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A Comprehensive Study on the Influence of Strength and Stiffness eccentricities to the On-plan Rotation of Asymmetric Structure

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Abstract. All buildings are subjected to some degree of torsion which in turn changes the member torsional demands from that of translation only. Torsional effects on buildings subjected to earthquakes are not found directly in structural analysis unless full three-dimensional inelastic dynamic time history analysis is conducted. Since design is often conducted using two-dimensional analysis, these effects are not directly considered. There is currently an understanding on how different factors may influence torsion, however, the degree to which these factors influence torsion is relatively unknown. Slab rotation effect is considered a major response parameter to represent the severity of the torsional response of eccentric systems; hence, it is considered in this study. The centre of strength (CR) and centre of stiffness (CS) are the two main factors under considerations. A comprehensive analysis on eighty different CR and CS conditions are applied to a three-dimensional, asymmetric building and their influences to slab rotation are observed. The CR/CS conditions are applied by varying strength eccentricities (er) and stiffness eccentricities (es) using two condition models. Then, earthquake ground motions are applied in z-direction under elastic and inelastic conditions. The results interpreted using a simple approach shows important slab rotation behaviour that forms interesting findings from this study. The slab rotation demand is found to reduce as strength eccentricity moves away from the Centre of Mass (CoM) but is independent of the stiffness eccentricity. The study also confirms finding of previous works which states that stiffness eccentricity plays a minor role when assessing the torsional behaviour of a ductile systems. Results from inelastic analysis shows slab rotation demand increases as strength eccentricity is closer to the CoM but it remains constant for elastic analysis.

INTRODUCTION

Buildings with non-uniform mass, stiffness and/or strength over their plan are often described as being torsionally irregular. Even for structures designed to be perfectly regular, the movement of live loads around the structure can cause torsional irregularity which in turn changes the member demands [2]. Torsional effects may significantly modify the seismic response of buildings, and they have caused severe damage or collapse of structures in past earthquakes. These effects occur due to different reasons, such as no uniform distribution of the mass, stiffness and strength and torsional components of the ground movement. Hence due to the torsional effects, the floors of the building not only translate laterally but also rotate about a vertical axis. In ductile structures, the main consequence of floor twist is an unequal demand of lateral displacements in the elements of the structure [1]. An example of severe

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damage occurred during the Michoacán Earthquake, Mexico, 1985 which shows the importance of torsional effects and highlights the need to understand the problem and improve the design requirements.

In practice, to consider torsional effects, buildings are generally designed using only walls orientated in the same direction to earthquake as torsionally unrestrained structure or a combination of walls with different orientations with respect to the earthquake as torsionally restrained [3, Design codes incorporate special requirements to take into account the torsional effects, which usually imply the amplification of eccentricity and the consideration of an accidental eccentricity. These requirements are mainly based on elastic considerations developed several decades ago. These criterion considers the torsional effect induced by the earthquake can be represented in the static analysis of building. When dynamic analysis is performed, only the accidental eccentricity is considered. [1].

Most building codes, as listed in IAEE 2000, over years, recommend equivalent static analysis to account for torsion. Concept of design eccentricity is suggested to account for seismic torsion owing to asymmetry [4]. As an example, the New Zealand Standard on Structural Design Actions- Earthquake Actions specifies that three dimensional time-history analysis is to be used when the structure is classified as torsionally sensitive. If a two-dimensional analysis is used for translational effects, torsional effects are considered by using a static analysis [5]. Since design of these building are often conducted using 2-D analysis, torsional effects are not considered explicitly since the inelastic behavior and torsional effects are not considered. Hence, if full three-dimensional inelastic dynamic time history analysis were conducted for all structures as part of design, any torsional response and the demands on the elements would be found directly.

Slab rotation effect is considered a major response parameter to represent the severity of the torsional response of eccentric systems [6] which is considered in this study. There is currently an understanding of how different parameters may influence torsion [2], however, the degree to which these factors influence torsion is relatively unknown.

Strength eccentricities (CR) and stiffness eccentricities (CS) are interdependent parameters and cannot be ignored in the seismic design of building. Design eccentricity related to locations of CR and CS continues to be practiced as a basic approach for design of asymmetric structures over years. Thus, the investigations on how to apply such provisions in real structures also attract the interest of researchers [4]. The CR and CS are the two main parameters under considerations in this study. Several studies were done by Tso and Myslimaj (2003) [7] where the CS is located at opposite side of CR with the same eccentricity or also called as a balanced CS-CR location. This criterion is used to minimize the torsion of asymmetric building. While DeStefano and Pintucchi (2010) [8] considered to put the CS and CR at the same side by using a one-story model and taking into account the fact that total strength is distributed proportionally among the vertical resisting elements. Moreover, to represent the real buildings, the CS has been put halfway between the CR and the CM to account for torsional effects unavoidably results in a more balanced strength distribution.

Significant parametric works have been done to quantify and/or predict the effect of torsional irregularity by considering CS and CR. However, these are largely using 2-D analyses [8] [2] [10] [11]. Hence, this study is done by conducting comprehensive investigations on CS and CR interdependence and to determine their effect on torsional demands by on using a 3-D analysis.

METHODOLOGY

The Structural Model

The building model used is a single-storey, asymmetric 3-D building with a rigid floor diaphragm supported by four shear walls as shown in Fig. 1(a). The walls are located at the perimeter of the building to provide lateral force resistance. The floor diaphragm concentrates the entire story mass at the Centre of Mass (CoM). The building is supported on fixed supports; neglecting soil-structure interaction. The model's width, B, is taken as 26m and breadth, L, as 15m. The dimensions of the model are based on Stefano and Pintucchi (2010) [8] where the non-dimensionalized mass radius, *p*, is taken as 0. 33, which is a value typical of many real buildings with plan aspect ratio *B/L*=0.577.

Fig. 1(b) shows the on-plan view of the shear wall elements of the model in the present study. The four shear walls, W1, W2, W3 and W4, are shown with dimensions in Table 1; where W1, W2 and W3 have fixed *b (breadth)* x *h (width)* while for E1, *b* is fixed with varying *h* values. The dimensions of *h* are obtained by varying CR positions. Hence, varying CR position leads to changing the strength eccentricity, *er* and stiffness eccentricities, *er*. At the same time, the fundamental period of vibrations, *T1* and wall stiffness, k, are kept constant. The *h* values that are used is shown in Table 2. The same model has been used by Suhaila (2016) [12] and verified using push-over analysis.

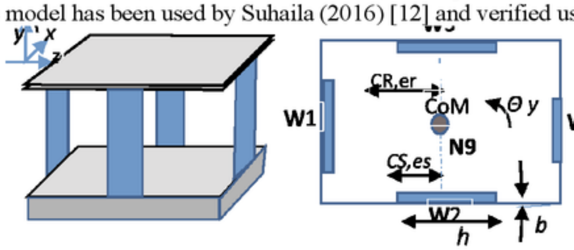

FIGURE 1.(a) Simple 3-D building model **(b)** on-plan view of shear wall elements

TABLE 1. Dimension of Wall elements

Wall Element	b (m)	h (m)
W1	0.5	varies
W2	3.5	0.5
W3	3.5	0.5
W4	0.5	2

TABLE 2. h values based on CR position

Position	*CR*	h (m)
1	0.05L	2.15
2	0.1L	2.32
3	0.15L	2.5
4	0.2L	2.71
5	0.25L	2.95
6	0.3L	3.24
7	0.35L	3.67
8	04L	429

The CoM, CR, CS, *er* and *es* are shown in Fig.1 (b) where the CoM, CR, CS, *er* and *es* denote the Center of Mass, Center of Rigidity, Center of Stiffness, strength eccentricity and stiffness eccentricity, respectively. The CR and CS are located along the x-axis at a given distance from CoM where *er* and *es* representing CR's and CS's respective distances from CoM. The CoM, coincides with the Geometric Center, GC, of the building. To simplify the analysis, a master node, node 9, located at the CoM of the floor and all nodes at the same floor are constrained to node 9 so that the maximum rotation about y-axis, theta-y, for the whole floor exhibited the same magnitude. The maximum rotation is the rotation that occurred over the whole course of the earthquake. Seven ground motions are applied in z-direction under elastic and inelastic conditions. The results of the analysis are given in terms of mean values (averaged over the considered input ground motions) of the elastic and inelastic maximum rotation at node 9. Averaged values have been used in other studies [8] [12].

The nonlinear time-history analyses of the 3D model are carried out using the structural analysis program "Ruaumoko3D" [13], a software used by Castillo (2004) [11], Beyer (2008) [9] for similar parametric studies but analysed for 2D systems. The analyses were performed with tangent-stiffness proportional Rayleigh damping of 5% damping for the second mode.

Strength and Stiffness eccentricities

The CS and CR coefficients designed in this study is to emphasize the strength and stiffness interdependence; as seen in Table 3. The five coefficients of CS/CR comprise of the criterions proposed by Tso and Myslimaj (2002) [7] as well as Stefano and Pintucchi (2010) [8]. The coefficients of CR are also based on the real building coefficient as proposed by Anagnostopoulos (2012) [14]. The varying CR and CS are applied by varying strength eccentricities *(er)* and stiffness eccentricities *(es)* respectively, along the x-axis from the CoM (where L is the slab width) as seen in Fig.2 (a)-(f) and Fig.3 (a)-(e). Positive CR/CS value refers to the `*er*' and `*es*' on the same side of each other, from the CoM (ie. left side of CoM). The more positive the CR coefficient, the `*er*' is closer to wall W1 leading to the increment of the wall strength of W1. When CS has negative coefficients, `*es*' is on the opposite side of `*er*', with CoM in between them resulting to `*es*' closer to wall W4.

TABLE 3. Variations of strength and stiffness eccentricities

	Models	CR	e_r (m) (from CoM)	CS/CR	e_s (m)
	1	0.05 L	13	CS = -1.0 CR	Opposite side (right
	2	0.1 L	26	CS = - 0.5CR	side of CoM)
	3	0.15 L	3.9		
CS = 0 CR					At CoM
	4	0.2 L	52	CS= 0.5CR	Same side
	5	0.25 L	65	CS= 1.0 CR	(left of CoM)
	6	0.3 L	7.8		
	7	0.35 L	9.1		
	8	0.4 L		1 0	. 4

The comprehensiveness of CS and CR conditions are to evaluate the influence of CS and CR that represents the real buildings in the real condition; since there are no building with the same distributions of mass, stiffness and strength based on the structural design aspect, usage as well as the aesthetical value.

Physical Arrangement of CM, CR and CS for Model A and Model B

Two situation models are proposed to study the variations of strength and stiffness. Models A is introduced to highlight the significant importance of CR on slab rotation as well as to address the distinctive gap from previous studies. Model A consists of 40 situations of constant CR with changing CS situations along the same x-axis. These situations are have not been used in other studies. Models B have been p by Suhaila [12] by considering 40 different situations of constant CS with changing CR.

Figure 2 (a)-(h) and Fig 3 (a)-(e) show the physical arrangements of the CoM, *er* and *es* for Model A and Model B respectively. The *es* positions are marked by the arrow label ( ) while the *er* uses the bar label ( ). The diagrams represents situations along x-axis of the slab of width + 13.0m to the left side of CoM (wall 1) or -13.0m to the right side of CoM (wall 4). The CoM is located at `0' from either walls. The physical display of *es* and *er* for every model are to easily visualize the positions of strength and stiffness eccentricities and to correlate with the on-plan slab rotations results.

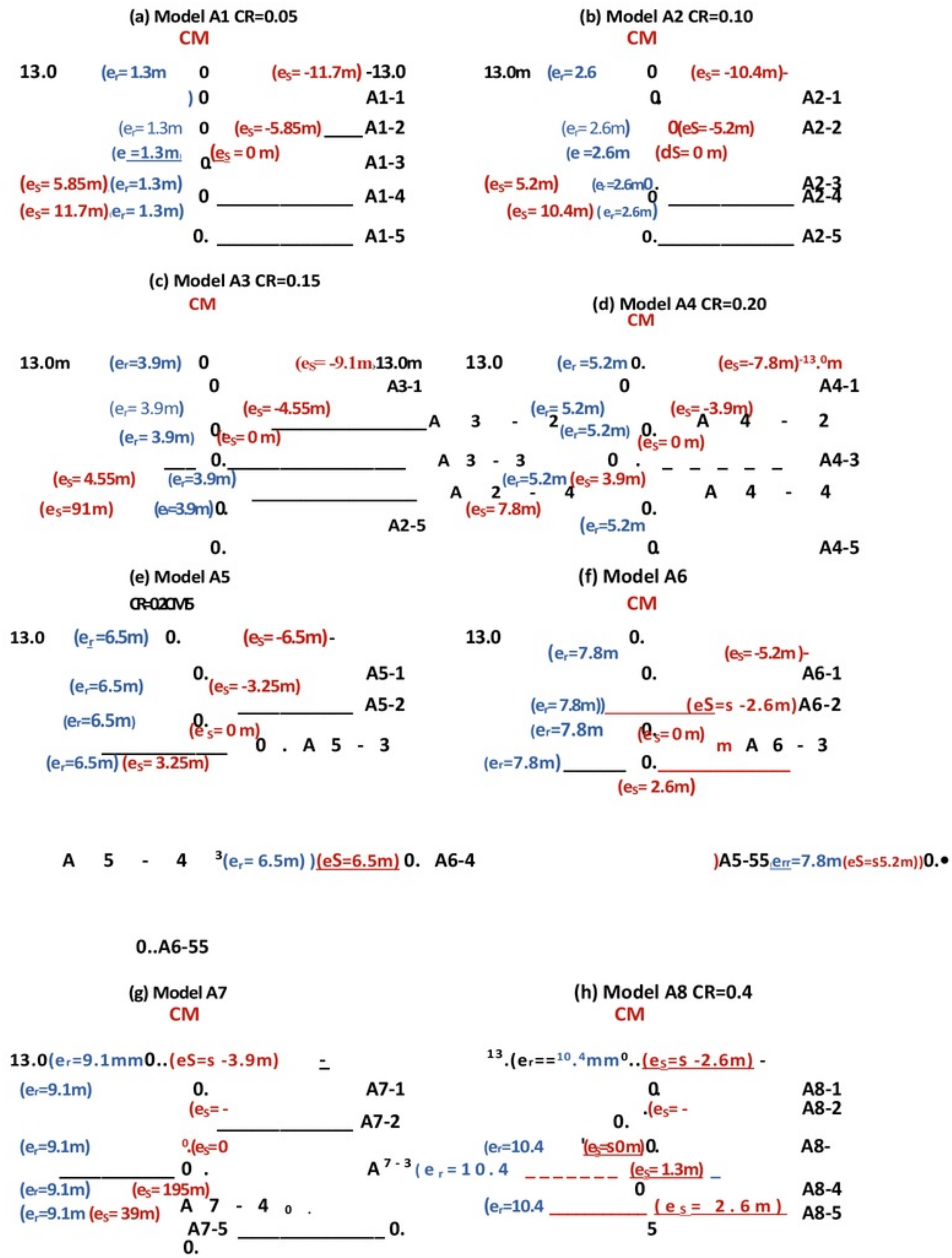

FIGURE 2 (a)- (h) Submodels for Model A: ModelA11 CR=0.05 to Model A8 CR=0.4

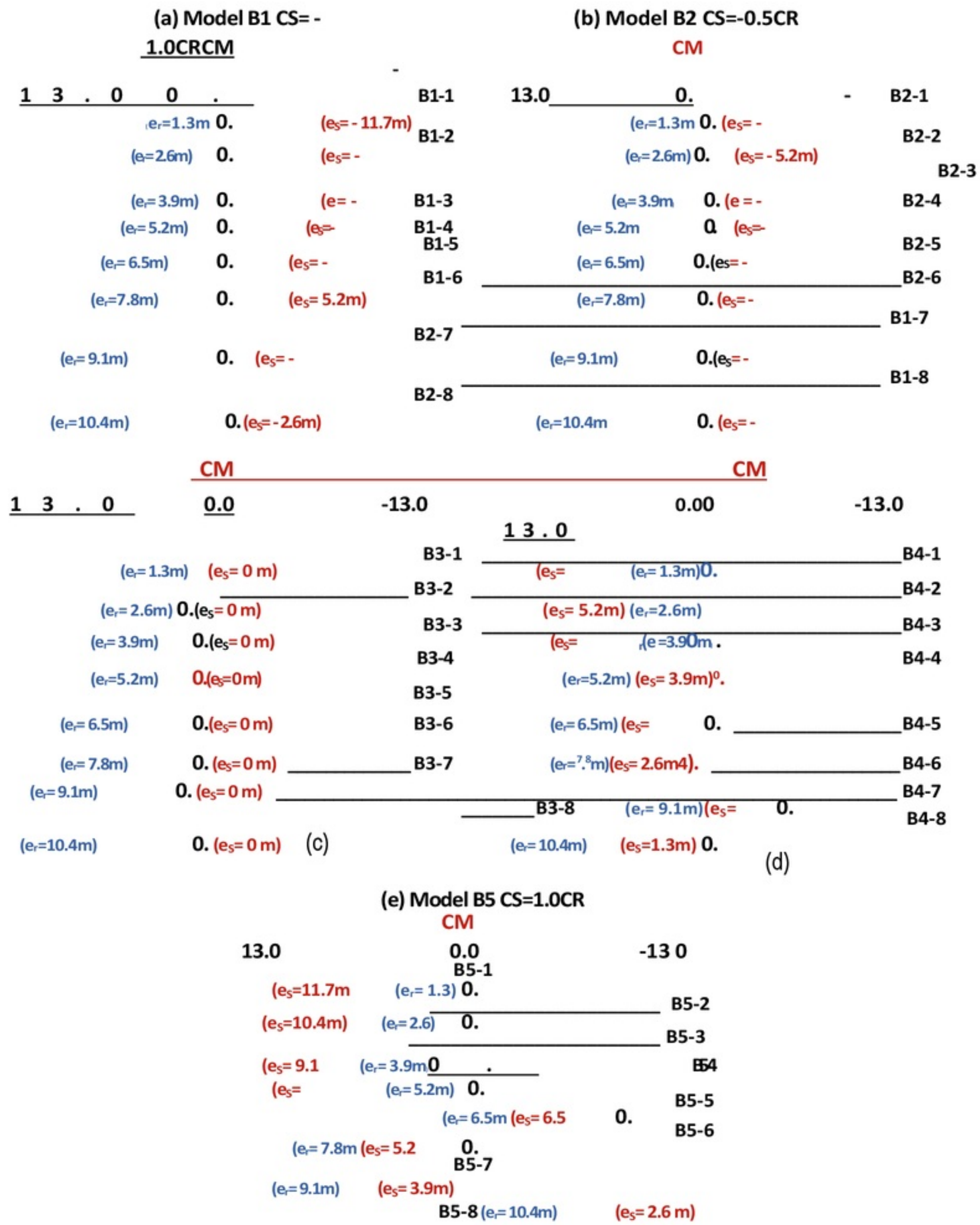

FIGURE 3. (a)- (e) Submodels for Model B: Model B1 CS=-1.0 CR to Model B5 CS=1.0 CR

RESULTS

Model A: Varying Centre of Strength, CR

Figure 4 (a) and (b) shows the graphs for inelastic and elastic maximum rotation versus the normalized *es/bz* along the slab x-axis for the 40 different CR/CS cases. The results for sub Models A must be read together with Fig. 2 (a)-(h). From Fig. 4 (a), graphs for Model A1 (i.e A1 CR=0.05) and Model A2 (i.e A2 CR=0.10) shows significant 'curve-in' from normalized es/bz = - 0.45 towards normalized es/bz =0 (i.e CS =0) and significant 'curve-out' towards normalized es/bz = 0.45. Graphs for Model A3 and Model A4 have gradual curve but has tendency to straighten out. Meanwhile, Models A5, A6, A7 and A8 have straight parallel graphs.

The maximum 'curve-in' value is the maximum inelastic slab rotation by Model A1 at CR= 0.05 as compared to the elastic rotation for the same model as seen in Fig. 4 (b). This may be due to at CR=0.05, *er* is closes to CoM but farthest from wall W1; thus resulting to the wall W1 with least strength and become inelastic during the slab rotation. The trend of increased rotations increases with strength eccentricity (i.e increase CR) as seen in Fig. 4 (a) and this is also observed by Beyer (2008) [9] although it was only for smaller strength and stiffness eccentricities. The rotation demand (ie. rotation difference between rotation at es/bz = 0.45 and =0) decreases as CR increases and becomes constant after CR=0.25 towards 0.4. The significant reason for these behaviour is because as CR increases, strength eccentricity *er* gets closer towards wall W1, the wall strength increases and able to maintain elastic condition with constant rotation.

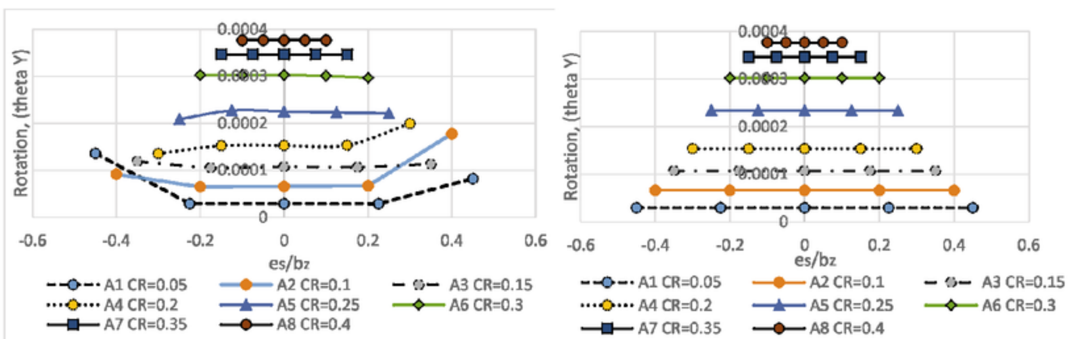

FIGURE 4 Model A: (a) Inelastic Rotation (b) Elastic rotation due to varying CR for Model A

Model B: Varying Centre of Stiffness, CS

Fig. 5 (a) shows the comparison between elastic and inelastic rotations for Model B. The results for Model B must be read together with Fig 3 (a)-(e). All sub models Model B1 to B5 produce the same graphs of inelastic and elastic rotation. This imply that different CS values has no or minimum effect on the rotation of the slab. This confirms findings by Sommer (2000) [10].

Results show that the maximum rotations of the model is generally greater for the elastic than for the inelastic model. This also confirms Sommer's (2000) [10] findings that approximating the rotation of the inelastic system by using the rotation of the elastic system is generally a conservative assumption. However, from the graph in Fig. 5(a), the difference in rotation between the elastic and inelastic model is not very significant if the strength eccentricity is larger than er/bz = 0.17 as compared to Fig. 5 (b), Beyer's (2008) [9] result has er/bz=0.14. Also from Fig. 5(a), for $er/\ bz \leq 0{:}17$, the maximum rotation is just about larger for the inelastic than for the elastic system. This is probably related to W1 l has brief excursions into the inelastic mode. This trend agrees with result by Beyer's (2008) [9] work as seen in Fig. 5 (b) where rotation becomes inelastic for smaller strength eccentricities and improves findings by

Sommer (2000) [10]. The result obtained from this study may be an extension to Beyer (2008) [9]'s and Sommer (2000) [10]'s works; that is, for systems with extreme strength and stiffness eccentricities.

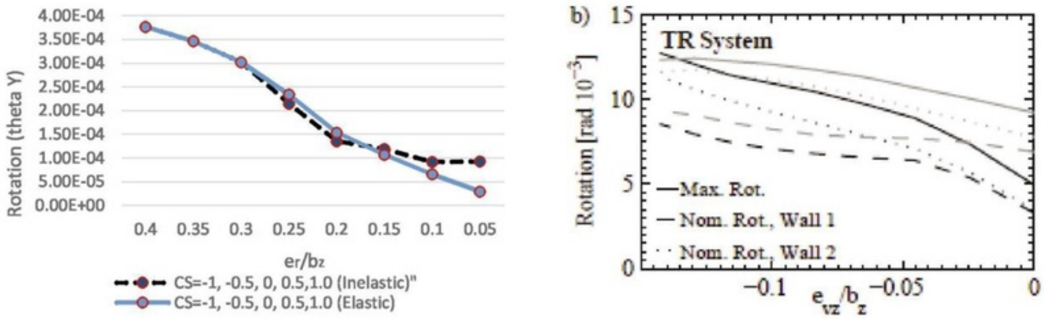

FIGURE 5 (a) Model B: Rotation for elastic and inelastic systems by varying CS by 3D analysis (b) extract from Beyer (2008) rotation for elastic and inelastic systems by 2D analysis

CONCLUSION

A comprehensive, three-dimensional study on the effect of stiffness and strength eccentricities on the torsional behaviour of a building model under unidirectional earthquake has been carried out. Slab rotation effect is taken as a major response parameter to represent the severity of the torsional response of eccentric systems. The result obtained for the elastic and inelastic analysis obtained are based on 3-D analysis as compared with that of past research which was from 2-D analysis. The result agreement are generally satisfactory and can serve as improvement to past research and design codes, especially for lower strength eccentricities i.e er/bz ≤ 0.17. The study also serves as an extension for systems with extreme strength and stiffness eccentricities since most studies limit the research eccentricities to about 0.2. The slab rotation demand is found to reduce as strength eccentricity moves away from the Centre of Mass and less dependent of the stiffness eccentricity positions. The study also confirms finding from previous works that stiffness eccentricity plays a minor role when assessing the torsional behaviour of a ductile systems. Results from inelastic analysis shows slab rotation demand increases as strength eccentricity moves towards the CoM but it remains constant for elastic analysis. The result from this study can contribute to improving the code design requirements related to torsion due to earthquake.

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