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BEHAVIOR OF ASYMMETRIC MULTI-STORY BUILDINGS SUBJECTED TO NEAR-FAULT GROUND MOTIONS

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ABSTRACT :

Near-fault ground motions impose large demands on structures compared to far-fault ground motions. Asymmetric buildings under earthquake excitations have a greater vulnerability compared to symmetric buildings. Torsional provisions of codes are based on the stiffness eccentricity, while effects of strength eccentricity on torsional response are also considerable. In recent studies which have been accomplished, it is concluded that yield displacement of structural walls is related to dimensions and yield strain of reinforcing steel. Therefore, the stiffness of the wall elements depended on the assigned strength and yield displacement. Different locations of strength and stiffness eccentricities to each other, is very effective on the torsional response variations. In near-fault motions researches, two main objectives are considered. In the first case, component characteristics of near-fault motions and equalizing fault-normal component with equivalent pulse are considered. While, the second case provides quantitative knowledge on response structures subjected to near-fault ground motions. In this study, based on the proposed procedure, torsional response of structure models which have different distributions of the strength and stiffness eccentricity under near-fault and far-fault excitations are considered. Since fault-normal components have large pulse period in the beginning of velocity time history, effects of pulse period on seismic responses are evaluated. The effects of near-fault and far-fault motions on torsional response in the different stories are also considered. Displacement demands on stiff side and soft side, story drift and story ductility demand under mentioned ground motions are calculated and compared. Moreover, strength effects by considering different reinforcing ratios are evaluated.

KEYWORDS: torsional response, asymmetric multi-story, near-fault, far-fault

1. INTRODUCTION

Asymmetric buildings with centers of stiffness and strength being different from the center of floor mass, respond to earthquake excitation in coupled modes, producing both lateral and torsional motions. Such buildings as reported by many researches [1-4] are highly vulnerable due to the torsional response. The position of the stiffness and strength centers towards the floor mass center could highly affect the torsional response. The torsional provisions of codes are based on the assumption that the stiffness of the RC walls can be estimated with some degree of accuracy prior to strength allocation, and will not be affected by the subsequent strength assignment process. The effectiveness of codified torsional provisions has been the subject of extensive study over the last ten years. In these studies the stiffness and strength of the wall elements are assumed independent. Recently, it has been pointed out that for many concrete resisting element such as bridge piers, flexural walls, ductile moment-resisting frames, the yield displacement depends only on material properties and the geometry of the element and can be considered to be independent of its strength for seismic design purpose. Paulay[3] showed that the yield displacement of shear walls depend only on the material properties, such as limiting strain, and the geometry of the components of structure elements. For design purposes generally yield displacements considered to be independent of the strength assigned to components or elements. Since in a plastic mechanism, the sequence of the onset of the components yielding, is independent of their strength, within rational limits, strengths may be assigned to components in the way that suits the designer’s intentions.

With re-defined stiffness, relating freely chosen strengths to strength-independent yield displacements enables a more realistic assessment of elements or of a system to be made. Tso and Myslimaj [4], proved that the yield displacement distribution-based strength assignments between resisting elements, does not require the knowledge of stiffness distribution prior to strength assignment. They concluded that, when strength and stiffness centers are two sides of the mass center, minimum torsional response could be obtained.
Present design codes try to improve the allowance made for the dynamic torsional response of asymmetric buildings based on elastic linear response assumptions by increasing the total strength. However, the relevant rules are controversial and do not comply with the effective non-linear dynamic torsional response. This paper presents a strength assignment approach between the resisting elements minimizing the torsional response. The effects of near-fault and far-fault motions on torsional response with regarding the proposed approach of strength distribution in the different stories are also considered. Displacement demands on stiff side and soft side, story drift demand, under mentioned ground motions, are calculated and compared.

2. SHEAR WALL SYSTEMS

Shear walls are often used to provide lateral support for buildings. In spite of their usual strength and stiffness, they will in most cases be expected to deform beyond their elastic limit. When studying inelastic structural response, it is important to clearly define and quantify, at least with acceptable approximations, those design parameters which characterize inelastic member and system response, such as element and system yield displacements and stiffness, where relevant. Moment-curvature analyses, taking into account the principal parameters of section response, such as material properties, reinforcement content and axial compression load intensity, have shown [3], that the reference yield curvature, ϕ_y, does not change significantly in typical rectangular walls. If it is assumed that curvatures over the height of a prismatic cantilever vary with the moments that correspond to the pattern of lateral static design forces, the reference yield displacement of the element is given by

$$\Delta_y = \frac{\phi_{yi} h_{wi}^{\ 2}}{\eta} \approx \left(\frac{2\xi_y h_{wi}^{\ 2}}{\eta} \right) \frac{1}{l_{wi}} \tag{2.1}$$

Where the coefficient η depends on the pattern of distributed lateral static forces used in the design. For a set of wall elements in a typical building all quantities within the brackets of Eqn. 2.1 will be the same. Therefore, the yield deflection, Δ_{yi}, is inversely proportional to the length, l_{wi}, of the element. When displacement ductilities, $\mu_{\Delta i}$, which are ratios, it is sufficient to use relative yield displacement.

$$\Delta_{yi} \propto \frac{1}{l_{wi}} \tag{2.2}$$

Important features and consequences of the relationship expressed by Eqn. 2.2, not widely appreciated, are:
1) The yield displacement is independent of the strength assigned to the element.
2) Elements with different lengths cannot yield simultaneously.
3) Based on the bilinear lateral force-displacement relationships, the stiffness of an element with respect to the lateral force, V_i, applied to it, can be defined for design purposes as

$$k_i = \frac{V_i}{\Delta_{yi}} \propto l_{wi} V_i \tag{2.3}$$

for the elastic range of response. Thus, contrary to the traditional definition, stiffness to be considered seismic design is strength dependent.

3. THE METHOD OF STRENGTH ASSIGNMENT

With the idea that the yield displacements of wall elements can be determined from architectural drawings, the yield displacement distribution of the structure is known. The asymmetry of such a distribution is characterized by the location of the center of the yield displacement in relation to the mass center. Using plastic mechanism analyses on a number of example structures [3] and focusing on the displacement ductility demand on the elements, it was concluded that, within rational limits, strength can be assigned to the elements in any way that suits the designer's intentions. A desirable strength distribution leads to establish strength centers that with due attention to the relation of stiffness to strength, different stiffness centers are created. Author's [6] favor a 'balanced CV-CR location' criterion to minimize the rotational response of asymmetric structures. In this method, stiffness and strength centers positions depend on β parameter. Previous studies have considered seismic demands of multi-story reinforced concrete asymmetric buildings assuming traditional behavior. Regarding the aforementioned discussions, seismic demands of idealized one-story reinforced concrete asymmetric structures, applying new concepts of behavior will have a significant difference with the quantities of demands assuming traditional behavior of codes [5]. The one-story structure behavior may indicate the approximate behavior of multistory structure but it can not show the overall behavior of the multi-story structure. Thus, the above said subject requires to be studied more.

To accurately characterize near-fault ground motions, it is therefore necessary to specify separate response spectra and time histories for the strike-normal and strike-parallel components of ground motion. The fault-normal component of a ground motion displays a long-period pulse in the acceleration history that appears as a coherent pulse in the velocity and displacement histories. Because of the unique characteristics of near-fault ground motion, structural response to near-fault ground motions has received much attention in recent years. In order to compare the effects of near-fault earthquake ground motions on rotation and displacement demands, two groups of records consisting of near-fault and far–fault records are selected with SD soil condition as per NEHRP. The set of 9 near-fault ground motions used in this study [5]. In order to compare the characteristics of near-fault and far-fault ground motions, it is also considered the set of 7 records of far-fault motions [5].

4. STRUCTURAL SYSTEM

Figure 1 presents the plan of one-story and multi-story buildings. The generic building model consists of rectangular concrete decks. Decks are supported by five reinforced concrete flexural wall elements in y-direction, and four equal wall elements at the edges in x-direction. According to the dimension of elements, yielding displacement elements in five story structure is δ_1=6 cm, δ_2=6.7 cm, δ_3=7.5 cm, δ_4=8.5 cm and δ_5=10 cm respectively. Thus, strength distribution between elements, stiffness of elements, strength and stiffness eccentricity will be as Table 4.1. Based on the code provisions, periods of five story and ten story buildings are 0.48 and 0.77 sec. respectively. However, based on the dependence of stiffness on strength, periods will be 0.97 and 2.5 sec. respectively.

Table 4.1 Strength distribution between elements

Shear wall	β =-0.5	β =-0.25	β=0	β=0.25	β=0.5	β=0.75	β =1
f_{E1}(ton)	122.9	111.4	99.1	86.0	71.9	56.8	40.5
f_{E2}(ton)	79.4	76.1	72.6	68.8	64.8	60.5	55.8
f_{E3}(ton)	66.4	66.4	66.4	66.4	66.4	66.4	66.4
f_{E4}(ton)	65.2	71.8	78.8	86.3	94.3	103.0	112.3
f_{E5}(ton)	53.8	62.0	70.8	80.2	90.2	101.1	112.7
K_{E1}(ton/m)	2048.1	1856.7	1652.2	1433.5	1198.8	946.5	674.5
K_{E2}(ton/m)	1184.5	1135. 6	1083.2	1027.3	967.3	902.7	833.1
K_{E3}(ton/m)	885.1	885.1	885.1	885.1	885.1	885.1	885.1
K_{E4}(ton/m)	767.1	844.3	926.8	1015.0	1109.6	1211.4	1321.1
K_{E5}(ton/m)	538.4	620.5	708.1	801.9	902.4	1010.5	1127.1
e_V(m)	-2.013	-1.040	0.000	1.112	2.306	3.589	4.972
e_K(m)	-3.235	-2.640	-2.008	-1.334	-0.616	0.153	0.977

5. THE EFFECTS OF NEAR-FAULT MOTIONS ON SEISMIC DEMANDS

Under near-fault ground motions, the normal component is applied in an asymmetric direction and the parallel component is applied in a symmetrical direction. As it can be seen in Fig. 2, in lower stories, maximum torsional response is developed for the maximum strength eccentricity. While in lieu of accordance of strength center on mass center, the minimum torsional response is developed. For higher stories, more stiffness eccentricity causes the torsional response increase. However, minimum torsional response is developed when stiffness and strength centers are located in opposite sides of the mass center. If the amounts of torsional demands of the multi-story building are compared with idealized one-story, it can be seen that the amount of the one-story building [5] is more than the amounts in multi-story buildings. Variation trend of the multi-story structure's torsional demands in equivalent height with one-story building is almost similar.

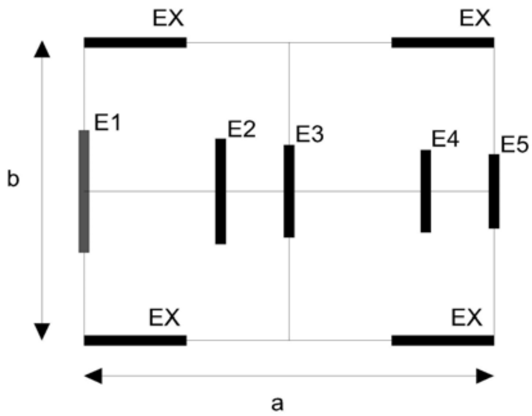

Figure 1 Position of resisting elements in two directions

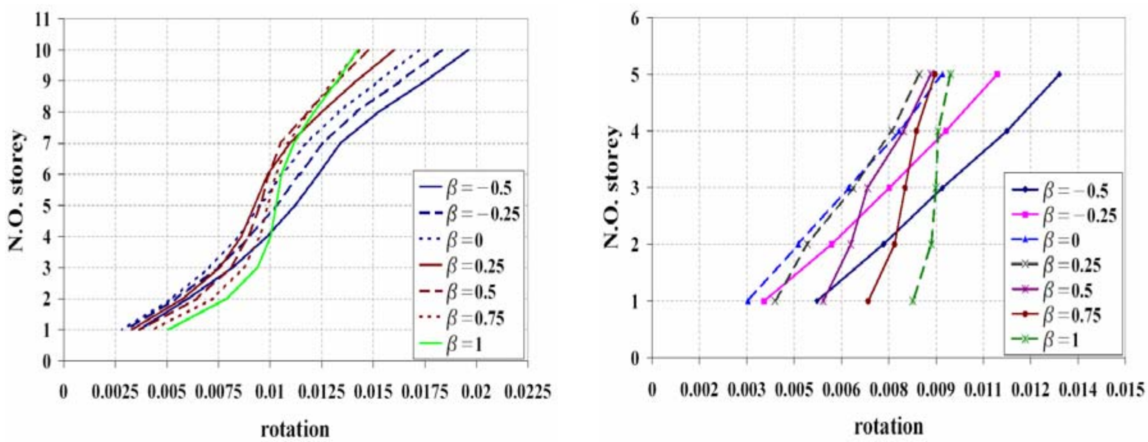

Figure 2 Torsional responses of multi-story buildings under near-fault motions

According to the Figure 3 in higher stories, the displacement of the soft side element is more than the identical amount of the stiff side element. In lower stories, by increasing the amount of β parameter, the displacement of stiff side is more than the soft side displacement. If the amounts of the displacement between two cases of multi-story and idealized one-story are studied, the amount of the idealized one-story building displacement is almost equal to the amounts of roof displacement in multi-story buildings [6]. One of the points to be studied is the manner of the story drift demands variation in the soft side of the structure.

As it can be observed in Figure 4, by increasing the strength eccentricity, the story drift demand in higher stories would increase. However, contrary to the stiff side, this process reverses in the lower story and the amounts of the mentioned demand increase by the increase of the stiffness eccentricity.

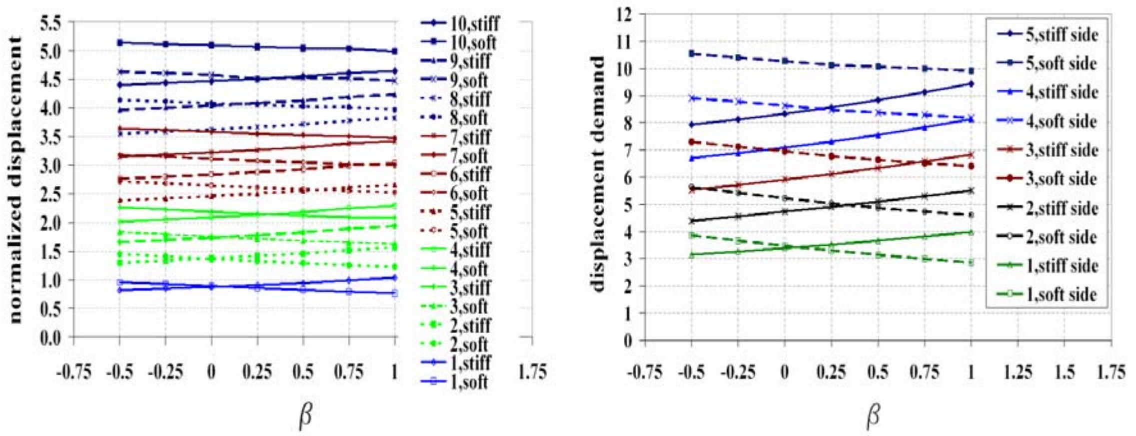

Figure 3 Displacement demands of multi-story buildings under near-fault motions

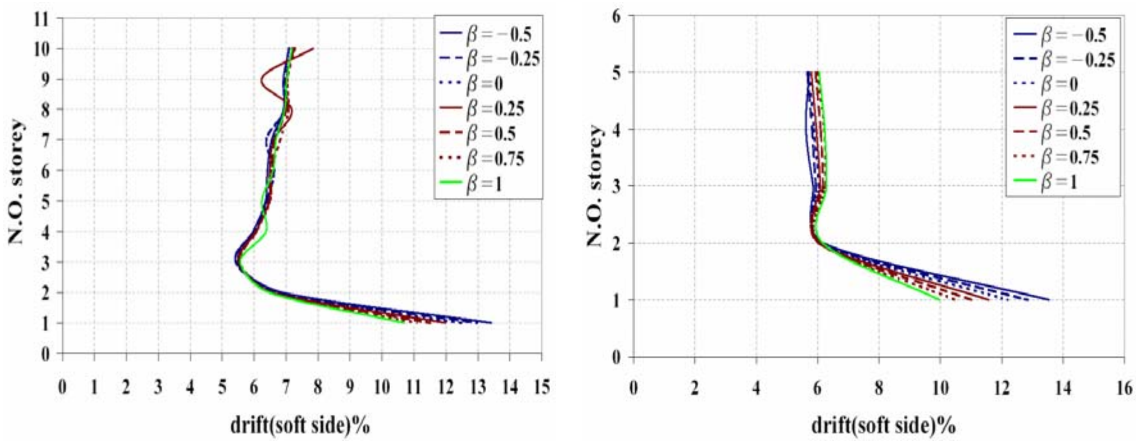

Figure 4 Story drift of multi-story buildings under near-fault motions

6. THE EFFECTS OF FAR-FAULT MOTIONS ON SEISMIC DEMANDS

Fig 5 shows the amounts of torsional demands under far-fault ground motions in different stories. Similar to one-story structures, dominant parameters under far-fault ground motions are stiffness eccentricity. Therefore, minimum torsional demand develops in β=1 and the maximum demand in β=-0.5.

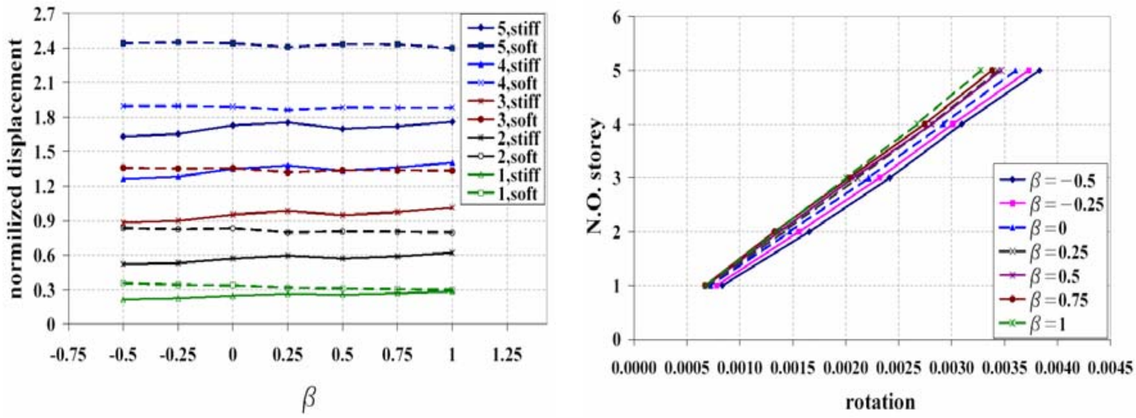

Figure 5 Torsional responses of multi-story buildings under far-fault motions

Torsional demand changes process has an increasing trend in a way that in the lower stories, the minimum rotation and in the higher stories, maximum rotation can be seen. The amounts of one-story building demand

are more than the amounts of torsional demands on higher stories of multi-story buildings. Thus, the amounts of torsional demands in idealized one-story building are more conservative [6]. Moreover, according to this Fig, soft side displacement demands in each story are significantly greater than identical amounts for the stiff side. These differences in lower stories are less and they increase in higher stories. The amounts of displacement demands in equivalent height of the multi-story building under far-fault motions are almost similar to the one-story building displacement demand [6].
Fig 6 presents the amounts and variation of the story drift demand in the soft side under the far-fault motions. For the soft and stiff sides in higher stories, the minimum story drift demand creates in minimum stiffness eccentricity and its maximum develops in minimum strength eccentricity. In near-fault motions, the story drift demand increases from higher stories to the lower ones. It is vice versa under far-fault motions. In lower stories, since strength eccentricity is the dominant parameter, thus the story drift of the soft side decreases.

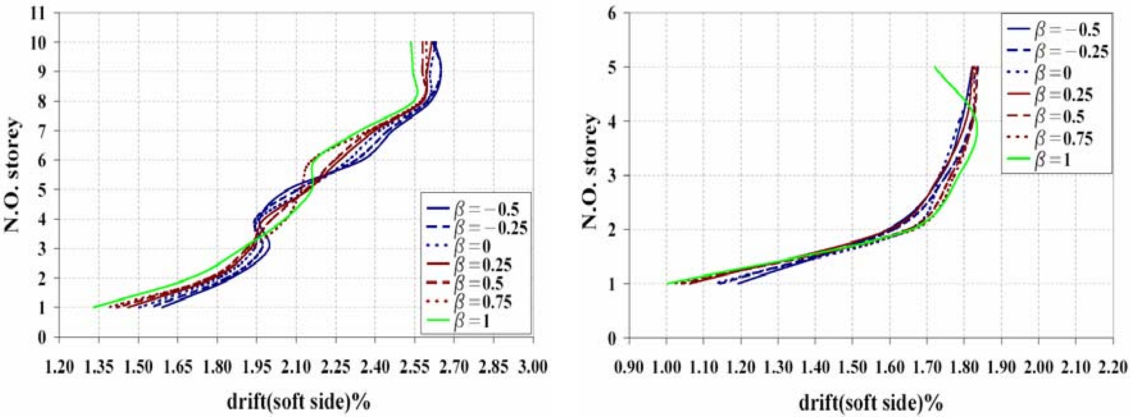

Figure 6 Story drift of multi-story buildings under far-fault motions

7. THE EFFECTS OF REINFORCEMENT ON SEISMIC DEMANDS

In this part, it is attempted to decrease the number of similar stories and instead of a general change in the concrete section, the reinforcement are changed. Torsional demand changes process in different stories for different positions of stiffness and strength centers are presented in Fig 7. In the primary model, in higher stories, the minimum torsional demand is minimized in lieu of balanced position (β=0.5) and in lower stories, the minimum is developed in lieu of maximum strength eccentricity. However, in optimum model [6], the minimum torsional demands are developed in lieu of the maximum strength eccentricity in higher stories.

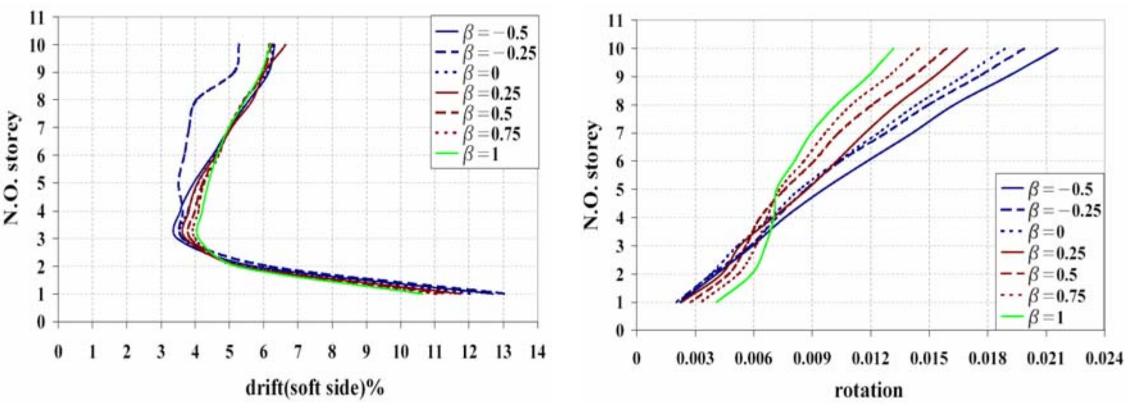

Figure 7 Seismic demands of optimum reinforced model

Furthermore, Fig 7 presents the amounts of story drift demand in an optimum model for soft side. In higher stories, the minimum story drift demand is different in two models of primary and optimum while the maximum story drift demand are similar in the mentioned models.

8. THE EFFECTS OF TRADITIONAL BEHAVIOR ON SEISMIC DEMANDS

Fig 8 indicates the amounts of torsional demand for different positions of stiffness and strength centers. As it can be obtained from this figure, maximum torsional demand is developed in lieu of the maximum stiffness eccentricity. The minimum torsional demand is created in minimum stiffness eccentricity. Therefore, the dominant parameter is stiffness eccentricity. Also the amounts of story drift in the soft side are presented in Fig 8. As it can be seen in the figure, for the longer pulse period, the variation trend has a fundamental difference with shorter pulse period. In longer pulse periods in higher stories, the story drift demand is almost stable, while in lower stories, this demand decreases. However, for shorter pulse period in higher and lower stories, the amounts of drift demand gain a decreasing process.

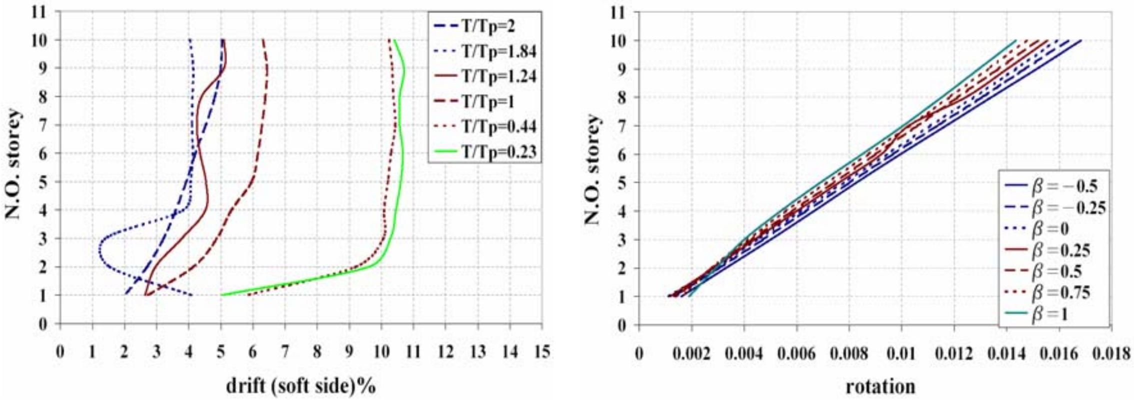

Figure 8 Seismic demands under near-fault motions by considering traditional behavior

9. THE EFFECTS OF EQUIVALENT PULSES ON SEISMIC DEMANDS

Fig 9 shows the average of torsional demands in different stories and different amounts of β parameter for equivalent sinusoidal pulses. As it can be seen in this Fig, except the first story in other stories, the minimum torsional demand is obtained in lieu of the minimum stiffness eccentricity and the maximum response is gained for maximum stiffness eccentricity. However, under near-fault ground motion, the trend of torsional demands is different to the equivalent sinusoidal pulse [6].

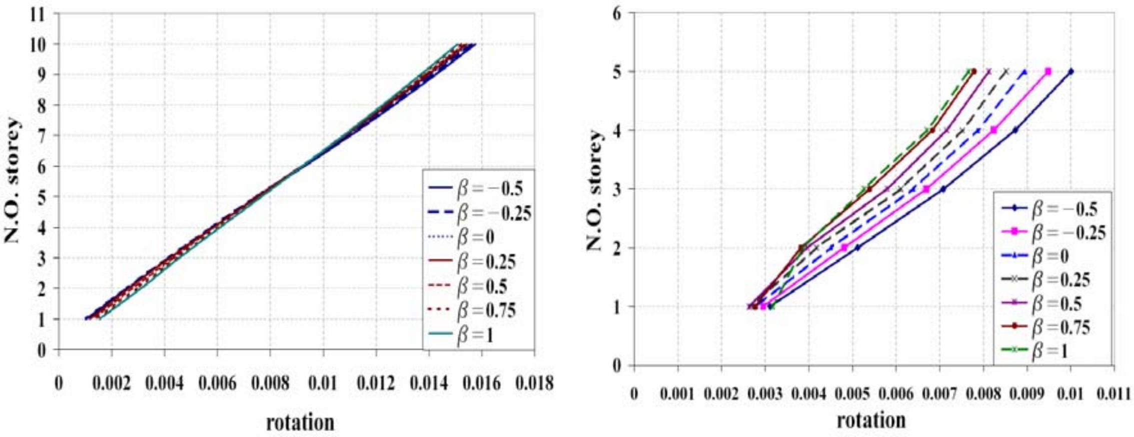

Figure 9 Torsional response of multi-story building under sinusoidal equivalent pulse

Fig 10 illustrates the amounts of torsional demand in different stories and in lieu of different β amounts for equivalent cosines pulses. Maximum torsional demand in lower stories is developed in lieu of maximum strength eccentricity and minimum torsional demand is developed for minimum strength eccentricity. In higher stories, maximum torsional demand is developed in lieu of the maximum stiffness eccentricity and the minimum torsional demand in lieu of the β=0.25 (balanced case). This change process is similar to the near-fault motions. It is remarkable that torsional demands under the two mentioned cases are almost the same.

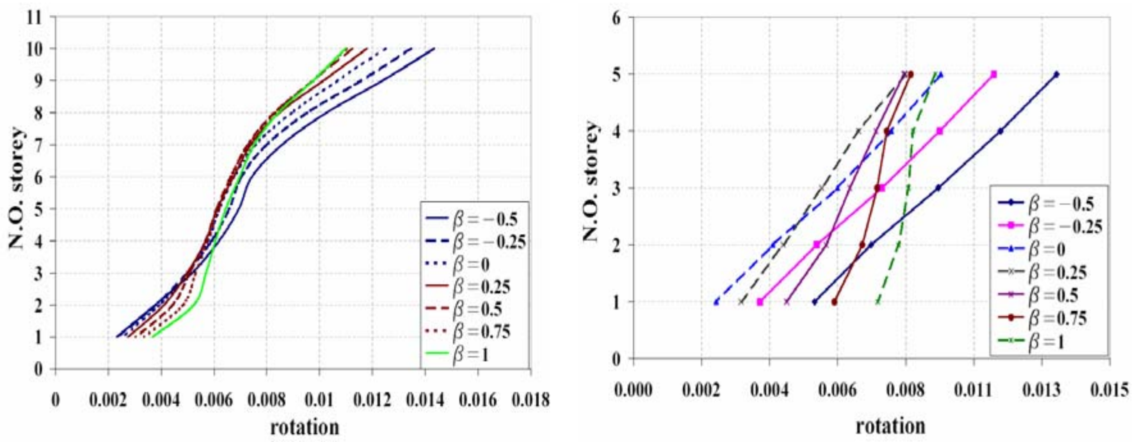

Figure 10 Torsional response of multi-story building under cosines equivalent pulse

10. CONCLUSION

The following conclusions are derived from this study:
In the near-fault ground motions, the minimum rotational response considering strength-stiffness dependent behavior could be achieved, when stiffness and strength centers are located on the opposite side of the mass center. However, general trends in the rotational demand with the assumption of traditional behavior method for the near-fault motions are similar to those of the far-fault motions with strength-stiffness dependent and traditional behavior assumptions. In the former cases, stiffness eccentricity determines the minimum and the maximum rotational responses. The amounts of torsional demands of idealized one-story buildings are more than the similar amounts of multi-story buildings. In higher stories of the multi-story buildings, comparable to the traditional behavior, the displacement of the soft side element is more than the displacement of the stiff side element. While, in the lower stories for greater β amounts, the displacement of the stiff side is more than the soft side displacement. In higher stories, the story drift demand of the soft side increases by the increase of strength eccentricity. However, opposite to the stiff side, in lower stories this process is reversed. In near-fault motions, the story drift demand increases from higher stories to the lower ones. Under far-fault motions, it is reversed. The trend of torsional demand variations under near-fault motions is different in comparison with the sinusoidal equivalent pulse in the multi-story buildings. Torsional demands under near-fault motions are almost the same as to the cosines equivalent pulse. This is valid for both the idealized one-story as well as the multi-story buildings.

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