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STRENGTH AND STIFFNESS DISTRIBUTIONS OF TORSIONAL BUILDING SYSTEMS

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ABSTRACT

Torsional response characteristics of building models of elastic and inelastic asymmetric reinforced concrete buildings were studied by analyzing the near-fault and far-fault ground motions recorded during earthquakes. The strength and stiffness eccentricities are the main parameters used in the present study contributing to the strength and stiffness distributions of building models. The displacement demands of all buildings under the stiff and flexible sides were obtained from the analysis due to different values of fundamental period of vibrations as well as behavior factors by using RUAUMOKO-3D program. All data were then summarized in accordance to the strength and stiffness distributions in order to determine the impact of either strength distribution or stiffness distribution to the torsional behavior of one-story asymmetric reinforced concrete buildings. The torsional behavior of all building models were presented in terms of the normalized displacements at the stiff and flexible sides by the ratio of the maximum lateral displacement at the stiff and flexible sides to the maximum lateral displacement at the center of the building models. The results of this study indicate that the torsional behavior of asymmetric reinforced concrete buildings were mainly depend on the stiffness distributions of lateral load resisting elements in the buildings rather than the strength distributions.

1. Introduction

Poor seismic performance of many reinforced concrete buildings occur during earthquake. After seismic events, the damage of reinforced concrete building becomes a major engineering concerns and one of the causes to the reinforced concrete damages is due to torsion. Torsion or building twist occur in one-story reinforced concrete buildings due to asymmetrical arrangement of vertical load resisting elements (VLRE). Damage analysis of this type of buildings has proven that torsion greatly produces additional displacements as reported by Ruternbeg (1998), DeStefano and Pintucchi (2010) and Alkanan (2011). During seismic events, the VLRE including walls and columns will vibrate back and forth. Torsion in buildings will make different portions to move horizontally by different amounts; hence brings more damages in walls and columns.

Asymmetric buildings due to strength and stiffness distributions recorded severe damage and collapse of buildings during earthquakes. From the past history, the buildings subjected to asymmetrical building configurations having severe damage to reinforced concrete buildings as reported in the 1964 Great Alaska Earthquake, the 1978 Miyagi-Ken Earthquake as well as the 1985 Mexico Earthquake where 42% of corner buildings suffered excessive damage due to torsion. In the 1995 Kobe Earthquake, the partial collapse of lots of corner building is reported due to torsion (Castillo et al., 2001).

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Buildings experience translations due to earthquakes. These translations are lateral translation as well as rotational translation induced by earthquake in asymmetric buildings. If a building has an asymmetric distribution of either mass, stiffness or strength, a lateral seismic load can cause a response in which the torsional and lateral motions of the building are coupled. These phenomena are called as torsionally coupled response in asymmetric building. The building model idealization as in Figure 1 was the theory suggested in DeStefano and Pintucchi (2010) considering one-story reinforced concrete building. The mass is concentrated at the geometric center of the building and the strength and stiffness are located in varies positions due to the changes occur in the VLRE in the building in terms of the wall system used.

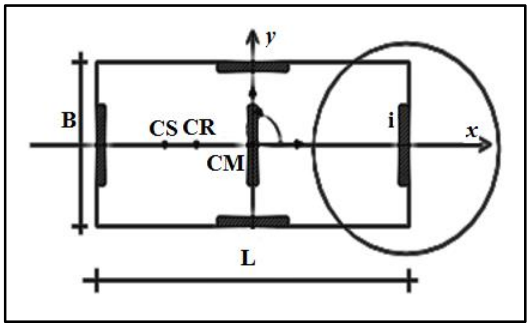


Figure 1: Model idealization

2. Problem Statement

Torsion in in-plan symmetric building occurs due to asymmetrical conditions of mass, stiffness and strength. When the center of mass CM, center of rigidity CR and center of strength CS coincide, no torsion will occur. Otherwise buildings will experience additional rotational translations, which can bring more damages to buildings. Torsion can be avoided by having the perfectly symmetric buildings. The idealization of one-story asymmetric building is depicted in Figure 1 which becomes the perfect idea done by Stefano and Pintucchi (2010). Location of CR depends on the characteristics of components of lateral load-resisting system including shear walls, moment frames and braced frames whereas location of CS depends on the building strength which is based on the design part of the building. The idea when the CM, CR and CS do not coincide presenting by asymmetric one-story reinforced concrete buildings happen due to unequal stiffness and strength distribution. Buildings under torsion may behave differently during earthquakes which bring severe damage to the buildings. In detail, torsion causes structural elements such as walls at the same floor level to move horizontally by different amount, as a result it bring more extensive damage to the columns and walls. Previous literature survey has found that few studies have examined the asymmetric buildings in accordance with stiffness eccentricity er that comes from the gap between the CM and CR. Nevertheless, the recent studies publish have not addressed the needs in engineering design properly when designing the building based on the seismic design provisions. Recently, Stefano and Pintucchi (2010) tried to address the lack of torsion study by including CR as well CS in their model as shown in Figure 1. Anyhow, they used CR and CS with the same distance at all models where CR and CS was located at the same side and CM was located at the geometric center GC of the building model. Tso and Myslimaj (2003) previously had found that the CR and CS locations if located on opposite sides of CM will bring less amount of lateral displacement under earthquake excitation. It is found that varies position of CR and CS with respect to the position of CM has not yet discussed and these drawback could lead to under estimation of the results of design drift of buildings, which could endanger the occupant during seismic event. Hence, it should be underlined that this study is done to have fully understanding on the stiffness and strength distributions of one-storey asymmetric reinforced concrete building.

3. Objectives

1. To analyze the elastic and inelastic displacement demand due to strength and stiffness distributions of one-story asymmetric reinforced concrete buildings.
2. To investigate the behavior of torsional building system on the elastic and inelastic dynamic response of a wide range of one-story asymmetric reinforced concrete.

4. Methodology

4.1 Development of structural model

The present work had been conducted by using generic building model adopted from DeStefano and Pintucchi (2010). All models used are asymmetric reinforced concrete building and analyze by using RUAUMOKO-3D program in order to demonstrate the torsional effect on buildings. This RUAUMOKO-3D program considers the response of the building system linked by a rigid diaphragm located at the center of the top floor of the building. The inelastic behavior of all lateral load resisting elements were represented by a bilinear relationship between the lateral force and displacement. The buildings were modelled as asymmetric model by designing the building with the center of mass CM, center of rigidity CR and center of strength CS do not coincide while the CS had been determined based on Eurocode 8 (EC8).

In the present study, the asymmetric reinforced concrete building is a moment resisting frame using the generic model in 3-dimensional one-story one-bay system. The model was developed based on the model of DeStefano and Pintucchi (2010). The modeling concept is previously proposed by Tso and Moghadam (2003). The concept was also used by Anagnostopoulos (2010) and Lin and Tsai (2007). The methodology comprises of several procedures starting from the development of elastic and inelastic reinforced concrete buildings, selection of ground motion, nonlinear analysis and statistical analysis. These procedures are depicted in Figure 2 as shown.

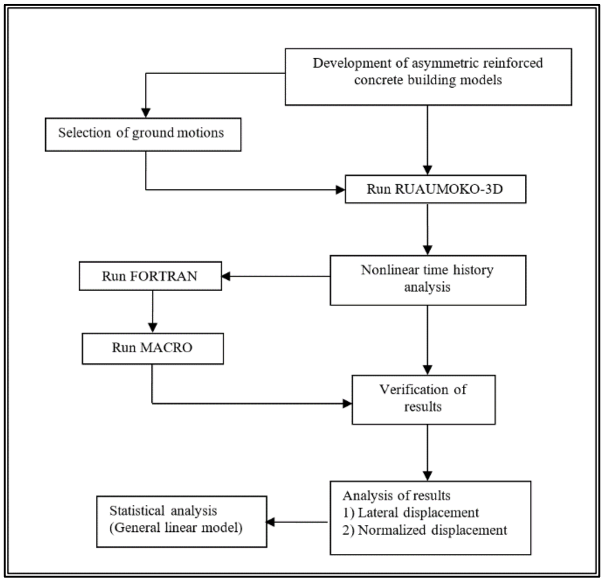


Figure 2: Flowchart of the methodology

4.2 Modelling of the building systems

Torsional behavior of asymmetric reinforced concrete building system is one of the most frequent sources of structural damage and failure during strong ground motions. The present study focused on the strength and stiffness distributions of elastic and inelastic buildings in order to understand the behavior of the torsional buildings during earthquakes. The Eurocode 8 (2004) was used as a guide in analyzing and designing all the building models. The strength and stiffness eccentricities, e_r and e_s have been set in various locations in order to represent the real building system. The e_r and e_s are the distance between the center of mass located at the geometric center of the building and the position of CR and CS, respectively.

$$e_r = e_{rx} = \frac{1}{L}\frac{\sum_{i=1}^{N} k_{yi}x_i}{K}$$

$$e_s = e_{sx} = \frac{1}{L}\frac{\sum_{i=1}^{N} F_{yi}x_i}{F}$$

The structural analysis and design of one-story reinforced concrete buildings have been started using a hypothetical building model as shown in Figure 3 below. The buildings were modeled as extremely torsional building system, adopted system as used in DeStefano and Pintucchi (2010) by using wall system located at perimeter of building model. In order to determine the results of torsion, the lateral displacements were determine at five locations labeled as node number as shown in Figure 4. For the system chosen in the present study, nodes 5, 6, 7 and 8 were labeled at the center of each edge to represent the wall system labeling. Node number 9 was used in the model as the compulsory requirement in modeling 3-dimensional buildings using RUAUMOKO-3D since the behavior of the building under torsion can be determined by the ratio of the maximum lateral displacement at nodes divided by the maximum lateral displacement at node 9.

The building models proposed by DeStefano and Pintucchi (2010) was used with various positions of center of strength CS and center of rigidity CR make total models equal to forty due to strength and stiffness distributions. DeStefano and Pintucchi (2010) have set the positions of CS and CR coincides for all models they used giving the same position of CS and CR for the model discussed, whereas the present study was due to the varying positions of strength and stiffness eccentricities for each forty building models.

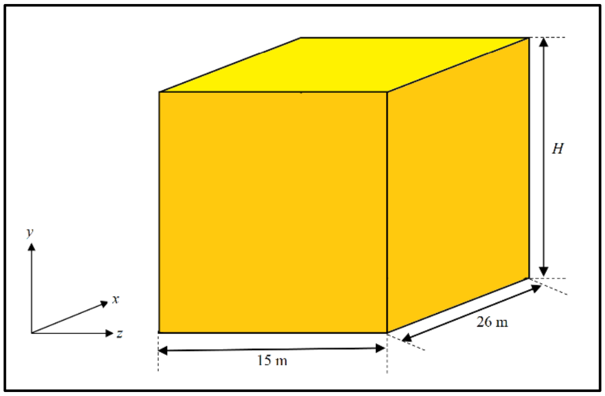


Figure 3: Simple 3-D building model

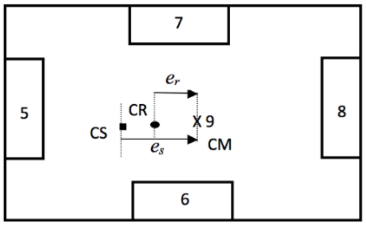


Figure 4: Node locations on top of building

Table 1 shows the variation of strength and stiffness eccentricities. These variations were considered in the present study in order to represent real building conditions since there are no building is symmetric. The diagrams were drawn along *x*-axis with the distance 26 m. The center of mass CM is located at the geometric center GC i.e. 13 m from edge. The reason for having varies CS and CR position at every model is to visualize the various strength and stiffness eccentricties as the gap of the present study.

During the early stages of analysis and design of asymmetric building system, there were nine CR's coeffient has been set from 0 to 0.4 with 0.05 gap. The zero coefficient was set to build the symmetrical condition of the building and for verification purpose. Nevertheless, the symmetrical building system has not being discussed further due to the scope of study. The CR coefficient values that have been set in the present study are based on the common values used in previous study and to represent the real building coeficients.

Strength eccentricity is another important parameter considered in the present study measured the distance from the center of mass CM and center of strength CS. The five coefficients of CS has been set based on the real building coefficient represent as proposed by Anagnostopoulos (2010). Since the interdependent of strength and stiffness as stated in Myslimaj and Tso (2005), the determination of the CS are based on the CR position. These correlation between the strength and stiffness eccentricities are important and will contribute to additional lateral displacement of buildings during earthquake events.

Table 1: Variation of strength and stiffness eccentricities

NO.	**CR**	**e_r(m)**	**e_s (m) M1**	**e_s (m) M2**	**e_s (m) M3**	**e_s (m) M4**	**e_s (m) M5**
1	0.05	1.3	-11.7	-5.85	0	5.85	11.7
2	0.10	2.6	-10.4	-5.2	0	5.2	10.4
3	0.15	3.9	-9.1	-4.55	0	4.55	9.1
4	0.20	5.2	-7.8	-3.9	0	3.9	7.8
5	0.25	6.5	-6.5	-3.25	0	3.25	6.5
6	0.30	7.8	-5.2	-2.6	0	2.6	5.2
7	0.35	9.1	-3.9	-1.95	0	1.95	3.9
8	0.40	10.4	-2.6	-1.3	0	1.3	2.6

4.3 Conceptual design of strength and stiffness distributions

As distances between the CR and CM is the stiffness eccentricity e_r while the distance between the CS and CM is the strength eccentricity e_s, the forty building models were built where five sets of building models under strength design criteria has been used. Each criteria have been decided based on the previous researchers and have been categorized under three groups. Tso and Myslimaj (2003) used the CS that is located at opposite side of CR with the same eccentricity or also called as a balanced CS-CR location as shown in Figure 5. The balanced CS-CR location criterion used to minimize the torsion of asymmetric building. Group number 2 as shown in Figure 6 was the idealization as proposed in DeStefano and Pintucchi (2010) where the CS and CR have been designed to be located at the same side of the building model. Moreover, to represent the real buildings, the CS has been put halfway between the CR and the CM as accounting for torsional effects unavoidably results in a more balanced strength distribution. Figure 7 shows the idealization made in the early study of torsional analysis of building where the strength distribution is not considered in the designed part of analysis.

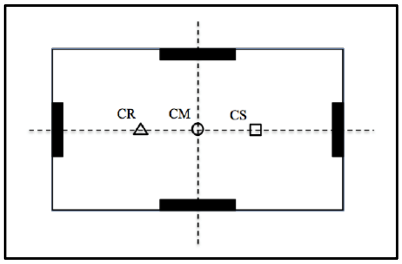


Figure 5: Simplified idealization model of asymmetric building (Tso and Myslimaj, 2003)

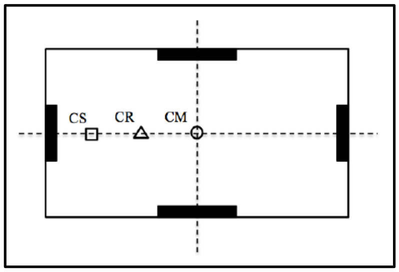


Figure 6: Simplified idealization model of asymmetric building (DeStefano and Pintucchi, 2010)

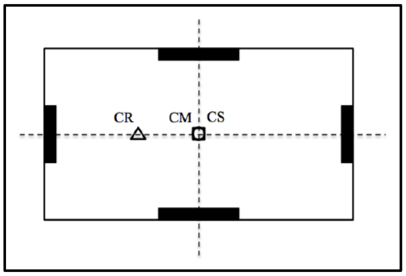


Figure 7: Simplified idealization model of asymmetric building (Common studies)

4.4 Ground motions selection

Since the torsional behavior of one-story asymmetric building is to be analyzed, the 3-dimensional generic model used in this study to accommodate the irregularity issues in plan. It is mainly intended to incorporate the bi-directional seismic action with considering the near-field ground motion (NFGM) as well as the far-field ground motion (FFGM) for comparison purposes. 7 sets of ground motions data have been selected from PEER (Pacific Earthquake Engineering Research Center) for the NFGM and FFGM as listed in Table 2 and 3.

Table 2: Near field ground motion (NFGM)

Year	Earthquake	Mag	Distance (km)	Station
1989	Loma Prieta	6.9	9.96	Gilroy - Gavilan Coll.
1994	Northridge-01	6.7	5.43	Jensen Filter Plant
1994	Northridge-01	6.7	5.43	Jensen Filter Plant Generator
1999	Kocaeli, Turkey	7.5	10.92	Gebze
1999	Chi-Chi, Taiwan	7.6	3.78	TCU049
1999	Chi-Chi, Taiwan	7.6	0.66	TCU052
1999	Chi-Chi, Taiwan	7.6	2.76	TCU076

Table 3: Far field ground motion (FFGM)

Year	Earthquake	Mag	Distance (km)	Station
1976	Friuli (aftersh.)	6	21	Breginj-Fabrika IGLI
1979	Montenegro	6.9	24	Ulcinj-Hotel Olimpic
1980	Campano Lucano	6.9	43	Brienza
2000	South Iceland	6.5	21	Selsund
1999	Duzce 1	7.2	26	LDEO Sta. D0531 WF
1999	Hector Mine	7.1	30.38	99999 Hector
1980	Victoria, Mexico	6.3	35.48	6604 Cerro Prieto

For all seven sets of ground motions for both NFGM and FFGM, the displacements due to these seven ground motions were converting to one value by using the average value of all ground motions separately.

Despite, the program used The motion of the building model using RUAUMOKO-3D for Loma-Prieta Earthquake is used in the verification model as shown in Figure 8.

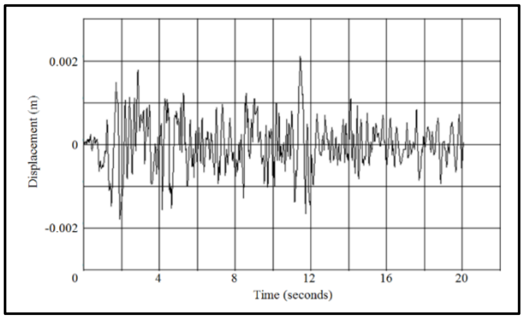


Figure 8: Building motion in RUAUMOKO-3D

5. Result and Discussion

5.1 Building model's verification

In DeStefano and Pintucchi (2010), all the models have been set to have the CS and CR at the same position. One of the model that meets the criteria used have been chosen as the control model and two more models have been reanalyzed for NFGM by using the Loma-Prieta earthquake. The control model as can be seen in Table 4 has three conditions. For verification purposes, one of the system was adopted in the present study was when the CR and CS where it is located at the same position i.e. 0.25CR. However, the present study used CR and CS as located at 0.24 CR and 0.26 CR. These three models were then remodelled to determine the lateral displacement at three positions on the top of the building.

Table 4: Top displacements for verification

	Top displacement (m)		
	0.24CR	0.25CR	0.26CR
Node 5	0.0762	0.0693	0.0634
Node 8	0.1803	0.1497	0.0947
Node 9	0.094	0.0838	0.0785

5.2 Effect on strength and stiffness distributions

Torsional behavior of building can usually be translated through the normalized displacement on the stiff and flexible sides of building models as discussed in DeStefano and Pintucchi (2010). The normalized displacements were then plotted as a comparison of four major systems including the near-field ground motion on the elastic system, near-field ground motion on the inelastic systems, far-field ground motion on the elastic system and far-field ground motion on the inelastic system. All forty models were studied based on five models of strength distribution and eight models of stiffness distribution were grouped together.

The behavior of torsional buildings are presented by the normalized displacements as done by various researchers including DeStefano and Pintucchi (2010), Anagnostopoulos et al (2010), Castillo (2004), Myslimaj and Tso (2005), Fajfar (2000). Normalized displacement is the ratio of maximum lateral displacement at stiff, center and flexible side divided by the lateral displacement at the center of the building. In the studies of torsional building responses, the normalized displacement at stiff, center and flexible side are used to visualize the in-plan building motion or behavior during earthquake event.

5.2.1 Strength distributions

There are five groups of strength distribution based on five CR locations. The graph in Figure 9 shows the normalized displacement for the elastic and inelastic building system under NFGM and FFGM. The amplification of the lateral displacement on the flexible side of the asymmetric building systems is equal for both elastic and inelastic response behavior. It shows that the elastic and inelastic lateral displacement do not have big different amount in the displacement, which confirm the study done by DeStefano and Pintucchi (2010). Besides, as can be seen, the normalized displacement of buildings do not have the significant changes since the displacement values are very small providing the normalized displacement close to unity for stiff and flexible edges of buildings. The same trend were also depicted in other eight groups of CR with changing of CS.

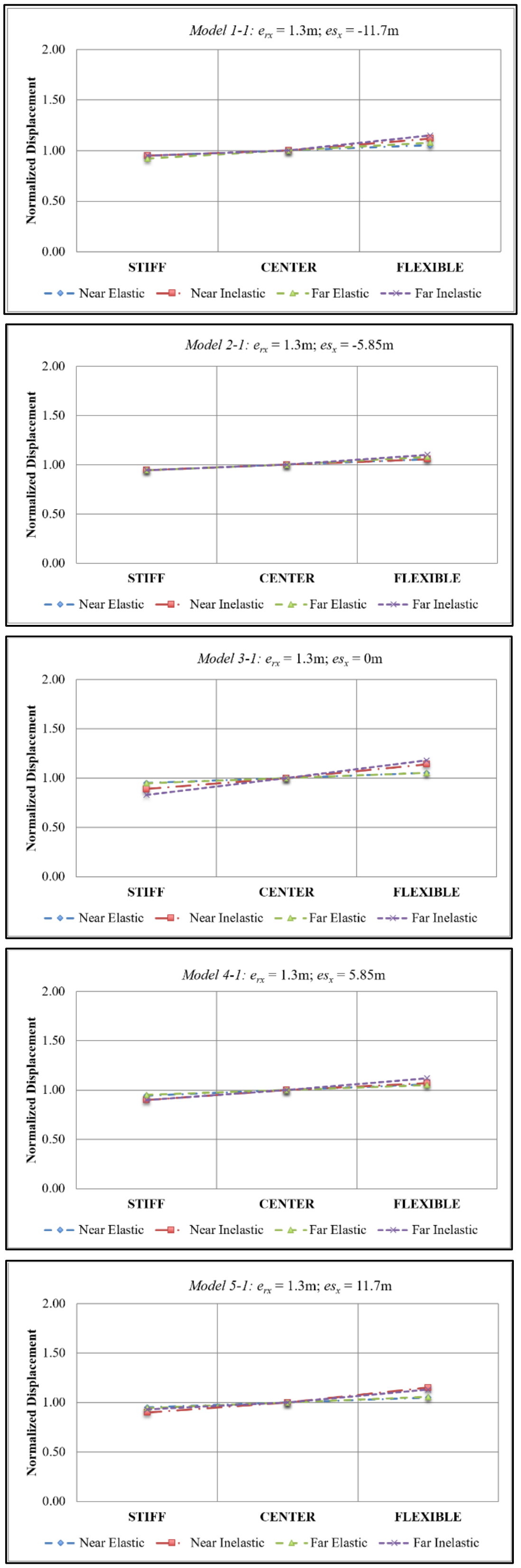


Figure 9: Normalized displacement in terms of strength distributions

5.2.2 Stiffness distributions

Unlike the normalized displacement for building under the effect of strength distribution, Figure 11 shows the changes in normalized displacement for eight different positions of CR with respect to CS. The results show the changes in the building behavior. Model 1-1 has the normalized displacement close to unity for stiff and flexible sides and it become far from unity for Model 1-8. Figure 10 shows CR and CS location for Model 1. From the graph in Figure 11, when the CR is located close to CM, the normalized displacement is close to unity while the normalized displacement is far from unity when CS close to unity.

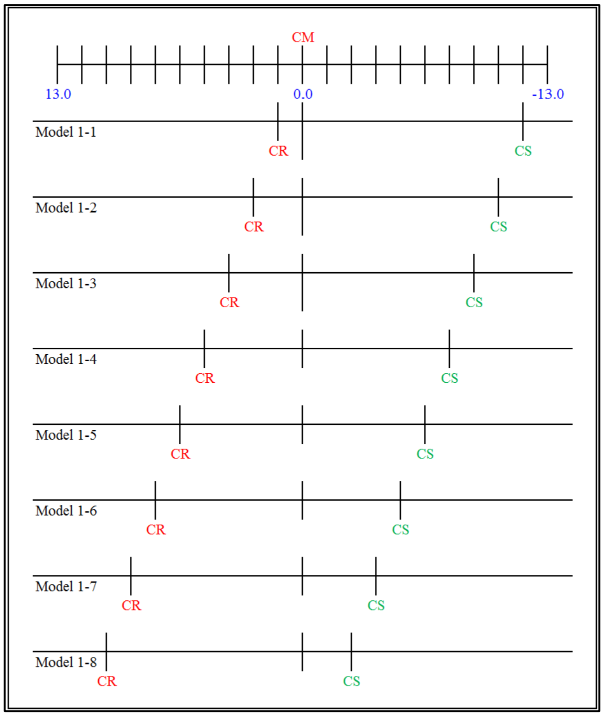
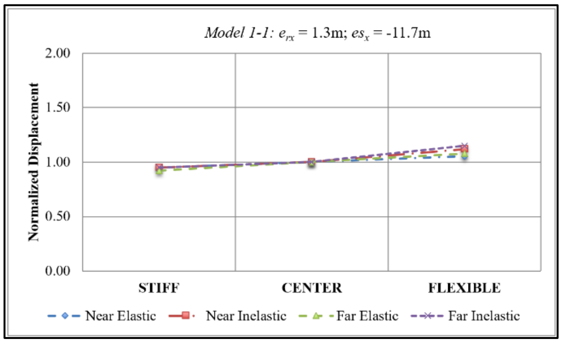
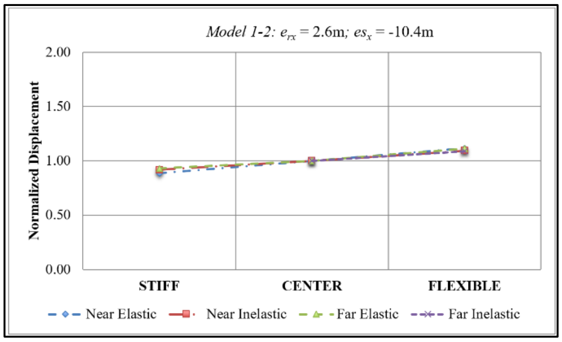
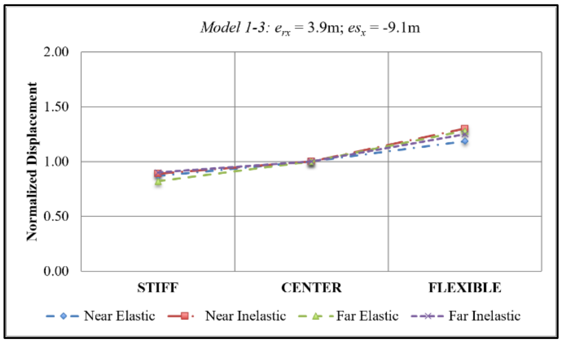
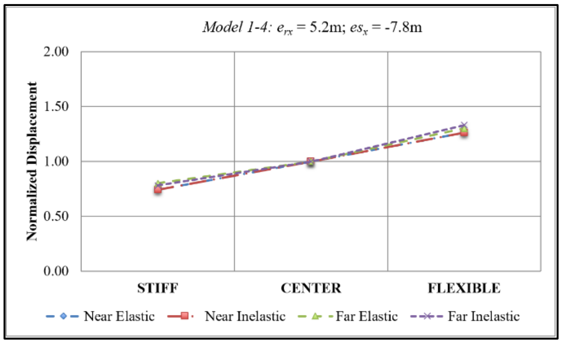


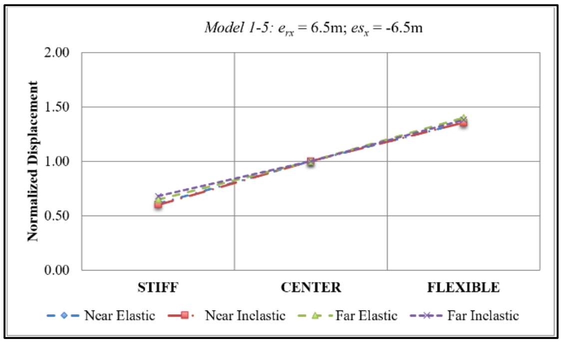
Figure 10: CR and CS arrangements for Model 1











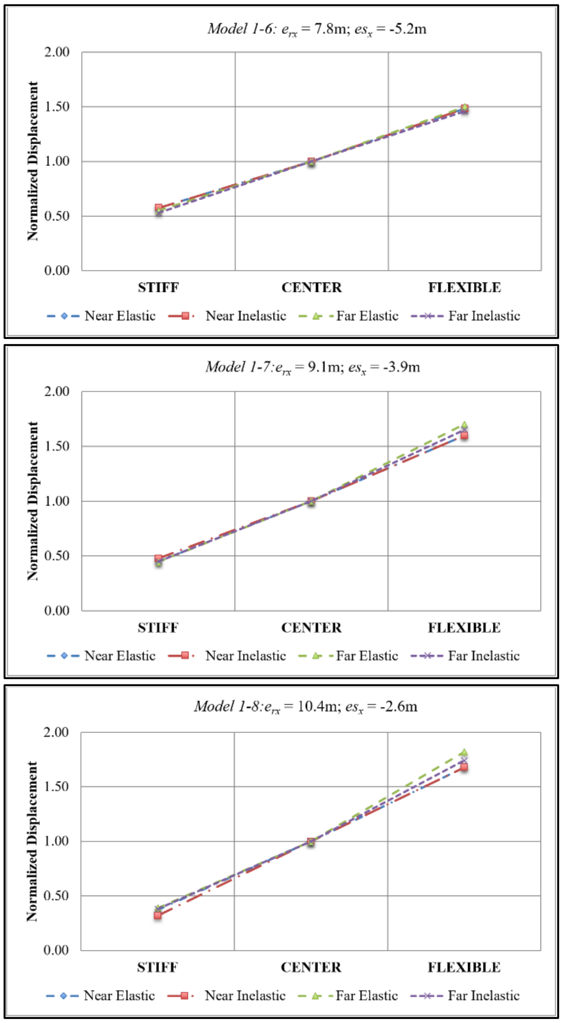


Figure 11: Normalized displacement in terms of stiffness distributions

6. Conclusions

The normalized displacements were found significant to visualise the torsional behavior of aysmmetric reinforced concrete buildings. However, the value was insignificant since the ratio of the maximum lateral displacement at stiff and flexible sides to the maximum lateral displacement at the center of mass were become equal regardless of any of these effects including strength and stiffness distributions. The normalized displacements of buildings with respect to strength distribution is conservative while the stiffness distribution was found significant in the present study.

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