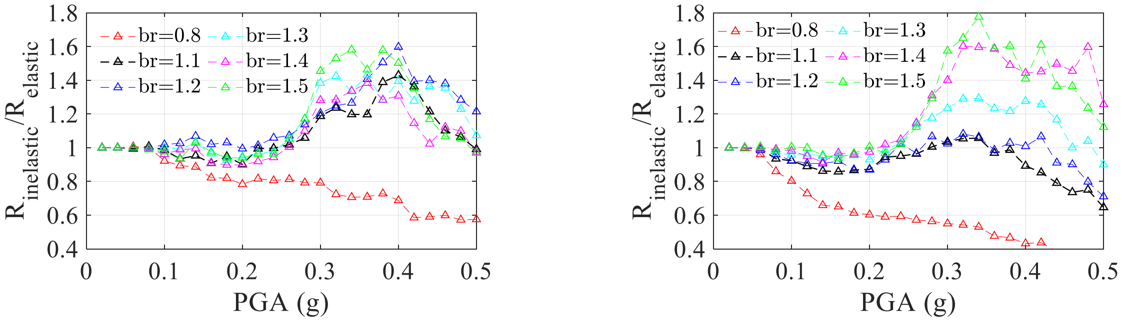
Figs. (5-6) present the trend in the torsional amplification factor along with the change of b_r values. The extremely low b_r values (i.e. 0.8) exhibit no torsional amplification because the insufficient torsional resistance leads to a much higher elastic seismic demand than that in the inelastic range. The undesirable torsional amplification can be readily identified by the elastic analysis. However, the increase of b_r values (i.e. >1.1) can significantly amplify the torsional effect of the building in the post-yield condition, especially for cases with high b_r and e_r values, see Fig. 5(b) and Fig. 6(b). In this case, the designer should be very careful about the potential seismic risks of buildings with high b_r values.



(a) e_r = 0.3, *yield ratio = 1*

(b) e_r = 0.5, *yield ratio = 1*

Figure 5. Torsional amplification of two-element models



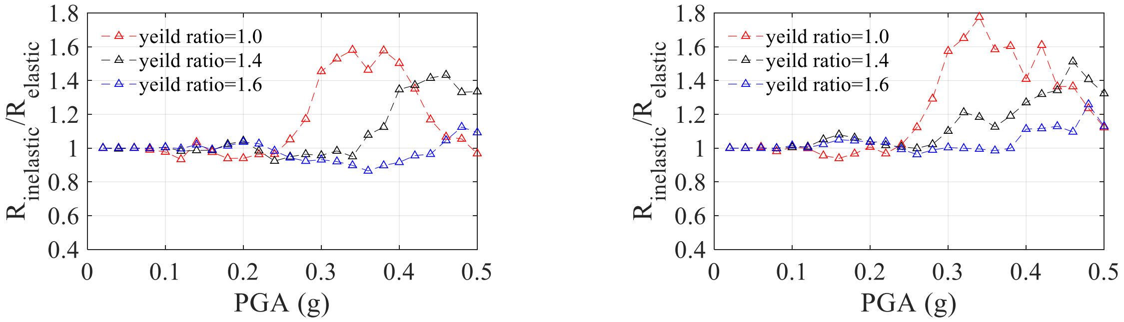
(a) e_r = 0.3, yield ratio = 1.0

(b) e_r = 0.5, yield ratio = 1.0

Figure 6. Torsional amplification of three-element models

3.3 The influence of yield ratio

The considerable torsional amplification is mainly caused by the premature yielding of the structural wall at the flexible edge. To control the torsional amplification in the post-yield condition, one possible solution is to control the premature yielding of the walls Therefore, shorter structural walls with larger yield displacement (Priestley and Kowalsky 1998) are configured at the flexible edge. A yield ratio of 1.0, 1.4 and 1.6 is considered to investigate the torsional amplification of a building with three elements, as shown in Fig. 7. A reduction in the torsional amplification factor is observed as the yield ratio increases. This is because the prolonged yield displacement of structural wall at the flexible edge eliminates the time gap of yielding between the walls at both edges, contributing a more balanced stiffness and strength distribution during the earthquakes. For the building with high e_r and b_r values, a yield factor of 1.6 is recommended to suppress the torsional amplification within 20% as compared to the elastic analysis result.



$e_r = 0.3,\ b_r = 1.5$ $e_r = 0.5,\ b_r = 1.5$

Figure 7 Torsional amplification of three-element models

4 Conclusions

This paper investigates the torsional amplification of plan-asymmetric building transitioning from the elastic to inelastic range. The possible torsional amplification that may occur in the post-yield condition is identified by parameters including e_r, b_r, and yield ratio. The torsional effect of a building with extremely low b_r (i.e. 0.8) is mainly controlled by the elastic analysis. With b_r increasing, low e_r may lead to a possible torsional amplification when the building yields. The buildings characterized by high e_r and b_r values are particularly vulnerable to significant torsional amplification. Such an undesirable torsional amplification can be suppressed by a larger yield ratio, implying having a larger yield displacement of structural walls at the flexible edge. To suppress the torsional amplification, a yield factor of greater than 1.4 is recommended based on the investigations into the impact of torsional parameters on torsion. The analysis results can serve as basic references to facilitate the seismic design of plan-asymmetric building during their initial design phase.

5 References

AS/NZS: Standards Australia and Standards New Zealand. 2001. AS/NZS 4671:2001 Steel Reinforcing Materials. Standards Australia International Ltd, Sydney and Standards New Zealand, Wellington.

Anagnostopoulos, S. A., Kyrkos, M. T., and Stathopoulos, K. G. 2015. Earthquake induced torsion in buildings: critical review and state of the art. Earthquakes and Structures, 8(2), 305-377.

Bhasker, R., and Menon, A. (2020, August). Torsional irregularity indices for the seismic demand assessment of RC moment resisting frame buildings. In Structures (Vol. 26, pp. 888-900). Elsevier.

Chandler, A. M., and Hutchinson, G. L. 1986. Torsional coupling effects in the earthquake response of asymmetric buildings. Engineering Structures, 8(4), 222-236.

CEN. 2005. Eurocode 8: Design Provisions for Earthquake Resistance of Structures, Part 1.1: General rules, seismic actions and rules for buildings. Brussels: European Committee for Standardization.

De La Llera, J. C., and Chopra, A. K. 1996. Inelastic behavior of asymmetric multistory buildings. Journal of structural engineering, 122(6), 597-606.

De Stefano, M., & Pintucchi, B. (2008). A review of research on seismic behaviour of irregular building structures since 2002. Bulletin of earthquake Engineering, 6, 285-308.

Eivani, H., Tena-Colunga, A., & Moghadam, A. S. (2022, June). Proper configuration of stiffness and strength centers in asymmetric single-story structures with semi-flexible diaphragms. In Structures (Vol. 40, pp. 149-162). Elsevier.

Hu, Y., Khatiwada, P., Lumantarna, E., and Tsang, H. H. 2023. Assessment of Torsional Amplification of Drift Demand in a Building Employing Site-Specific Response Spectra and Accelerograms. CivilEng, 4(1), 248-269.

Hu, Y., Lam, N.T. K., Menegon, S., and Wilson, J. 2022. The Selection and Scaling of Ground Motion Accelerograms For use in Stable Continental Regions. Journal of Earthquake Engineering, Journal of Earthquake Engineering, 26(12): 6284-6303.

Humar, J. L., and Kumar, P. 1999. Effect of orthogonal inplane structural elements on inelastic torsional response, Earthquake Engineering & Structure Dynamics, 28: 1071-1097.

Khatiwada, P., Lumantarna, E., Lam, N., and Looi, D. 2020. Fast Checking of Drift Demand in Multi-Storey Buildings with Asymmetry. Buildings, 11(1), 13.

Khatiwada, P., and Lumantarna, E. 2021. Simplified Method of Determining Torsional Stability of the Multi-Storey Reinforced Concrete Buildings. CivilEng, 2(2), 290-308.

Lucchini, A., Monti, G., & Kunnath, S. (2009). Seismic behavior of single‐story asymmetric‐plan buildings under uniaxial excitation. Earthquake Engineering & Structural Dynamics, 38(9), 1053-1070.

Lam, N. T., Wilson, J. L., and Lumantarna, E. 2016. Simplified elastic design checks for torsionally balanced and unbalanced low-medium rise buildings in lower seismicity regions. Earthquakes and structures, 11(5), 741-777.

Menegon, S. J., Wilson, J. L., Lam, N. T., & Gad, E. F. (2017). Experimental testing of reinforced concrete walls in regions of lower seismicity. Bulletin of the New Zealand Society for Earthquake Engineering, 50(4), 494-503.

Priestley, M. J. N., and Kowalsky, M. J. 1998. Aspects of drift and ductility capacity of rectangular cantilever structural walls. Bulletin of the New Zealand Society for Earthquake Engineering, 31(2), 73-85.

Sritharan, S., Beyer, K., Henry, R.S., Chai, Y.H., Kowalsky, M., and Bull, D. 2014. Understanding Poor Seismic Performance of Concrete Walls and Design Implications. Earthquake Spectra. 30(1):307-334. doi:10.1193/021713EQS036M.