



## THE EFFECT OF POTENTIAL TORSION ON SEISMIC RESPONSE OF REGULAR MID-RISE RC BUILDINGS

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### ABSTRACT

The aim of this study is to evaluate the existence of torsion due to nonlinear behavior of lateral load resisting elements during moderate or strong earthquakes and to check the validity of pushover analysis of existing regular buildings. Therefore, torsion due to unsymmetrical distribution of lateral load resisting elements in the plan of the structure is not in the scope of the current study.

Two reference RC buildings, 4- and 7-story, are selected for the purpose the current study. The other set of buildings is obtained from reference buildings by adding heavy overhangs with and without edge beams. The building models considered in the current study are subjected to 12 ground motion records using SAP2000 program to carry out nonlinear time history analyses. Displacement demands at the center of mass and corner points of the building were obtained for both X and Y directions. The maximum interstory displacement drift demand ratio (IDR) values are determined. Then, torsional irregularity factors are calculated for the story with maximum IDR according to definition given in TEC-2007. Similarly, torsional irregularity factors for nonlinear static (pushover) analyses are also determined.

Similar to other codes, TEC-2007 consider 5% additional eccentricities for  $\eta_{bi}$  values greater than 1.2 for the design of buildings to take into account for torsion. Also it is widely accepted that pushover analysis is applied to buildings with torsional irregularity factor,  $\eta_{bi}$  smaller than 1.4 without considering accidental eccentricity. Since the buildings considered in the study do not have unsymmetrical distribution of lateral load resisting elements,  $\eta_{bi}$  values are smaller than 1.2 for all cases when static analyses are considered. The  $\eta_{bi}$  values from pushover analyses show that 4-story building has a torsional tendency in y direction while potential torsion for the 7-story building is in x direction. This observation is consistent with displacement demands obtained from time history analyses. Potential torsion directions of both 4- and 7-story buildings have higher torsional irregularity factors, consistently.

Maximum  $\eta_{bi}$  value is calculated as 1.49 for 4-story HO-1.1 model during Koc-Dzc 270 record at y direction. It's approximately 45% higher than the value obtained by pushover analysis. Although the torsional irregularity factors rarely exceed the pushover limit 1.4, they are beyond 1.2, limit for additional eccentricity, for considerably higher number of times. The effect of overhang irregularities on torsional irregularity factors are limited for the scope the current study. Because the overhangs do not changes the distance between center of mass and center of rigidity by a remarkable amount. There is no clear trend between the irregularity factor and displacement increase due to torsion although the corner displacements slightly tend to increase as  $\eta_{bi}$  values get larger. Peak displacement demands at the corner are about 10% higher than those obtained at the center of mass in the scope this study.

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## INTRODUCTION

Past studies have shown that torsional irregularity may exist in structures, which are symmetric regarding to both plan geometry and stiffness distribution of structural elements (Ozmen, 2002). However, 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 (Miranda et al., 2012). The studies also conclude that seismic torsion leads to increased displacement at the extremes of the building and may cause distress in the lateral load-resisting elements located at the edges, particularly in buildings that are torsionally flexible.

There are studies in literature to evaluate torsional response of buildings due to different parameters such as unsymmetrical distribution of mass or lateral load resisting elements in the plan of the structure or inelastic behavior of resisting elements and loss of the resistance of such an element during an earthquake (Paulay, 2001; Newmark, 1969; Kilar and Fajfar, 1997; Ladjinovic and Folic, 2008). Inelastic behavior of lateral load resisting elements and loss of resistance of such an element during a moderate or strong earthquake are also a source of torsional response.

Seismic performance of existing buildings is generally evaluated using nonlinear static analysis that has limitations in terms of building height and irregularities. Pushover analysis uses equivalent seismic load method as nonlinear static analysis. This method is applied to buildings not exceed 25 m and, 8 storey and buildings with torsional irregularity factor,  $\eta_{bi}$  smaller than 1.4 without considering accidental eccentricity. Torsional irregularity factor,  $\eta_{bi}$ , is defined for any of the two orthogonal earthquake directions as the ratio of the maximum relative story drift at any story to the average relative story drift at the same story in the same direction. Also, earthquake codes consider 5% additional eccentricities for  $\eta_{bi}$  values greater than 1.2 (e.g. 2007 Turkish Earthquake Code) for the design of buildings.

The aim this study is to evaluate the existence of torsion due to nonlinear behavior of lateral load resisting elements during moderate or strong earthquakes and to check the validity of pushover analysis of existing regular buildings. Therefore, torsion due to unsymmetrical distribution of lateral load resisting elements in the plan of the structure is not in the scope of the current study.

Two reference RC buildings, 4- and 7-story, are selected to represent major portion of existing building stock. The other set of buildings is obtained from reference buildings by adding heavy overhangs with and without edge beams. A set of 12 ground motion records is selected from past earthquakes with different characteristics and peak ground acceleration values in order to carry out nonlinear dynamic analysis. SAP2000 is used for nonlinear time history analyses. Beam and column elements are modelled as nonlinear frame elements with lumped plasticity by defining plastic hinges at both ends of beams and columns.

## BUILDING DESCRIPTION AND MODELLING APPROACH

Two RC buildings, 4- and 7-story, are selected to represent reference mid-rise buildings located in the high seismicity region of Turkey. The selected buildings are typical beam-column RC frame buildings with no shear walls. Outcomes of detailed field and archive investigation (about 500 buildings) established building models; number of columns, column and beam dimensions, floor area or other parameters reflects a typical constructed building (Inet et al., 2009). These buildings are used to obtain buildings with heavy overhangs with and without edge beams.

The selected reference buildings are designed according to pre-modern Turkish Earthquake Code (TEC-1975), considering both gravity and seismic loads. A design ground acceleration of 0.4 g and soil class Z3 is assumed. Concrete compressive strength and yield strength of both longitudinal and transverse reinforcement values are considered to be 16 MPa and 220 MPa, respectively.

Figure 1 shows plan views of the selected buildings. All building plans are shown in the same plot. The buildings without shaded area as overhangs are reference buildings. The overhang amounts are based on the detailed field and archive investigation. HO-1 stands for average overhang amount from the study while HO-2 stands for average plus half standard deviation. The models for reference and OH-1 are shown in Figure 1. Figure 2 illustrates the HO-2 models. Based on the inventory study

by Inel et al. (2011), the overhang amount of 4-story building is 7.6% and 10.9% of floor area for HO-1 and HO-2 cases, respectively while that of 7-story building is 5.8% and 8.5% for HO-1 and HO-2 cases. In Figure 2, 4-story HO-1.0 corresponds to 4-story building having average overhang amount without edge beams while 4-story HO-1.1 denoted the same building with edge beams.

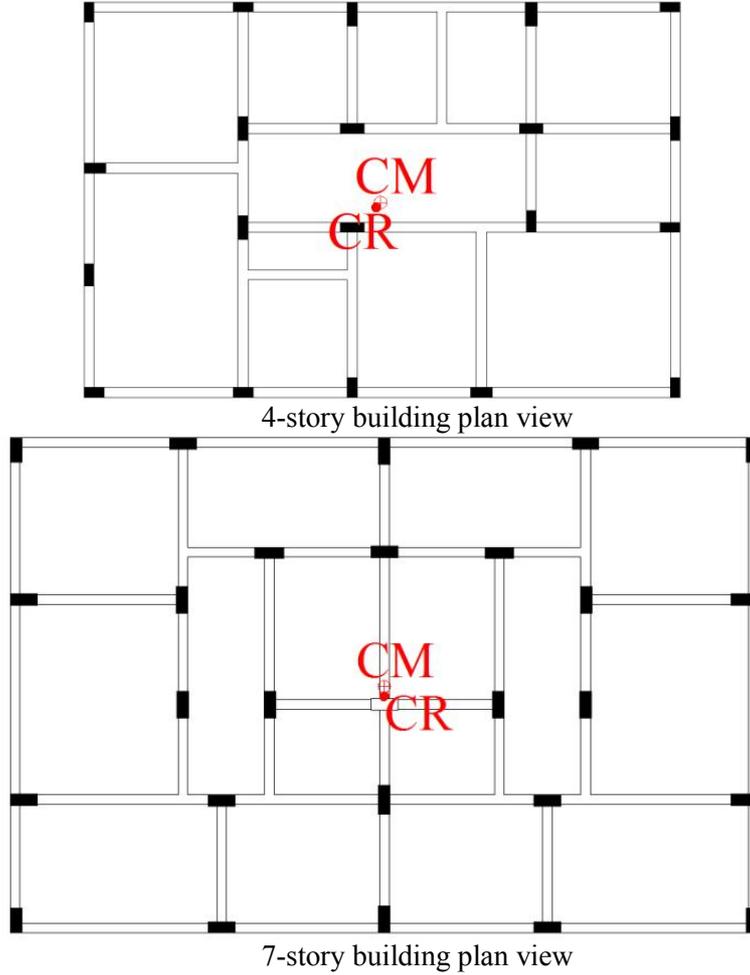


Figure 1. Plan views of 4- and 7-story reference buildings

As shown in Figure 3, five points labeled A, B, C, D, and E define force-deformation behavior of a plastic hinge. The values assigned to each of these points vary depending on type of element, material properties, longitudinal and transverse steel content, and axial load level on the element. Note that number of plastic hinges to be generated for each building is in the order of 500, 800 and 1800 for the 2-, 4- and 7-story buildings, respectively. Plastic hinge length is assumed to be half of the section depth as recommended in 2007 Turkish Earthquake Code. Also, effective stiffness values are obtained per the code;  $0.4EI$  for beams and values between  $0.4$  and  $0.8EI$  depending on axial load level for columns.

In 2007 Turkish Earthquake Code, torsional irregularity factor,  $\eta_{bi}$ , is defined for any of the two orthogonal earthquake directions as the ratio of the maximum relative story drift at any story to the average relative story drift at the same story in the same direction. Figure 4 shows corner point displacements of a typical floor under an earthquake in  $y$  direction.  $\eta_{bi}$  is calculated as shown in Equations 1 and 2.  $(\Delta_i)_{max}$  and  $(\Delta_i)_{min}$  are maximum and minimum displacements at the corners of  $i^{\text{th}}$  floor.

$$\eta_{bi} = \frac{(\Delta_i)_{max}}{(\Delta_i)_{average}} \quad (1)$$

$$(\Delta_i)_{average} = \frac{(\Delta_i)_{max} + (\Delta_i)_{min}}{2} \quad (2)$$

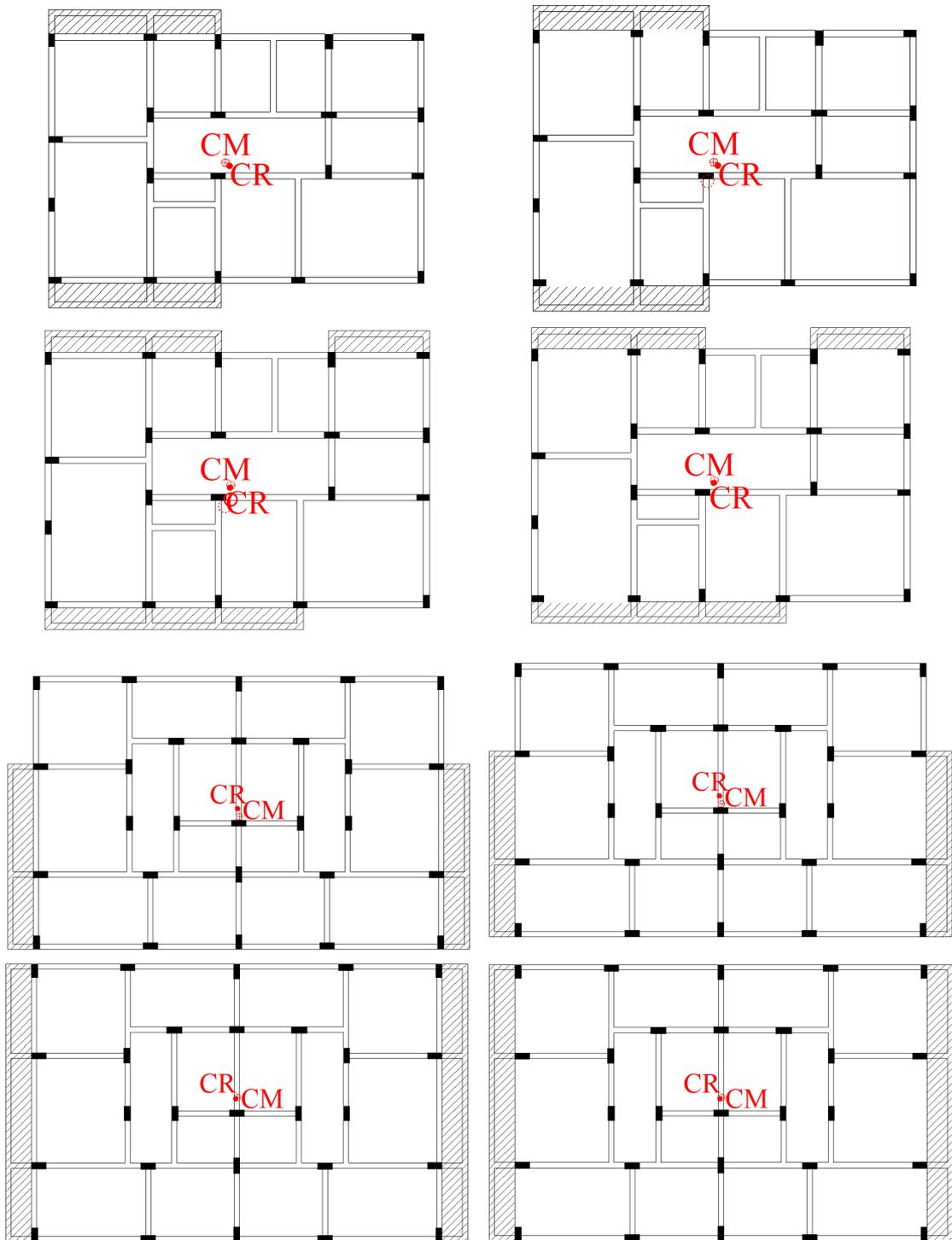


Figure 2. Plan views of 4- and 7-story buildings with heavy overhangs

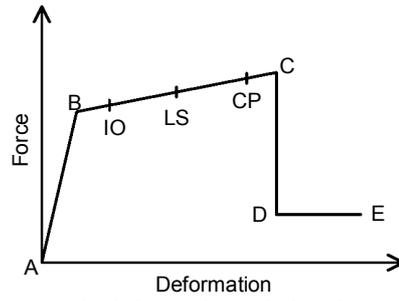
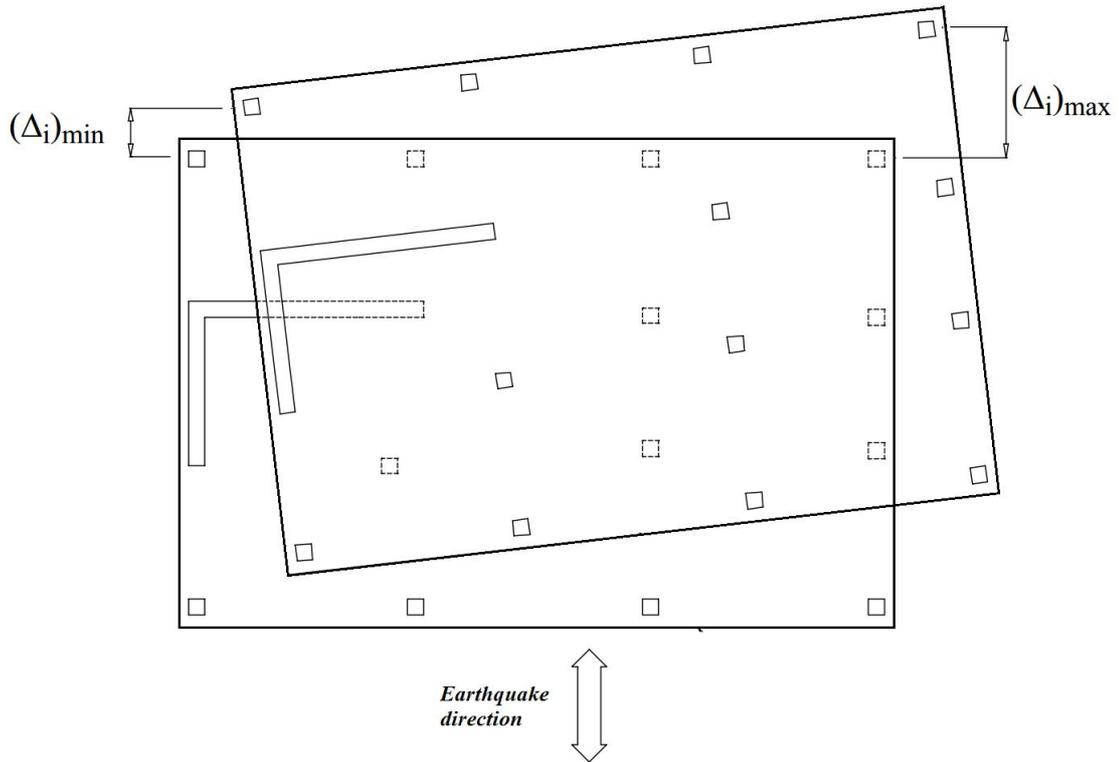


Figure 3. Typical strength-deformation relation for a plastic hinge

Figure 4. Torsional irregularity factor,  $\eta_{bi}$ , defined in TEC-2007

## GROUND MOTIONS

The ground motion records used in nonlinear time history analysis are selected from destructive earthquakes in the past. This set provides an opportunity to examine the effect of characteristics of ground motions on torsion behaviour of regular buildings. Table 1 lists the records considered in this study.

Response spectrum and average response spectrum of 12 ground motion records for 5% damping is plotted in Figure 5 as well as demand spectrum provided in Turkish Earthquake Code-2007 for design earthquake with 10% probability of exceedance in 50 years on Z3 soil class (compatible to soil class C of FEMA-356). As seen in the figure, average spectrum for the considered records is higher than the code spectrum of design earthquake (approximately up to 30-35%) within the period of interest for the mid-rise buildings. The code spectrum is provided to visualize the demand of selected records. No special effort has been given to fit the average of selected records to the code spectrum.

Table 1. Records from destructive earthquakes in Turkey over past two decades

Identifier	Earthquake	Date (dd/mm/yy)	Magnitude	Station	Comp. (°)	PGA (g)	PGV (m/s)	Dist. (km)
CM92PETR. 090	Cape Mendocino	25.04.1992	$M_W=7.1$	Petrolia	090°	0.662	0.897	9.5 <sup>1</sup>
ER92ERZN. 090	Erzincan	13.03.1992	$M_W=6.9$	Erzincan	East	0.496	0.643	2 <sup>1</sup>
GZ76GAZ. 000	Gazli	17.05.1976	$M_W=6.8$	Karakyr	360°	0.608	0.654	3 <sup>2</sup>
IV79ARY5. 140	Imperial Valley	15.10.1979	$M_W=6.5$	El Centro Array #5	140°	0.519	0.469	1 <sup>1</sup>
KC99DUZC. 180	Kocaeli	17.08.1999	$M_W=7.4$	Duzce	180°	0.312	0.588	12.7 <sup>1</sup>
KC99DUZC. 270	Kocaeli	17.08.1999	$M_W=7.4$	Duzce	270°	0.358	0.464	12.7 <sup>1</sup>
LP89HOOL. 360	Loma Prieta	18.10.1989	$M_W=6.9$	Hollister- South & Pine	360°	0.371	0.624	28.8 <sup>1</sup>
NR94PACO. 360	Northridge	17.01.1994	$M_W=6.7$	Pacoima Kagel Canyon	360°	0.433	0.515	8.2 <sup>1</sup>
NR94SEPU. 360	Northridge	17.01.1994	$M_W=6.7$	Sepulveda VA	360°	0.939	0.766	8.9 <sup>1</sup>
NR94SYLM. 090	Northridge	17.01.1994	$M_W=6.7$	Sylmar - Olive View Med FF	090°	0.604	0.782	6.4 <sup>1</sup>
NR94TARZ. 360	Northridge	17.01.1994	$M_W=6.7$	Tarzana, Cedar Hill	360°	0.99	0.776	17.5 <sup>1</sup>
PS86NRPS. 210	N. Palm Springs	08.07.1986	$M_W=6.0$	North Palm Springs	210°	0.594	0.733	8.2 <sup>1</sup>

1 Closest distance to fault rupture    2 Hypocentral

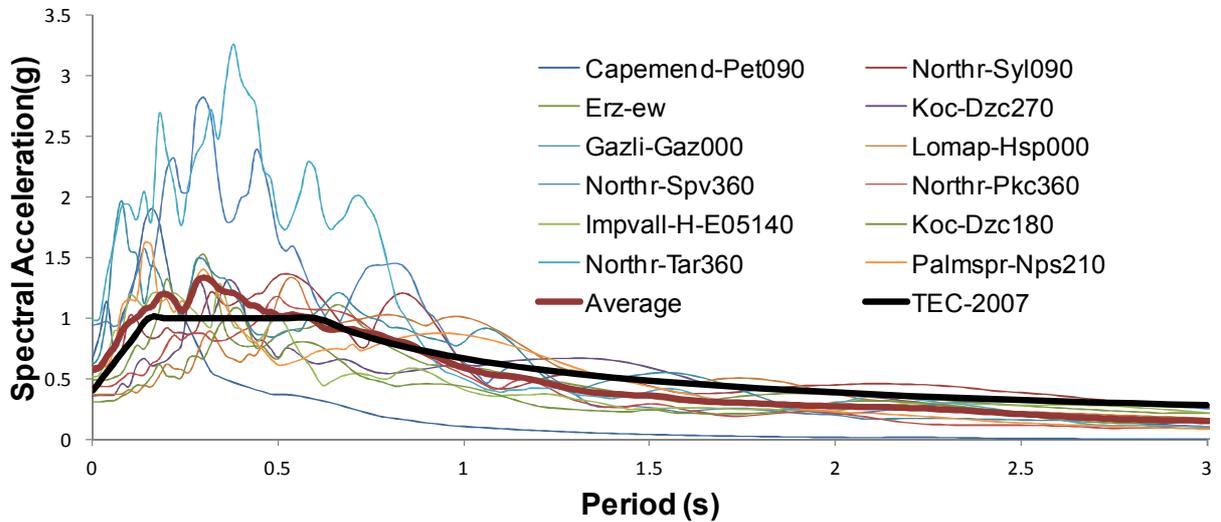


Figure 5. Response spectrum of ground motion records

## ANALYSIS AND FINDINGS

The aim this study is to evaluate the existence of torsion due to nonlinear behavior of lateral load resisting elements during moderate or strong earthquakes and to check the validity of pushover analysis of existing regular buildings. Therefore, torsion due to unsymmetrical distribution of lateral load resisting elements in the plan of the structure is not in the scope of the current study.

The building models considered in the current study are subjected to 12 ground motion records using SAP2000 program to carry out nonlinear time history analyses. Displacement demands at the

center of mass and corner points of the building were obtained for both X and Y directions. The maximum interstory displacement drift demand ratio (IDR) values are determined. Then, torsional irregularity factors are calculated for the story with maximum IDR according definition given in TEC-2007. Similarly, torsional irregularity factors for nonlinear static (pushover) analyses are also determined.

Torsional irregularity factors determined from nonlinear static and dynamic analyses are illustrated in Figures 6 and 7 for 4- and 7-story buildings. Torsional irregularity is defined per TEC-2007 in case of torsional irregularity factor values greater than 1.2 with considering accidental eccentricity for design stage. Also it is widely accepted that pushover analysis is applied to buildings with torsional irregularity factor,  $\eta_{bi}$  smaller than 1.4 without considering accidental eccentricity.

Since the buildings considered in the study do not have unsymmetrical distribution of lateral load resisting elements,  $\eta_{bi}$  values are smaller than 1.2 for all cases when pushover analyses are considered as seen in Figures 6 and 7.

The  $\eta_{bi}$  values from pushover analyses in Figures 6 and 7 show that 4-story building has a torsional tendency in y direction while potential torsion for the 7-story building is in x direction. This observation is consistent with displacement demands obtained from time history analyses. Potential torsion directions of both 4- and 7-story buildings have higher torsional irregularity factors, consistently. The factor varies with the ground motions. Maximum  $\eta_{bi}$  value is calculated as 1.49 for 4-story HO-1.1 model during Koc-Dzc 270 record at y direction. It's approximately 45% higher than the value obtained by pushover analysis.

Pushover analysis uses equivalent seismic load method as nonlinear static analysis. This method is applied to buildings with torsional irregularity factor,  $\eta_{bi}$  smaller than 1.4. Since the buildings selected for this study has regular geometry and distribution of stiffness, torsional irregularity factors obtained from nonlinear time history analyses are not extremely high. However, it should be noted that these buildings were considered to have no torsional effects according to the pushover analyses by having the highest  $\eta_{bi}$  value of 1.07. The outcomes of the time history analyses suggest that the torsional irregularity factors may increase to significant values under earthquakes especially for the buildings with slightly unsymmetrical distribution of stiffness.

The current study also shows that the amount and location of heavy overhangs used in the current study do not affect the seismic behavior, significantly. There is no obvious trend between the building models with different heavy overhangs and arrangements. Although the torsional irregularity factors have a tendency to be higher for both y direction of 4-story and x-direction of 7-story buildings, it is hard to reach a reliable conclusion.

Torsional irregularity factors obtained from time history analyses and their averages and the factors obtained from pushover analysis are given in Tables 2 and 3. The tables show that although the torsional irregularity factors rarely exceed the pushover limit 1.4, they are beyond 1.2, limit for additional eccentricity, for considerably higher number of times. 23.3% of  $\eta_{bi}$  values are calculated as greater than 1.2 limit for y direction of 4-story building while this ratio is 38.8% for x direction of 7-story building for time history analyses using 12 ground motions. Except one case for 4-story building,  $\eta_{bi}$  values satisfy the requirement for pushover analyses, indicating the regularity of the selected buildings in terms of both geometry and stiffness distribution.

The effect of overhang irregularities on torsional irregularity factors are limited for the scope the current study. Because the overhangs do not changes the distance between center of mass and center of rigidity by a remarkable amount. The authors also emphasize that the effect of overhang irregularity might be significant on statically asymmetric structures.

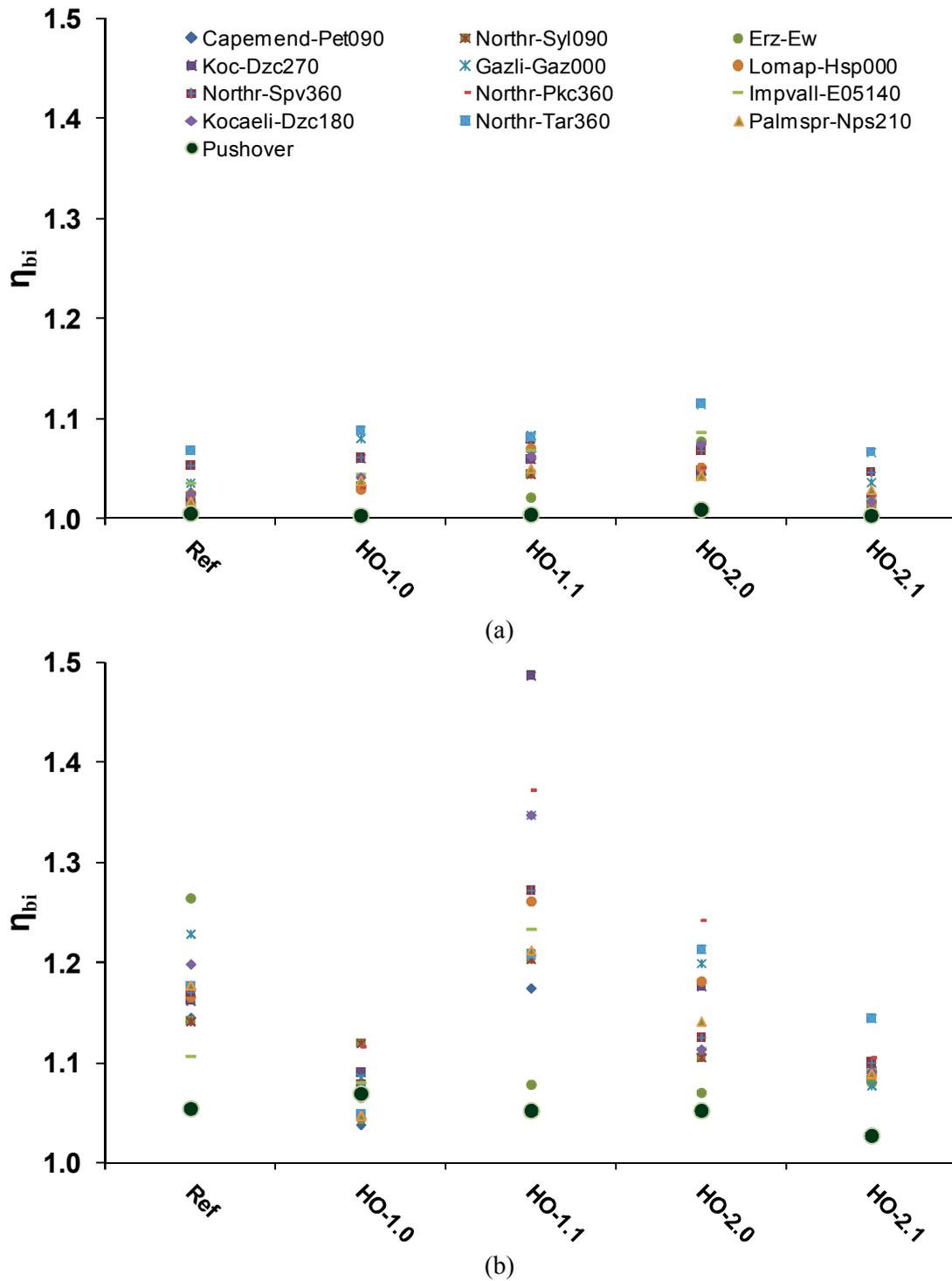


Figure 6. Torsional irregularity factors of 4-Story TEC 1975 models for (a) x-direction and (b) y-direction.

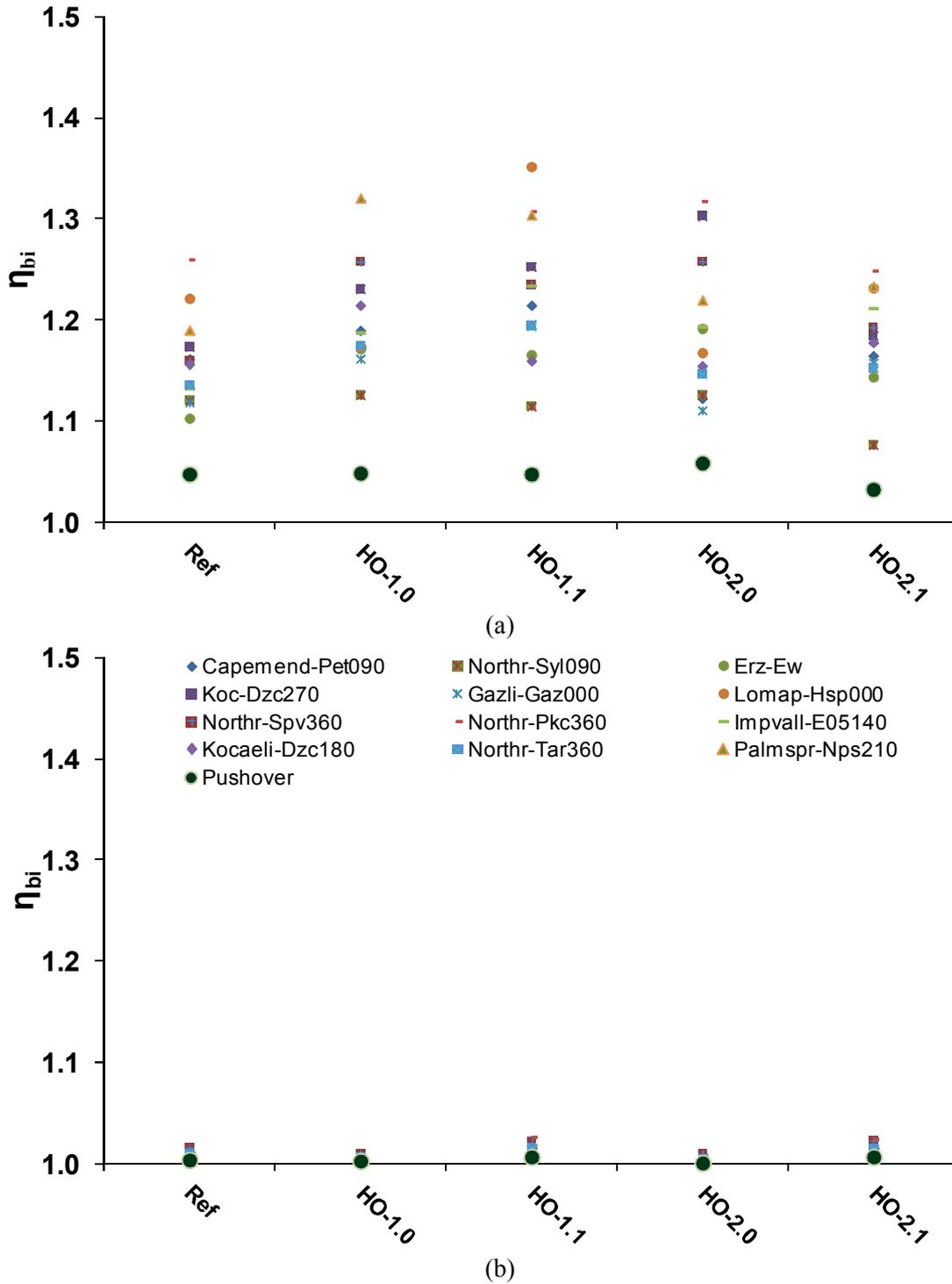


Figure 7. Torsional irregularity factors of 7-story models for (a) x-direction and (b) y-direction.

The relation between torsional irregularity factors and maximum displacement of center of mass normalized by maximum displacement of critical corner are given for 4-story and 7-story buildings in Figure 8. It is apparent that there is no clear trend between the irregularity factor and displacement increase due to torsion although the corner displacements slightly tend to increase as  $\eta_{bi}$  values get larger. It should be also noted that the calculated  $\eta_{bi}$  values do not necessarily correspond to peak values of displacements. Peak relative displacements are not highly sensitive torsion behaviour of regular buildings. Torsion effects increases with distance from the center of mass and reaches maximum value at corner points. Thus, evaluation of torsion behaviour with relative displacements at

corner points is a valid approach. Figure 8 clearly shows that peak displacement demands at the corner are almost 10% higher than those are obtained at the center of mass

Table 2. Torsional irregularity factors obtained from time history and pushover analyses for 4-story building

	X Direction					Y Direction				
	Ref	HO-1.0	HO-1.1	HO-2.0	HO-2.1	Ref	HO-1.0	HO-1.1	HO-2.0	HO-2.1
Capemend-Pet090	1.027	1.034	1.068	1.045	1.019	1.146	1.039	1.175	1.109	1.08
Northr-Syl090	1.017	1.033	1.045	1.043	1.016	1.142	1.120	1.204	1.106	1.08
Erz-Ew	1.017	1.033	1.022	1.078	1.016	1.265	1.045	1.079	1.071	1.08
Koc-Dzc270	1.022	1.061	1.060	1.049	1.021	1.163	1.091	1.487	1.177	1.09
Gazli-Gaz000	1.037	1.081	1.084	1.073	1.037	1.229	1.086	1.348	1.200	1.08
Lomap-Hsp000	1.025	1.030	1.071	1.052	1.018	1.166	1.066	1.262	1.182	1.09
Northr-Spv360	1.054	1.062	1.080	1.069	1.047	1.171	1.079	1.273	1.126	1.10
Northr-Pkc360	1.027	1.032	1.061	1.052	1.024	1.174	1.117	1.373	1.243	1.11
Impvall-E05140	1.036	1.045	1.069	1.087	1.020	1.107	1.081	1.234	1.115	1.09
Kocaeli-Dzc180	1.025	1.042	1.063	1.075	1.018	1.199	1.074	1.348	1.114	1.09
Northr-Tar360	1.069	1.089	1.082	1.115	1.067	1.177	1.050	1.209	1.214	1.15
Palmspr-Nps210	1.018	1.039	1.051	1.044	1.030	1.178	1.048	1.213	1.142	1.09
<b>Average</b>	<b>1.029</b>	<b>1.045</b>	<b>1.059</b>	<b>1.061</b>	<b>1.026</b>	<b>1.167</b>	<b>1.074</b>	<b>1.251</b>	<b>1.142</b>	<b>1.090</b>
Pushover	1.006	1.004	1.005	1.010	1.004	1.055	1.070	1.053	1.053	1.028

Table 3. Torsional irregularity factors obtained from time history and pushover analyses for 7-story building

	X Direction					Y Direction				
	Ref	HO-1.0	HO-1.1	HO-2.0	HO-2.1	Ref	HO-1.0	HO-1.1	HO-2.0	HO-2.1
Capemend-Pet090	1.162	1.190	1.215	1.123	1.165	1.005	1.006	1.010	1.005	1.010
Northr-Syl090	1.121	1.126	1.115	1.126	1.077	1.007	1.004	1.011	1.004	1.010
Erz-Ew	1.103	1.172	1.166	1.192	1.144	1.005	1.006	1.010	1.004	1.011
Koc-Dzc270	1.174	1.231	1.253	1.303	1.185	1.008	1.006	1.022	1.004	1.020
Gazli-Gaz000	1.119	1.162	1.196	1.111	1.158	1.006	1.004	1.015	1.005	1.012
Lomap-Hsp000	1.222	1.174	1.352	1.168	1.232	1.009	1.005	1.017	1.005	1.017
Northr-Spv360	1.160	1.258	1.235	1.258	1.193	1.016	1.010	1.020	1.010	1.023
Northr-Pkc360	1.260	1.318	1.308	1.318	1.249	1.011	1.009	1.027	1.009	1.025
Impvall-E05140	1.133	1.188	1.234	1.194	1.212	1.010	1.005	1.019	1.003	1.016
Kocaeli-Dzc180	1.157	1.215	1.160	1.155	1.178	1.010	1.007	1.015	1.005	1.015
Northr-Tar360	1.136	1.175	1.194	1.147	1.153	1.010	1.006	1.016	1.005	1.015
Palmspr-Nps210	1.190	1.321	1.304	1.220	1.234	1.006	1.003	1.010	1.003	1.009
<b>Average</b>	<b>1.153</b>	<b>1.198</b>	<b>1.214</b>	<b>1.183</b>	<b>1.170</b>	<b>1.008</b>	<b>1.006</b>	<b>1.015</b>	<b>1.005</b>	<b>1.015</b>
Pushover	1.048	1.049	1.048	1.059	1.033	1.004	1.003	1.007	1.001	1.007

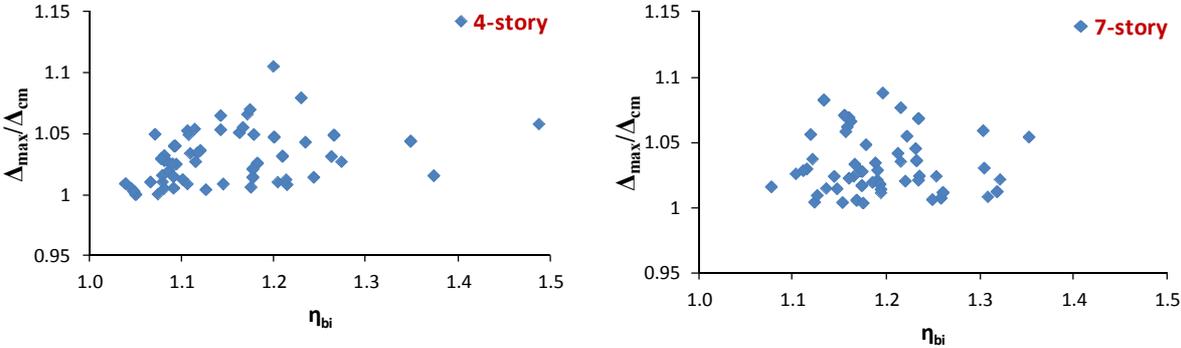


Figure 8. The relation between torsional irregularity factors and maximum displacement of center of mass normalized by maximum displacement of critical corner

## SUMMARY AND CONCLUDING REMARKS

The aim of this study is to evaluate the existence of torsion due to nonlinear behavior of lateral load resisting elements during moderate or strong earthquakes and to check the validity of pushover analysis of existing regular buildings. Therefore, torsion due to unsymmetrical distribution of lateral load resisting elements in the plan of the structure is not in the scope of the current study.

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1. Similar to other codes, TEC-2007 consider 5% additional eccentricities for  $\eta_{bi}$  values greater than 1.2 for the design of buildings to take into account for torsion. Also it is widely accepted that pushover analysis is applied to buildings with torsional irregularity factor,  $\eta_{bi}$  smaller than 1.4 without considering accidental eccentricity.
2. Since the buildings considered in the study do not have unsymmetrical distribution of lateral load resisting elements,  $\eta_{bi}$  values are smaller than 1.2 for all cases when static analyses are considered.
3. The  $\eta_{bi}$  values from pushover analyses show that 4-story building has a torsional tendency in y direction while potential torsion for the 7-story building is in x direction. This observation is consistent with displacement demands obtained from time history analyses. Potential torsion directions of both 4- and 7-story buildings have higher torsional irregularity factors, consistently.
4. The factor varies with the ground motions. Maximum  $\eta_{bi}$  value is calculated as 1.49 for 4-story HO-1.1 model during Koc-Dzc 270 record at y direction. It's approximately 45% higher than the value obtained by pushover analysis.
5. Pushover analysis uses equivalent seismic load method as nonlinear static analysis. This method is applied to buildings with torsional irregularity factor,  $\eta_{bi}$  smaller than 1.4. Since the buildings selected for this study has regular geometry and distribution of stiffness, torsional irregularity factors obtained from nonlinear time history analyses are not extremely high. However, it should be noted that these buildings were considered to have no torsional effects according to the pushover analyses by having the highest  $\eta_{bi}$  value of 1.07. The outcomes of the time history analyses suggest that the torsional irregularity factors may increase to significant values under earthquakes especially for the buildings with slightly unsymmetrical distribution of stiffness.
6. Although the torsional irregularity factors rarely exceed the pushover limit 1.4, they are beyond 1.2, limit for additional eccentricity, for considerably higher number of times. 23.3% of  $\eta_{bi}$  values are calculated as greater than 1.2 limit for y direction of 4-story building while this ratio is 38.8% for x direction of 7-story building for time history analyses.
7. The effect of overhang irregularities on torsional irregularity factors are limited for the scope the current study. Because the overhangs do not changes the distance between center of mass and center of rigidity by a remarkable amount. The authors also emphasize that the effect of overhang irregularity might be significant on statically asymmetric structures.
8. There is no clear trend between the irregularity factor and displacement increase due to torsion although the corner displacements slightly tend to increase as  $\eta_{bi}$  values get larger.
9. Peak displacement demands at the corner are about 10% higher than those obtained at the center of mass in the scope this study.

10. Remarkable rate of symmetrical buildings used in this study have torsional irregularity with some degree in nonlinear analysis. Thus, more detailed study including different properties of existing structures should be carried out to understand torsional behavior of existing buildings.

## ACKNOWLEDGEMENT

The authors acknowledge support provided by Pamukkale University Research Fund Unit (PAU-BAP).

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