The Effects of Building Parameters on the Modal Displacement Shapes of Tall Buildings

Massoud Sofi[1], James Helal[1], Elisa Lumantarna[1], Colin Duffield[1], Priyan A. Mendis[1]

1) Department of Infrastructure Engineering, The University of Melbourne, Parkville 3010, Australia

Email: Massoud Sofi (massoud@unimelb.edu.au)

ABSTRACT

Understanding the behaviour of tall buildings subjected to dynamic loads is essential to ensure efficient and safe structural design. Non-structural components (NSCs) are an integral part of buildings; however, their effects have traditionally been overlooked in the design of tall buildings.

This paper presents the results of parametric studies investigating the change of modal displacement shapes of building in regards to displacement sensitive NSCs in varying quantities, strengths and length as well as building parameters such as height and the number and width of frames. Three-dimensional structural models were developed and analysed using finite element modelling. Dynamic modal analyses were performed on the models to investigate the inherent relationships between the aforementioned parameters and the dynamic response behaviour of buildings. Results indicate significant effects of displacement sensitive NSCs on the modal displacement shapes of tall buildings.

Keywords: Non-structural components, high rise buildings, dynamic modal analysis

1. Introduction

Tall buildings are classified as structures whose governing behaviour has moved from the field of statics into the field of dynamics (Mendis et al., 2007). The control of deflection, drift and accelerations is imperative for tall buildings with designs usually governed by serviceability limit state rather than ultimate limit state design (Li, 2010). The increasing importance and heights of high-rise buildings has generated considerable interest in understanding the potential impact of various building parameters such as number of frames, frame width, height and the effect of NSCs on structural behaviour. Interest in determining the impact of NSCs on building behaviour has been heightened by studies showing that the real-time performance of structures experiencing seismic forces can be greater than those estimated by design codes, which are traditionally assumed to be conservative by nature. Obscuring the issue is the complexity of interactions which occur between NSCs and the structural system. Studies have shown that while NSCs can provide additional strength to a building in particular loading conditions, thus reducing structural damage, the same arrangement applied to a different loading condition can cause additional damage. An extensive review of research in this field has indicated that no comprehensive study has been undertaken with intent to quantify the individual impact of NSCs with consideration for their material property, location, orientation and quantity (Sofi et al., 2014).

In an earlier contribution, dynamic modal analyses were performed on the building finite element models to investigate the effects of different building parameters on the dynamic response behaviour of buildings (Sofi et al., 2013). Results of the modal analyses demonstrated that moment resisting frames orientated parallel to the motion contribute towards the modal displacements of the buildings. It was further shown that the inclusion of displacement sensitive NSCs increases the moment resisting frame's contribution towards a building's lateral resistance. The simplified drift model as proposed by Fardipour et al. (2011) was found to reasonably represent the modal behaviour of buildings when the effects of NSCs are excluded. Further, it was indicated that building models with existing open plans (soft-storey features) contribute to the discrepancies as compared to existing models (Sofi et al, 2013).

In this paper, the results of the dynamic modal analyses of the Redmond Barry Building (RBB) are presented. Building parameters such as height of the building (m), number of frames, width of frame (m), height (m) and the effect of displacement sensitive NSCs by the number of concrete masonry infill walls per floor and average length of infill wall (m) are discussed. Additionally, to evaluate the effect of material properties of infill walls on the inter-storey drift of the building, two different types of masonry infill walls are considered. These are represented by their different material properties such as elastic modulus of elasticity.

2. Redmond Barry Building (RBB) and the Modelling Approach

The Redmond Barry Building (RBB) is located at the Parkville campus of the University of Melbourne. The building holds laboratories and offices in largely open floor plans at the lower levels and a mixture of offices and teaching rooms at the upper stories. The building is 12 storeys tall with a height of 39 m. An extension of the elevator core on the Eastern side takes the overall height to 48.6 m. The building plan is rectangular in shape. The lateral force resisting structural system consists of reinforced concrete moment-resisting frames attached to the concrete core wall and a shear wall located at the Western boundary. The structural analysis software ETABS is used to model RBB in order to conduct parametric analysis. The model was validated by comparison with the measured dynamic properties of the building and has been presented in reference (Sofi et al., 2013). The properties of the finite element models are presented in Tables 1 and 2.

Table 1 - Finite Model Material Properties

Properties	RC	CM1	CM2
Mass per Unit Volume (kg/m^3)	2548	1800	1800
Modulus of Elasticity (GPa)	24.8	2.0	0.8
Poisson's ratio	0.2	0.15	0.15
Shear Modulus (GPa)	10.3	0.9	0.9
Compressive strength (MPa)	27.6	-	-

Note: Reinforced Concrete (RC); Concrete Masonry 1 (CM1); and, Concrete Masonry 2 (CM2)

Table 2 - Finite Model Geometric Properties

Properties	Core Wall	Infill Wall	Beam	Column
Material	RC	CM1 or CM2	RC	RC
Width (mm)	100	190	280	280
Depth (mm)	-	-	620	610

The modified finite element models of the RBB were used for parametric analysis with the aim of determining the effect of various building parameters on the modal displacement shapes. These models were created as part of a broader research effort focusing on the effects of non-load bearing NSCs on the structural dynamics of high-rise buildings. NSCs were represented by the presence of concrete masonry infill walls in a uniform layout throughout all floors of the finite element models which are assumed to be non-load bearing. The infill walls were modelled with fixed supports connected to the top and bottom floors slabs in order to represent internal partitions. The models were also modified to achieve symmetry in order to avoid any effects of building torsional behaviour. Thus, an identical elevator core was added to the western side of the finite element models of the building. Only a stair case is present in reality. The ground floor of the models was assigned a height of 3.8 m while subsequent floors were assigned a height of 3.2 m. This is representative of the soft storey features of the real building. At level 12, the building reaches a height of 35.8 m. The extension of the both elevator cores increases the overall height to 48.6 m. Model RBB 337, one of the finite element models of the representative structure, is presented in Figures 1 and 2.

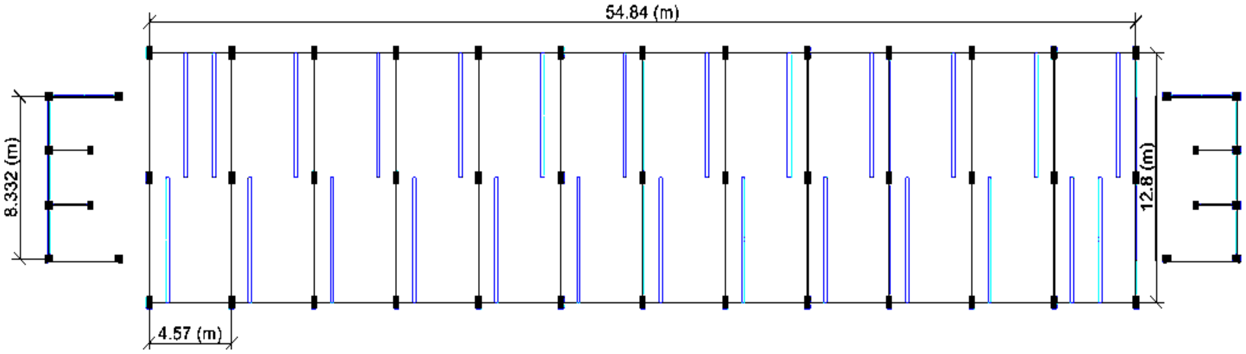


Figure 1 - Floor Plan of Finite Element Model RBB 337

The parametric study analysed the effects of various building parameters on the modal displacement shapes of the building. These parameters covered the presence of non-structural components (represented by concrete masonry infill walls) in varying quantities, strengths and length. Exploring the inherent relationships between these variables and the modal displacement shapes required the modal analysis of various finite element models and the plotting of their results for a graphical visualization of the relationships. Table 3 presents a description of the finite element models used for each test of the parametric study. Unless otherwise stated in Table 3, the finite element models have the number of storeys as 11, number of frames as 12, frame width as 4.75 m and height of the building as 48.6 m.

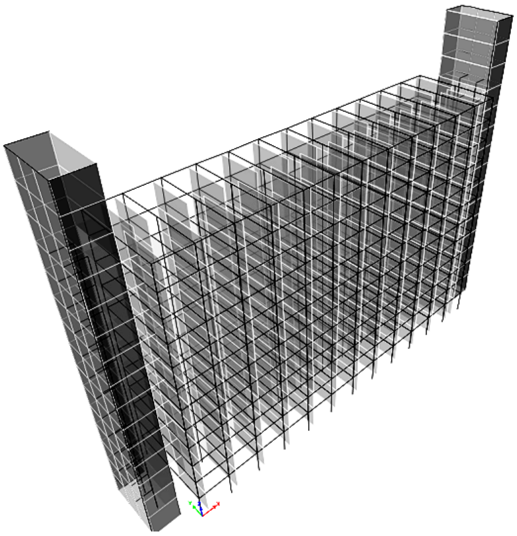


Figure 2 - 3D Rendering of Finite Element Model RBB 337

Table 3 - Finite Element Models Used in Parametric Studies

Model	**Building Description**	**Av. Infill length (m)**	**Number of Walls/floor**	**CM Elastic Modulus (GPa)**
Effects of height	**11-storeys (48.6m)**	0	0	N/A
	12-storeys (51.8m)	0	0	N/A
	13-storeys (55.0m)	0	0	N/A
Effects of number of frames	**Wall + 1 frame**	0	0	N/A
	Wall + 7 frames	0	0	N/A
	Wall + 12 frames	0	0	N/A
Effects of masonry infills as internal walls	**Without infills**	0	0	N/A
	With infills	6.4	26	2
Effects of number of walls	**6.4 m long infill**	6.4	26	8
	3.2 m long infill	3.2	26	8
	1 m long infill	1	26	8
Effects of Young's modulus values	**E_{infill} = 2 GPa**	6.4	26	2
	E_{infill} = 8 GPa	6.4	26	8

3. Results and Discussion

Figure 3 presents the modal displacements of buildings with 11, 12 and 13 storeys. It is shown that modal displacements of multi-storey buildings are not sensitive to incremental change in height. This result supports an earlier finding of parametric studies conducted by Fardipour et al. (2011). Multi-storey buildings are commonly laterally supported by a combination of walls and frames. Hence, the modal displacements of the combined types of lateral resisting elements were investigated. Sensitivity analyses were performed by incrementally increasing the number of frames in the building model. Results from the sensitivity analyses are presented in Figure 4 along with the modal displacements of buildings laterally supported by walls and frames only for comparison. It is shown that the moment frames in buildings shift the modal displacement curves down when compared to the modal displacement curves of buildings that are only laterally supported by walls. However, the difference is shown to be insignificant even with the model with a large number of frames. The addition of adjacent frames into a building that is laterally supported by walls is shown to have no significant effects on the modal displacements of the building.

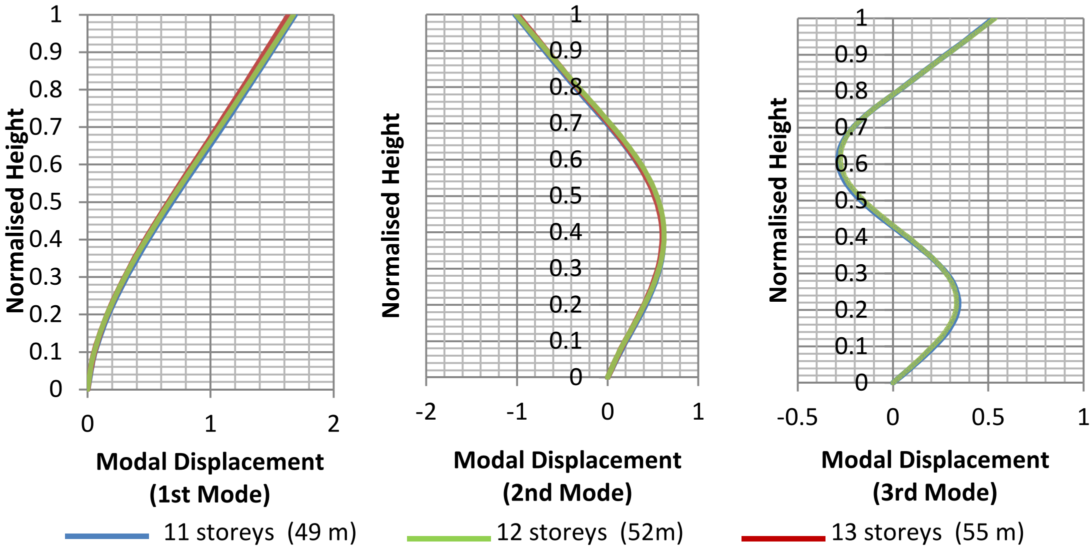


Figure 3 - Effects of height of the building on modal displacements

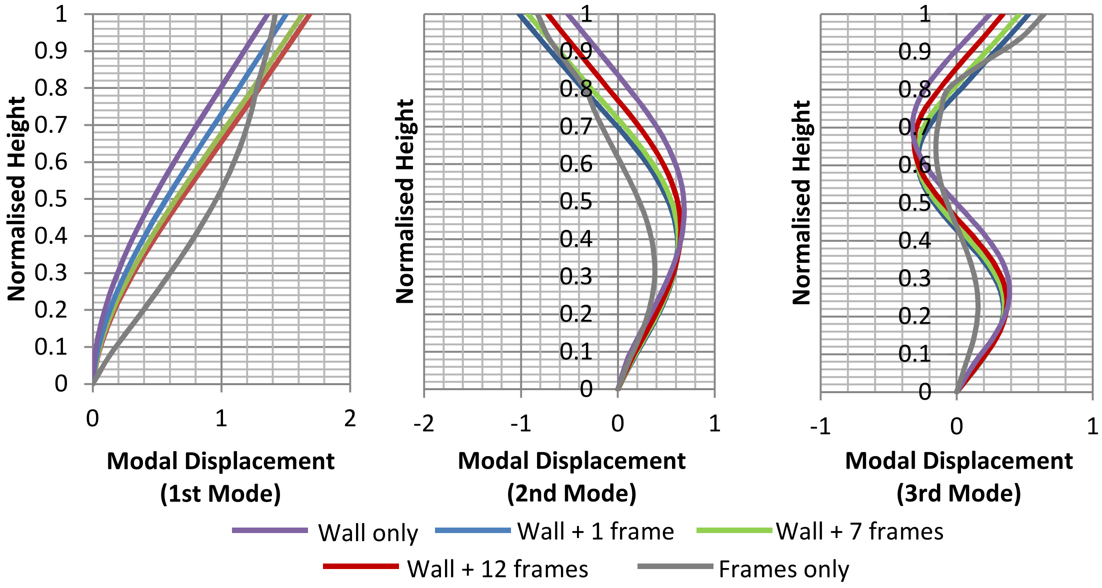


Figure 4 - Effects of number of frames in the building on modal displacements

The effects of concrete masonry infill walls on modal displacements have been investigated. It is shown in Figure 5 that the concrete masonry infill walls do not have significant effects on the modal displacements of the buildings. Similarly, the modal displacements are not shown to be significantly affected by the number of infill walls within each floor of the buildings (Figure 6).

In older buildings, the mechanical properties of construction materials (e.g. modulus of elasticity and strength) can significantly vary due to the quality of workmanship and age of buildings. To investigate the effects of variation in material characteristics, sensitivity analyses were conducted by varying the values of modulus of elasticity of concrete masonry that make up the infill walls. It is shown in Figure 7 that the variation in modulus of elasticity values of the concrete masonry infill walls does not have significant effects on the modal displacements of the buildings.

The observed trends (Figures 3-7) can be expected as the concrete masonry infill walls are modelled as walls that are simply supported to simulate the behaviour of interior partitions (Section 2). The walls have little effects on the lateral stiffness and consequently on the displacement behaviour of the buildings. The walls affect the natural period of vibration of the buildings due to their mass.

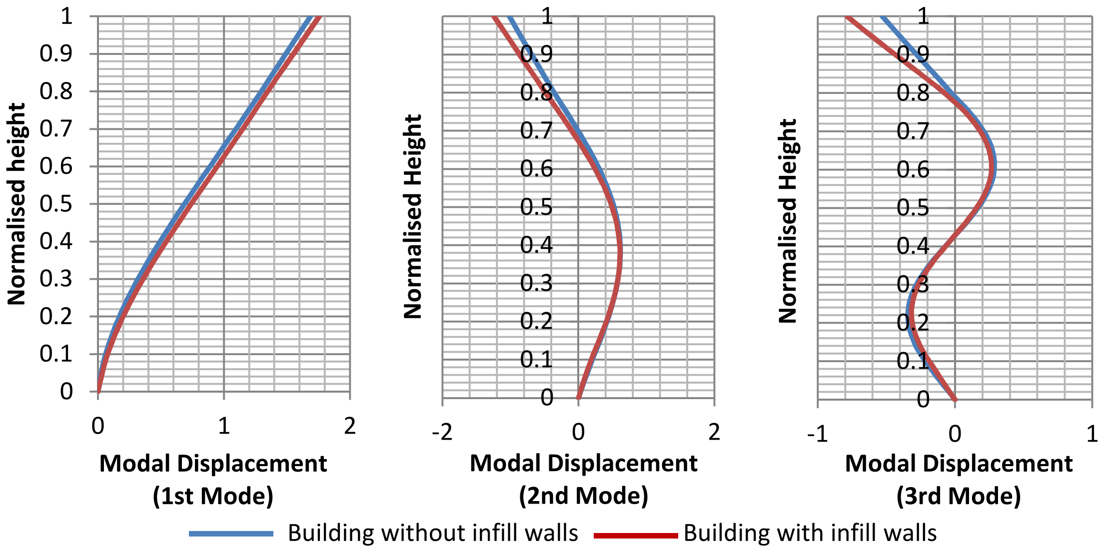


Figure 5 - Effects of concrete masonry infill walls on modal displacements

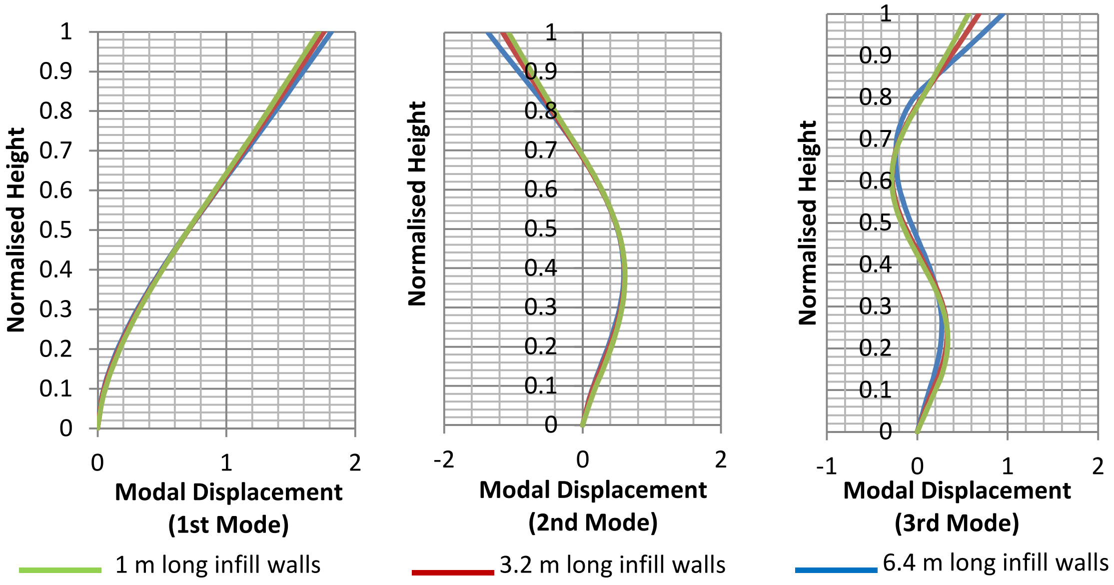


Figure 6 - Effects of number of infills on modal displacements

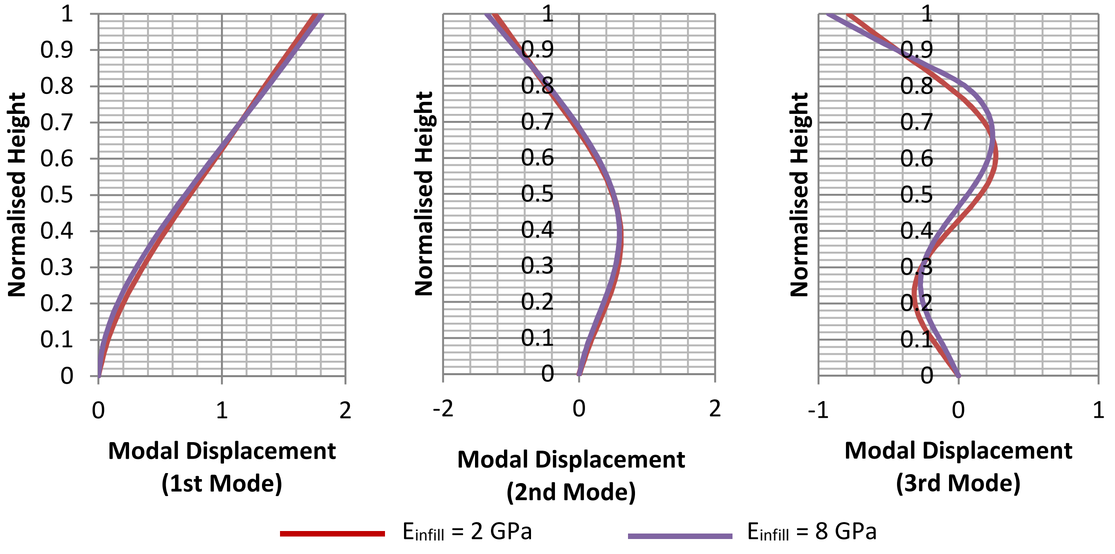


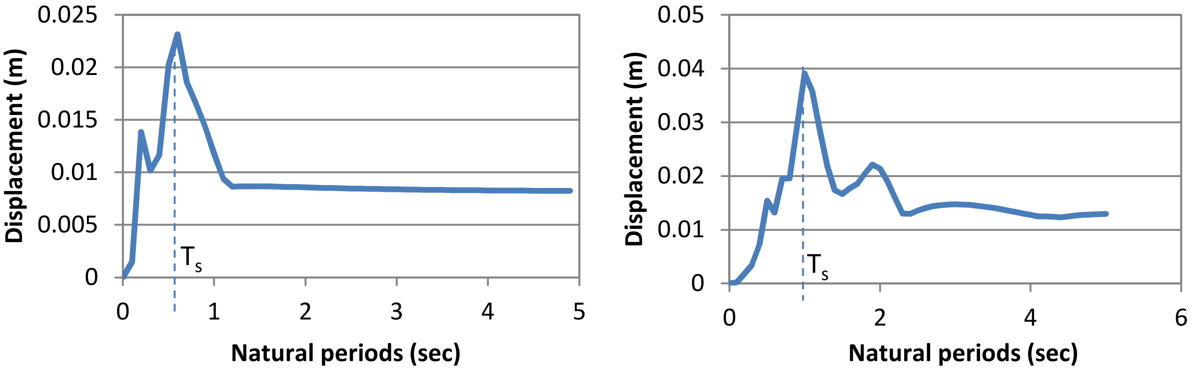
Figure 7 - Effects of the Young's Modulus values of concrete masonry on modal displacements

The natural periods of vibrations of the buildings shown in Figures 3-7 are presented in Table 4. The addition of frames to lateral load resisting elements is shown to result in an increase of the natural periods of the buildings which is caused by the increase in seismic mass. Interestingly the concrete masonry infill walls that are added as internal partitions are shown to have increased the natural period of vibrations of the buildings. This indicates that the infill walls have little effects on the lateral stiffness of the buildings and instead only add to the seismic mass. The infill walls are only shown to reduce the natural period of buildings if a large number of infill walls existed in the buildings.

Table 4 Natural period of vibrations of buildings

Figure Reference	**Building Description**	T_1 (sec)	T_2 (sec)	T_3 (sec)
Effects of height	**11-storeys**	0.75	0.18	0.09
	12-storeys	0.84	0.20	0.10
	13-storeys	0.94	0.22	0.11
Effects of number of frames	**Wall + 1 frame**	0.60	0.13	0.06
	Wall + 7 frames	0.67	0.16	0.08
	Wall + 12 frames	0.75	0.18	0.09
Effects of masonry infills as internal walls	**Without infills**	0.75	0.18	0.09
	With infills	0.79	0.18	0.09
Effects of number of walls	**1m longinfill wall**	0.80	0.19	0.09
	3.2mlong infill wall	0.80	0.19	0.09
	6.4mlong infill wall	0.67	0.15	0.07
Effects of Young's modulus values	E_{infill} **= 2 GPa**	0.79	0.18	0.09
	E_{infill} **= 8 GPa**	0.66	0.14	0.07

The variations in natural period of vibrations of the buildings could affect the displacement response of the buildings under seismic excitations. Response spectrum analyses can be used to obtain estimates of displacement response of multi-storey buildings if linear elastic behaviour is assumed. Response spectrum analyses have been conducted to investigate based on the modal displacements presented in Figures 3 to 7 and the natural period of vibrations of the buildings presented in Table 4. The analyses were undertaken using accelerograms that are simulated to represent earthquake excitations based on earthquake scenarios which produce peak ground velocity (PGV) value on rock that is equal to 60 mm/sec. The PGV value is consistent with the seismic hazard value for major Australian cities (SA, 2007). Program GENQKE (Lam et al., 2000) was used to generate accelerograms on rock, program SHAKE (Ordonez, 2013) was used to generate accelerograms that represents earthquake excitations on class C and D sites in accordance with AS1170.4-2007 (SA, 2007). The displacement response spectra of the generated accelerograms are presented in Figure 8.



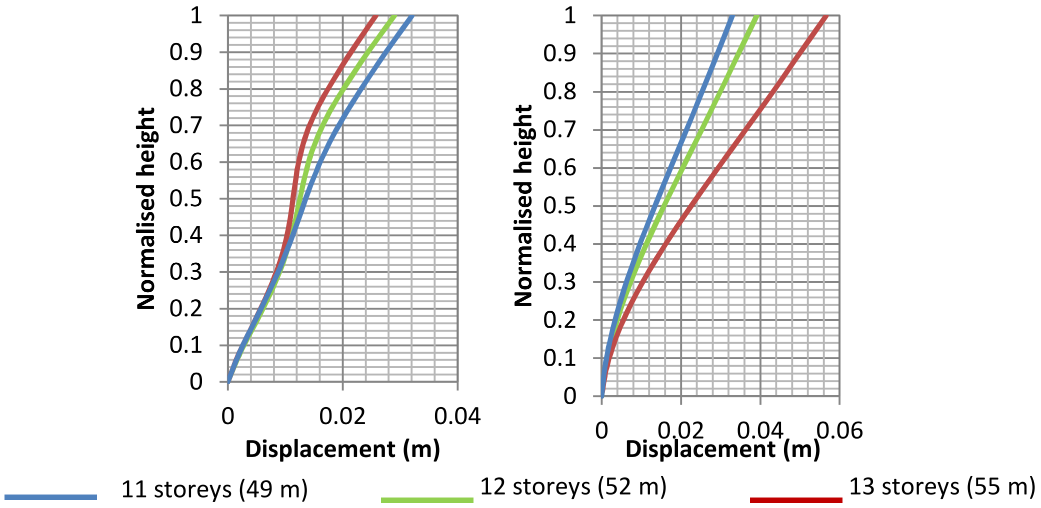
(a) Excitation for class C (M = 5.5, R = 17km) (b) Excitation for class D (M = 6.5, R = 40 km)

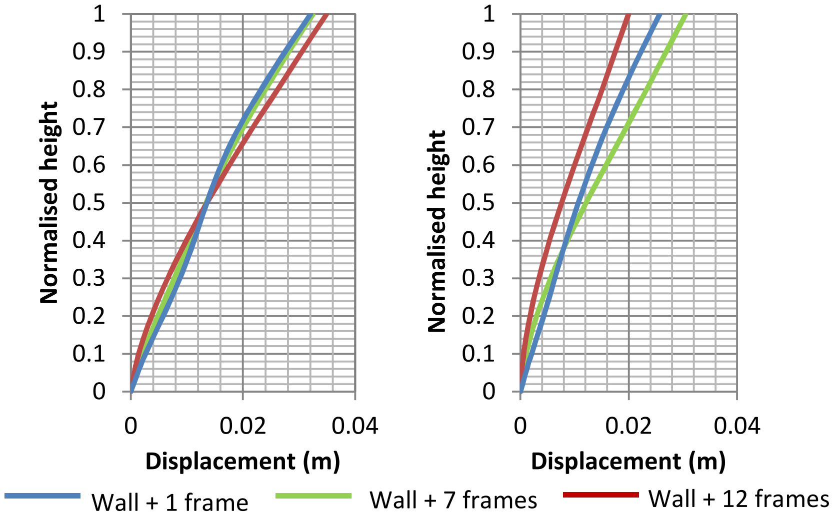
Figure 8 - The displacement response spectra of the generated accelerograms

The displacement profiles of the buildings subjected to excitations are presented in Figure 9 (a to e). The displacement profiles are shown to be affected by height and contribution of frames, although the difference was found to be insignificant for the range of parameters investigated. The displacement profiles were generally not found to be significantly affected by the addition of masonry infill walls (Figure 9). The difference in the magnitude of the displacement profiles was found to be larger when the buildings are subjected to the excitation on a class D site. The natural periods of vibrations of the buildings are lower than the site period (indicated by T_s in Figure 8b) and consequently the natural periods fall on the increasing part of the displacement response spectrum. The displacement values increase with the increase in natural periods of the buildings. The displacement profiles indicate a dominant first mode of vibration as the response spectral displacement value at the first modal period is higher than those at the second and third modal periods.

On the other hand, the displacement profiles of the buildings subjected to earthquake excitation on a class C site indicate some contribution from higher modes. Importantly, the difference in the displacement values of the buildings was not found to be significant. The first modal periods of the buildings in this case are higher than the period of the site. An increase in natural periods does not necessarily result in the increase in displacement as the natural periods of the buildings fall in the constant range of the displacement response spectrum.

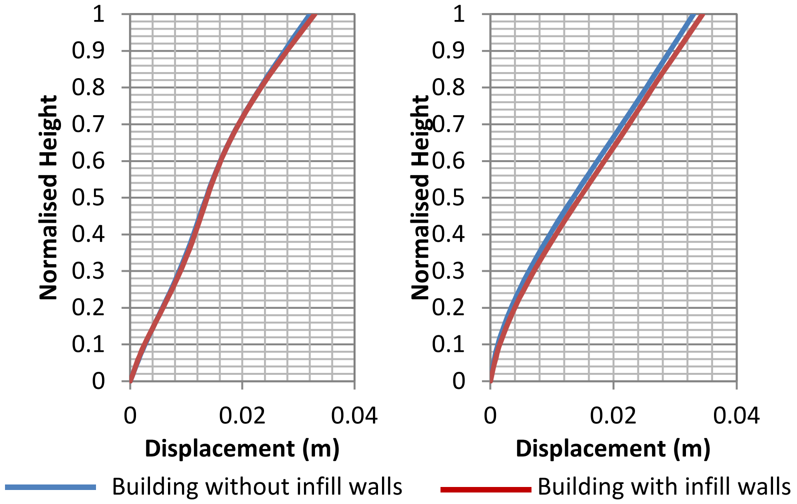
Class C (a) **Class D (a)**





Class C (b)

Class D (b)



Class C (c)

Class D (c)

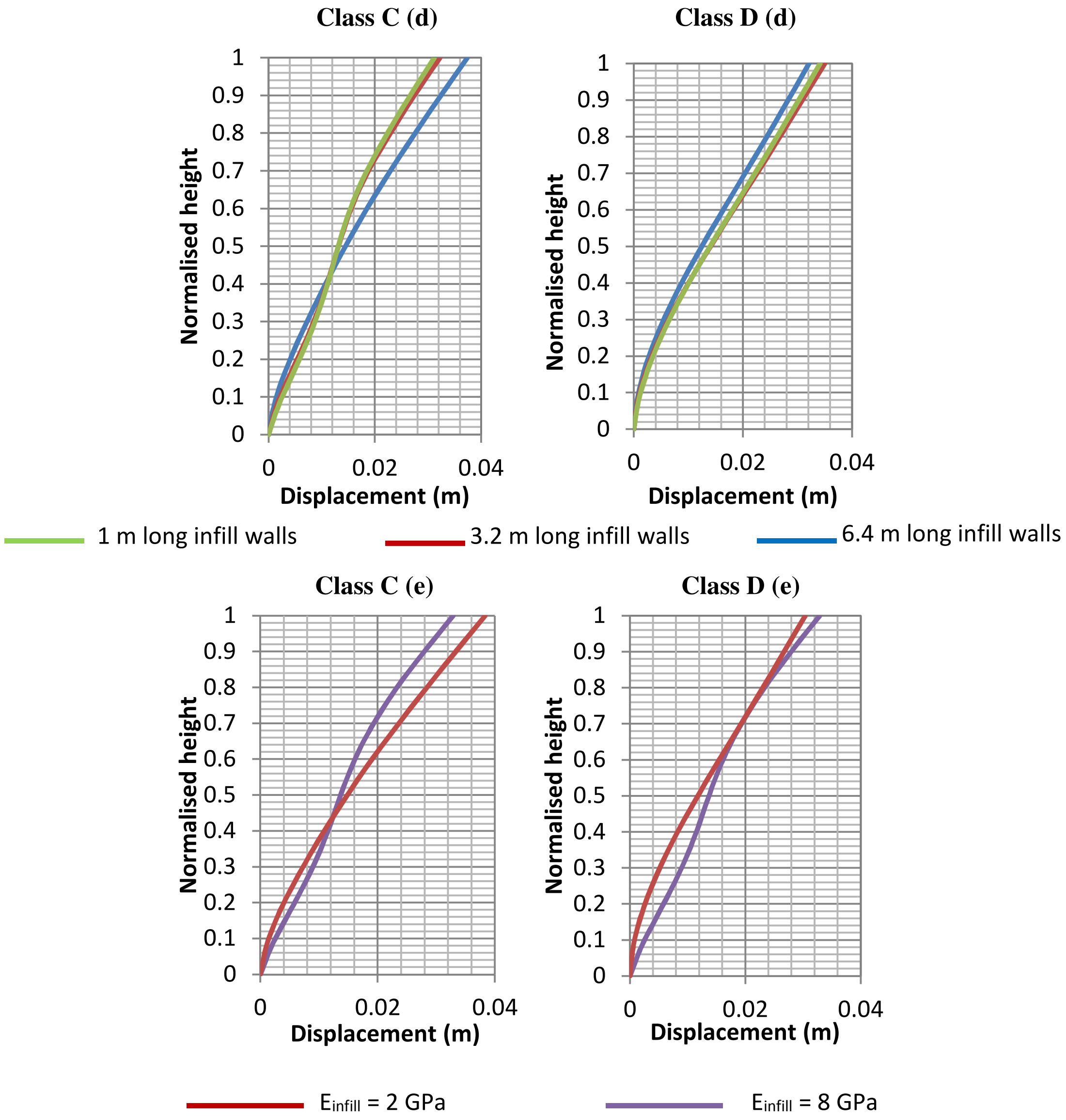


Figure 9 (a-e) - The displacement response spectra of the generated accelerograms

4. Concluding remarks

This paper presented parametric studies of modified finite element models of RBB and the associated results which form part of an ongoing investigation at the University of Melbourne. The building parameters investigated include the effects of building height, number of frames and the effect of NSCs. The objective of the parametric study is to establish the effects of these parameters on the building performance, and in particular, modal displacement shapes. The results of the parametric study show that the building parameters, such as the height and number of frames, appear to have little effect on the modal displacement of the building when compared to the effect of NSCs as partition walls. The displacement response of buildings depends on the period of vibration of the building as well as the dominant site period. The building with the first modal period that is lower than the dominant site period is shown to be more affected by the changes in parameters. The observations made and the results presented herein cannot be conclusive as they apply to only one type of building.

Acknowledgements

The authors would like to acknowledge and thank the Australian Research Council for its Linkage Project Grant (LP100100193).

References

Mendis, P, Ngo, T, Haritos, N, Hira, A, Samali, B, Cheung, J (2007). Wind Loading on Tall Buildings, *Electronic Journal of Structural Engineering*, vol.7, no.1, pp 41-54.

Li, B, Hutchinson, GL, Duffield, CF (2010). Contribution of Typical Non-Structural Components to the Performance of High-Rise Buildings Based on Field Reconnaissance, *Journal of Building Appraisal*, vol. 6, no.2, pp. 129-151.

Lam, NTK, Wilson, JL and Hutchinson, GL (2000). Synthetic Earthquake Accelerograms using Seismological Modelling: A Review, *Journal of Earthquake Engineering*, vol. 4, pp. 321-354.

Ordonez, G.A. (2013). SHAKE2000 (Version 9.99.2 - July 2013). Retrieved from http://www.geomotions.com

Sofi, M, Duffield, C and Hutchinson, GL (2015). Review of Techniques for Predicting the Fundamental Period of Multi-Storey Buildings: Effects of Nonstructural Components, *International Journal of Structural Stability and Dynamics*, vol. 15, no. 2, (In press).

Sofi, M, Lumantarna, E, Helal, J, Letheby, M, Rezapour, A, Duffield, C. Hutchinson, GL (2013). The Effects of Building Parameters on Seismic Inter-Storey Drifts of Tall Buildings, Proceedings of Australian Earthquake Engineering Society 2013 Conference, Nov 15-17, Hobart, Tasmania.

Standards Australia (2007). AS 1170.4-2007: Structural design actions, Part 4: Earthquake actions in Australia. Sydney: Standards Australia.

Fardipour, M, Lumantarna, E, Lam, N, Wilson, J, Gad, E (2011). Drift Demand Predictions in Low to Moderate Seismicity Regions, *Australian Journal of Structural Engineering*, vol. 15, no.3, pp. 195-206.