SECOND EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING
AND SEISMOLOGY, ISTANBUL AUG. 25-29, 2014

SEISMIC DISPLACEMENT DEMANDS OF LOW AND MID-RISE RC BUILDINGS WITH NONLINEAR STATIC AND DYANAMIC ANALYSES

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ABSTRACT

Low and mid-rise reinforced concrete (RC) buildings consist of a remarkable portion of the building stock in many earthquake prone countries. Considerable economic loss and casualties after earthquakes have emphasized inadequate seismic performance of these buildings, most of which are less than eight stories in height. The number of buildings and their share in the stock underlines the importance of understanding their seismic behaviour.

This study aims to evaluate seismic displacement estimates of existing low and mid-rise RC building stock by nonlinear static and dynamic analyses. Nonlinear static analyses per 2007 Turkish Earthquake Code and nonlinear response history analyses are used to estimate displacement demands of representative 3-D building models and the results are compared. The selected representative building models reflect existing building stock in Turkey or other earthquake prone countries with similar construction practice. The selected reference buildings are designed according to pre-modern and modern Turkish Earthquake Codes (1975 and 1998).Two different concrete compressive strength values are considered for each code, resulting in 12 building models with 24 principal directions. 12 ground motion records with two components resulting in 24 records are selected and scaled according to for design earthquake with 10% probability of exceedance in 50 years on Z3 soil class. Total of 24 3-D nonlinear static analyses are carried out to obtain capacity curves of the models using SAP2000 to determine displacement demands in accordance with the methodology of TEC 2007. 576 3-D nonlinear time history analyses are made using scaled 24 ground motion records for Z3 soil class (compatible to class C of FEMA-356).

The concrete strength has limited effect in displacement demands of the buildings for the considered cases in this study. Buildings constructed per TEC 1998 are significantly stronger than those constructed per TEC 1975 due to higher requirements of newer code. Comparison of 1975 and 1998 codes for each building group signifies the improvements in TEC 1998. The variation in displacement demands is considerably high and the observed difference between maximum and minimum demands may change 2 to 7 times for many building models which is attributable to the chaotic nature of earthquakes. Since the selected records are scaled for the code spectrum, it is expected that the mean displacement values of 24 records are comparable to nonlinear displacement demand estimates given in the code. However, it is hard to reach a clear conclusion based on the results obtained from nonlinear static and dynamic analyses. The interpretation of the outcomes is that the TEC-2007 underestimates the displacement of 4- and 7-story buildings designed per 1975 Earthquake Code while the other TEC-2007 estimates are almost safe or conservative for the other buildings, especially for the 2-story buildings.

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INTRODUCTION

Despite its high earthquake threat, an important portion of existing building stock in Turkey is susceptible to earthquake-induced damage. Low and mid-rise reinforced concrete (RC) buildings consist of major part of the stock under risk. Therefore, understanding their seismic behaviour and proper seismic evaluation of these buildings is essential for seismic mitigation studies. Displacement estimate is an important issue for performance and displacement based seismic evaluation studies. This study focuses on that phase and aims to evaluate seismic displacement demands of low- and mid-rise RC buildings in Turkey, considering nonlinear behaviour of reinforced concrete components as well as masonry infill walls. Nonlinear static analysis is carried out to estimate displacement demands of representative 3-D building models using SAP2000 according to criteria of 2007 Turkish Earthquake Code. Also nonlinear response history analysis is used to estimate displacement demands with the scaled ground motion records for code design spectrum on Z3 soil class (compatible with type C class of FEMA-356). Then these displacement demands are compared for existing low and mid-rise buildings for differences between nonlinear static and nonlinear time history analyses.

Outcomes of a detailed inventory study (approximately 500 existing buildings) established building models to reflect existing building stock (Inel et al., 2009). This study considers 24 3-D building models to reflect existing building stock with different parameters. Capacity curves of investigated building sets are determined by nonlinear static analyses conducted in two principal directions using SAP2000. Beam and column elements are modelled as nonlinear frame elements with lumped plasticity by defining plastic hinges at both ends of beams and columns. Effect of infill walls is modelled through diagonal struts as suggested in FEMA-356 and similar documents (FEMA-356, 2000). Shear hinges take into account possible shear failures in existing reinforced concrete buildings.

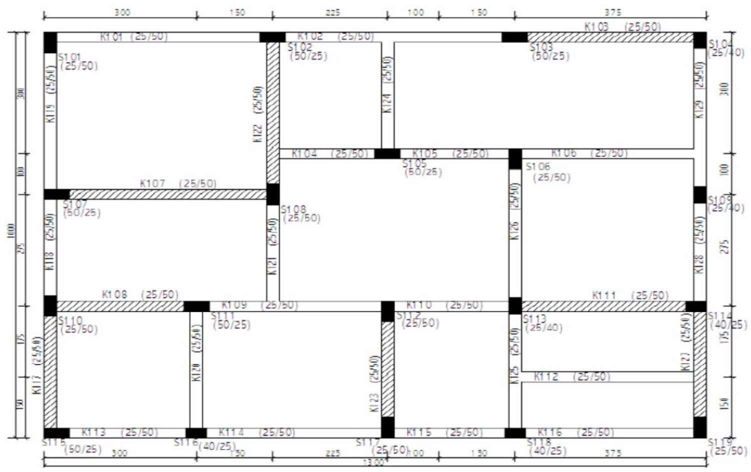
MODELING APPROACH

Three RC building sets, 2-, 4- and 7-story, are selected to represent reference low- and 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 (Inel et al., 2009). Plan views of buildings are given in Figure 1. The load carrying infill-walls are shown in the figure by shaded areas.

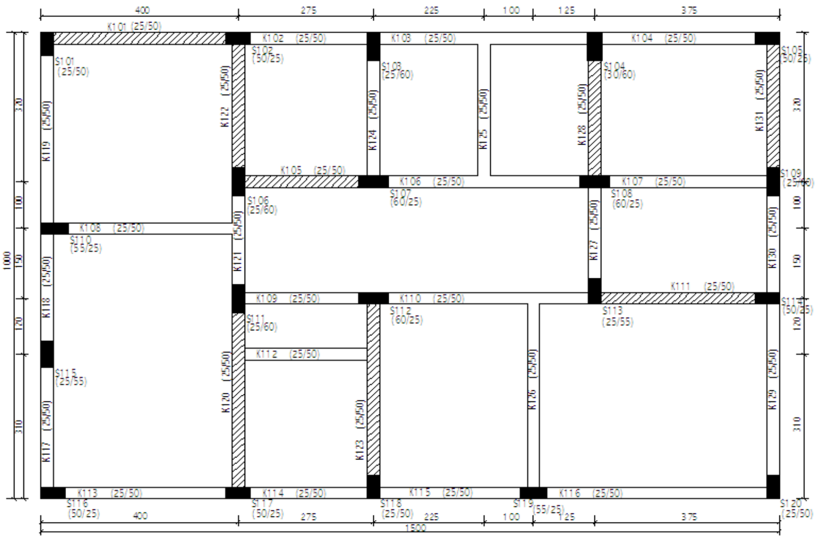
Two different concrete compressive strength values are considered; 10 and 16 MPa for the pre-modern code and 16 and 25 MPa for the modern code. The yield strength of both longitudinal and transverse reinforcement is assumed to be 220 and 420 MPa for the pre-modern and modern codes, respectively. Strain-hardening of longitudinal reinforcement has been taken into account.

Reference form of 2-, 4- and 7-story buildings are designed as per 1975 and 1998 Turkish Earthquake Codes for the gravity and seismic loading and dimensions described based on field and archive investigations. A design ground acceleration of 0.4 g and soil class Z3 that is similar to class C soil of FEMA-356 is assumed for the design. Then using the outcome member size and reinforcements, structures are modelled for nonlinear analysis. No simplifications are made for the reinforcements of members; like rounding-off or grouping members ones with close reinforcement amount. All members are modelled as given in the design.

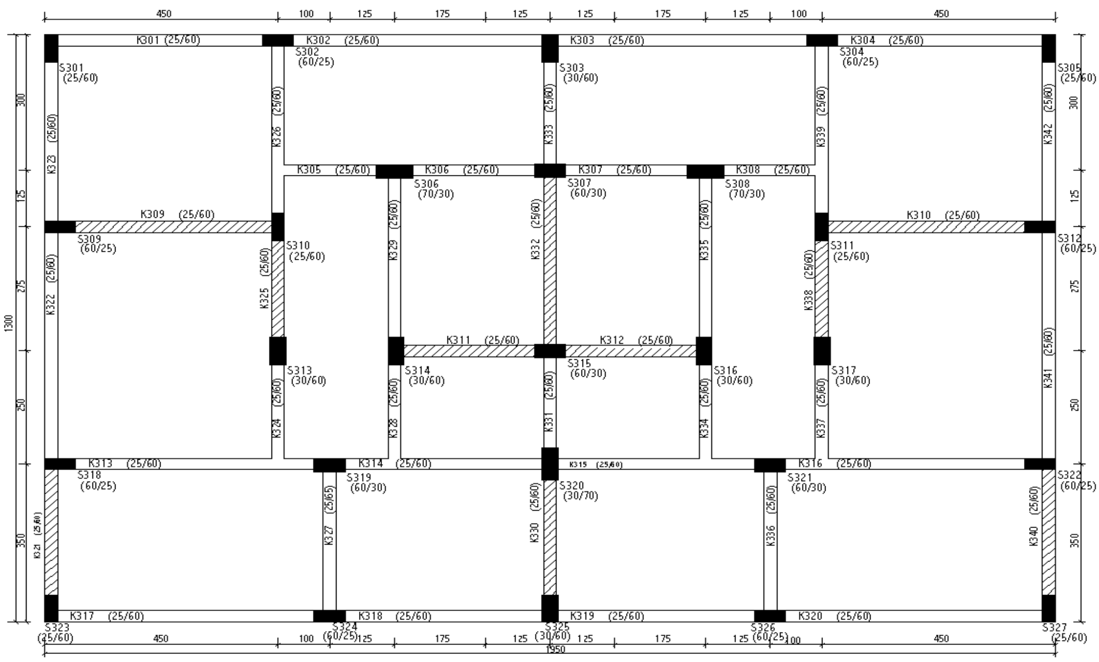
As shown in Figure 2, five points labelled A, B, C, D, and E define force-deformation behaviour of a plastic hinge. The values assigned to each of these points vary depending on type of element, material properties, longitudinal and transverse steel content, and axial load level on the element. Note 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 08EI depending on axial load level for columns.



2-story building plan view



4-story building plan view



7-story building plan view

Figure 1. Plan views of the considered buildings (load carrying infill-walls are shaded)

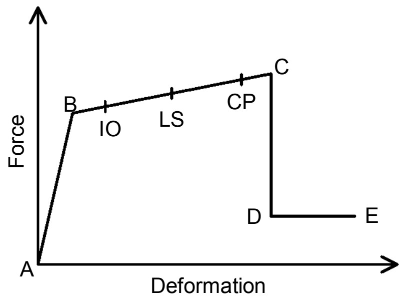


Figure 2. Typical strength-deformation relation for a plastic hinge

In existing reinforced concrete buildings, especially with low concrete strength and/or insufficient amount of transverse reinforcement, shear failures of members should be taken into consideration. For this purpose, shear hinges are introduced for beams and columns. Because of brittle failure of concrete in shear, no ductility is considered for this type of hinges. Shear hinge properties are defined such that when the shear force in the member reaches its strength, the member fails, immediately. The shear strength of each member is calculated according to TS 500 (TS 500, 2000).

Effect of infill walls are modelled through diagonal struts as suggested in TEC-2007 and FEMA-356. Nonlinear behaviour of infill walls is reflected by assigned axial load hinges on diagonal struts whose characteristics are determined as given in FEMA-356. Material properties are taken from TEC-2007 to reflect characteristics of infill walls in Turkey; 1000 MPa, 1 MPa and 0.15 MPa were assumed as modulus of elasticity, compressive strength and shear strength values, respectively. Range of some important properties of the building models is given in Table 1. "Seismic weight" values in the table correspond to the dead loads plus 30 % of the live loads. "Lateral strength ratio" is the ratio of yield strength to the seismic weight. High lateral strength ratios up to 68 % of seismic weight are generally for the two story buildings constructed according to TEC-1998 and attributable to higher overstrength ratio because of minimum requirements of code and infill-wall contributions.

Table 1. Range of some important properties of the building models

Parameter	**2-story**	**4-story**	**7-story**
Seismic Weight (kN)	2488-2499	6216-6473	18621-20065
Period (s)	0.18-0.22	0.34-0.48	0.55-0.70
Lateral Strength Ratio	0.43-0.68	0.22-0.39	0.13-0.25

GROUND MOTION RECORDS

Ground motion records are selected and scaled according to Z3 soil class (compatible to soil class C of FEMA-356) for code design spectrum as Z3 is the common soil class in Turkey. Scale factors are defined between 0.7 and 5. 12 scaled ground motion records with two components are used for the study. USGS soil class based on the average shear wave velocity to a depth of 30 m (V_{s30}) is used for determination of soil class of the selected records (USGS). V_{s30} for C soil class is assumed to be between 180 and 360 m/s. All earthquake records are taken from PEER website (PEER, http://peer.berkeley.edu)and shown in Table 2

Table 2. Features of ground motion records used in the study

No	Earthquake	Year	Station	Comp.	Scale Factor	Magnitude	PGA (g)	PGV (cm/s)	Vs30 (m/s)
1	Big Bear	1992	San Bernardino - E & Hospitality	FN	4.481	6.46	0.355	58.057	271.4
2	Big Bear	1992	San Bernardino - E & Hospitality	FP	4.481		0.451	61.381	
3	Chi-Chi	1999	CHY101	FN	1.294	7.62	0.585	110.729	258.9
4	Chi-Chi	1999	CHY101	FP	1.294		0.489	140.386	
5	Duzce	1999	Duzce	FN	1.086	7.14	0.388	67.531	276
6	Duzce	1999	Duzce	FP	1.086		0.564	86.276	
7	Erzincan	1992	Erzincan	FN	1.12	6.69	0.545	106.846	274.5
8	Erzincan	1992	Erzincan	FP	1.12		0.47	50.723	
9	Hector Mine	1999	Amboy	FN	2.573	7.13	0.502	67.223	271.4
10	Hector Mine	1999	Amboy	FP	2.573		0.521	56.214	
11	Imperial Valley	1979	EC County Center FF	FN	2.057	6.53	0.37	112.072	192.1
12	Imperial Valley	1979	EC County Center FF	FP	2.057		0.457	88.363	
13	Kobe	1995	Shin-Osaka	FN	2.144	6.9	0.4	64.254	256
14	Kobe	1995	Shin-Osaka	FP	2.144		0.582	89.694	
15	Kocaeli	1999	Yarimca	FN	1.632	7.51	0.455	78.615	297
16	Kocaeli	1999	Yarimca	FP	1.632		0.509	118.983	
17	Landers	1992	Yermo Fire Station	FN	2.193	7.28	0.486	116.525	353.6
18	Landers	1992	Yermo Fire Station	FP	2.193		0.488	54.677	
19	Loma Prieta	1989	Salinas - John & Work	FN	4.917	6.93	0.468	66.509	271.4
20	Loma Prieta	1989	Salinas - John & Work	FP	4.917		0.431	62.905	
21	Northridge	1994	Canoga Park - Topanga Can	FN	1.267	6.69	0.476	67.833	267.5
22	Northridge	1994	Canoga Park - Topanga Can	FP	1.267		0.453	54.181	
23	Superstition Hills	1987	El CentroImp.Co.Cent	FN	1.698	6.54	0.524	88.105	192.1
24	Superstition Hills	1987	El Centro Imp.Co.Cent	FP	1.698		0.379	61.34	

FN: Fault Normal, FP: Fault Parallel

Average response spectrum of 24 ground motion records for 5% damping is plotted in Figure 2 as well as demand spectrum provided in Turkish Earthquake Code-2007 for design earthquake with 10% probability of exceedance in 50 years.

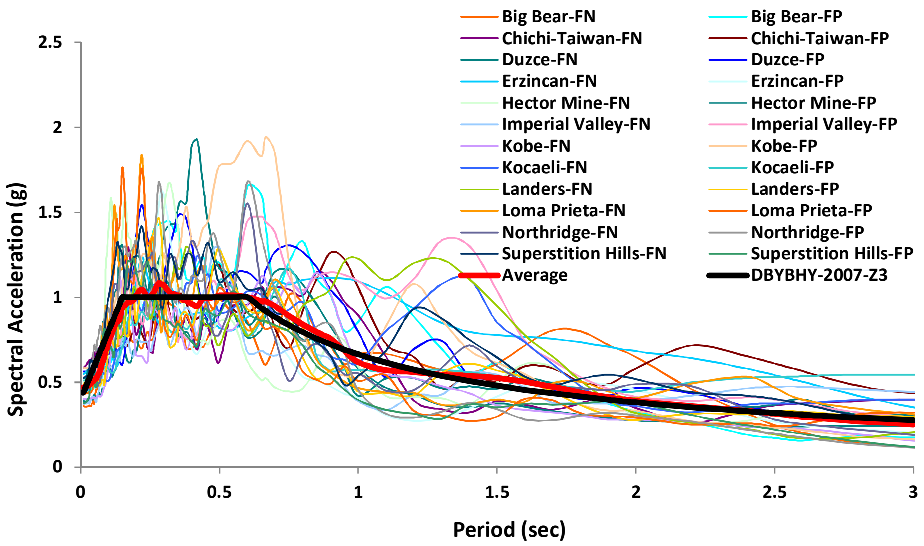


Figure 2. Average response spectrum of ground motion records for 5% damping

SEISMIC CAPACITY AND DEMAND

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. The capacity curve of each building obtained from pushover analysis was approximated with bilinear curves using TEC-2007 and displacement demands are obtained using spectrum given in TEC-2007 on soil class Z3. Nonlinear time history analyses of the 3-D buildings are conducted for 24 ground motion records to obtain displacement demands from nonlinear dynamic response analyses. The nonlinear static and dynamic displacements at the roof level are compared.

SEISMIC DEMAND EVALUATION

Seismic demand of the 3-D 2-, 4- and 7-story buildings obtained from nonlinear static and nonlinear response history analysis are summarized and discussed. Displacement demands obtained from nonlinear analysis is an indicator of building damage during earthquakes. Roof displacement demands of the considered buildings are reported in Tables 3 and 4 for two concrete strength value of each building group (10-16 MPa for 1975 code and 16-25 MPa for 1998 code). . Minimum, maximum and mean values of nonlinear response history analysis results and nonlinear static analysis results for TEC 2007 are also provided in the tables. Summary for the interstory displacement demands of the considered buildings are given in Tables 5 and 6 for two concrete strength value of each building group for nonlinear response history analysis results. Roof displacements are normalized by building height and called “roof drift ratio” while interstory displacement demands are normalized by story heights and called “interstory drift ratio”. The tables also provides coefficient of variation for response history analyses defined as standard deviation divided by mean values. The figures and tables indicate that the concrete strength has limited effect in displacement demands of the buildings for the considered cases in this study.

Figure 3 plots peak displacement demands of two components for 12 records, their average and TEC-2007 displacement estimate values for the 2-, 4- and 7-story buildings. The demand estimates clearly indicates considerable variation. Both displacement demands and the variation are significantly higher for the 4- and 7-story buildings compared to the 2-story buildings.

Displacement demands of 2-story buildings are considerably lower than that of the 4- and 7-story buildings for both codes. This is mainly due to higher overstrength ratio because of minimum requirements of code and relatively higher infill-wall contributions for the 2-story buildings. Figure 3 also indicates that there is not a clear difference between 4- and 7-story displacement demands although 7-story buildings demand the maximum displacement for several records.

Table 3. Roof Drift Ratio demands of 2-,4- and 7-story TEC 1975 buildings (%)

		2-story 1975 buildings				4-story 1975 buildings				7-story 1975 buildings			
		C10-x	**C10-y**	**C16-x**	**C16-y**	**C10-x**	**C10-y**	**C16-x**	**C16-y**	**C10-x**	**C10-y**	**C16-x**	**C16-y**
Records	**Minimum**	0.21	0.21	0.20	0.22	0.53	0.44	0.48	0.40	0.51	0.44	0.48	0.42
	Maximum	0.61	0.59	0.50	0.52	2.19	1.93	1.95	1.81	2.51	2.37	2.44	2.28
	Average	0.37	0.38	0.32	0.34	0.87	0.90	0.86	0.82	1.03	0.99	0.99	0.96
	COV	0.29	0.27	0.27	0.25	0.42	0.41	0.38	0.41	0.53	0.56	0.53	0.54
	TEC 2007	0.52	0.64	0.53	0.59	0.87	0.77	0.83	0.73	0.83	0.83	0.80	0.78
	Ratio (Records/TEC 2007)	0.70	0.60	0.61	0.57	1.01	1.17	1.04	1.13	1.24	1.20	1.25	1.23

Table 4. Roof Drift Ratio demands of 2-,4- and 7-story TEC 1998 buildings (%)

		2-story 1998 buildings				4-story 1998 buildings				7-story 1998 buildings			
		C16-x	**C16-y**	**C25-x**	**C25-y**	**C16-x**	**C16-y**	**C25-x**	**C25-y**	**C16-x**	**C16-y**	**C25-x**	**C25-y**
Records	**Minimum**	0.15	0.17	0.14	0.16	0.36	0.25	0.34	0.25	0.31	0.30	0.31	0.30
	Maximum	0.36	0.39	0.31	0.37	1.12	0.99	1.03	0.93	1.40	1.29	1.25	1.16
	Average	0.24	0.27	0.22	0.25	0.59	0.49	0.54	0.45	0.63	0.63	0.61	0.60
	COV	0.22	0.23	0.22	0.22	0.32	0.38	0.33	0.37	0.39	0.38	0.43	0.39
	TEC 2007	0.39	0.48	0.37	0.45	0.67	0.58	0.63	0.54	0.66	0.65	0.62	0.62
	Ratio (Records/TEC 2007)	0.62	0.56	0.59	0.55	0.87	0.85	0.86	0.83	0.96	0.97	0.98	0.97

Table 5. Interstory Drift Ratio demands of 2-, 4- and 7-story TEC 1975 buildings (%)

Records	2-story 1975 buildings				4-story 1975 buildings				7-story 1975 buildings			
	C10-x	**C10-y**	**C16-x**	**C16-y**	**C10-x**	**C10-y**	**C16-x**	**C16-y**	**C10-x**	**C10-y**	**C16-x**	**C16-y**
Minimum	0.26	0.25	0.25	0.27	0.79	0.71	0.76	0.66	0.74	0.75	0.74	0.70
Maximum	1.01	0.79	0.80	0.68	4.33	4.02	3.73	3.72	4.93	5.17	4.55	4.80
Average	0.55	0.50	0.46	0.44	1.59	1.67	1.51	1.48	1.82	1.91	1.66	1.78
COV	0.37	0.29	0.34	0.28	0.49	0.47	0.44	0.49	0.61	0.66	0.58	0.63

Table 6. Interstory Drift Ratio demands of 2-, 4- and 7-story TEC 1998 buildings (%)

Records	**2-story 1998 buildings**				**4-story 1998 buildings**				**7-story 1998 buildings**			
	C16-x	**C16-y**	**C25-x**	**C25-y**	**C16-x**	**C16-y**	**C25-x**	**C25-y**	**C16-x**	**C16-y**	**C25-x**	**C25-y**
Minimum	0.16	0.19	0.15	0.17	0.55	0.35	0.49	0.35	0.53	0.42	0.47	0.49
Maximum	0.46	0.49	0.39	0.45	1.92	1.75	1.78	1.61	2.86	2.55	2.45	2.38
Average	0.27	0.30	0.25	0.28	0.97	0.77	0.88	0.69	1.15	1.12	1.10	1.07
COV	0.26	0.26	0.25	0.25	0.36	0.46	0.37	0.45	0.44	0.46	0.48	0.46

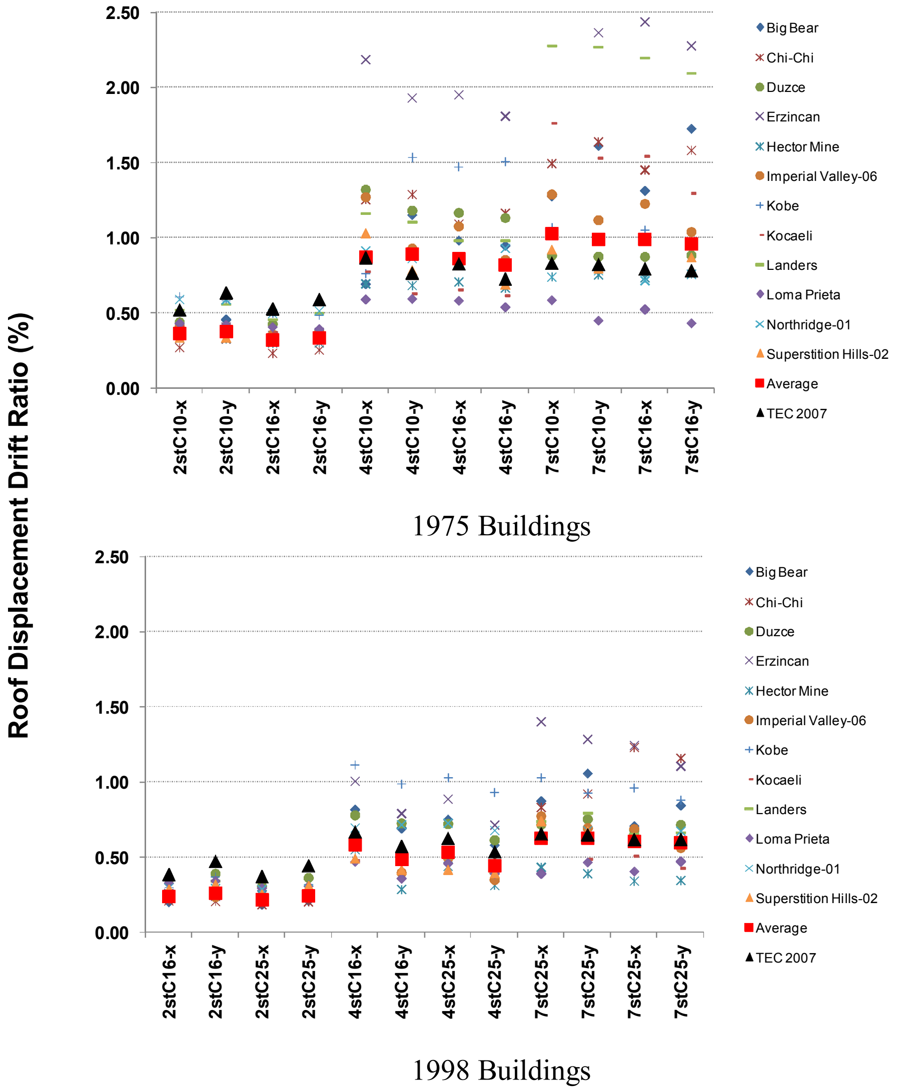


Figure 3. Roof displacement drift ratio of 2-, 4- and 7-story buildings; peak values of records and their averages and TEC-2007 demand estimates

Since the selected records are scaled for the code spectrum, it is expected that the mean displacement values of 24 records are comparable to nonlinear displacement demand estimates given in the code. However, it is hard to reach a clear conclusion based on the results given in Figure 3 and

Tables 3 and 4. It is obvious that the mean displacement demands obtained from nonlinear response history analyses are considerably lower than the code estimates for both 1975 and 1998 2-story buildings. The ratio of displacement estimates obtained by response analyses to code estimates ranges from 0.52 to 0.64. The reason might be the period of these buildings are small and displacement estimate are highly sensitive to small changes for the code estimates.

The code underestimates displacement demands for both 4- and 7-story buildings per 1975 code as being unsafe for seismic evaluation studies. The code estimates are only higher than the displacement demands of several records for these buildings. However, the code estimates of 4- and 7-story buildings per 1998 Earthquake Code are considerably well as having the ratio of 0.83 to 0.98 (average record estimates/TEC-2007 estimates). Tables 3 and 4 also indicate that the variability of displacement demands increases as the number of stories (or periods) increases.

Another interpretation of the outcomes is that the TEC-2007 underestimates the displacement of 4- and 7-story buildings designed per 1975 Earthquake Code while the other TEC-2007 estimates are almost safe or conservative for the other buildings, especially for the 2-story buildings.

Tables 3 and 4 point out that the variation in displacement demands is considerably high; the observed difference between maximum and minimum demands may change 2 to 7 times for many building models. The demands in 4- and 7- story buildings both per 1975 code and per 1998 code are almost 3 and 4 times higher than the demands of the 2-story buildings. The demands for the 2- and 4-story buildings per 1998 code decreases significantly, implying the better performance improvement of the 2- and 4-story buildings.

Tables 5 and 6 summarizes the interstory displacement demands of the considered buildings for two concrete strength value of each building group for nonlinear response history analysis results. The comparison of roof drift and interstory drift ratios indicates similar trends except that the interstory displacement demands ranges 1.5-2.0 times of the roof displacement demands for 4- and 7-story buildings. The interstory displacement demands of 2-story buildings are about 1.5 times of roof displacement demands.

Tables 3, 4, 5 and 6 show that coefficient of variation values are considerably high for 4-story and 7-story buildings. They tend to increase as the number of stories or periods increase; the highest values are observed for 7-story buildings per 1975 TEC. This observation indicates the variations in displacement estimates of mid-rise buildings.

SUMMARY and CONCLUSIONS

Seismic displacement demands of low and mid-rise buildings are evaluated in this study. Nonlinear static analyses per 2007 Turkish Earthquake Code and nonlinear response history analyses are used to estimate displacement demands of representative 3-D building models and the results are compared. The selected representative building models reflect existing building stock in Turkey or other earthquake prone countries with similar construction practice. The parameters for the investigation were number of stories, design code as pre-modern and modern and concrete strength. The selected reference buildings are designed according to pre-modern and modern Turkish Earthquake Codes (1975 and 1998).Two different concrete compressive strength values are considered; 10 and 16 MPa for the pre-modern code and 16 and 25 MPa for the modern code, resulting in 12 building models with 24 principal directions. 12 ground motion records with two components resulting in 24 records are selected and scaled according to for design earthquake with 10% probability of exceedance in 50 years on Z3 soil class. Total of 24 3-D nonlinear static analyses are carried out to obtain capacity curves of the models using SAP2000 in order to determine displacement demands in accordance with the methodology of TEC 2007. 576 3-D nonlinear time history analyses are made using scaled 24 ground motion records for Z3 soil class (compatible to class C of FEMA-356)
The following observations are made:

1. The concrete strength has limited effect in displacement demands of the buildings for the considered cases in this study.

2. Buildings constructed per TEC 1998 are significantly stronger than those constructed per TEC 1975 due to higher requirements of newer code. Comparison of 1975 and 1998 codes for each building group signifies the improvements in TEC 1998.
3. The variation in displacement demands is considerably high; the observed difference between maximum and minimum demands may change 2 to 7 times for many building models which is attributable to the chaotic nature of earthquakes. The scatter is lesser for TEC 1998 buildings, which have higher strength and rigidity.
4. Since the selected records are scaled for the code spectrum, it is expected that the mean displacement values of 24 records are comparable to nonlinear displacement demand estimates given in the code. However, it is hard to reach a clear conclusion based on the results obtained from nonlinear static and dynamic analyses.
5. For both TEC 1975 and TEC 1998 2-story buildings, the displacement demands determined by TEC 2007 method are on the safe side. Except for one case, TEC 2007 values are greater than the maximum demand of the earthquake records. The ratio of displacement estimates obtained by response analyses to code estimates ranges from 0.52 to 0.64. The reason might be the period of these buildings are small and displacement estimate are highly sensitive to small changes for the code estimates.
6. Roof drift demands of 4- and 7-story TEC 1975 buildings may be underestimated by TEC 2007. Even the average displacement demands for the records are larger than the code values.
7. The displacement demands determined by TEC 2007 method have a good agreement with the average demands of the earthquake records for the 4- and 7-story buildings per 1998 TEC.
8. The interpretation of the outcomes is that the TEC-2007 underestimates the displacement of 4- and 7-story buildings designed per 1975 Earthquake Code while the other TEC-2007 estimates are almost safe or conservative for the other buildings, especially for the 2-story buildings.
9. The comparison of roof drift and interstory drift ratios indicates similar trends except that the interstory displacement demands ranges 1.5-2.0 times of the roof displacement demands for 4- and 7-story buildings and about 1.5 times for 2-story buildings.

AKCNOWLEDGEMENT

The authors acknowledge support provided by Project No: 2014FBE006 of Pamukkale University Research Fund Unit (PAU-BAP).

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