Proceedings of the Tenth Pacific Conference on Earthquake Engineering
Building an Earthquake-Resilient Pacific
6-8 November 2015, Sydney, Australia

Drift Demand Prediction of Gravitational Load Carrying Reinforced Concrete Frames in Australia

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ABSTRACT: Existing medium to high rise building stock in Australia typically consists of reinforced concrete constructions with reinforced concrete cores and frames as structural elements. The structural elements are designed without any considerations of ductile detailing making them vulnerable under seismic actions. The vulnerability of the buildings can be exacerbated by vertical and/or plan irregularities which can be caused by discontinuities of structural elements or eccentrically located cores. This paper presents interim findings of a study which is aimed to develop a simple and accurate method to provide estimates of the drift demand of reinforced concrete buildings that feature irregularities. The study is a part of collaborative research which is aimed to assess seismic vulnerability of reinforced concrete buildings in Australia.

1 INTRODUCTION

With an earthquake action having only been reinforced in Australia since mid-1990s many Australian buildings are expected to be vulnerable in an earthquake. The vulnerability of buildings was evident in the Newcastle Earthquake of 1989 which has been reported to have caused an estimated total economic loss of AU$ 4 billion. Reinforced concrete buildings have been identified as one of building types that are vulnerable in an earthquake.

Reinforced concrete (RC) building in Australia commonly comprises of reinforced concrete walls or cores and moment resisting frames. The reinforced concrete walls are often designed as lateral load resisting elements whilst the moment resisting frames are designed as gravitational load resisting elements. The structural elements are designed without any considerations of ductile detailing making them vulnerable under seismic actions.

The study presented in this paper is a part of collaborative research activities aimed towards assessing seismic vulnerability assessment of reinforced concrete buildings. The activities contribute to BNHCRC project aimed to develop risk mitigation and retrofitting strategies for the most vulnerable Australian buildings subject to earthquakes.

2 RESEARCH ACTIVITIES ON SEISMIC VULNERABILITY ASSESSMENT OF RC BUILDINGS IN AUSTRALIA

Various research activities in the University of Melbourne and Swinburne University of Technology contributing to the seismic assessment of RC buildings are briefly summarised in this section.

Studies on the definition of hazard intensity have been conducted to establish seismic hazard values on rock sites (Lam et al., 2015a). Seismic hazard values and response spectrum on rock have been determined based on a broad source zone model approach. The seismic hazard values can be adopted as the minimum values of hazard in regions lacking of historical data. The seismic hazard values in these regions could be significantly underestimated when a finely divided source zone (commonly adopted in the conventional probabilistic seismic hazard assessment) is used. The seismic hazard values for Melbourne, Sydney and Brisbane at 0.3, 0.5 and 1.0 sec are presented and compared with the values developed by Geoscience Australia (Leonard et al., 2013) in Table 1. The seismic hazard values proposed are not shown to be significantly different. The values for 0.3, 0.5 and 1.0 sec can be used to define response spectrum on rock at the acceleration and velocity controlled regions as presented in Lam et al. (2015b) and can be combined with the second corner period values proposed by Lumantarna et al. (2012) to define the displacement controlled region of the spectrum. The displacement can be modified to take into account the effects of soil amplification by site response spectra such as those proposed by Tsang et al. (2015) and Amirsardari et al. (2014).

Table 1. Seismic hazard values for Melbourne (based on Lam et al. (2015a) and Leonard et al. (2013))

	All Eastern seaboard		Melbourne		Sydney		Brisbane	
	500 yr RP	2500 yr RP	500 yr RP	2500 yr RP	500 yr RP	2500 yr RP	500 yr RP	2500 yr RP
	Lam[1]	Lam[1]	GA[2]	GA[2]	GA[2]	GA[2]	GA[2]	GA[2]
0.3 sec (g)	0.07 – 0.12	0.18 – 0.28	0.11	0.29	0.16	0.27	0.09	0.23
0.5 sec (g)	0.04 – 0.06	0.10 – 0.16	0.08	0.19	0.07	0.18	0.06	0.15
1.0 sec (g)	0.01 – 0.03	0.04 – 0.07	0.03	0.09	0.03	0.07	0.015	0.06

[1]Obtained from Lam et al. (2015a)

[2]Obtained from GA report (Leonard et al., 2013)

Extensive studies are currently being conducted to assess the seismic performance of reinforced concrete walls. Experimental works have been undertaken in Swinburne's state-of-the-art Smart Structures laboratory to investigate the collapse behaviour of reinforced concrete walls. Specimens representing the boundary elements of RC walls were subject to cyclic axial loading to simulate "push and pull" actions which occur on the walls when they are subject to earthquake excitation. Complimentary analytical studies have also been conducted in the University of Melbourne to develop force-deformation backbone curve of the lightly reinforced concrete walls. It has been found from both the experimental and analytical studies that lightly reinforced concrete walls (with longitudinal reinforced ratio lower than 0.65%) can fail in a very brittle manner with formation of one or two major horizontal cracks with all of inelastic deformation concentrated around the region. The reinforcement ratio of 0.65% is well above the minimum reinforcement requirement currently set in the Australian Standard AS3600 (SA, 2009). The lightly reinforced concrete walls possess very limited displacement capacity post yield as shown in Figure 1. Further works are currently well underway on the investigation of seismic performance of reinforced concrete C-shaped walls.

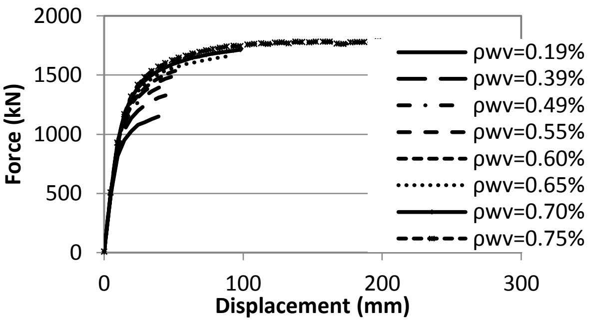


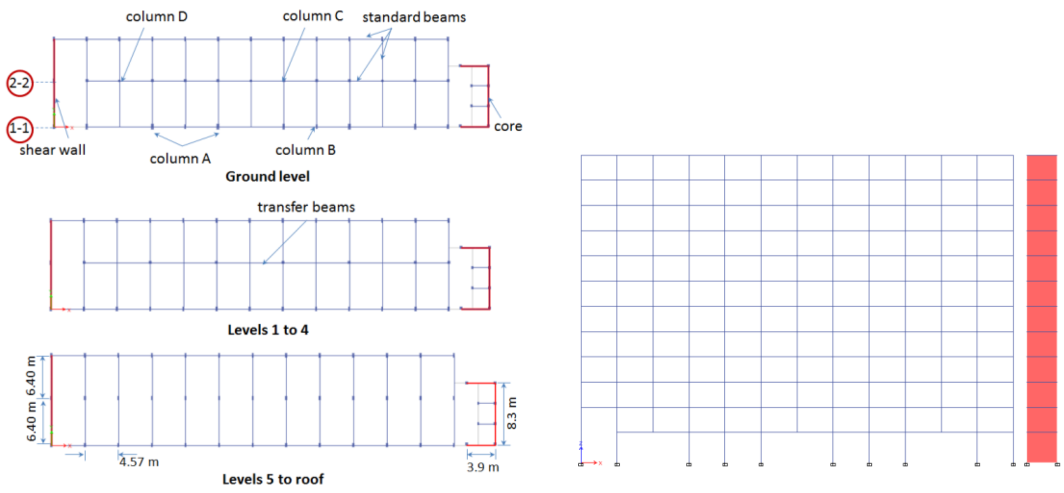
Figure 1. Force deformation behaviour of lightly reinforced concrete walls (Hoult et al., 2015)

Meanwhile, experimental and analytical studies are being conducted to assess the seismic performance of reinforced concrete frames. Central to the research efforts are the development of force-deformation backbone curve to determine displacement capacity of moment resisting frames and the development of a methodology for drift demand predictions which can be imposed on the reinforced concrete frames. The recent progress on the modelling of the force-deformation behaviour of moment reinforced concrete frames are reported in Amirsardari et al. (2015).

This study focuses on the development of a simple method to provide estimates of drift demand that will be imposed on reinforced concrete frames. This paper presents a case study which has been undertaken based on an RC building consisting of reinforced concrete walls and moment resisting frames. Studies have been undertaken to investigate the displacement response behaviour of multi-storey buildings supported by a combination of moment resisting frames and structural walls (e.g., Miranda and Reyes, 2002; Akkar et al., 2005; Miranda and Akkar, 2006). However, the studies were generally conducted on multi-storey buildings without irregularities. The building used in this study features vertical irregularities caused by discontinuities for gravitational load carrying elements and plan asymmetry due to eccentrically located reinforced concrete cores (Section 3). Contemporary earthquake design standards and assessment procedures (e.g., Eurocode 8 (EN 1998-1, 2004), AS 1170.4-2007 Commentary (SA, 2009), FEMA 356 (ASCE, 2000)) require dynamic analyses to be performed on such structures. Interim findings based on the analyses of the case study building are presented in Section 4.

3 DESCRIPTION OF BUILDING MODEL AND ANALYSES

The case study presented in this paper was based on an RC building located in Melbourne. The building was built in 1960s and is representative of a common type of existing reinforced concrete building stock. The lateral load resisting elements consist of reinforced concrete core and shear wall located on the east and west end of the building, respectively. The gravitational load resisting elements are made up of reinforced concrete moment resisting frames with unreinforced masonry infills located on the north and south face of the building. Some of the columns in the moment resisting frames are discontinuous at the 1st to 4th level, resulting in vertical irregularities in the building. The plan views at various levels and the north (and south) elevation view of the building are presented in Figure 2. The geometric and material properties of the elements of the building are presented in Tables 2 and 3. As the displacement behaviour of the moment resisting frames is expected to be significantly influenced by the reinforced concrete walls and cores, a three-dimensional building model was developed including all structural elements. Frequency analyses were performed on the case study building with the rotational degree of freedom about the vertical axis (the z-axis) being restrained. The unreinforced masonry infills were ignored in these initial analyses. The first three modal periods of the building are **1.02, 0.24 and 0.11 sec** in the y-direction and **2.29, 0.56 and 0.25 sec** in the x-direction.



(a) plan views (b) elevation view

Figure 2. Case study building

Dynamic modal and static analyses were performed on the case study building assuming linear elastic behaviour. The linear elastic behaviour was assumed in view of the limited displacement capacity of lightly reinforced concrete wall post-yield (Section 2). It is however noted that walls with higher longitudinal reinforcement content will have higher post-yield displacement capacity. The analyses will be extended to account for non-linear behaviour of the structural elements in the future studies. Static analyses were applied in accordance with AS1170.4-2007 (SA, 2007) using seismic hazard value (Z) of 0.08g and assuming that the building is founded on class B, C and D sites. The fundamental period of the building was obtained from the frequency analyses. The mass (m_{eff}) used in the static analyses was obtained using Eq. (1):

$$m_{eff} = \frac{(\sum m_i \delta_i)^2}{\sum m_i {\delta_i}^2} \quad (1)$$

where, m_i is the mass of floor i and δ_i is the displacement at floor i due to an arbitrary lateral load.

The design response spectra in accordance with AS1170.4-2007 (SA, 2007) and response spectra from accelerograms generated on class B, C and D were used in the dynamic modal analyses. The accelerograms were generated using program GENQKE (Lam et al., 2000) based on an earthquake scenario that produces peak ground velocity on rock of 60 mm/sec (which equates to seismic hazard Z value of 0.08g). The program SHAKE (Ordonez, 2013) has been used to generate accelerograms that are representative of earthquake excitations on class C and D sites in accordance with AS1170.4-2007 (SA, 2007). The response spectra of the generated accelerograms are presented in Figure 3. The 1st and 2nd modal periods of the building in the x- and y-direction are superimposed on the figure.

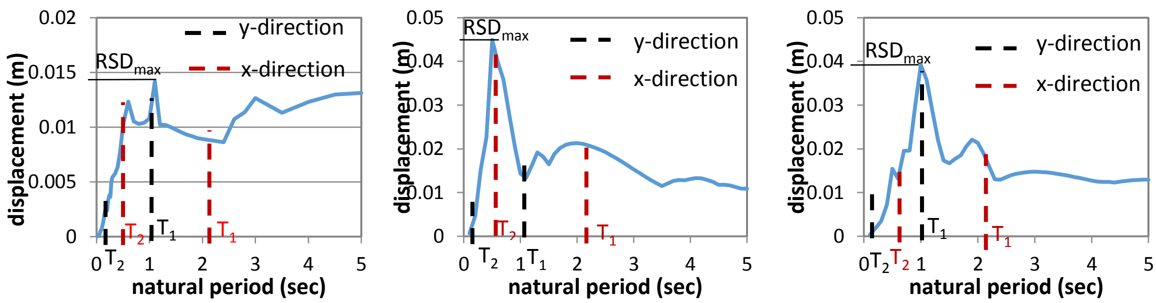
Table 2. Geometric properties used in the case study building

Element	Walls			Beams		Columns			
Type	**Façade**	**Core**	**Shear**	**Standard**	**Transfer**	**A**	**B**	**C**	**D**
Material	M[1]	RC[2]	RC	RC	RC	RC	RC	RC	RC
Width (mm)	110	110	110	280	280	375	280	400	300
Depth (mm)	-	-	-	620	1000	810	610	400	300
Length (mm)				-	-				

[1]M - Clay brick masonry
[2]RC- Reinforced concrete

Table 3. Material properties used in the model

Properties	Reinforced Concrete	Concrete Masonry	Masonry
Mass Per Unit Volume (kg/m^3)	2548	1800	1800
Modulus of Elasticity (GPa)	24.8	8.0	3.0



(a) Class B earthquake (b) Class C earthquake (c) Class D earthquake

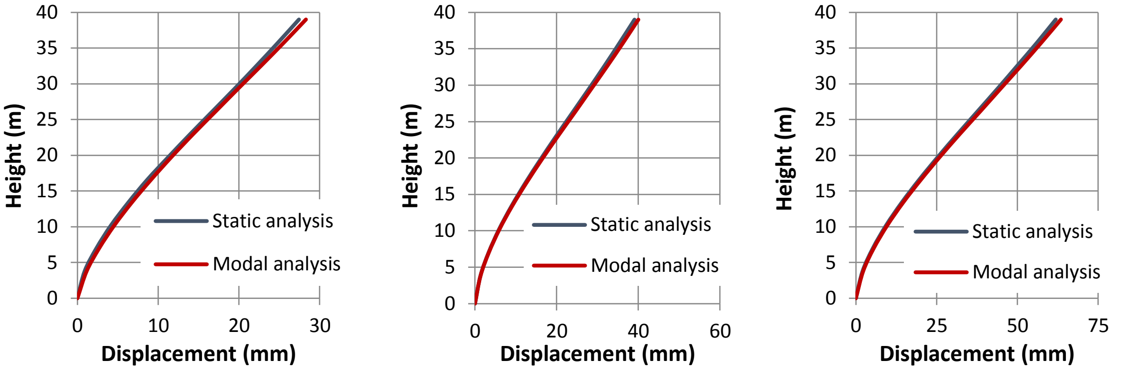
Figure 3. Displacement response spectra of generated accelerograms

4 RESULTS AND DISCUSSIONS

The response of the case study building in the y-direction of motion subjected to a class B, C, and D earthquake is presented in Figure 4 and 5 in displacement and inter-storey drift ratio format, respectively. The analyses were performed based on the design response spectrum with the rotational degree of freedom about the building's vertical axis (the z-axis) being restrained, hence the effects of torsion were ignored. It is shown that both static and dynamic analyses provide similar trend of the displacement response. Despite the vertical irregularities in the building, the static analysis is shown to be able to provide reasonable estimates of the displacement and drift response of the building.

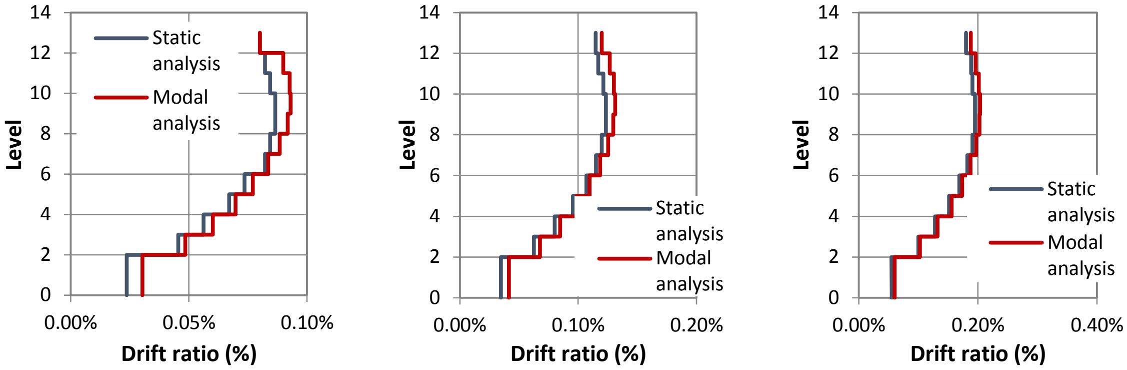
The displacement response of the building based on the design response spectrum in the x-direction of motion is presented in Figure 6. The results from the dynamic analyses deviated slightly from the results from the static analyses, showing some contributions from higher mode. However, the higher mode effects are much more significant when the generated earthquake record is used (Figure 7). The observed trends were caused by the response spectral displacement value at the second modal period of vibration (RSD(T_2)) that is higher than that at the first modal period of vibration (RSD(T_1)) (Figure 3a). The analyses based on the design response spectrum are shown to provide conservative estimates of the displacement response of the building, but the effects of higher mode cannot be well captured by the analyses. Only results based on Class C earthquake are presented, however similar trends were observed from other site classes. The location of the maximum inter-storey drift is also critical in the vulnerability assessment of reinforced concrete buildings. Whilst the maximum inter-storey drift ratio was generally found to occur at 3/4th height of the building (Figure 6b), the maximum inter-storey drift shifted close to the top of the building when higher mode effects are significant (Figure 7b).

Higher mode effects can occur when the first modal period of the building (T_1) is higher than the dominant period of earthquake excitations (the site period). The site period for the generated earthquake records used in this study is 0.5 and 1.0 sec, for Class C and Class D, respectively (Figure 3). Static analyses were found to provide poor estimates of the displacement in the x-direction (T_1 = 2.2 sec) (compare Figure 7a with Figure 6a). The results presented also highlight the limitations of using a design code spectrum in dynamic analyses. It is recommended herein that dynamic analyses should be performed using recorded (or generated) records when the buildings first modal periods are higher than the site period.



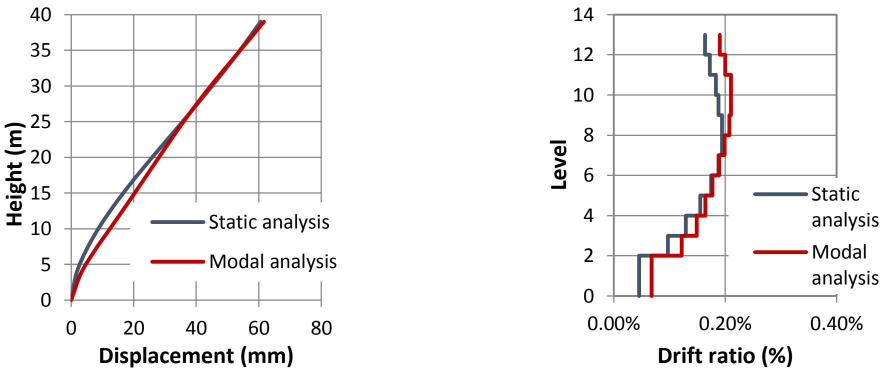
(a) Class B (b) Class C (c) Class D

Figure 4. Displacement response in the y-direction (based on design response spectrum)



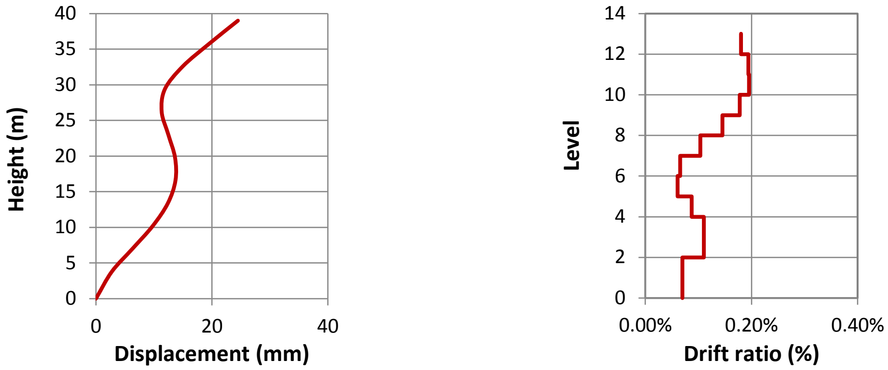
(a) Class B (b) Class C (c) Class D

Figure 5. Drift ratio in the y-direction (based on design response spectrum)



(a) Displacement response (b) Drift ratio

Figure 6. Displacement response in the x-direction (based on design response spectrum Class C)



(a) Displacement response (b) Drift ratio

Figure 7. Displacement response in the x-direction (based on generated earthquake record Class C)

Dynamic and static analyses were also performed on the case study building incorporating the effects of masonry infills. The elevation view of the north (and south face) of the building is presented in Figure 8. The masonry infills only exist on the north and south face of the building, resulting in a decrease in the fundamental period of the building to 1.2 sec for the x-direction. The masonry infills have insignificant effects on the displacement response of the building in the y-direction as they only caused a slight increase in the fundamental period due to the increase in mass.

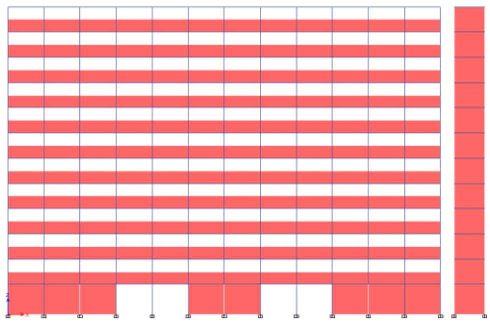
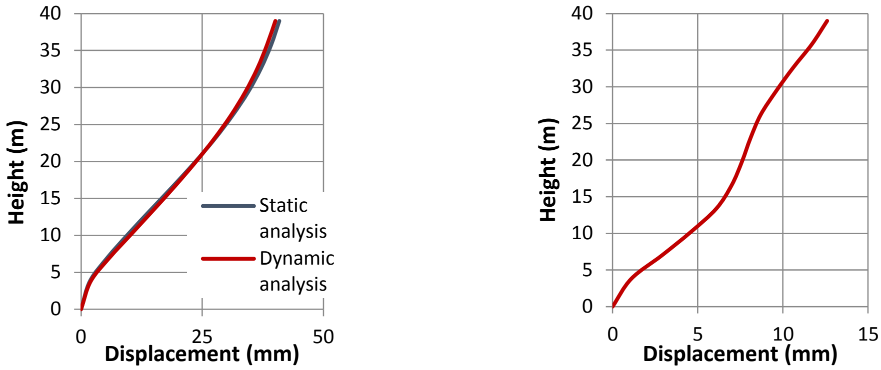


Figure 8. Elevation view of the north and south face of the case study building

In the x-direction of motion, results based on Class C earthquake indicate higher mode effects (Figure 9b). The higher mode effects are expected as the first modal period of the building (T_1) in the x-direction is higher than the site period. The effects are underestimated when the design response spectrum is used in the analyses (Figure 9a). The displacement response presented in Figure 9 indicates that the masonry infills can alter the displacement profile, indicating higher contribution of the moment resisting frames to the response of the building.

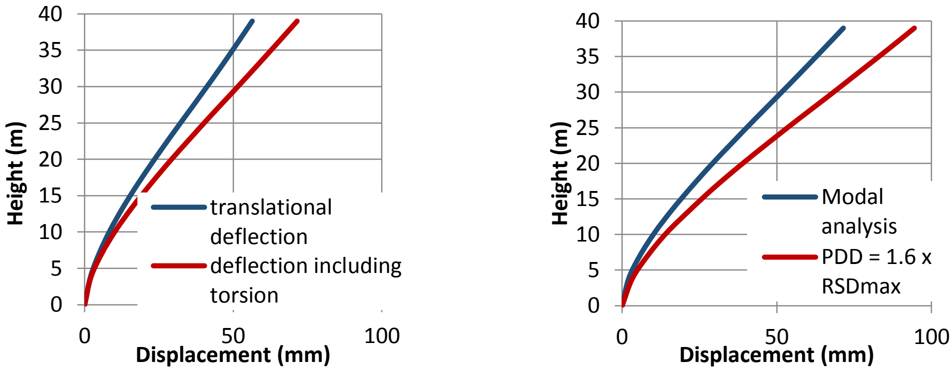
To investigate the effects of plan asymmetry on the displacement response of buildings, dynamic analyses were conducted with the rotation about the vertical axis of the building (the z-axis) being released. The case study building was slightly adjusted by reducing the length of the shear wall located at the west end to 8.4 m to introduce large plan eccentricity within the building. The eccentricity of each storey normalised to the radius of gyration of the building plan varies between 0.3 and 0.8. The displacement response of the torsionally unbalanced building is compared with the displacement response of the corresponding torsionally balanced building in Figure 10a. It is shown that the plan asymmetry causes amplification of the displacement of the building. However, the displacement profile of the torsionally unbalanced building is not altered by the asymmetry.



(a) Based on design response spectrum (b) Based on generated earthquake record

Figure 9. Displacement response in the x-direction (Class C)

Studies undertaken by the authors on a single-storey asymmetrical building model have found the maximum displacement of asymmetrical buildings to be insensitive to the building parameters such as eccentricity and torsional stiffness (Lumantarna et al., 2013). It was proposed that an amplification factor of 1.6 can be applied to the maximum point of the displacement response spectrum (RSD_{max}) to obtain conservative estimates of the maximum displacement demand on asymmetrical buildings. The displacement response estimates based on the proposed method was compared with the displacement response obtained from modal analyses in Figure 10b. It is shown that despite the varying values of plan eccentricity within the building, the displacement response can be conservatively estimated by the method.



(a) comparison with translational displacement (b) comparison with method from Lumantarna et al. (2013)

Figure 10. Displacement response in the y-direction (based on design response spectrum Class C)

5 CLOSING REMARKS

This paper presents interim findings of a study aimed to develop a method which provides estimates of drift demand imposed on reinforced concrete frames. Modal dynamic and static analyses were conducted on a case study building based on the design response spectra recommended in AS 1170.4 and generated earthquake records. It has been found that static analyses can represent the displacement response behaviour of the building when higher mode effects are likely to be insignificant. It is recommended that static analyses can be performed when the first modal period of the building is lower than the dominant period of the earthquake excitations (the site period). Higher mode effects are likely to be significant and hence dynamic analyses should be performed when the first modal period of the building is higher than the dominant period of the earthquake excitations. Plan asymmetry has been shown to amplify the displacement response of the building. However, the magnitude of the amplification appears to be relatively unaffected by the varying values of eccentricity between levels. The amplification factor previously recommended by the authors has been shown to provide conservative estimates of the displacement response.

6 ACKNOWLEDGEMENT

The support from the Bushfire & Natural Hazards CRC for the project entitled "Cost-Effective Mitigation Strategy Development for Building Related Earthquake Risk (A9)" is gratefully acknowledged.

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