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COMPARISON OF EQUIVALENT SDOF AND 2D MODELS FOR NONLINEAR SEISMIC DISPLACEMENT DEMAND ESTIMATES

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ABSTRACT

This study compares displacement estimates of mid-rise reinforced concrete (RC) buildings subjected to recorded motions in past earthquakes obtained from nonlinear time history estimates of 2D and “Equivalent” Single-Degree-Of-Freedom (ESDOF) models. Two structures selected as 10 and 15 stories were considered to represent mid-rise reinforced concrete buildings in the scope of the study. The building models are modelled as two dimensional frame elements. The selected ground motion records are scaled to be compatible with spectrum in the draft Turkish Building Earthquake Code-2016. In total, 44 nonlinear dynamic time history analyses of 2D models and 44 nonlinear time history analyses for the ESDOF systems were carried out to obtain inelastic displacement demand values. The study shows that although the displacement demand estimates have a wide scatter, the mean estimates of the considered buildings range in a very narrow band. The mean roof displacement demand ratios changes between 0.85% and 1%, indicating moderate displacement demands compared to their displacement capacities for 10- and 15-story buildings. The ratio of ESDOF system to 2D model indicates a significant variation and dependence on the model for certain records. It is hard to identify the reason or which ground motion is more sensitive to the model choice. The comparison of ESDOF and 2D model estimates clearly shows that the characteristic of ground motion record affects the ESDOF estimates. The outcomes indicate that the ESDOF models provide somewhat conservative estimates on average. In general, the ESDOF model represents its 2D model reasonably well.

Keywords: Displacement demands; “equivalent” SDOF systems; nonlinear time history analyses; reinforced concrete; 2D building models

1. INTRODUCTION

Proper displacement demand estimates of building stock in earthquake prone countries are essential for seismic performance evaluation. Static or dynamic analysis can be used in estimating displacement demands of structures. Although nonlinear time history (dynamic) analysis provides the most precise estimates, static (pushover) analysis is preferred because of its practical and close estimates. This study aims to compare displacement demand estimates of mid-rise reinforced concrete buildings subjected to recorded motions in past earthquakes. Nonlinear time history estimates of two dimensional (2D) and “equivalent” Single-Degree-Of-Freedom (SDOF) models of reinforced concrete buildings are used for comparison.

In this study, two structures selected as 10 and 15 stories are considered to represent mid-rise reinforced concrete buildings. These buildings are modelled as two dimensional frame elements without shear walls in SAP2000 (SAP2000 V-19 2016). The selected interior frames in two principal directions represent 2D models of these buildings. Beam and column elements are modelled as nonlinear frame elements with lumped plasticity by defining plastic hinges at both ends of beams and columns. Characteristics of building in SAP2000 are reflected by the user-defined hinge properties

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using SEMAp (SEMAp 2008), software for moment-curvature analyses of RC members (Ozmen et al. 2007).

The inelastic dynamic characteristic of a building is represented by a bilinear “equivalent” SDOF system based on its capacity curve obtained by nonlinear static analysis. SAP2000 is used for 2D nonlinear static and nonlinear time history analyses. 11 records from past earthquakes are selected for nonlinear time-history analysis. Ground motion records are scaled to be compatible with spectrum in the draft Turkish Building Earthquake Code-2016 (TBEC-2016).

Seismic displacement demand estimates of 2D buildings and “equivalent” SDOF systems are compared each other. In addition, the obtained values based on past earthquakes are compared to inelastic displacement demand estimates of the draft Turkish Earthquake Code. The outcomes and findings of the study are useful to better understand the consequences and issues in simplification of building models as “equivalent SDOF” systems.

2. DESCRIPTION OF STRUCTURES AND MODELING APPROACH

Two structures selected as 10 and 15 stories are considered to represent mid-rise reinforced concrete buildings for this study. The buildings were modelled with a typical beam-column RC frame system with no shear walls. Both buildings have the same plan and dimensions. The plan view of buildings and the selected interior axes for the 2D models were given in Figure 1. The selected buildings were designed according to modern Turkish Earthquake Code (TEC-2007) considering both gravity and seismic loads. Design ground acceleration of 0.4 g and soil class Z3 that is similar to class C soil of FEMA-356 (FEMA-356 2000) was assumed.

The concrete compressive strengths for both buildings were considered as 35 MPa while the yield strength of both longitudinal and transverse reinforcement was assumed to be 420 MPa. The period, seismic weight, lateral strength normalized by seismic weight, predominant mode participation factor, predominant mode effective mass coefficient and post-yield stiffness ratio (post-yield stiffness divided by initial stiffness) values are provided in Table 1. The building models are labeled as number of floor and direction taken into account for analysis. For example, 10s-x represents 10-story building in x direction.

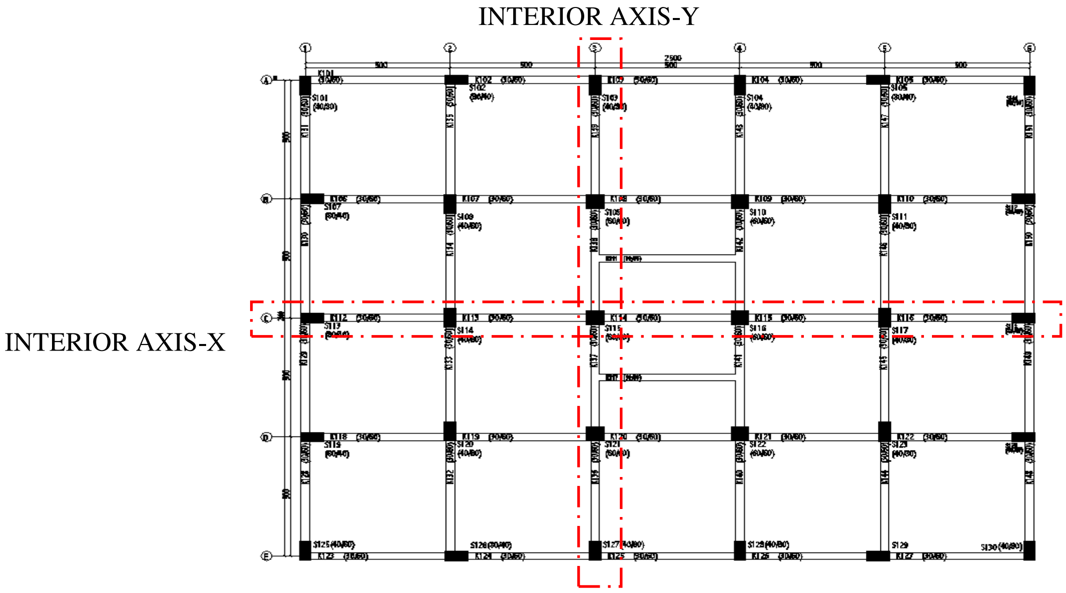

Figure1. Plan view of the considered buildings (Selected frame models are also marked.)

The nonlinear behavior is taken by lumped plasticity model by defining plastic hinges at both ends of beams and columns. Beam and column elements were modeled as nonlinear frame elements with lumped plasticity by defining plastic hinges at both ends of beams and columns. Five points labeled A, B, C, D, and E define force-deformation relation of a typical plastic hinge as shown in Figure 2. The assigned values 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. The plastic hinge length is taken as half of the section depth as recommended in 2007 Turkish Earthquake Code. The software SEMAp was used for moment-curvature analyses of RC sections considering the Mander confined concrete model (Mander et al. 1988). Effective stiffness values are obtained per TEC-2007; 0.4EI for beams and values between 0.4 and 08EI depending on axial load level for columns.

Capacity curves of the buildings were obtained by nonlinear static analyses using SAP2000 in two principal directions. The lateral forces applied at mass center were proportional to the product of mass and the first mode shape amplitude at each story level under consideration. P-Delta effects were taken into account. Figure 3 plots capacity curves for the 10- and 15-story buildings. The vertical axis is base shear strength normalized by seismic weight while the horizontal axis is displacement at the roof level divided by building height.

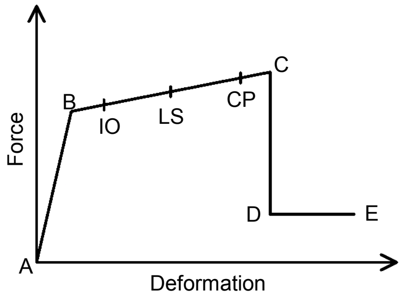

Figure 2. Typical strength-deformation relation for a plastic hinge

Table 1. Important properties of the 10- and 15-story building models

Parameter	10-story buildings		15-story buildings	
	10s-x	10s-y	15s-x	15s-y
W: Seismic Weight (kN)	13028	10822	19435	15179
T_1: Period (s)	1.37	1.31	2.11	1.97
V_y/W: Lateral Strength Ratio	0.14	0.15	0.09	0.09
Γ_1: First Mode Participation Factor	1.33	1.32	1.34	1.33
α_1: First Mode Mass Coefficient	0.79	0.79	0.78	0.78
K_h/K: Post-Yield Stiffness Ratio	0.01	0.07	0.01	0.03

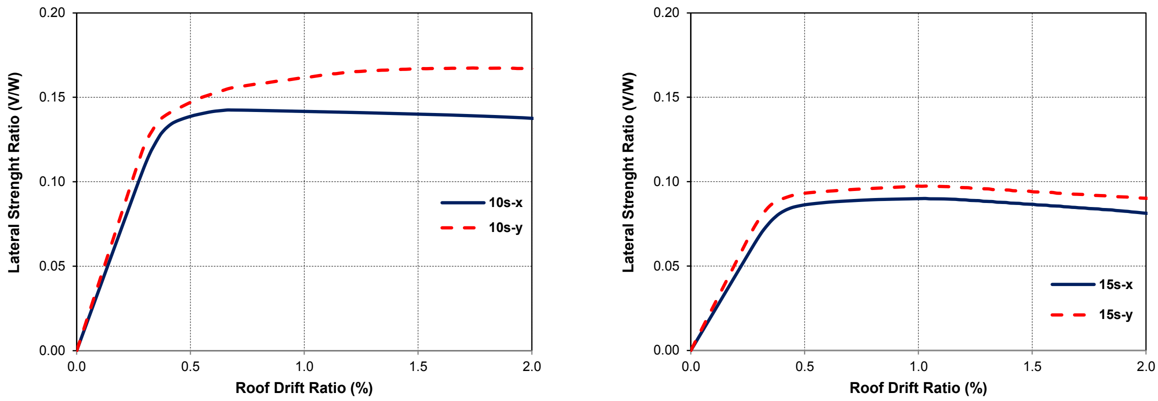

Figure 3. Capacity curves for 10- and 15-story buildings

3. GROUND MOTION AND RESPONSE HISTORY ANALYSIS

This study used 11 earthquake records selected and scaled by PEER ground motion database. Only one horizontal component of these records was scaled according to the elastic acceleration spectrum for a 5% damping ratio. Spectral matching, the most commonly proposed earthquake record selection method by seismic codes (Kayhan et al., 2011), was used. The advantage of using spectrum matching is that the dispersion among analyses is reduced, allowing a stable estimate of the median response using fewer ground motions (NEHRP, 2011; Karakutuk, 2015). The buildings were assumed to be located at the location with highest seismicity region in Denizli, Turkey. Peak and design spectral acceleration coefficients for the assumed location were obtained from Seismic Hazard Maps interactive web application for Turkey (at https://testtdth.afad.gov.tr/).

According to draft TBEC (2016), the rules to be applied for the selection and scaling of earthquake ground motions are defined below.

- The number of earthquake records to be selected shall be at least 11. The number of records to be selected from the same earthquake shall not exceed 3.
- The average of the spectrum of all selected records for one or two dimensional calculations between $0.2T_p$ and $1.5T_p$ periods can never be less than 90% of the design spectrum ordinates (T_p is the fundamental period of the structure in the direction where the accelerogram will be applied).

In addition to these, the following criteria are added for the current study;

- The magnitude of earthquakes was selected in the range of 5.0-7.6.(Ergun and Ates, 2014)
- Vs_{30} range: 180 to 360 m/s to represent soil type ZC
- The maximum distance to the rupture is 25 km (Ay and Akkar, 2012).
- The scale coefficient was aimed to be between 1.5 and 4.

Scale factors and characteristics of earthquake records are given in Table 2. Elastic acceleration spectrum for the 5% damping ratio of the selected records are given in Figure 4. In addition, the average spectrum of the records and the response spectrum provided in draft Turkish Building Earthquake Code (TBEC, 2016) according to design earthquake with 10% probability of exceedance in 50 years for ZC type soil were also provided in the same figure. It seems that the average spectrum and design spectrum are very close especially for the period range of the considered building models. The mean value of structural response quantities from all analyses was used as allowed in Eurocode 8 when seven or more ground motion records are used in nonlinear response history analysis.

Table 2. Earthquake acceleration records used in the study and their characteristics

Identifier	**Earthquake**	**Date (dd/mm/yy)**	**Station**	**Comp. (°)**	**PGA (g)**	**Vs30 (m/)s**	**Scale Factor**
RSN169	Imperial Valley-06	15.10.1979	Delta	262	0.236	242.1	2.00
RSN266	Victoria Mexico	09.06.1980	Chihuahua	102	0.151	242.1	2.80
RSN316	Westmorland	26.04.1981	Parachute Test Site	225	0.232	348.7	2.04
RSN549	Chalfant Valley-02	21.07.1986	Bishop - LADWP South St	180	0.249	303.5	2.94
RSN728	Superstition Hills-02	24.11.1987	Westmorland Fire Sta	090	0.173	193.7	2.72
RSN737	Loma Prieta	18.10.1989	Agnews State Hospital	000	0.170	239.7	3.20
RSN850	Landers	28.06.1992	Desert Hot Springs	000	0.171	359.0	3.50
RSN985	Northridge-01	17.01.1994	LA - Baldwin Hills	360	0.239	297.1	3.02
RSN1100	Kobe Japan	16.01.1995	Abeno	000	0.221	256.0	3.36
RSN2752	Chi-Chi Taiwan-04	20.09.1999	CHY101	101	0.177	258.9	3.56
RSN5652	Iwate Japan	13.06.2008	IWTH20	020	0.245	288.8	3.34

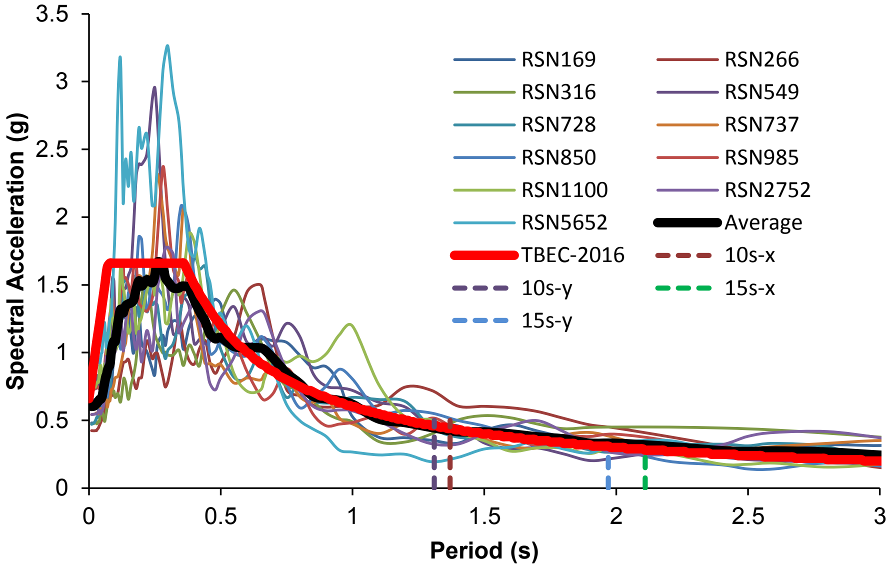

Figure 4. Elastic acceleration spectrum for 5% damping of earthquake acceleration records used in the study

4. “EQUIVALENT” SDOF IDEALIZATION OF 2D BUILDING RESPONSE

The “Equivalent” Single-Degree-Of-Freedom (ESDOF) representation of a Multi-Degree-Of-Freedom (MDOF) system, requires knowledge of the distribution of mass, a deflected shape characteristic of the response, and the lateral load-deformation response of the building as it responds in its predominant “mode” (also termed as capacity curve). The response of the building in its predominant “mode” is determined by nonlinear static (pushover) analysis with lateral loads imposed that are consistent with the shape vector and mass distribution. The displacement of the structure is monitored at the roof level.

The capacity curve obtained by pushover analysis is curvilinear. The nonlinear dynamic response of an ESDOF system based on this capacity curve may be computed by fitting a multilinear curve or a bilinear curve to the capacity curve. If a bilinear curve is fitted, the response may be computed using the simple hysteretic models available in common computer programs for nonlinear dynamic analysis, such as BISPEC (Hachem, BiSpec V-2.20 2012) and USEE 2001 (Inel et al. 2001).

Several techniques for establishing an “equivalent” SDOF system have been recommended in the literature (e.g. list ATC-40 1996 and FEMA-356 2000). The basic assumption common to all techniques is that a single shape vector represents the normalized deflected shape of the MDOF system throughout its response history. Then, the relative lateral displacements of the MDOF system, $\mathbf{u}(t)$, may be defined as

$$\mathbf{u}(t) = \boldsymbol{\phi} u_{roof}(t) \tag{1}$$

where u_{roof}= the displacement of the building at roof level and $\boldsymbol{\phi}$= the shape vector normalized to have a value of unity at roof ($\phi_{roof} = 1.0$).

Yield strength coefficient, yield displacement and post-yield stiffness parameters describe ESDOF models of buildings. FEMA-356 and ATC-40 provide guidance for “equivalent” SDOF representation of building capacity curve. FEMA-440 (2005) compared performance of FEMA-356 and ATC-40 “equivalent” SDOF systems and recommends the use of ATC-40 representation. The capacity curve of each building was converted to an ESDOF system using ATC-40 representation in which yield displacement, Δ_y, and yield strength coefficients, C_y, are given by

$$\Delta_y = \frac{\Delta_{y,roof}}{\Gamma_1} \tag{2}$$

$$C_y = \frac{S_a}{g} = \frac{V_{y,mdof}/W}{\alpha_1} \tag{3}$$

where $\Delta_{y,roof}$ = the roof displacement at yield, Γ_1 = the first (predominant) mode participation factor, S_a = the pseudo-acceleration associated with yield of the "equivalent" SDOF system, g= the acceleration of gravity, $V_{y,mdof}$ = the base shear strength of the multi-degree-of-freedom (MDOF) system or building at global yield, W= seismic weight of the MDOF system, and α_1= the modal mass coefficient of the predominant mode. The displacement demand of the ESDOF system, u^*, may be estimated using one of the available techniques (e.g. a smoothed design spectrum obtained with suitable R-μ-T relations, displacement coefficient methods in FEMA-356 and FEMA-440 and direct computation of SDOF response to one or more ground motions).

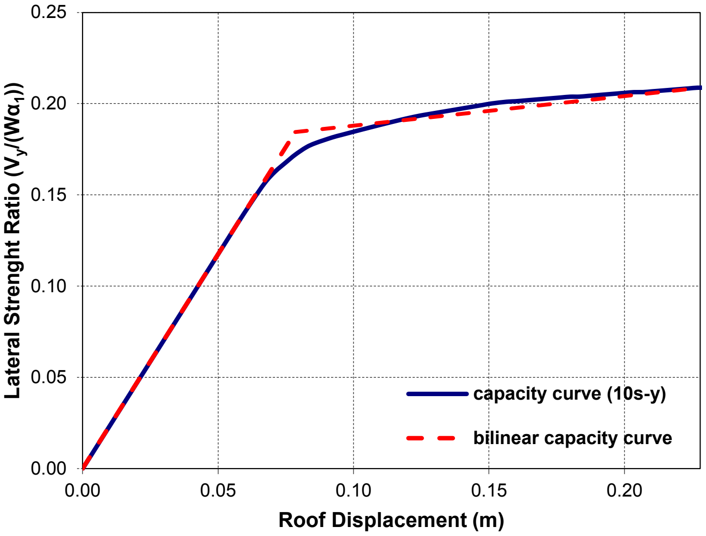

Figure 5. Capacity curve and its bilinear ESDOF representation is provided for transverse direction (y-direction) of 10-story building.

A typical capacity curve and its bilinear ESDOF representation is provided in Figure 5 for transverse direction (y-direction) of the 10-story building. The inelastic dynamic characteristic of each building is represented by a bilinear "equivalent" SDOF system. The seismic displacement demand is obtained subjecting such SDOF system to time history analysis under selected ground motions listed in Table 2. The "equivalent" SDOF nonlinear response history analyses were carried out using BISPEC (Hachem, BiSpec). The "equivalent" SDOF displacement demands were then converted into building displacement demands at the roof level multiplying by the first mode participation factor, Γ_1.

5. SEISMIC DEMANDS

Seismic demands of the 10- and 15-story buildings were obtained from nonlinear response history analysis for both 2D and ESDOF models. The roof drift ratio demands (roof displacements normalized by the building height) of the 10- and 15-story buildings obtained from ESDOF nonlinear time history analyses are given in Table 3. The inelastic displacement demand estimates calculated according to the draft Turkish Earthquake Code spectrum were also provided in the table. The average roof drift ratios vary between 0.85% and 1%, indicating moderate displacement demands for 10- and 15-story buildings for the selected ground motion records. The variation of displacement demands is similar for the selected building set. Since the average of the selected ground motion set is scaled to the draft TBEC-2016 spectrum, it is expected that the average of displacement demands of nonlinear time history analyses and the demand estimate of the code should be similar. Except y-direction of 10-story building demand, the 2D building model estimates and the code demand estimates are very similar.

Figure 6 plots ESDOF estimates versus 2D model estimates. The estimates for 15-story buildings models are closely around the equal estimate line, indicating less scatter and higher success of the ESDOF representation while there is significant scatter and no trend for the estimates of 10-story building models.

Table 3. Roof Drift Ratio demands of 10- and 15-story buildings obtained from "equivalent" SDOF and 2D nonlinear time history (%)

Records	**10-story buildings**				**15-story buildings**			
	10s-x		**10s-y**		**15s-x**		**15s-y**	
	2D	**ESDOF**	**2D**	**ESDOF**	**2D**	**ESDOF**	**2D**	**ESDOF**
RSN266	**1.66**	1.70	**1.56**	1.48	**0.91**	1.04	**0.85**	1.01
RSN1100	**0.64**	0.63	**0.93**	0.55	**0.79**	0.92	**0.70**	0.73
RSN169	**0.83**	0.84	**0.98**	0.67	**1.06**	1.00	**0.88**	0.91
RSN2752	**1.59**	1.60	**1.36**	1.29	**1.07**	1.49	**1.13**	1.42
RSN316	**0.87**	1.58	**1.26**	1.15	**1.49**	1.65	**1.45**	1.69
RSN549	**0.77**	0.80	**0.97**	0.60	**0.66**	0.81	**0.70**	0.49
RSN5652	**0.69**	1.00	**0.60**	0.75	**0.66**	0.83	**0.61**	0.65
RSN728	**0.67**	1.33	**0.78**	0.71	**0.90**	0.95	**0.90**	0.90
RSN737	**0.77**	1.09	**0.82**	0.83	**1.19**	1.47	**1.08**	1.26
RSN850	**0.63**	0.71	**0.95**	0.64	**0.50**	0.80	**0.48**	1.07
RSN985	**0.64**	0.69	**0.82**	0.83	**0.66**	0.69	**0.54**	0.61
Minimum	**0.63**	0.63	**0.60**	0.55	**0.50**	0.69	**0.48**	0.49
Maximum	**1.66**	1.70	**1.56**	1.48	**1.49**	1.65	**1.45**	1.69
Average	**0.89**	1.09	**1.00**	0.86	**0.90**	1.06	**0.85**	0.98
Draft TBEC (2016) Demands	0.91		0.86		0.92		0.85	

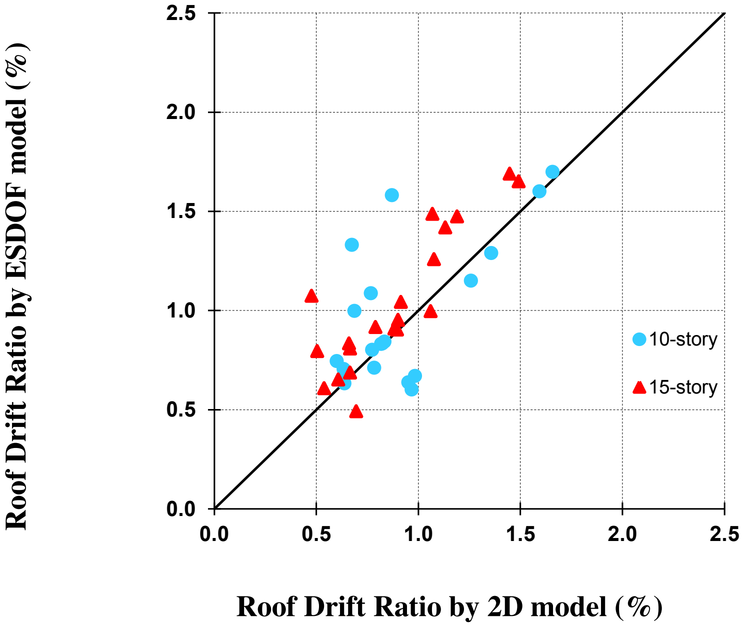

Figure 6. Comparison of roof drift ratio demands of "equivalent" SDOF and the 2D model at 10- and 15-story buildings

Table 4. Comparison of "equivalent" SDOF and the 2D displacement demands of 10- and 15-story buildings at roof level ($\Delta_{\mathrm{ESDOF,\ roof}}/\Delta_{\mathrm{2D,\ roof}}$)

Records	**10-story buildings**		**15-story buildings**	
	10s-x	**10s-y**	**15s-x**	**15s-y**
RSN266	1.03	0.95	1.14	1.19
RSN1100	1.00	0.59	1.16	1.03
RSN169	1.01	0.68	0.94	1.03
RSN2752	1.00	0.95	1.39	1.25
RSN316	1.82	0.92	1.11	1.17
RSN549	1.04	0.62	1.22	0.71
RSN5652	1.45	1.24	1.26	1.08
RSN728	1.98	0.91	1.06	1.01
RSN737	1.42	1.01	1.24	1.17
RSN850	1.11	0.67	1.58	2.26
RSN985	1.08	1.02	1.03	1.13
Minimum	1.00	0.59	0.94	0.71
Maximum	1.98	1.24	1.58	2.26
Average	**1.27**	**0.87**	**1.19**	**1.18**

Table 4 lists the ratio of displacement demand estimates obtained by ESDOF model to that by 2D model for the10- and 15-story buildings. The displacement ratios are also plotted in Figure 7. As it is seen from the table, the displacement estimate ratios change between 0.59 and 2.26. The mean values for 11 ground motion records of each building group vary from 0.87 to 1.27. The estimates of 15-story building is better than that of the 10-story building. Except the y-direction of 10-story building, the average values of $\Delta_{\mathrm{ESDOF,\ roof}}/\Delta_{\mathrm{2D,\ roof}}$ are around 1.2 meaning that the ESDOF models provide about 20% higher estimates. The obtained results indicate that the ESDOF models provide somewhat conservative estimates on average as observed in previous studies for the other building set with different number of stories (Inel at al. 2010). In general, the ESDOF model represents its 2D model reasonably well.

The ratio of ESDOF system to 2D model indicates a significant variation and dependence on the model for certain ground motion records. It is hard to identify the reason or which ground motion is more sensitive to the model choice. For example, the ESDOF model subjected to RSN728 record provides reasonably well estimates except x-direction of 10 story building which is almost twice of the 2D estimate. Similarly, the ESDOF model subjected to RSN1100 record significantly underestimates the demand for y-direction of 10-story building. The comparison of ESDOF and 2D model estimates clearly shows that the characteristic of ground motion record affects the ESDOF estimates.

The ESDOF system and the average spectrum were used to estimate the inelastic displacement demand per the draft Turkish Earthquake Code. The estimates are very close those of the 2D models. This shows that the ESDOF system can represent the building model reasonably well. The differences in nonlinear time history analysis are related to the characteristic of the records.

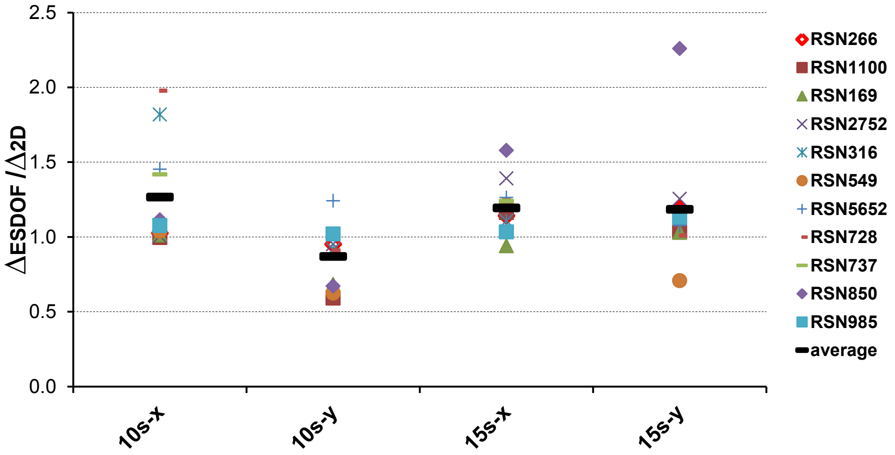

Figure 7. Comparison of roof drift ratio demands of "equivalent" SDOF and the 2D model for 11 ground motion records

6. CONCLUSIONS

This study aims to compare displacement demand estimates of mid-rise reinforced concrete buildings subjected to recorded motions in past earthquakes scaled to the code spectrum. Nonlinear time history estimates of two dimensional (2D) and "equivalent" Single-Degree-Of-Freedom (SDOF) models of reinforced concrete buildings are used for comparison. Two structures selected as 10 and 15 stories were considered to represent mid-rise reinforced concrete buildings in the scope of the study. The inelastic dynamic characteristics are represented by the ESDOF systems using the capacity curves of buildings. The capacity curves of investigated buildings were determined by nonlinear static analyses using SAP2000. 11 records from past earthquakes are selected for nonlinear time-history analysis. Ground motion records are scaled to be compatible with spectrum in the draft Turkish Building Earthquake Code-2016 (TBEC-2016). In total, 44 nonlinear dynamic time history analyses of 2D models and 44 nonlinear time history analyses for the ESDOF systems were carried out to obtain inelastic displacement demand values. The observations and finding are summarized below:

- The outcomes shows that although the displacement demand estimates have a wide scatter, the mean estimates of the considered buildings range in a very narrow band. The mean roof displacement demand ratios changes between 0.85% and 1%, indicating moderate displacement demands compared to their displacement capacities for 10- and 15-story buildings for the selected ground motion records.
- The ratio of ESDOF system to 2D model indicates a significant variation and dependence on the model for certain ground motion records. It is hard to identify the reason or which ground motion is more sensitive to the model choice.
- The comparison of ESDOF and 2D model estimates clearly shows that the characteristic of ground motion record affects the ESDOF estimates.
- Except the y-direction of 10-story building, the average estimates are around 1.2 meaning that the ESDOF models provide about %20 higher estimates. The obtained results indicate that the ESDOF models provide somewhat conservative estimates on average as observed in previous studies. In general, the ESDOF model represents its 2D model reasonably well.
- The ESDOF system and the average spectrum were also used to estimate the inelastic displacement demand per the draft Turkish Earthquake Code using nonlinear static analysis. The estimates are very close to those of the 2D models using nonlinear dynamic analysis. This shows that the ESDOF system can represent the building model reasonably well. The differences observed in nonlinear

time history analysis of the ESDOF models are related to the characteristic of the records.

- The buildings used in the study are reinforced concrete frame buildings without any shear walls. The findings may not be valid for the buildings with shear walls.

7. ACKNOWLEDGMENTS

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