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The Effects of Building Parameters on Seismic Inter-Storey Drifts of Tall buildings

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ABSTRACT

Tall buildings are becoming an increasingly important and prevalent part of urban life as available land decreases. Understanding the behaviour of tall buildings is an essential component to ensure efficient and safe structural design. Non-structural components (NSCs) are an integral part of structures, yet their effects have traditionally been ignored for the seismic assessment of tall buildings.

This paper presents interim findings of a research study aimed at developing a simple and reliable procedure to estimate the seismic inter-storey drifts of tall buildings, while incorporating the effects of various building parameters, including NSCs. Three-dimensional structural models were developed and validated by comparison with field measurements. Dynamic modal analyses were performed on the models to investigate the dynamic response behaviour of buildings. The results of the analyses were compared to a previously developed simplified drift model, one which is based on simplified two-dimensional building models. Results indicated significant effects of NSCs and soft-storey features on the dynamic response behaviour of buildings.

Keywords: non-structural components, tall buildings, inter-storey drift, lateral stiffness

1. Introduction

Non-structural components (NSCs) are classified as building elements that are primarily architectural and are considered non-load bearing (Bachman & Dowty 2008). Examples of common NSCs include infill walls, partition walls, façades, elevator shafts and stairs (Li et al. 2010). Current Australian and international design practices neglect NSCs and treat them as independent from the structural frame (Su et al. 2005; Li et al. 2010). This occurs despite the knowledge that NSCs interact with the structural system and can have a significant impact on the lateral stiffness and dynamic behavior of the building (Negro &Verzeletti 1996; Chaker & Cherifati 1999; Lee & Woo 2002).

Extensive studies have been undertaken to develop simplified models for obtaining estimates of inter-storey drift demand of multi-storey buildings. The models generally consist of vertical elements to represent the contribution from moment resisting frames and/or shear walls to the lateral resistance of the buildings. For example, models developed by Iwan (1997) and Gülkan and Akkar (2002) were of the form of simple shear beams in which flexural actions of the shear walls have not been included. More elaborate models based on the joint contributions of a shear beam element (representing moment resisting frames) and a vertical cantilever element (representing shear walls) have also been developed (Miranda 1999; Miranda & Akkar 2006). However, the effects of NSCs have been generally excluded in these models.

A simplified drift model has been previously proposed by the authors and co-investigators (Fardipour et al. 2011; Lumantarna 2012). The model can provide estimates of the maximum seismic drift demand of multi-storey buildings using simple expressions. The models are able to account for the effects of the variation of mass and stiffness up the height of the building, structural configurations and form of construction on the response behaviour of multi-storey buildings.

This paper presents a comparison of the simplified drift model (Lumantarna et al. 2009; Fardipour et al. 2011) with results from three-dimensional dynamic modal analyses of two real buildings. The developed simplified drift model is summarised in Section 2. The model was compared with the results obtained from dynamic modal analysis of the two buildings, Hong Kong University's Swire (HUS) and Melbourne University's Redmond Barry (MURB) buildings. The modelling of HUS building was based on Su et al. (2005). Description of the buildings and the adopted modelling approach are presented in Section 3. Both models were validated against building vibration measurements as demonstrated in Section 4. The models were developed in stages, where the structural system was modelled first and the NSCs added sequentially. This allowed a modelling simulation that considered the effects of different NSCs on the mode shape of the building. The HUS building model was validated by comparison against results from Su et al. (2005). The results of the modal analyses were then compared with the simplified model proposed by Fardipour et al. (2011) as illustrated in Section 5. Concluding remarks are presented in Section 6.

2. Summary of Simplified Drift Model

Previous parametric studies have been undertaken to investigate the effects of various building parameters on the modal response of multi-storey buildings (Lumantarna et al. 2009; Fardipour et al. 2011). Investigated parameters include the total height of the building, the disposition of lumped masses up the building height and the degree of wall-frame interactions. It was found that the modal response of multi-storey buildings is insensitive to the variation in parameter values. The insensitivity of modal displacement to the height of buildings is illustrated in Figure 1. A simplified drift model which provides estimates of inter-storey drifts of tall buildings, as proposed by Lumantarna et. al (2009) and Fardipour et al. (2011), is summarised in this section.

The top level modal displacement coefficient (DC) values for buildings of 3, 10, 20 and 30 storeys are shown in Table 1. Since the increase in DC values becomes insignificant when the number of storeys exceeds 20, the top level DC values can be conservatively estimated to be 1.54, 0.83 and 0.46 for the 1st, 2nd and 3rd mode of vibration respectively.

The DC values can be combined with the respective response spectral displacement ordinates (RSD) for calculation of the top level displacement (Δ_{top}). The maximum displacement demand at the top level of the buildings is defined by Equation (1), based on *square-root-of-the sum-of-the square* SRSS (Chopra 2000).

$$\Delta_{\max} = \sqrt{\left(1.54 \times RSD\left(T_{1st}\right)\right)^2 + \left(0.83 \times RSD\left(T_{2nd}\right)\right)^2 + \left(0.46 \times RSD\left(T_{3rd}\right)\right)^2} \tag{1}$$

where $RSD(T_{1st})$, $RSD(T_{2nd})$ and $RSD(T_{3rd})$ are response spectral ordinates for the 1st, 2nd and 3rd mode of vibration respectively.

The average angle of drift (θ_{ave}) can then be obtained using Equation (2).

$$\theta_{ave} = \frac{\Delta_{\max}}{h} \tag{2}$$

where h is the total height of the building.

The maximum drift angle $\theta_{max,i}$ (i.e. rate of increase in drift at the roof level), attributed to vibration mode i, is defined by the following equation:

$$\theta_{max,i} = \left(\frac{DC_i(1.0h) - DC_i(0.9h)}{0.1h}\right)_{max} RSD(T_{i^{th}}) \tag{3}$$

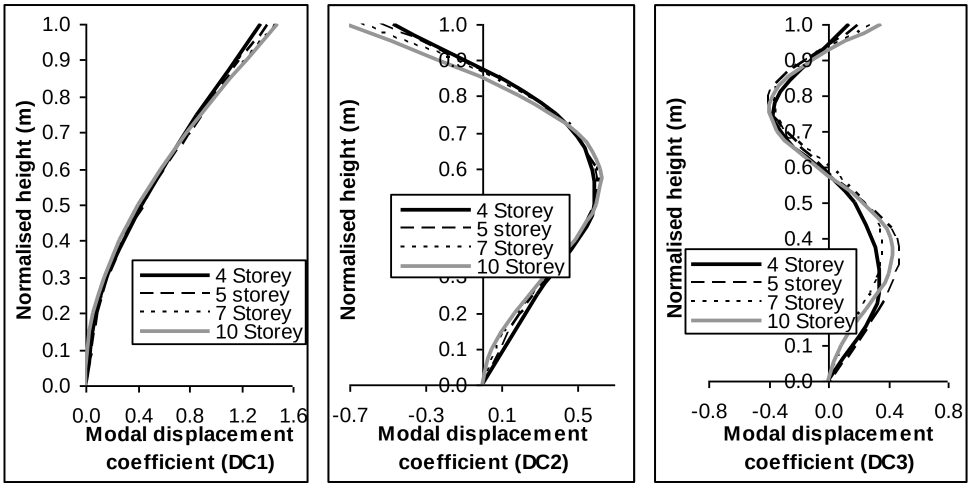


Figure 1 - Modal displacement profiles (Fardipour et al. 2011)

Table 1 - Modal displacement coefficient values for estimation of roof displacement (Fardipour et al. 2011)

No of stories	3	10	20	30
DC1 (Mode1)	1.29	1.48	1.52	1.54
DC2 (Mode2)	0.36	0.70	0.79	0.83
DC3 (Mode3)	0.07	0.34	0.43	0.46

where $\left(\frac{DC_i(1.0h) - DC_i(0.9h)}{0.1h}\right)_{\max}$ is the modal drift angle, $DC_i(1.0h)$ and $DC_i(0.9h)$ are the modal displacement coefficients at normalised heights of *1.0h* and *0.9h* for the i^{th} mode of vibration respectively (Fig.1) and $RSD(T_{ith})$ is the response spectral displacement for the i^{th} mode of vibration.

Parametric studies revealed that the calculated modal drift angle was not significantly affected by the building height (Fardipour et al. 2011). Consequently, solutions to Equation (3) can be simplified as follows:

$$\theta_{\max 1} = 0.23/(0.1h) \times RSD(T_{1st}) \qquad \text{for mode 1} \tag{4a}$$

$$\theta_{\max 2} = 0.46/(0.1h) \times RSD(T_{2nd}) \qquad \text{for mode 2} \tag{4b}$$

$$\theta_{\max 3} = 0.44/(0.1h) \times RSD(T_{3rd}) \qquad \text{for mode 3} \tag{4c}$$

The calculated modal drift angles can be combined to estimate the maximum resultant storey drift ($\theta_{\max}$) using Equation (5) based upon the SRSS combination rule.

$$\theta_{\max} = \frac{2.3}{h}\sqrt{\left(RSD(T_{1st})\right)^2 + 4\left(RSD(T_{2nd})\right)^2 + 3.7\left(RSD(T_{3rd})\right)^2} \tag{5}$$

Based on the bi-linearised displacement response spectrum, estimates for the average angle of drift (θ_{ave}) can be simplified to the following expressions:

$$\theta_{ave} = \frac{1.03}{h} RSD_{max} \qquad \text{for } T_{1st}/T_2 \leq 1 \tag{6a}$$

$$\theta_{ave} = \frac{1.6}{h} RSD_{max} \qquad \text{for } 1 < T_{1st}/T_2 \leq 2 \tag{6b}$$

$$\theta_{ave} = \frac{1.7}{h} RSD_{max} \qquad \text{for } 2 < T_{1st}/T_2 \leq 4.3 \tag{6c}$$

The maximum drift angle (θ_{max}) can be obtained using the following expressions:

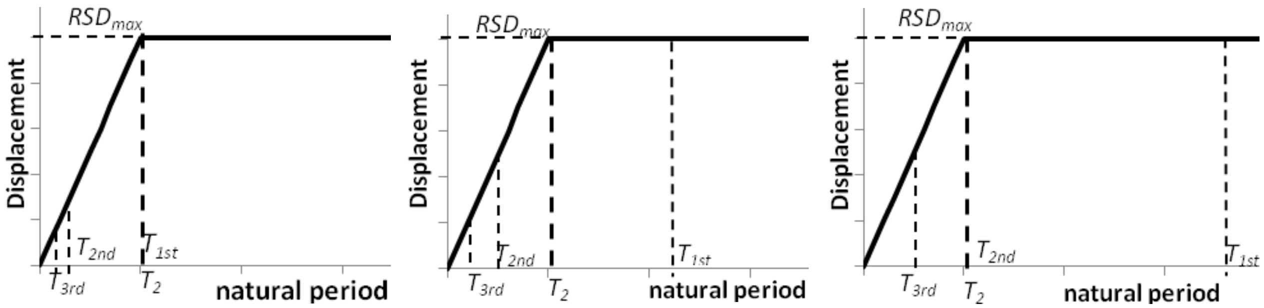
$$\theta_{max} = \frac{2.6}{h} RSD_{max} \qquad \text{for } T_{1st}/T_2 \leq 1 \tag{7a}$$

$$\theta_{max} = \frac{3.2}{h} RSD_{max} \qquad \text{for } 1 < T_{1st}/T_2 \leq 2 \tag{7b}$$

$$\theta_{max} = \frac{5.4}{h} RSD_{max} \qquad \text{for } 2 < T_{1st}/T_2 \leq 4.3 \tag{7c}$$

where T_{1st}, T_{2nd} and T_{3rd} are the 1st, 2nd and 3rd natural periods of vibration and T_2 is the second corner period of the bi-linear displacement response spectrum model (Fig. 2).

The proposed simplified drift model does not take into account abrupt changes in the lateral stiffness and mass values. The predictive model was tested against existing building models considered for approximate global analysis.



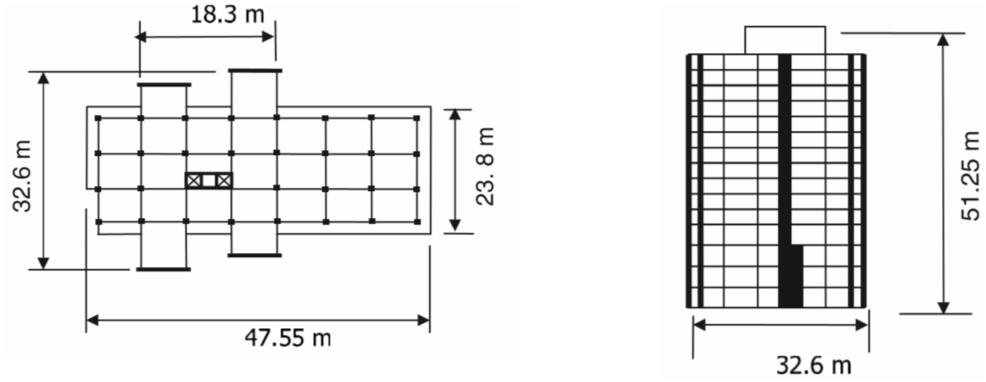
(a) Basis for Eq. (6a) and (7a) (b) Basis for Eq. (6b) and (7b) (c) Basis for Eq. (6c) and (7c)

Figure 2 - Displacement response spectra in bi-linear form used for Equations (7.9) and (7.10) (Fardipour et al. 2011)

3. Building Models and Modelling Approach

3.1. Swire Building (HUS) based on Su et al. (2005) study

Swire Building (HUS) is located at the Hong Kong University campus and is typical of tall building structures constructed in Hong Kong. It is 15 storeys tall with an overall height of 51.25m. The shape of the building is irregular but consists of two distinguishable parts. The first part, consisting of the floors from the lower ground floor to the ground floor, has a rectangular shape; the second part, comprising floors from the upper ground floor to the penthouse floor, has an H-shape. The typical storey height is 3.6m for the lower part floors, and 2.9 m for the upper part floors. The plan dimensions of the building are 47.5m × 32.6m. The lateral force resisting structural system consists of four reinforced concrete (RC) shear walls at the plan edges and RC moment-resisting frames attached to the concrete core walls at the centre. The general plan of HUS is presented in Figure 3.

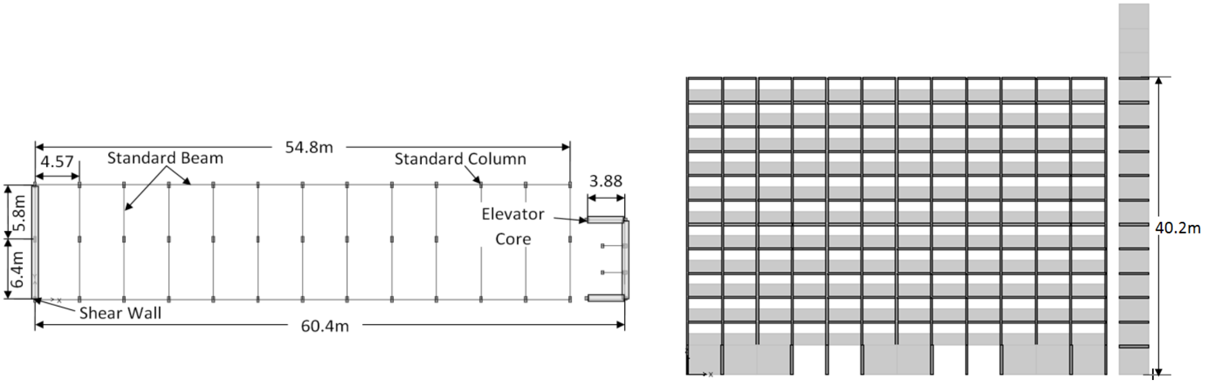


a) Plan b) Elevation

Figure 3 - General layout of HUS building (Su et al. 2005)

3.2. Redmond Barry Building (MURB)

The Redmond Barry Building (MURB) is located at The University of Melbourne Parkville campus. The building houses laboratories and offices in largely open floor plans at the lower levels and a mixture of offices and teaching rooms at the upper stories. An extension of the elevator core to the Eastern side increases the overall height to 48.6m. The building is 12 storeys tall with a height of 39m. An extension of the elevator core on the Eastern side takes the overall height to 48.6m. The building plan is rectangular in shape. The lateral force resisting structural system consists of RC moment-resisting frames attached to the concrete core wall and a shear wall located at the Western boundary. The general plan of MURB is presented in Figure 4.



a) Plan b) Elevation

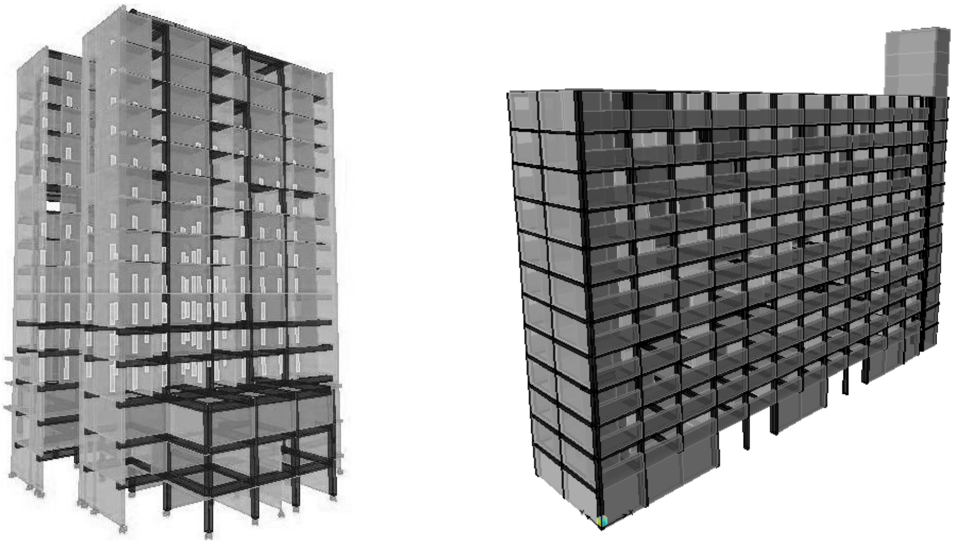
Figure 4 - General layout of MURB building

3.3. Modelling Approach to HUS and MURB

The modelling approach to computer-aided analysis aims to create representative models of real structures that not only overcome the limitations of classical shorthand methods, but also provide meaningful and reliable results compared to their detailed counterparts. An investigation of ETABS package features and functions indicated that there are elements that easily facilitate the modelling of claddings and interior infill walls for the purpose of dynamic analysis (Computers and Structures Inc. 2003). The HUS and MURB buildings were idealised as an assemblage of area, line and point objects. These objects were used to represent different elements such as columns, beams, walls and slabs.

The extruded models of the representative structures are presented in Figure 5. The representation of the HUS structural system and NSCs, as presented by Su et. al (2005), is comprehensive. However, the HUS model presented in this study features only a single material property, based on average material properties of commonly used masonry units in Hong Kong, to represent all exterior and interior infill walls. Due to the lack of access to as-built building plans, the representative model was constructed based on information provided by Su et al. (2005) as well as publically available material such as fire evacuation plans and photographs of the building’s interior and exterior. The member sizes and layout of structural components and NSCs and their respective material properties were based on data provided by Su et al. (2005) having empirically incorporated post-earthquake effects in material properties by reducing the stiffness of structural members. The information on material properties of both the HUS and MURB building is listed in Table 2.

The MURB model was based on architectural and structural drawings provided by Property and Campus Services at the University of Melbourne. Additional site visits were conducted to aid with the process of modelling. Geometric properties of the MURB are presented in Table 3.



a) HUS building b) MURB building

Figure 5 - Extruded models of the buildings

Table 2 - Material properties used in the models

Properties	MURB		HUS (Fardipour et al. 2011)	
	Concrete	Concrete Masonry	Concrete	Concrete Masonry
Mass Per Unit Volume (kg/m^3)	2548	1800	2407	2000
Modulus of Elasticity (GPa)	24.8	8.0	24.0	7.0
Poisson’s Ratio	0.2	0.15	0.2	0.2
Shear Modulus (GPa)	10.3	0.9	10.0	2.9
Compressive Strength (MPa)	27.6	-	30	-

Table 3 - Geometric properties used in the MURB model

Element	Wall				Beam		Column
Type	Infill	Outer	Core	Shear	Standard	Transfer	Standard
Material	CM*	CM	RC**	RC	RC	RC	RC
Width (mm)	190	450	110	110	280	280	280
Depth (mm)	-	-	-	-	620	1000	-
Length (mm)	190	450	110	110	-	-	610

* CM – Concrete masonry ** RC – Reinforced concrete

4. Comparison with Field Measurements

Su et al. (2005) verified the HUS model by comparison with dynamic properties obtained using real-time vibration measurements. The characteristic frequencies in each vibrational direction were found from the peak amplitudes of the power spectra that were determined from spectral analysis of the recorded time histories by applying the Fast Hartley Transform (FHT) technique. Dynamic modal analyses were performed in order to identify the transverse, longitudinal and torsional modes of the buildings. Three-dimensional mode shapes, frequencies and modal participation factors were also found using eigenvector analysis.

MURB building model was equally verified by comparison with dynamic properties obtained using real-time vibration measurements. Kionix KXRB5-2050, a tri-axis accelerometer with a full-scale output range of +/-2g was used for this purpose (Kionix Inc. 2010). The sample rate frequency for this measurement was configured to 128Hz. In order to reduce the level of noise in the original data, the sampling rate was reduced to 64Hz by block averaging three records. A time length of record (T) of 2812 seconds was considered for the FHT. Field measurements of MURB showed that the 1st and 2nd modes of frequencies are 1.364Hz and 1.759Hz respectively (Fig. 6). It is shown that the modal frequencies are well represented by the model which exhibited 1.302Hz and 1.752Hz for the 1st and 2nd modes of frequency respectively.

Table 4 - Validation of HUS Model - Incorporating contributions of NSCs (Su et al. 2005)

	Representative Model	Experimental Results
Fundamental Period X-translation (sec)	0.62	0.60
Fundamental Period Y-translation (sec)	0.53	0.57
Fundamental Rotational Period (sec)	0.44	0.43

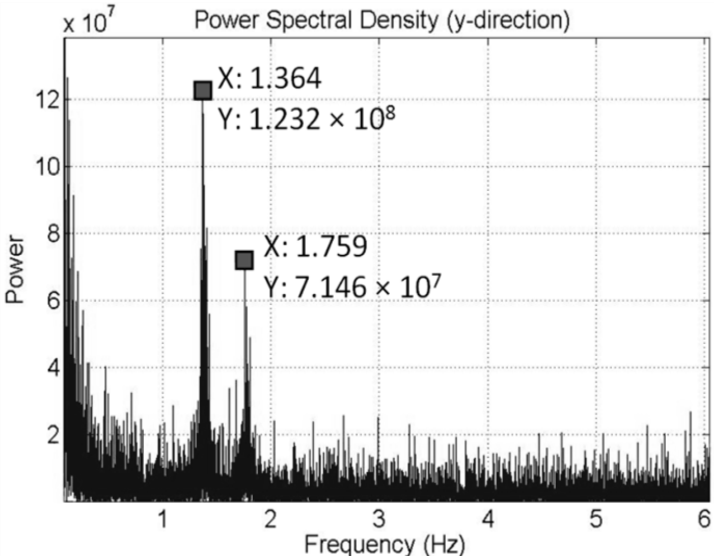


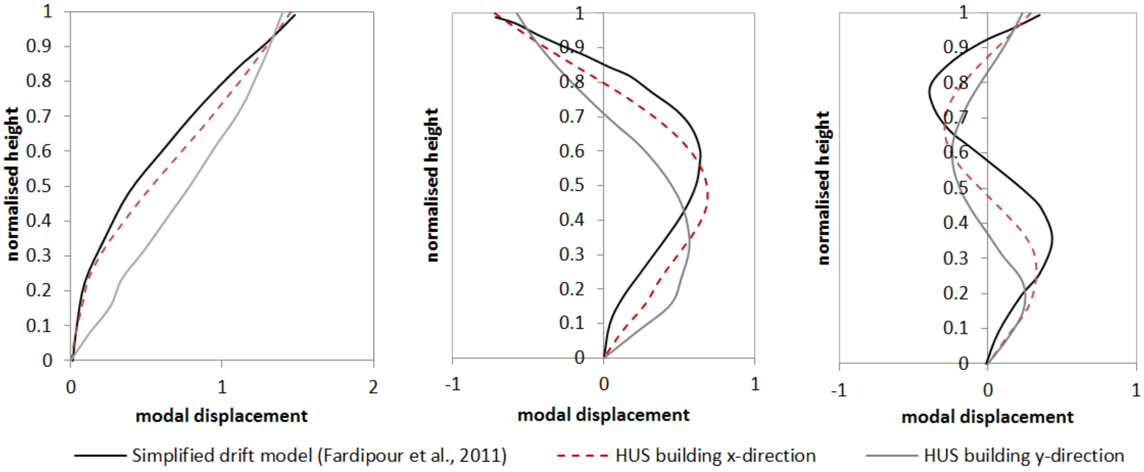
Figure 6 - Power Spectral Density (y-direction) showing the 1st and 2nd modes of frequency

5. Comparison between Modal Analysis Results and Simplified Drift Model

The modal displacements for the first three modes of the multi-storey buildings, having incorporated non-structural components, are presented in Figures 7 and 8. The modal displacements based on the simplified drift model by Fardipour et al. (2011) are also presented for comparison. With the exception of the HUS when subjected to the x-direction of vibration, the first modal displacements indicate contributions from moment frames (Fig. 7(a) and 8(a)). The contributions of moment frames are shown to be significant for MURB when subjected to x-direction of vibration (Fig. 8(a)). The observed trend is expected as the lateral load resisting element in the x-direction is dominated by moment frames (Fig. 8).

The simplified drift model by Fardipour et al. (2011) was found to represent the first mode behaviour and hence provide reasonable estimates of the average drift angle of the multi-storey buildings when their lateral load resisting element is dominated by shear walls (Fig. 7(a)). Some discrepancies were observed in the higher mode behaviour. However, the simplified drift model was found to provide conservative estimates of the maximum drift angle of the multi-storey buildings.

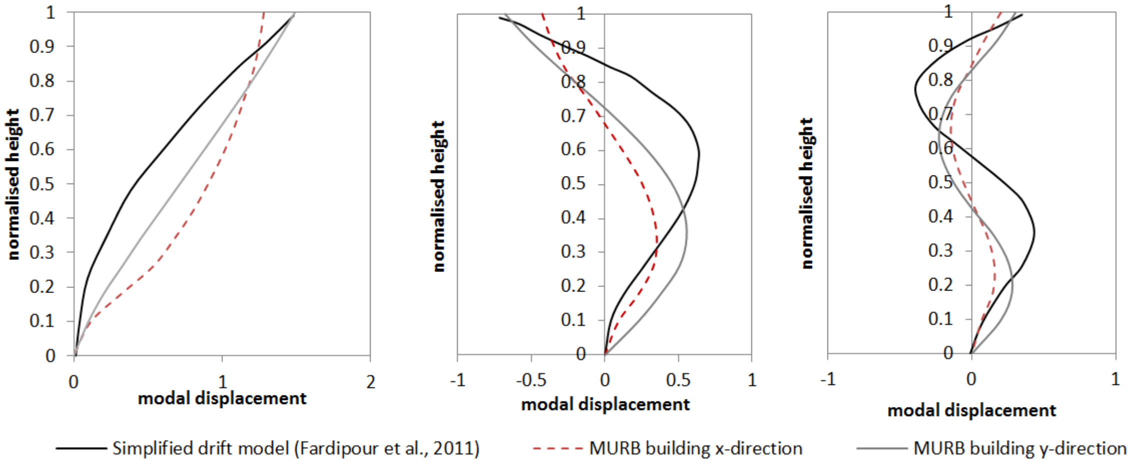
A comparison of MURB modal displacement, with and without NSCs, found that NSCs have a significant effect on the modal response of the building. Modal analyses comparison results are presented in Figure 9 for MURB. It is shown that the non-structural components increased moment resisting frame contributions to the building's lateral resistance. Similar trends were observed in the HUS building model. The simplified drift model (Fardipour et al. 2011) is shown to better represent the modal behaviour of buildings without NSCs. However, some discrepancies were still observed between the modal analyses results and the simplified drift model.



(a) 1st Mode (b) 2nd Mode (c) 3rd Mode

Figure 7 - Comparison between the simplified drift model (Fardipour et al. 2011)

and 3D HUS building model (Su et al. 2005)

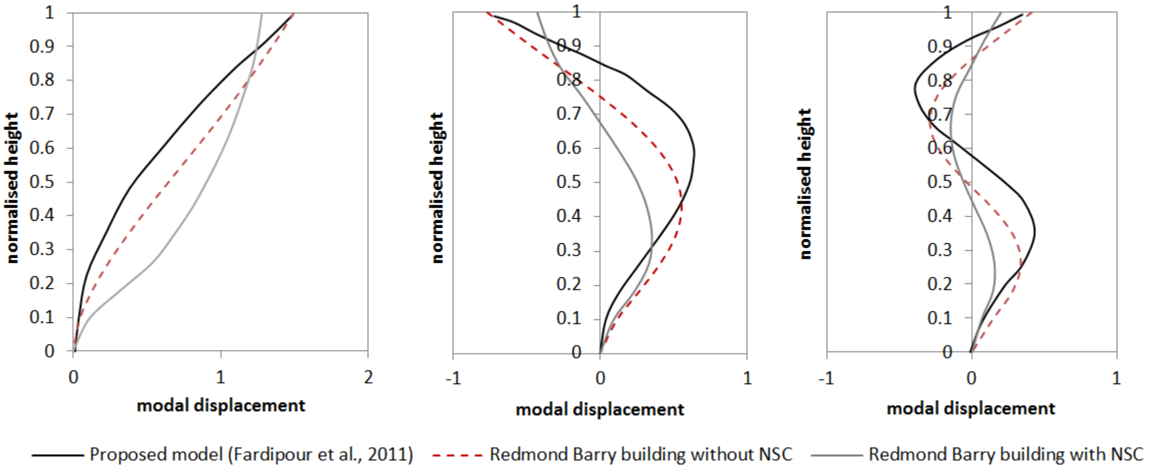


(a) 1st Mode (b) 2nd Mode (c) 3rd Mode

Figure 8 - Comparison between simplified drift model (Fardipour et al. 2011) and 3D MURB building model

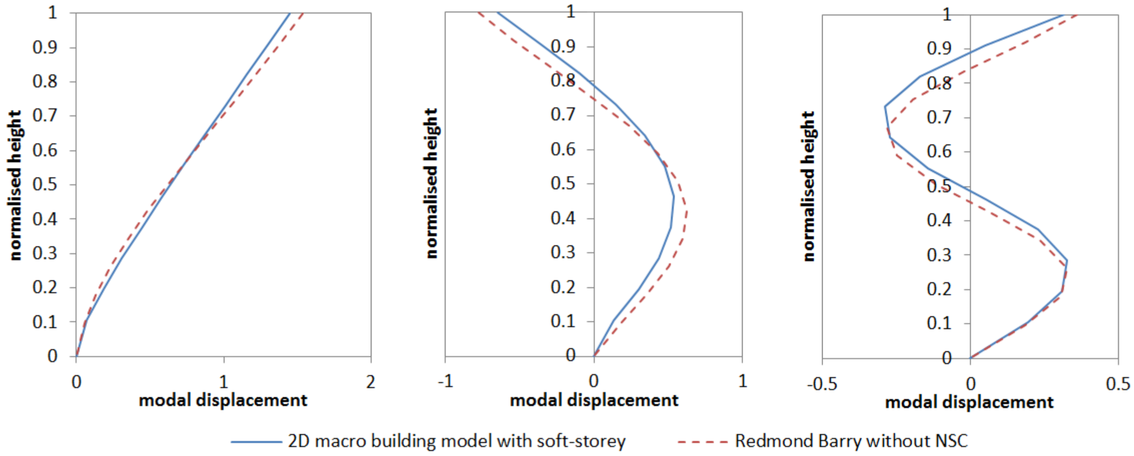
The simplified drift model was based on parametric studies conducted by two-dimensional macro models where lateral stiffness decreased with increasing building height. Previous studies do not include building models with abrupt changes in the values of lateral stiffness. Both HUS and MURB feature open plan ground floors (soft-storeys), which could result in significant reduction of the lateral stiffness values of the buildings.

Modal analyses were conducted on the two-dimensional macro models. The lateral stiffness values of the models at the ground floor were adjusted to half of the floor above to simulate the behaviour of multi-storey buildings with a soft-storey. The lateral stiffness value was kept constant for all floors above the ground floor. Results from the modal analyses were compared with the results of the three-dimensional analyses of MURB (Fig. 10). It is shown that the simplified two-dimensional macro models, as proposed by Fardipour et. al (2011) with the lateral stiffness on the ground floor adjusted to feature soft-storey behavior, match reasonably well with the results of the three-dimensional analysis of MURB. The open plan features seem to have contributed to the discrepancies observed in Figures 8 and 9.



(a) 1st Mode (b) 2nd Mode (c) 3rd Mode

Figure 9 - Comparison between building models with and without NSCs



(a) 1st Mode (b) 2nd Mode (c) 3rd Mode

Figure 10 - Comparison between 2D model and 3D MURB building model

6. Concluding Remarks

This paper presents the interim findings of a research study aimed at developing a simple and reliable procedure to estimate the seismic inter-storey drifts of tall buildings, while incorporating the effects of nonstructural components (NSCs) and other building parameters. Structural models of two real buildings, namely, Hong Kong University's Swire and Melbourne University's Redmond Barry buildings have been developed. The structural models have been validated by comparison with data from literature and field measurements. Dynamic modal analyses were performed on the building models to investigate the effects of different building parameters on the dynamic response behaviour of buildings. Results of the modal analyses demonstrated that moment resisting frames contribute towards the modal displacements of the buildings. It is further shown that the inclusion of NSCs increases the moment resisting frame's contribution towards a building's lateral resistance.

Comparison with a previously developed drift model shows some discrepancies. However, the simplified drift model was found to reasonably represent the modal behaviour of buildings when the effects of NSCs are excluded. Further analyses of simplified building models featuring ground floor soft-storeys indicated that the commonly existing open plan features of real buildings contribute to the discrepancies. Incorporating the effects of NSCs and soft-storey features in the drift model warrants further studies.

Acknowledgements

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