Torsional Responses of Building Structures to Earthquake Loadings Defined in AS1170.4-2007

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Abstract

The torsional responses of asymmetric structures to earthquake ground motions have been studied intensively in the past few decades. However, no study has been reported regarding the adequacy of torsional provisions in the current 2007 Australian Earthquake Loading Code. This study performs dynamic response analyses of single-storey, two-storey and five-storey asymmetric structural models to simulated ground motions compatible to the design response spectrum defined in the Australian Earthquake Loading Code. The effects of one-way and two-way eccentricity, the uncoupled torsional to lateral vibration frequency ratio, and uni-directional and bi-directional ground motion inputs on torsional responses of single-storey and multi-storey structures are investigated. The adequacy of the torsional provisions in the current Australian Standards is also discussed.

Keywords: Asymmetric structure; Trosional response; Eccentricity; Bi-directional input

1. INTRODUCTION

Despite many decades of study, there is still a large percentage of damages and collapses of buildings due to torsional response in major earthquakes. One of the most intensively investigated earthquake damages is the 1985 Mexico earthquake. It was reported that a total of 177 buildings collapsed completely and 85 buildings suffered partial collapse, among them 15% were attributed to the coupled torsional responses and of these 42% were corner buildings (Scholl, 1989). In the recent Christchurch earthquake in 2011, a number of buildings around the Central Business District were observed experiencing significant torsional responses which resulted in structural damage (Chouw et al., 2011). Despite the building codes for earthquake resistant design of Mexico and New Zealand are among the most advanced, the events showed there was a lack of knowledge in this field and that the provisions employed against torsional response were not always adequate. This paper performs numerical simulations of torsional responses of building structure models to ground motions defined in the Australian Earthquake Loading Code and evaluate the adequacy of torsional provisions given in AS1170.4-2007 (Australian Standard 2007).

Based on intensive studies by many researchers, the important governing parameters of the torsional responses of asymmetric structures include the ratio of the uncoupled torsional to translational frequency of the structure, the eccentricity between the centre of mass and the centre of stiffness, the uncoupled vibration frequencies and the damping ratio (Sfura 2003). These parameters have been intensively studied over the last couple of decades and some general observations have been made on elastic torsional responses of structures to earthquake ground motions. Many researchers have also performed inelastic torsional response analyses, and made observations based on the results they obtained (e.g., Goel and Chopra 1990, Ferhi 1998, Bugeja et al. 1999, Riddell and Santa-Maria 1999, Fajfar et al. 2000, Stathopoulos and Anagnostopoulos 2003, Perus and Fajfar 2005, Stefano et al. 2006, and Dutta and Roy 2012, etc). However, unlike elastic torsional response, there is no general conclusion that can be made about the inelastic behaviour of the asymmetric buildings and the governing parameters (Fajfar et al. 2004). This is mainly due to the contradictory conclusions found in many past studies (Humar and Kumar 1998). This is because the parameters governing the torsional response changes during the plastic deformation since the stiffness, radius of gyration, the location of the centre of rigidity, and the eccentricities are changing constantly. For these reasons, in order to have a general observation in the present study, only the elastic torsional responses of asymmetric buildings subjected to simulated ground motions compatible to response spectrum defined in AS1170.4-2007 are studied and the results are compared with the design specifications.

Early studies of coupled elastic lateral-torsional responses can be traced back to 1970's. Kan and Chopra (1977) investigated the torsional response of a single storey asymmetric model. It was found that the uncoupled torsional to lateral frequency ratio affects the torsional coupling responses, especially when the ratio is around one, and torsional coupling always reduces base shear as compared to that in the corresponding symmetric system. Increasing the eccentricity perpendicular to the ground motion generally resulted in an increase in torque. However, increasing eccentricity in the direction of ground motion generally decreases the torque. Study by Tso and Dempsey (1980) found that building structures are susceptible to torsional response when the frequency ratio is between 0.75 and 1.25 for small eccentric buildings, when the eccentricity is large, the frequency ratio does not have a significant effect. Study by Chandler and Hutchinson (1986) confirms these observations, and the authors further pointed out that the increase in the eccentricity is nonlinear to the increase in the torsional response, and that the increase in the torsional response is more substantial at small eccentricities. In addition, torsional coupling effects can significantly increase the lateral displacement of the resisting elements. A sufficiently large eccentricity can cause an increase in the displacement of the element by 50% when compared to the corresponding symmetrical structure.

All the above analyses are based on single-storey models. Hejal and Chopra (1989) analysed a five storey building model and found that the lateral and torsional coupling responses are similar to those of a single storey structure. Torsional coupling caused decreases in the base shear, the base overturning moment and the top floor lateral displacement, but increases in the base torque. Similar to single storey structure, the effects of the torsional response were more evident when the uncoupled frequency ratio was close to unity and/or when the eccentricity was large. It was also observed that the height-wise variation of forces due to the torsional coupling were insignificant. Study by Hutchinson et al. (1993) of an idealised 20 storey buildings found that the distribution of the torsional coupling behaviour is not uniform over the height of the building, with the top floor having the largest torsional coupling effect. Goel and Chopra (1994) noted it was difficult to analyse multi-story building due to the various definitions of centre of resistance, and the difficultly in determining the exact location of the centre of resistance for the structure. However, other researchers commented that single storey models can lead to an accurate evaluation of the asymmetric multistorey structures for the elastic torsional behaviour (Stefano et al. 2006).

The above reviewed studies considered only uni-axial ground motions and one-way eccentric structures. In reality, earthquake ground motions come in both horizontal directions and building eccentricity can be in both directions. Some researchers also investigated the responses of one-way and two-way eccentric structures to uni- and bi-directional ground excitations (De Stefano et al. 1998, Hernandez and Lopez 2000, Fajfar et al. 2000, Ghersi and Rossi, 2001, Heredia-Zavoni and Machicao-Barrionuevo 2004, Perus and Fajfar 2005, Magliulo and Ramasco 2007). Most of those studies found that structural responses obtained by bi-directional ground motion and uni-directional ground motion are very different. Bi-directional ground motion inputs result in significant increases in the torsional responses, especially when the structure has similar lateral stiffness in both directions. Magliulo and Ramasco (2007) suggested that uni-directional excitation analysis is basically not suitable. However, some contradicting observations have also been reported. For example, Ghersi and Rossi (2001) studied the effects of bi-directional ground motion on a single storey structure and found that the second component of ground motion only affects the inelastic response of the structure in an insignificant way when compared to a uni-directional excitation analysis.

All the above studies assumed uniform ground motions in the analysis although most of them compared the adequacy of accidental eccentricity specified in various design codes. The accidental eccentricity accounts for the difference between the actual eccentricity and the design eccentricity of a structure when an earthquake strikes, and the torsional responses induced by torsional and spatially varying ground motions. Hao (1997, 1998) studied torsional responses of one-way and two-way eccentric structures to spatially varying uni- and bi-directional ground motions, and examined the influences ground motion spatial variations on torsional responses.

2. CODE PROVISIONS

All the seismic design codes give analysis and design guides to account for torsional responses of building structures. Generally, most codes allow for a static elastic analysis to be carried out where the torsional moment of each floor is obtained by multiplying the storey shear by the design eccentricity from the centre of mass. The design eccentricity is of the form:

$$e_d = \alpha e \pm \beta d \tag{1}$$

where e is the actual eccentricity between center of mass and center of stiffness, d is the dimension of the structure in the direction perpendicular to the ground motion direction. The first term accounts for the effects caused by actual eccentricity and α is an coefficient to amplify this effect in the design; the second term accounts for the torsional responses caused by torsional and spatially varying ground motions and by errors of actual eccentricity and that used in the analysis, and β is an accidental eccentricity coefficient. Different codes give different α and β

values. The 2003 EuroCode 8, 2003 International Building Code, and the 2006 Turkish Code specify α = 1.0 and β =0.05, while the 1995 National Building Code of Canada and the 1995 Mexico City Building Code recommends α = 1.5 and β = 0.05. Australian and New Zealand seismic codes use α = 1.0 and β =0.1

Most design codes around the world for structures responding with nominal ductility or in the elastic range consider the effects of the two horizontal components of ground motion by using a beta-percentage combination, where the effects of one horizontal excitation are taken fully but only a proportion of the second component of motion is taken. In most cases, this percentage is usually 30% or 40%, and is used to estimate the response. A recent investigation by Heredia-Zavoni and Machicao-Barrionuevo (2004) found that using either 30% or 40% of the second component of ground motion had no significant effect on improving the estimation of the total response, as there was only a 5% difference between the responses obtained from using either percentage. Studies by Magliulo and Ramasco (2007) stated that the 30% to take into account the effects of the second ground motion component are too conservative and should be reduced.

Some researchers have studied the adequacy of the torsional provisions in many standards. In a study undertaken by Tso and Dempsey (1980) to investigate whether the building codes of Mexico, New Zealand, Canada, ATC and Germany are sufficient in estimating the torque in structures. It was found that only the building code from Germany was sufficient, while the other codes underestimated the effects. Hao (1997) investigated the code provisions that had α = 1.5 and β = 0.1 and found that they were inadequate for torsionally flexible structures induced by ground motion with significant spatially variations. Humar and Kumar (1998) also investigated the sufficiency of the National Building Code of Canada against torsional response with α = 1.5 and β = 0.1. It was observed that design eccentricity was overly conservative for the flexible side. Similar conclusions were also made by Rutenberg and Pekau (1987).

Many researchers have also studied the accidental eccentricity component. Pekau and Guimond (1988) investigated the effects of accidental eccentricity because of variation in the strength of elasto-plastic resisting elements. It was found that when the static plastic eccentricity is large, the β = 0.05 is not sufficient. Recently, Stathopoulos and Anagnostopoulos (2010) performed an extensive study into the effectiveness of the accidental component in the design eccentricity in the inelastic range. A multiple degree of freedom plastic hinge structure was analysed and found that generally the accidental design eccentricity was not effective in reducing or distributing the ductility demands on the resisting elements of the structure. The authors suggested that over simplification of past models had resulted in these contradictory findings. They recommended that the accidental component in the design eccentricity should be eliminated.

Most design codes estimate torsional responses of structures by using storey shear force times the design eccentricity. The 2004 Eurocode takes into account the torsional response of structure by performing both static and dynamic analysis depending on the specific conditions defined in the code (Eurocode 8, 2004). The Chinese Seismic code requires modal analysis of torsional responses for regular structures and time history analysis for structures with significant eccentricity and irregularity. In a recent study by Ghersi et al. (2007) it was observed that the modal analysis of multi-storey asymmetric buildings resulted in a satisfactory performance of torsionally flexible structure, while the static analysis was unable to satisfy the maximum ductility requirement.

The current Australian Standard takes into account the torsional effects caused by earthquakes on an asymmetric structure by applying a horizontal equivalent static force at a position that is perpendicular to the eccentricity plus ±0.1b from the centre of mass, where b is the plan width of the building. This specification implies α=1.0 and β=0.1 in calculating the design eccentricity. The equivalent static force applied along one of the horizontal directions consists of 100% of the load, while in the other horizontal direction 30% of the load is considered (Australian Standard, 2007). Study of the adequacy of this specification using the specific ground motions defined in the code cannot be found in the literature. This paper performs intensive numerical simulations to analyse the torsional responses of asymmetric structures subjected to simulated ground motions compatible to the design response spectrum defined in AS1170.4-2007. The adequacy of the provision in AS1170.4-2007 to account for torsional responses will be examined.

3. STRUCTURAL MODEL

Three structural models, representing single-storey, two-storey and five-storey building structures as shown in Figure 1 are considered. The single-storey model consists of a rigid deck, supported by four columns at its corners. The column is fixed at its base. The stiffness center (CS) of each storey coincides with the geometric center, while the mass center (CM) varies with eccentricity e_x and e_z in two horizontal directions. The structure is square in the plan-view with dimension of 10m, and a height of 4m. For the multi-storey structures, the same simple model is used but is stacked on top of one another to form the two-storey and the five-storey model.

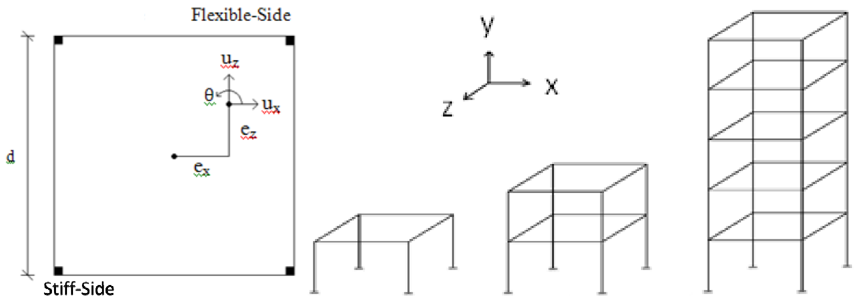

Fig. 1 Structural models

In numerical simulations, the eccentricities e_x and e_z are varied independently from 0.0 to 3.0 m with an increment of 0.5 m. The eccentricities at different floors of multi-storey structure models are also varied independently, i.e., eccentricities of different floors might be different. Owing to page limit, in this paper only the results with regular eccentricities, i.e., all the floors have the same eccentricities, are presented. Three torsional rigidity conditions are considered. They are torsionally flexible, with the uncoupled torsional vibration frequency to lateral vibration frequency, $\Omega=\omega_\theta/\omega_x=0.75$; torsional intermediate stiff with $\Omega=1.0$; and torsionally stiff with $\Omega=1.5$, in which

$$\omega_x = \sqrt{\frac{4K}{M}}, \qquad \omega_\theta = \sqrt{\frac{K(2d^2 + 4e_x^2 + 4e_z^2)}{I}} \tag{1}$$

where *K* is the column lateral stiffness, *M* is the lumped mass of the structure, and *I* is the mass polar moment of inertia about the vertical axis through the centre of mass. Without loss of generality, the steel columns are assumed to be square with Young's modulus 200 GPa, cross sectional area 24000 mm^2 and moment of inertia in both the X and Z directions 164490000 mm^4. The lumped mass is 25 tonnes, and the mass polar moment of inertia for torsional flexible case is 2222.18 tone-m^2, torsionally intermediate stiff case is 1249.97 tone-m^2 and torsionally stiff case is 555.54 tone-m^2. In numerical simulations, 5% Rayleigh damping corresponding to the fundamental translational and rotation modes are assumed. Computer program DRAIN-3DX (Powerll and Campbell 1994) is used to calculate the structural responses.

4. GROUND MOTION SIMULATIONS

In this study, 10 sets of ground motion time histories are stochastically simulated and used as input in structural response analysis. Each simulated time history is compatible to design spectrum defined in AS1170.4-2007 for soft soil condition and normalized to 0.09g (Australian Standard 2007). The duration of strong ground motion is assumed to be 20.48 sec, and sampling rate is 0.01 sec in the simulations. The ground motions in the two horizontal directions are assumed to be stochastically independent. Figure 2 shows a typical set of simulated ground motions in the X and Z directions. Figure 3 shows the comparisons of the design response spectrum and the response spectrum of the two simulated ground motions.

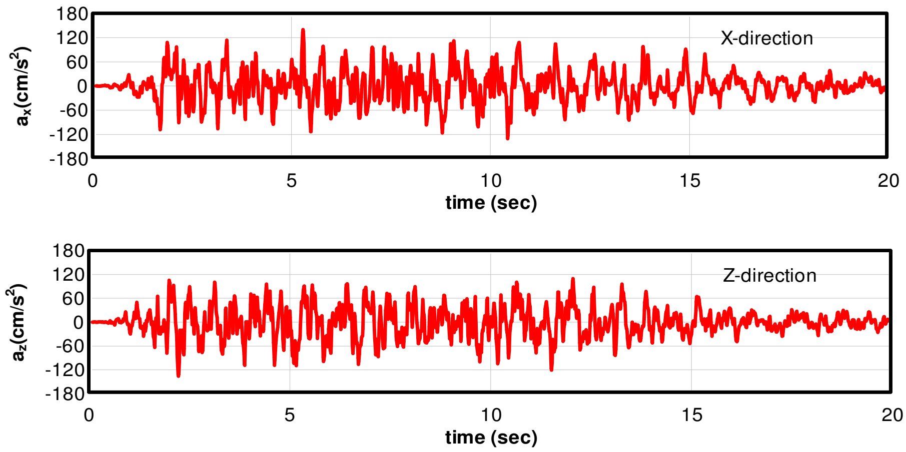

Fig. 2 A typical set of simulated ground motion time histories in X and Z direction

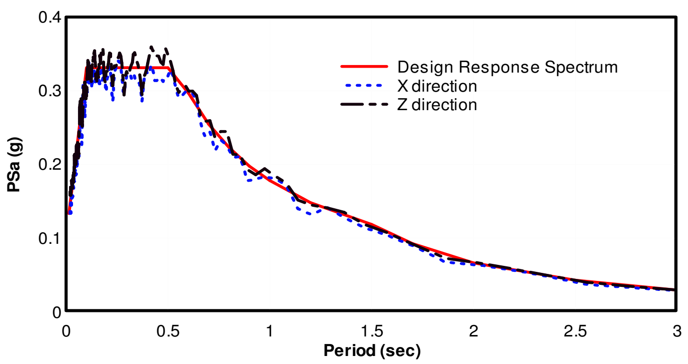

Fig. 3 Design response spectrum and the response spectrum of the simulated ground motion

5. NUMERICAL RESULTS AND DISCUSSIONS

Numerical simulations are carried out to investigate the influences of eccentricity and torsional rigidity on building structure responses. The effects of bi-directional ground motion inputs on one-way and two-way eccentric structure responses, as well as the adequacy of code specifications, are evaluated. For each case, 10 simulations are carried out using the 10 sets of simulated ground motions as inputs and assemble mean responses and standard deviations are obtained. Since the standard variations are all substantially smaller than the corresponding mean values, only the mean responses are presented. Without losing the generality, only the base shear force in X-direction is presented as that in the Z-direction has the similar trend.

5.1 Effects of Eccentricity

Figure 4 shows the normalized mean base shear in X-direction, torque, normalized displacement responses on the stiff and flexible sides of the torsionally intermediate stiff single-storey model subjected to bi-directional ground excitations, in which V_0 is the base shear of the corresponding symmetric model. As shown, the base shear decreases almost monotonically with the increase of the eccentricity in either side, while torque increases with the eccentricity. These results are consistent with those observed by many researchers. Kan and Chopra (1976) showed that there is an interaction equation that exists between the base shear and the torque as

$$V_x^2 + V_z^2 + T^2 = 1.0 \tag{2}$$

indicating generating of torque owing to torsional response is associated with a reduction in the base shear, i.e., the dynamic torque amplification effect is offset by the corresponding base shear reduction. As shown, the maximum torque does not necessarily occur at the largest eccentricity. This is because the torsional vibration frequency changes with the eccentricity and both the eccentricity and the resonance of the torsional response mode with ground motion affect the torsional responses. It can also be observed that the increase in torque and the decrease in the normalised base shear are not linearly proportional to the increase in eccentricity. The increase in the torque and the decrease in the normalized base shear are generally more rapid at small eccentricities, implying the large amplification caused by the torsional coupling occurs at small eccentricities. This observation is consistent with the findings made by Chandler and Hutchinson (1986) when considering a single-storey one-way eccentric structure subjected to uni-axial ground excitation.

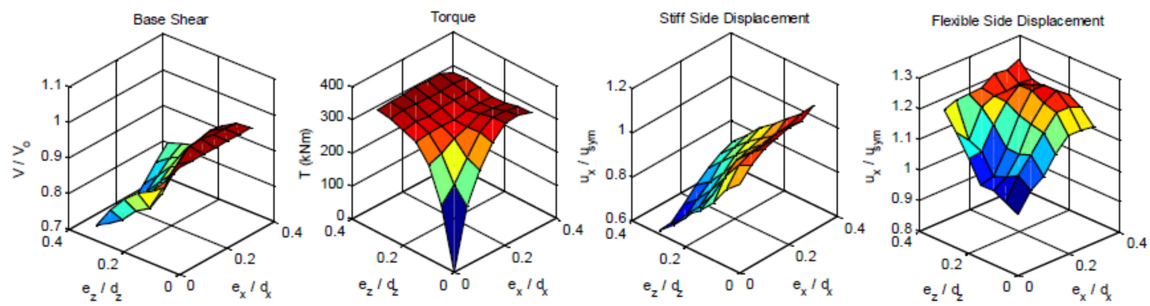

Fig. 4. Normalized base shear, torque and normalized displacements of the torsionally intermediate stiff single-storey model subjected to bi-directional ground excitations

It can be seen that increasing the eccentricity generally results in an increase in the normalised flexible side displacement and reduces that on the stiff side, indicating the increase in the shear forces in the columns on the flexible side of the asymmetric structure. Proper design considerations of these columns are therefore needed to prevent torsional damage.

5.2 Influences of Uncoupled Torsional to Lateral Vibration Frequency Ratio

Uncoupled torsional to lateral vibration frequency ratio measures the coupling effects of the torsional and lateral responses, and the dominance of response mode. For a torsionally flexible structure, torsional response usually dominates the overall responses, while it is governed by the lateral response for a torsionally stiff structure. Figures 5 and 6 show the normalized base shear, torque and normalized displacement responses of the stiff and flexible sides of the single-storey model subjected to bi-directional ground motion inputs. Comparing the results in Figures 4 to 6, it is obvious that torsional response is the most pronounced when the structure is torsionally flexible, and least prominent when it is torsionally stiff. In other words, when the structure is torsionally flexible, the generated torque from the same ground motions is the largest.

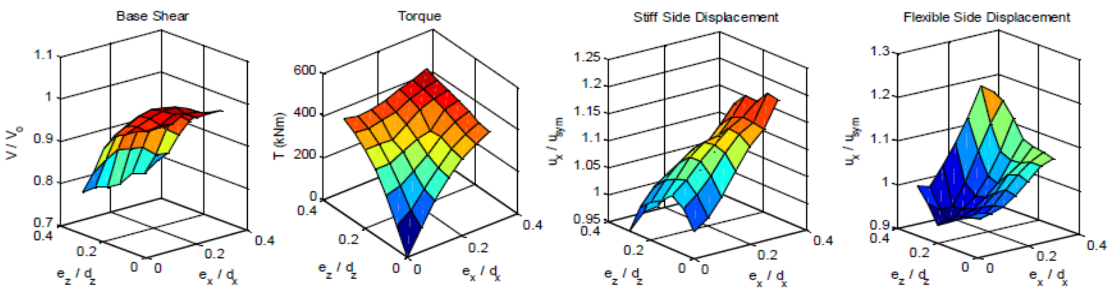

Fig. 5 Normalized base shear, torque and normalized displacements of the torsionally flexible single-storey model subjected to bi-directional ground excitations

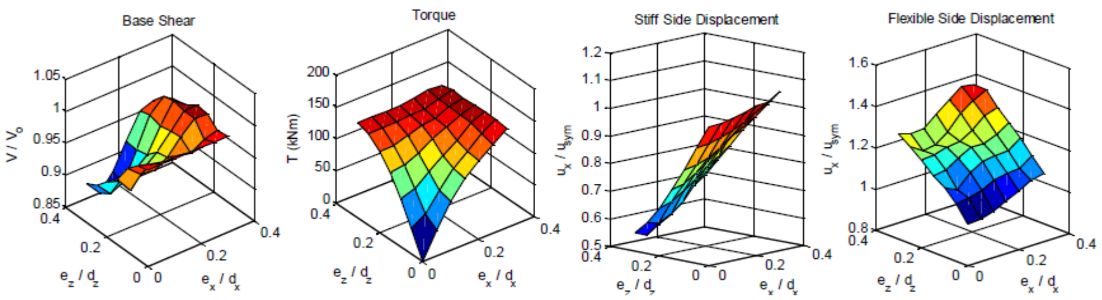

Fig. 6 Normalized base shear, torque and normalized displacements of the torsionally stiff single-storey model subjected to bi-directional ground excitations

It can also be noted that the torsionally intermediately stiff structure experiences the greatest torsional coupling effects. Consequently, it results in the largest decrease in the normalised base shear compared to the other two structures.

5.3 Uni-Directional Ground Motion Input

The above results are obtained by using simultaneous bi-directional ground motion inputs. Most previous studies used only uni-axial ground motion input. Design codes also allow consideration of ground motion inputs in two perpendicular directions separately. It is therefore interesting to compare the responses obtained by using uni-axial and bi-directional ground motion inputs. Figure 7 shows torque of the single-storey model obtained by uni-directional (X-direction) ground excitation. As shown, eccentricity in X-direction does not induce torsional responses if the structure is symmetric in the Z-direction. This is expected because eccentricity in the X-direction does not induce torsional response by ground excitation also in the X-direction. However, eccentricity in the X-direction will slightly affect the torsional response when the structure is asymmetric in the Z-direction. Comparing the corresponding torque obtained by bi-directional inputs shown in Figures 4 to 6, it can be noted that bi-directional ground excitations may increase the torsional responses of the structure, especially when the structure has significant two-way eccentricities.

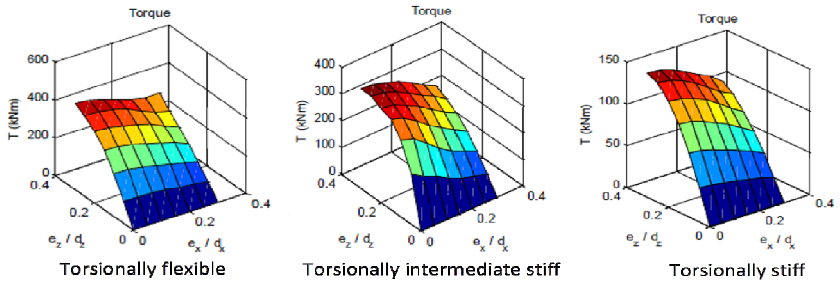

Fig. 7 Torque of the single-storey model subjected to uni-directional ground excitation

5.4 Multi-Storey Eccentric Structures

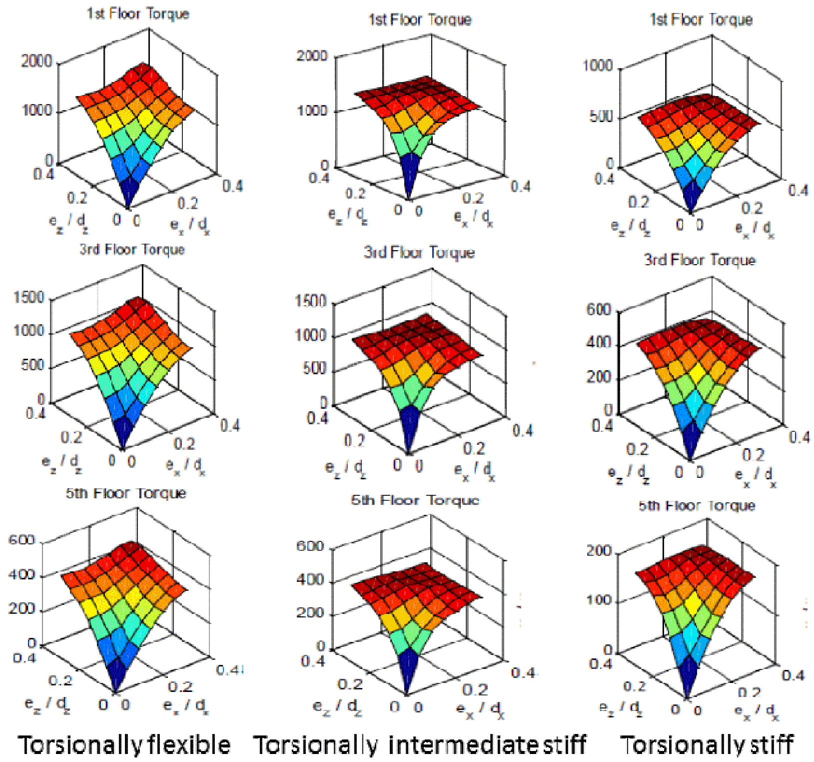

Fig. 8 Torque of five storey model with regular eccentricities in all the floors to bi-directional ground motion

Responses of two and five storey model shown in Figure 1 with different eccentricities subjected bi-directional ground motions are calculated. Figure 8 shows the calculated torque of the first, third and fifth storey of the five storey model with three torsional stiffness. As shown, because regular eccentricities are assumed, the characteristics of torsional responses of all the storeys are qualitatively similar, and they are also similar to those of the single storey model as shown in the above figures. The torque decreases with the storey number because of the decrease in the shear force in the storey. The base shear and displacement response, as well as the results of the two storey model, which are not shown here owing to page limit, also have the same trend as those of the single storey model. These observations indicate that the analysis using single storey models, as in most of previous studies, well capture the torsional response characteristics of multiple-storey structures if the structure has the same eccentricities along the building height. However, it should be noted that if the multiple-storey structure has different eccentricities at different floors, its torsional response is very different from those of the single-storey model. Similar observations were made by other researchers. Dutta and Roy (2012) investigated the torsional responses of low-rise structures with varying storey eccentricity. It was found that the ductility demands were significantly greater than that experienced by single storey structure, lower stories of the buildings experienced high ductility demand on the flexible side elements, while the upper stories experience greater ductility demand on the stiff side. It has been established that single storey models can lead to an accurate evaluation of the asymmetric multistorey structures for the elastic torsional behaviour, provided that the principal axes of resistance for each storey of the structure are identically oriented along the two orthogonal directions, the resisting elements are distributed the same on each floor, the mass centres are aligned in a vertical line, and the mass radii of gyration are the same on each floor. Otherwise the torsional response of multi-storey structures analysis cannot be simplified to a single storey model, as it cannot represent the actual cause of the torsional response mechanism that develops in multistorey structures (Stefano et al., 2006)

5.5 Comparison with Code Specifications

As discussed above, the Australian Standard AS1170.4 allows consideration of bi-directional ground motion separately, and the largest torque is determined by totalling 100% and 30% of those induced by ground motions in the two directions independently. This means the torque of each floor can be calculated by

$$T_0 = V_x e_{dx} + 0.3 V_z e_{dz} \quad \text{or} \quad T_0 = V_z e_{dz} + 0.3 V_x e_{dx} \tag{3}$$

whichever is larger; in which e is the design eccentricity defined in Eq. (1) and V the storey shear force. It is interesting to note that the amplification coefficient of the dynamic eccentricity, α, is not defined in the current Australian Standard and only the coefficient accounting for the accidental eccentricity, β, is given as ± 0.1. In this present study, the dynamic eccentricity component is taken as 1.0.

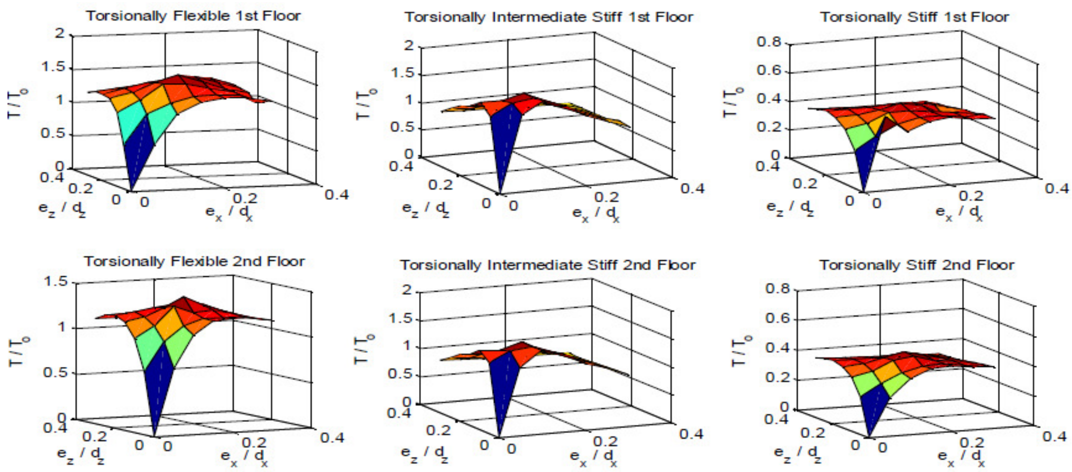

Fig. 9 Normalized torque of two-storey model with bi-directional ground motion inputs

Figure 9 shows the calculated torque of two-storey model with same eccentricities in the both storeys to bi-directional ground motion inputs normalized by the design torque defined by Eq. (3). The results for the single-storey and five-storey model have the similar trend and are therefore not shown here. As shown, the code specified torque is adequate for torsionally intermediate and torsionally stiff structures, but not adequate for torsionally flexible structures, with the *T/To* values slightly greater than one when the structure has significant eccentricities.

It is important to note that these observations are made based on the three structural models under linear elastic responses. Torsional response not only depends on the torsional to lateral vibration frequency ratios, but also depends on the torsional vibration frequency. When the torsional vibration frequency coincides with the dominant ground motion frequency, torsional responses will be amplified owing to resonance. Moreover, the torsional response characteristics are different if different storeys have different eccentricities. Nonlinear inelastic response will also change the torsional response characteristics, especially when this response turns an elastically torsionally stiff building into an inelastically torsionally flexible building, due to differential inelastic response of the seismic-resisting systems. This has been a feature of the response of a number of high-rise buildings in the 22 February 2011 earthquake in Christchurch, New Zealand, in which the horizontal East-West component was appreciably stronger than the horizontal Nort-South component. Therefore the above observations might be different for different structures. Nonetheless, they demonstrate that the current code provisions in estimating the torque in building structures might not be adequate, especially when structures are torsionally flexible. These observations are consistent with a previous study in evaluating the adequacy of the Mexico City Building Code (1995) and the National Building Code of Canada (1995) with α=1.5 by Fahjar et al., (2006). It was found that although the static eccentricity is amplified by 50%, i.e., α=1.5 instead of 1.0, it needs to use β=0.25 in estimating the design eccentricity to satisfy all the three torsional to lateral vibration frequency ratio cases considered in the study.

6. CONCLUSION

This study presents an analysis of the elastic torsional response of single-storey, two-storey and five-storey models with two-way eccentricities subjected to uni-directional and bi-directional ground motions. It is found that increasing the eccentricity in either direction generally increases the torque and decreases the normalised base shear. The increase in torque is usually steeper when the eccentricity is small, illustrating a large amplification effect. Generally the flexible side displacement increases while the stiff side displacement decreases with the eccentricity.

The torsional to lateral frequency ratio and the eccentricity have significant effect on the torsional response. Torsionally flexible structures tend to have a larger torque, as the system response is dominated by the torsional response, while torsionally stiff structures tend to have a larger base shear, since the system is dominated by the lateral translational response. It is observed that uni-directional ground motion analysis is only acceptable to use for a one-way eccentric system. For a two way eccentric system, the analysis underestimates the base shear and torque. It is also found that the provision on torsional responses of building structures in the current Australian code might not be adequate, especially when the structures are torsionally flexible.

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