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Seismic performance of RC buildings subjected to past earthquakes in Turkey

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Abstract. This study aims to evaluate seismic performance of existing low and mid-rise reinforced concrete buildings by comparing their displacement capacities and displacement demands under selected ground motions experienced in Turkey as well as demand spectrum provided in 2007 Turkish Earthquake Code for design earthquake with 10% probability of exceedance in 50 years for soil class Z3. It should be noted that typical residential buildings are designed according to demand spectrum of 10% probability of exceedance in 50 years. Three RC building sets as 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. The outcomes of detailed field and archive investigation including approximately 500 real residential RC buildings established building models to reflect existing building stock. Total of 72 3-D building models are constructed from the reference buildings to include the effects of some properties such as structural irregularities, concrete strength, seismic codes, structural deficiencies, transverse reinforcement detailing, and number of story on seismic performance of low and mid-rise RC buildings. Capacity curves of building sets are obtained by nonlinear static analyses conducted in two principal directions, resulting in 144 models. The inelastic dynamic characteristics are represented by "equivalent" Single-Degree-of- Freedom (ESDOF) systems using obtained capacity curves of buildings. Nonlinear time history analysis is used to estimate displacement demands of representative building models idealized with (ESDOF) systems subjected to the selected ground motion records from past earthquakes in Turkey. The results show that the significant number of pre-modern code 4- and 7-story buildings exceeds LS performance level while the modern code 4- and 7-story buildings have better performances. The findings obviously indicate the existence of destructive earthquakes especially for 4- and 7-story buildings. Significant improvements in the performance of the buildings per modern code are also obvious in the study. Almost one third of pre-modern code buildings is exceeding LS level during records in the past earthquakes. This observation also supports the building damages experienced in the past earthquake events in Turkey.

Keywords: existing buildings; low and mid-rise buildings; nonlinear analysis; reinforced concrete; seismic code; seismic performance; structural irregularities

1. Introduction

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Over the past several decades Turkey has been hit by several moderate to strong earthquakes that caused significant loss of life and property (i.e., 1992 Erzincan, 1995 Dinar, 1998 Adana-Ceyhan, 1999 Kocaeli, 1999 Duzce, 2002 Afyon-Sultandagi, 2003 Bingol, 2011 Simav and 2011 Van Earthquakes). In literature, there are many earthquake reports and studies about performance of existing structures, earthquake damages and reasons of damages (Scawthorn and Johnson 2000, Sucuoglu 2000, Adalier and Aydingun 2001, Sezen *et al.* 2003, Dogangun 2004, Dogangun and Sezen 2012, Bayraktar *et al.* 2013a, Inel *et al.* 2013, Korkmaz *et al.* 2013, Ozmen *et al.* 2013, Tama *et al.* 2013, Yon *et al.* 2013, Cakir and Uysal 2014, Ozmen *et al.* 2014, Sayin *et al.* 2014, Isik and Kutanis 2015, Korkmaz *et al.* 2015, Siddiqui *et al.* 2015, Yon *et al.* 2015, DEMP 2016). These studies show that structural deficiencies such as the non-ductile details, the soft and weak stories, poor concrete quality, short columns, strong beams-weak columns, large and heavy overhangs, inadequate transverse reinforcement, plan irregularity, lack of shear walls were among main reasons of the observed damages.

A period of high residential building demand during 1980's due to high population growth and migration from rural areas to the urban areas has caused non-engineered or low construction quality structures. As a result, major portion of Turkey's existing building stock is susceptible to earthquake-induced damage despite its high earthquake threat. A large portion reinforced concrete building stock in Turkey is low-and mid-rise buildings with 8 or less stories. Since Turkey is on active earthquake zone, performance evaluation of existing buildings is a need to minimize the possible casualties and economic losses as experienced in the past earthquakes given in Table 1.

This study aims to evaluate seismic performance of existing low and mid-rise reinforced concrete buildings by comparing their displacement capacities and displacement demands under selected ground motions experienced in Turkey as well as demand spectrum provided in 2007 Turkish Earthquake Code (TEC 2007) for design earthquake with 10% probability of exceedance in 50 years for soil class Z3. It should be noted that typical residential buildings are designed according to demand spectrum of 10% probability of exceedance in 50 years. Besides, this

Table 1 Destructive earthquakes in Turkey over past several decades (DEMP 2016)

Date (dd/mm/yy)	Magnitude	Location	# of deaths	# of injuries	#of heavily damaged buildings	Latitude (N)	Longitude (E)	Depth (km)
13.03.1992	$M_S = 6.8$	Erzincan	653	3850	6702	39.68	39.56	27
01.10.1995	$M_S = 5.9$	Dinar	94	240	4909	38.18	30.02	24
27.06.1998	$M_S = 5.9$	Adana–Ceyhan	146	940	4000	36.85	35.55	23
17.08.1999	$M_S = 7.4$	Kocaeli	15 000	32 000	50 000 or 100 000	40.70	29.91	20
12.11.1999	$M_W = 7.2$	Duzce	845	4948	15 389	40.79	31.21	11
03.02.2002	$M_W = 6.5$	Afyon–Sultandagi	42	325	4401	38.46	31.30	6
01.05.2003	$M_W = 6.4$	Bingol	176	521	1351	38.94	40.51	6
19.05.2011	$M_L = 5.7$	Simav	3	122	3066	39.13	29.08	24
23.10.2011	$M_W = 7.0$	Ercis	604	1936	28000	38.69	43.47	19
09.11.2011	$M_W = 5.6$	Edremit	40	30	7000	38.44	43.28	21

spectrum has been used for the pre-modern and modern code buildings with small modifications.

Effect of infill walls is modeled through diagonal struts as suggested in FEMA-356 (2000) and similar documents such as TEC (2007). Capacity curves of all models considered in the current study are determined by non-linear static analysis. Building performance levels and displacement capacities are obtained according to TEC (2007). The "equivalent" Single-Degree-of- Freedom (ESDOF) approach is used to obtain displacement demands according to TEC (2007) response spectrum. Furthermore, the "equivalent" SDOF models are subjected to non-linear time history analysis using selected ground motion records from destructive earthquakes experienced during last 30 years in Turkey. Seismic performance of existing building stock is evaluated by comparing displacement capacities of considered building models and their displacement demands for TEC (2007) response spectrum and selected ground motion records. Effects of ground motion records, seismic design codes, irregularities and number of stories on seismic performance of the buildings are evaluated.

2. Description of structures

Three RC building sets as 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. Floor plans of 2-, 4- and 7-story reference buildings are shown in Fig. 1.

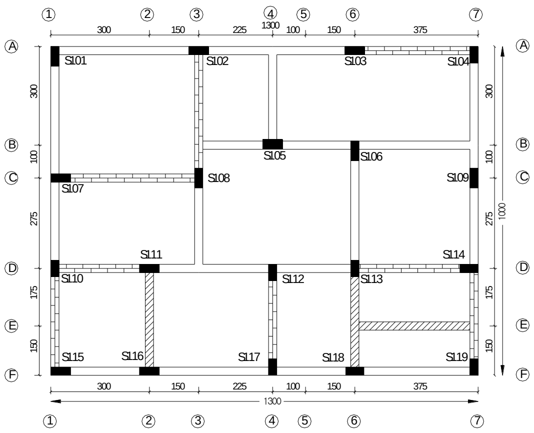
The outcomes of detailed field and archive investigation including approximately 500 real residential RC buildings established building models to reflect existing building stock (Ozmen *et al.* 2015). This study considers 72 3-D building models to reflect existing building stock with different parameters such as plan dimensions, story height, total column area per unit area, total load carrying infill-wall (satisfying TEC (2007) criteria) area per unit area for building level. Section dimensions and reinforcement detailing for member level are taken into consideration. Existing structural irregularities are reflected in building models as soft story and heavy overhangs.

Soft story usually occurs due to insufficient lateral resistance and lack of rigidity of first story. For this reason, buildings with soft story were created by increasing the first story height of reference buildings. Heavy overhang increases mass of structure and internal forces due to separation of mass and rigidity centers under earthquake loading. The statistical data obtained from detailed field and archive investigation including approximately 500 real residential RC buildings are reflected in modeling of soft story and heavy overhangs as shown in Fig. 2.

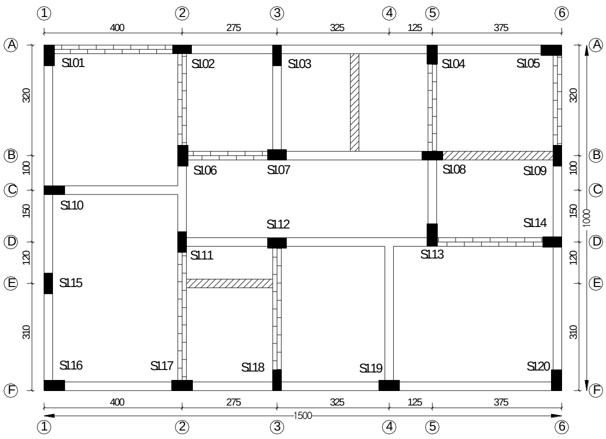
Since the majority of buildings in Turkey were constructed according to pre-modern (TEC 1975) and modern (TEC 1998) Turkish Earthquake Code, building models were designed according to these codes. Design ground acceleration of 0.4 g (complying with high seismicity region for Turkey) and soil class Z3 that is similar to soil type C of FEMA-356 (2000) is assumed.

Poor and average concrete quality and transverse reinforcement amount are considered for each code to investigate the effect of material quality and reinforcement detailing on seismic performance. Two different concrete compressive strength values are considered; 10 (C10) and 16 MPa (C16) for TEC (1975) buildings and 16 (C16) and 25 MPa (C25) for the TEC (1998) buildings. Conforming and non-conforming transverse reinforcement to related codes are represented as 100 mm (ductile) and 200 mm (non-ductile) spacing. The yield strength of both longitudinal and transverse reinforcement is assumed to be 220 and 420 MPa for TEC (1975) buildings and TEC (1998) buildings, respectively. The longitudinal reinforcement ratio of columns varies between 1% and 1.5%. The first and second story columns have higher ratio of longitudinal reinforcement and the column dimensions get smaller up to higher stories especially in pre-modern buildings. It should be noted that the beams at the overhang zone are removed for the buildings with heavy overhang irregularity compatible with the statistical data of field and archive investigation of approximately 500 buildings (Ozmen *et al*. 2015).

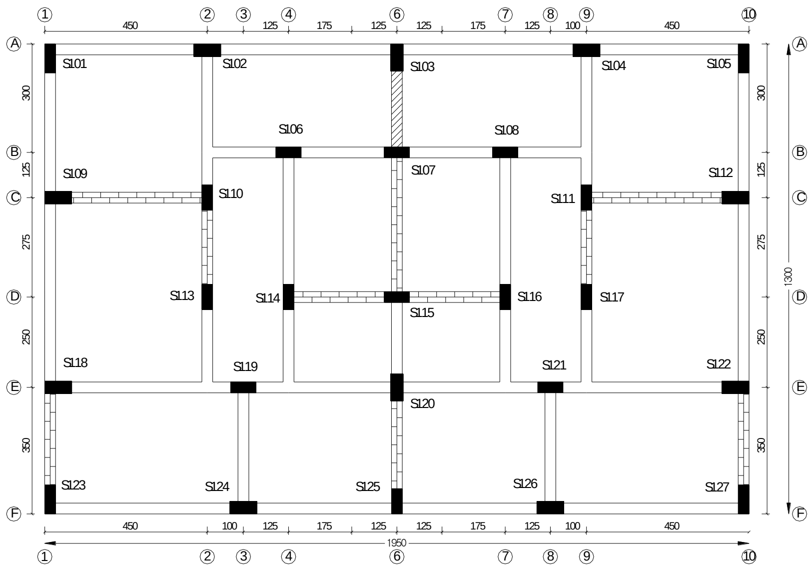
Effect of infill walls are modeled through diagonal struts as suggested in FEMA-356 (2000) and TEC (2007). Material properties are taken from TEC (2007) to reflect characteristics of infill walls in Turkey; 1000 MPa, 1 MPa and 0.15 MPa were assumed as modulus of elasticity, compressive strength and shear strength values, respectively.



(a) 2-story

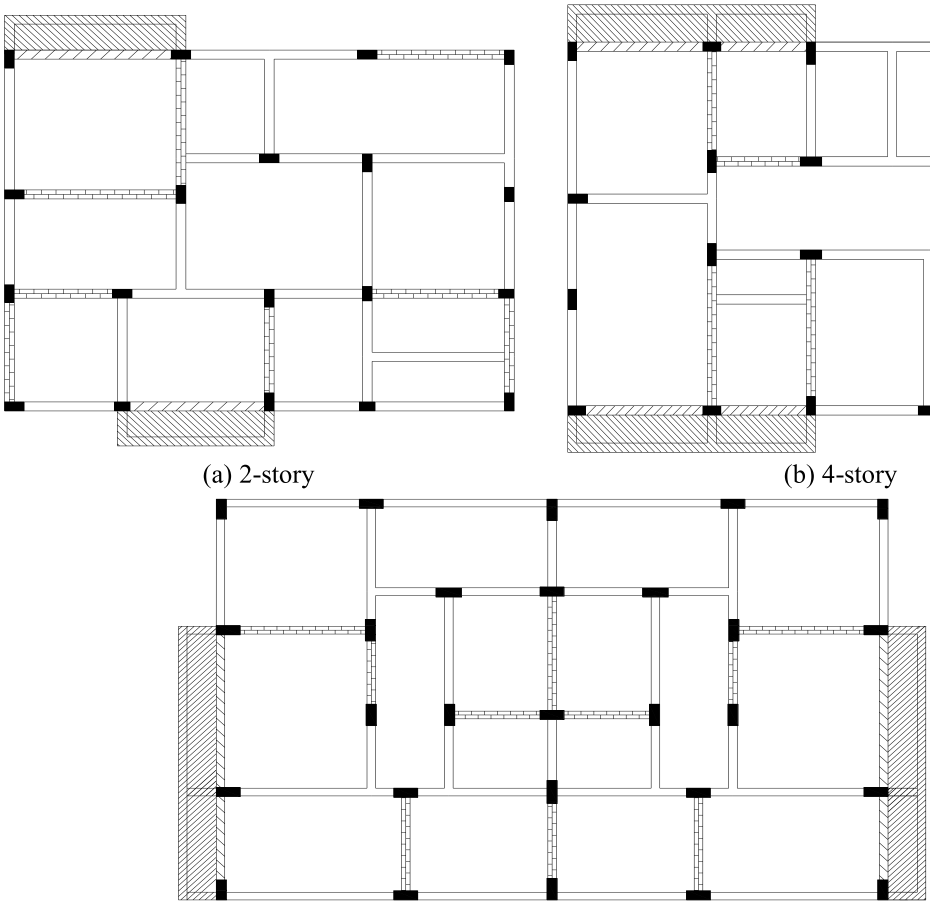


(b) 4-story



(c) 7-story

Fig. 1 Plan view of the considered reference buildings (load carrying infill-walls are hatched)



(a) 2-story (b) 4-story

(c) 7-story

Fig. 2 Plan view of the buildings with heavy overhangs

Table 2 lists the ranges of natural periods and seismic weights of 2-, 4- and 7-story reference buildings. The 72 building models successfully reflect low- and mid-rise reinforced concrete building stock as seen in the table. The model identifiers and definitions are provided in Table 3.

Table 2 Structural properties of 2-, 4- and 7-story reference buildings: seismic weight and natural period

Building	**Building ID**	**Code**	**Weight (kN)**	**Period range (sec)**
2-story	S2	TEC (1975)	2440	0.24-0.26
		TEC (1998)	2451	0.22-0.24
4-story	S4	TEC (1975)	6096	0.45-0.52
		TEC (1998)	6348	0.37-0.45
7-story	S7	TEC (1975)	18263	0.72-0.76
		TEC (1998)	19679	0.60-0.64

Table 3 Building descriptions considered in the study

Model identifier	Description of building
REF	Reference building
SS	Soft story due to 3.65 m first story height (instead of 2.8 m)
HO	One sided overhang building

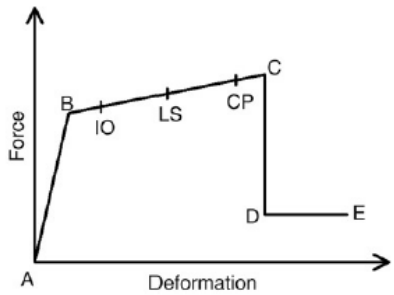


Fig. 3 Force-deformation relationship of a typical plastic hinge

3. Modeling approach

Structural analysis program SAP2000 (2007) is used in non-linear analyses of 3D building models. Structural element such as beam and column elements are 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 behavior of a typical plastic hinge in Fig. 3. The values assigned to each of these points vary depending on element size, material properties, longitudinal and transverse reinforcement amount and detailing and axial load level on the element. The definition of user-defined hinge properties reflecting existing section and material properties requires moment-curvature analysis of each structural element. Moment-curvature analyses of members are carried out according to TEC (2007) by using SEMAp software (Inel 2008).

Plastic hinge length is assumed to be half of the section depth of elements as recommended in TEC (2007). Also, values of the effective bending stiffness of the cracked section are obtained per the code; 0.4EI for beams and values between 0.4EI and 08EI, depending on axial load level, for columns.

4. Ground motion records

The ground motion records used in nonlinear time history analysis are selected from destructive earthquakes in Turkey over past several decades in order to examine reasons of building damages without any categorization of the records as listed in Table 4. Linear base line correction and 4th order Butterworth bandpass filtering of raw acceleration records using frequencies of 0.1 and 25 Hz are processed by SeismoSignal software for unprocessed records (Antoniou and Pinho 2008). Table 4 also shows the Pseudo Spectral Acceleration (PSA) for 1 and 5 Hz. to see the level of intensity of earthquakes. The earthquake records include all significant earthquakes with significant building damage.

Table 4 Records from destructive earthquakes in Turkey over past several decades

Identifier	Earthquake	Date (dd/mm/yy)	Magnitude	Station	Comp. (°)	PGV (m/s)	PGA (g)	PSA (1Hz) (g)	PSA (5Hz) (g)	Dist. (km)
AF02AFYO.360	Afyon-Sultandag	03.02.2002	M_W= 6.5	Afyon	North	0.110	0.114	0.223	0.203	73.9[1*]
AF02AFYO.090	Afyon-Sultandag	03.02.2002	M_W= 6.5	Afyon	East	0.086	0.094	0.224	0.203	73.9[1]
BN03BING.360	Bingol	01.05.2003	M_W= 6.4	Bingol	North	0.449	0.546	0.205	1.043	10.5[1]
BN03BING.090	Bingol	01.05.2003	M_W= 6.4	Bingol	East	0.199	0.277	0.171	0.764	10.5[1]
AD98CEYH.090	Adana-Ceyhan	27.06.1998	M_S = 5.9	Ceyhan	East	0.200	0.274	0.338	0.602	32.0[1]
AD98CEYH.180	Adana-Ceyhan	27.06.1998	M_S = 5.9	Ceyhan	South	0.250	0.223	0.399	0.365	32.0[1]
DN95DINA.090	Dinar	01.10.1995	M_S = 5.9	Dinar	East	0.360	0.330	0.608	0.714	10.8[1]
DN95DINA.180	Dinar	01.10.1995	M_S = 5.9	Dinar	South	0.276	0.282	0.356	0.752	10.8[1]
DZ99BOLU.360	Duzce	12.11.1999	M_W= 7.2	Bolu	360°	0.564	0.728	0.719	1.551	17.6[2]
DZ99BOLU.090	Duzce	12.11.1999	M_W= 7.2	Bolu	090°	0.621	0.822	1.157	0.923	17.6[2]
DZ99DUZC.180	Duzce	12.11.1999	M_W= 7.2	Duzce	180°	0.600	0.348	0.534	0.558	8.2[2]
DZ99DUZC.270	Duzce	12.11.1999	M_W= 7.2	Duzce	270°	0.835	0.535	0.757	1.301	8.2[2]
ER92ERZN.360	Erzincan	13.03.1992	M_S = 6.8	Erzincan	North	0.840	0.515	0.848	0.817	2.0[2]
ER92ERZN.090	Erzincan	13.03.1992	M_S = 6.8	Erzincan	East	0.643	0.496	0.590	1.321	2.0[2]
KC99DUZC.180	Kocaeli	17.08.1999	M_S = 7.4	Duzce	180°	0.589	0.312	0.435	0.525	12.7[2]
KC99DUZC.270	Kocaeli	17.08.1999	M_S = 7.4	Duzce	270°	0.464	0.358	0.609	0.648	12.7[2]
KC99GEBZ.180	Kocaeli	17.08.1999	M_S = 7.4	Gebze	180°	0.503	0.244	0.229	0.478	17.0[2]
KC99IZMT.090	Kocaeli	17.08.1999	M_S = 7.4	Izmit	090°	0.298	0.220	0.279	0.620	4.8[2]
KC99YARM.060	Kocaeli	17.08.1999	M_S = 7.4	Yarimca	060°	0.657	0.268	0.326	0.458	2.6[2]
KC99YARM.330	Kocaeli	17.08.1999	M_S = 7.4	Yarimca	330°	0.622	0.349	0.378	0.521	2.6[2]

*[1] Distance to epicenter
[2] Closest distance to fault rupture

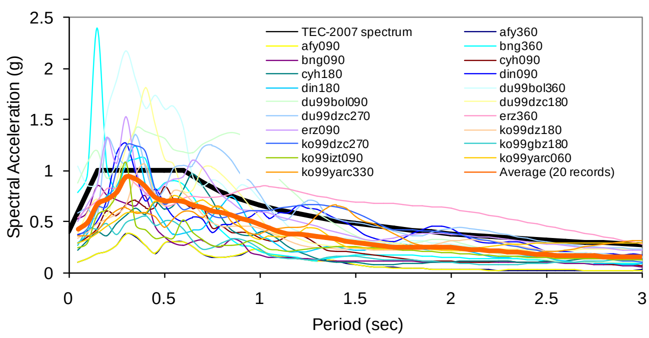


Fig. 4 Average response spectrum of ground motion records from Turkey for 5% damping

Average response spectrum of 20 ground motion records for 5% damping is plotted in Fig. 4 as well as demand spectrum provided in TEC (2007) for design earthquake with 10% probability of exceedance in 50 years. As seen in the figure, average spectrum for the considered records is lower than the code spectrum of design earthquake (approximately 80-85%) within the period of interest for the low- and mid-rise buildings. The code spectrum is provided to visualize the demand of selected records. Since the aim of the study is to investigate the performance of existing buildings subjected to past earthquakes, the scaling is not implemented for the selected ground motion records to simulate code spectrum.

5. "Equivalent" Single Degree of Freedom (ESDOF) idealization of structure response

A capacity curve obtained from pushover analysis represents the relationship between the base shear force and the displacement of the roof. The base shear is normalized by building seismic weight while the roof level displacement is normalized by building height to represent shear strength coefficient and roof displacement drift, respectively. The capacity curve of each building was approximated with a bilinear curve using TEC (2007) with engineering judgment and guidelines given in ATC-40 (1996) and FEMA-440 (2005). A typical example of idealized capacity curve is shown in Fig. 5. A set of capacity curves is provided in Fig. 6. Samples of the capacity curves of buildings reflecting different cases are given in Fig. 6 for the pre-modern code buildings. As it is seen from the figure, the irregularities affect both lateral load and displacement capacities depending on building properties (such as number of stories, concrete strength and transverse reinforcement). Soft story (SS) irregularity has considerably higher effect on 2-story buildings by decreasing both lateral load and ultimate displacement capacities. Heavy overhang (HO) irregularity significantly decreases lateral load capacity of 4-story buildings while SS irregularity caused lower displacement capacity of 4-story buildings. The effect of irregularities is considerably limited for 7-story buildings. Fig. 6 obviously illustrates that there is no clear trend on capacity curves of the selected buildings due to irregularities.

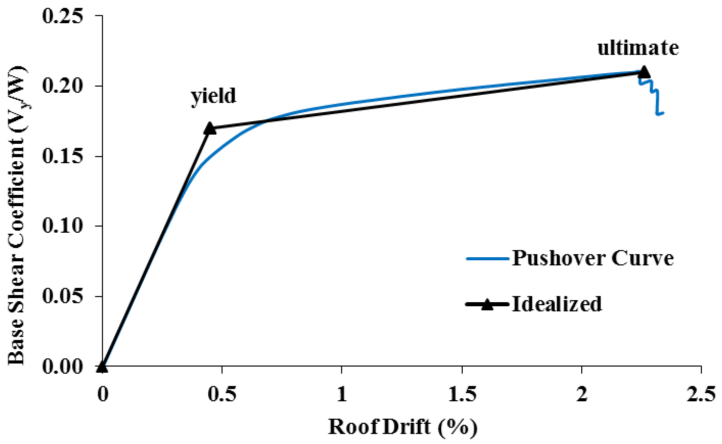
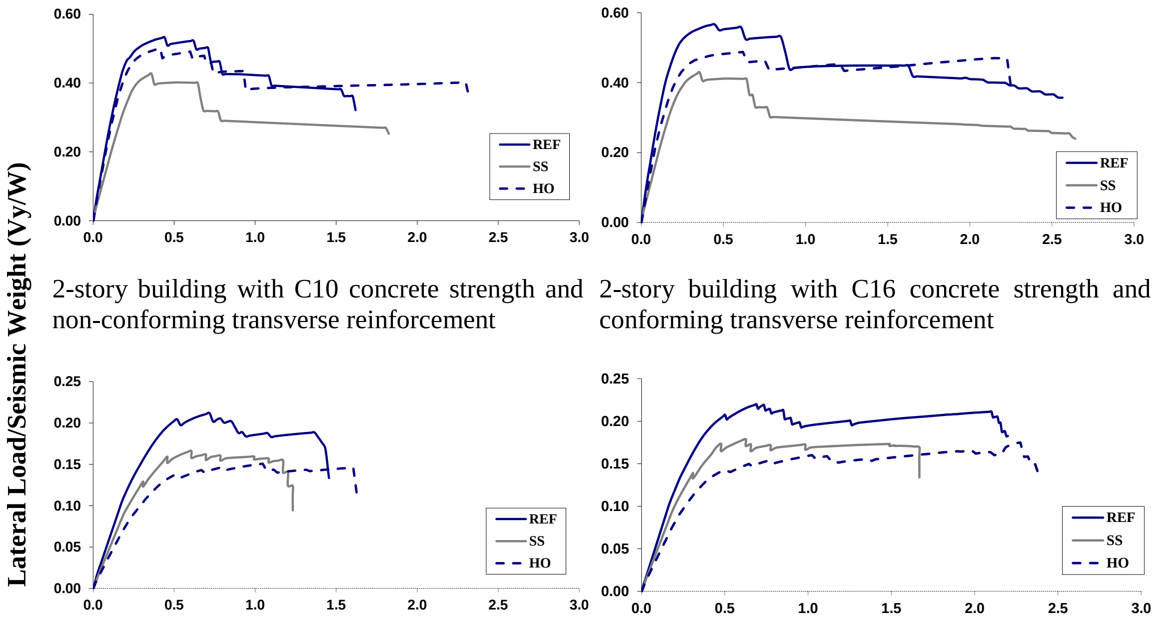


Fig. 5 Typical pushover and idealized capacity curves

The inelastic dynamic characteristics are represented by "equivalent" SDOF systems using obtained capacity curves of reference (REF), soft story (SS) and heavy overhang (HO) buildings from pushover analysis. The capacity curves also reflect the irregularities in terms of base shear, yield and ultimate displacement capacities. 72 building models were idealized as "Equivalent" SDOF system in two lateral directions (total of 144 models) and subjected to nonlinear response history analysis by using ground motion records with the software BiSpec to determine displacement demands using nonlinear response history analysis (Hachem 2004). The ESDOF displacement demands were then converted into building displacement demands at the roof level multiplying by the first mode participation factor to obtain building displacement demands. Although the buildings include structural irregularities, their mass participation factors for the first mode are within limits of nonlinear static analysis (higher than 0.70).

6. Building performance evaluation

Seismic performance evaluation of the investigated buildings is carried out using the recently published TEC (2007). Four performance levels, immediate occupancy (IO), life safety (LS), collapse prevention (CP) and collapse (CO) are considered as specified in this code and several other international guidelines such as FEMA-356 (2000) and ATC-40 (1996). Criteria given in the code for four performance levels are listed in Table 5.



2-story building with C10 concrete strength and non-conforming transverse reinforcement

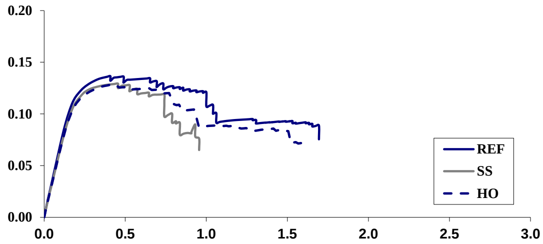
2-story building with C16 concrete strength and conforming transverse reinforcement

4-story building with C10 concrete strength and non-conforming transverse reinforcement

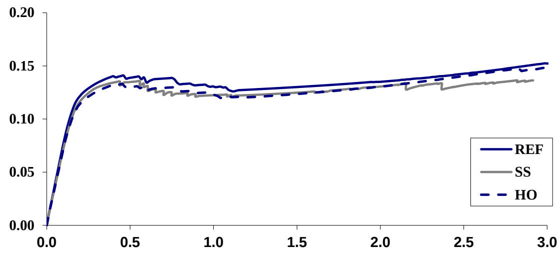
4-story building with C16 concrete strength and conforming transverse reinforcement

Roof Displacement/Building Height (%)

Fig. 6 Capacity curves for representative pre-modern code building models



7-story building with C10 concrete strength and non-conforming transverse reinforcement



7-story building with C16 concrete strength and conforming transverse reinforcement

Roof Displacement/Building Height (%)

Fig. 6 Continued

Building capacity is generally represented by lateral strength and ultimate drift capacities. The capacity of 72 buildings used in the current study is provided in Table 6. The given range in the table represents the capacities in two principal directions (x and y). The lateral strength ratio represents lateral strength normalized by seismic weight while ultimate drift capacity is displacement capacity at the roof level normalized by the building height.

Table 6 is obviously illustrates that heavy overhang and soft story irregularities decrease the lateral strength ratio capacity of buildings depending on number of stories. As the number of stories increases the effect of irregularities decreases. However, it is hard to mention about a similar trend for displacement capacity. Displacement capacities depend on the predefined performance criteria and damage states of beams and columns. Fig. 6 and Table 6 obviously show

Table 5 Performance levels and criteria provided in TEC (2007)

Performance Level	Performance Criteria
Immediate Occupancy (IO)	1. There shall not be any beams exceeding LS. 2. There shall not be any column or shear walls exceeding IO level. 3. The ratio of beams in IO-LS region shall not exceed 10% in any story.
Life Safety (LS)	1. The ratio of beams in LS-CP region shall not exceed 20% in any story. In any story, the shear carried by columns or shear walls in LS-CP region shall not exceed 20% of story shear. This ratio can be taken as 40% for roof story. In any story, the shear carried by columns or shear walls yielded at both ends shall not exceed 30% of story shear. 4. There shall not be any columns or shear walls exceeding CP.
Collapse Prevention (CP)	1. The ratio of beams exceeding CP region shall not exceed 20% in any story. In any story, the shear carried by columns or shear walls exceeding CP region shall not exceed 20% of story shear. This ratio can be taken as 40% for roof story. In any story, the shear carried by columns or shear walls yielded at both ends shall not exceed 30% of story shear.
Collapse (CO)	1. If a building cannot satisfy CP level, it is considered as CO.

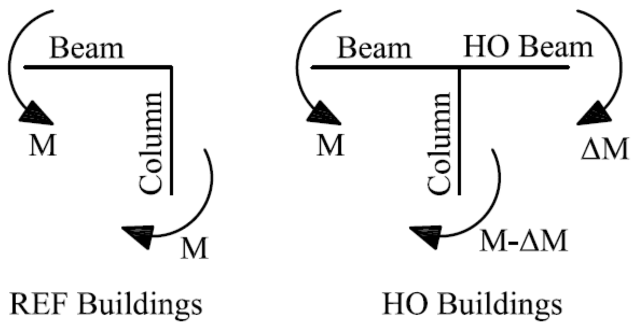


Fig. 7 Reducing moment demand on columns at the overhang zone for the buildings with heavy overhang (HO) irregularity

that the absence of beams at the overhang zone has significant effect on the displacement capacity of the buildings. It is well known that the columns at the overhang zone are subjected to lower moment due to absence of beams as shown in Fig. 7. This situation changes damage state of columns that is a major factor for determining displacement capacity at different performance levels. Although heavy overhang irregularity seems to provide higher displacement capacity, it has significant negative effects on seismic demand of the buildings.

Contribution of infill-wall rapidly decreases with increasing damage due to their brittle behavior. Moreover, the infill-wall has limited influence for 7-story buildings as it is well known that the amount of infill-wall is related to architectural features of buildings. Therefore, it is independent of number of stories.

The residential buildings are designed for Life Safety performance level under the design earthquake with 10% probability of exceedance in 50 years. The performance of buildings are evaluated for LS performance level. The roof drift (roof displacement divided by building height) capacities of the reference buildings corresponding to LS performance level are provided in Table 7 for different concrete strength values, conforming and non-conforming detailing of ductile design and pre-modern and modern codes. The roof drift capacities of considered buildings are based on nonlinear static analyses (pushover analysis) and the performance level criteria provided in TEC (2007) as shown Table 5. The capacity values are compared to demand values for performance evaluation.

The comparison of inelastic displacement demands obtained using nonlinear time history analyses and ultimate and Life Safety (LS) roof drift capacities determined using pushover analysis obviously shows that displacement estimates of 4- story buildings per pre-modern code do not always ensure safe performances as seen in Fig. 8.

The positive effects of higher concrete strength, transverse reinforcement detailing for ductile design and design code are obvious for the displacement capacities of the RC residential buildings. Although there is no significant differences in displacement capacities of 16 MPa and 25 MPa concrete, the differences are quite obvious for 10 MPa and 16 MPa concrete. Moreover, the differences between conforming and nonconforming transverse reinforcement detailing are evident in the displacement capacities.

The inelastic displacement demands of the 144 ESDOF systems (2 principal directions of 72 buildings) were obtained using response history analyses for 20 ground motions. Inelastic spectral displacement demand of each model was also obtained using design earthquake spectrum with

Table 6 Lateral load ratio and ultimate drift capacities of buildings considered in the current study

Building		Lateral Strength Ratio			
		Pre-modern code buildings		Modern code buildings	
		C10 (10 MPa)	C16 (16 MPa)	C16 (16 MPa)	C25 (25 MPa)
2-story	REF	0.42-0.53	0.44-0.52	0.57-0.68	0.59-0.72
	SS	0.36-0.40	0.39-0.42	0.50-0.58	0.50-0.59
	HO	0.43-0.44	0.42-0.46	0.54-0.60	0.56-0.62
4-story	REF	0.21-0.24	0.23-0.25	0.35-0.38	0.36-0.39
	SS	0.18-0.20	0.19-0.22	0.29-0.34	0.31-0.35
	HO	0.16-0.21	0.17-0.22	0.26-0.34	0.27-0.36
7-story	REF	0.13-0.15	0.13-0.15	0.24-0.25	0.25-0.26
	SS	0.11-0.13	0.13-0.14	0.23-0.24	0.24-0.25
	HO	0.11-0.12	0.12-0.12	0.20-0.23	0.22-0.23
Building		**Ultimate Roof Drift Capacity (%)**			
		Pre-modern code buildings		Modern code buildings	
		C10 (10 MPa)	C16 (16 MPa)	C16 (16 MPa)	C25 (25 MPa)
2-story	REF	1.03-1.93	1.07-2.49	1.77-3.87	2.26-3.60
	SS	0.98-1.57	1.29-1.58	1.67-3.71	2.18-3.47
	HO	1.52-1.91	0.77-2.65	1.86-3.96	2.36-3.57
4-story	REF	0.69-0.87	0.87-1.18	1.00-2.57	1.18-2.70
	SS	0.61-0.89	0.86-1.23	0.80-1.75	1.02-1.90
	HO	1.12-1.30	1.45-1.73	0.97-2.72	1.25-3.02
7-story	REF	0.77-1.57	0.98-2.04	0.96-2.14	1.22-2.70
	SS	0.55-0.97	0.78-1.40	0.76-1.53	0.93-2.05
	HO	0.74-1.57	1.06-2.01	0.98-2.04	1.21-2.62

Table 7 Roof drift capacities of reference buildings corresponding to Life Safety performance level (%)

Building	Direction	Pre-modern code buildings				Modern code buildings			
		C10 (10 MPa)		C16 (16 MPa)		C16 (16 MPa)		C25 (25 MPa)	
		Conf.*	Non-Conf.*	Conf.*	Non-Conf.*	Conf.*	Non-Conf.*	Conf.*	Non-Conf.*
2-story	*x*	1.089	0.905	1.680	0.940	2.551	1.522	2.368	2.007
	y	1.548	1.270	2.116	1.795	2.557	1.652	2.412	2.150
4-story	*x*	0.669	0.600	0.904	0.777	1.904	0.921	1.842	1.287
	y	0.729	0.635	0.980	0.846	1.517	0.849	1.764	1.022
7-story	*x*	1.166	0.674	1.624	1.011	1.504	0.819	1.930	1.054
	y	0.914	0.683	1.322	0.876	1.949	0.934	2.058	1.294

*Conf. and Non-Conf. refer to conforming and non-conforming transverse reinforcement amount and details given in the related code for ductile design

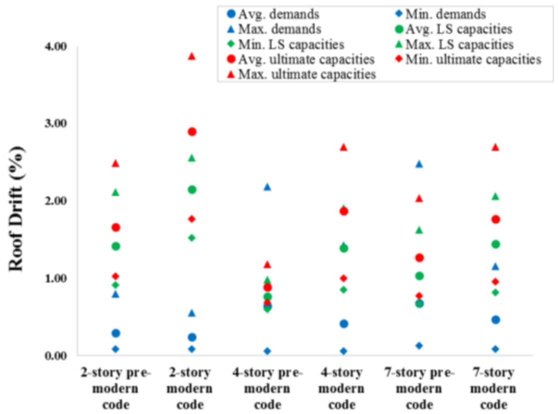
10% probability of exceedance in 50 years and displacement coefficient method given in TEC

(2007) similar to the procedure of FEMA-356 (2000). In this method, the inelastic displacements are obtained by multiplication of the elastic spectral displacement values and a factor of coefficient given in Eq. (1). According to the TEC (2007), if the building period is greater than the characteristic period of the soil type (0.6 s for Z3) the equal displacement rule is valid and the inelastic displacement demand is taken equal to the elastic one (C_{R1} is equal to 1). If the building period is smaller than the soil characteristic period (T_B), the elastic displacement demand is increased by multiplying a factor (C_{R1}) depending on parameters such as lateral strength and stiffness which is given as

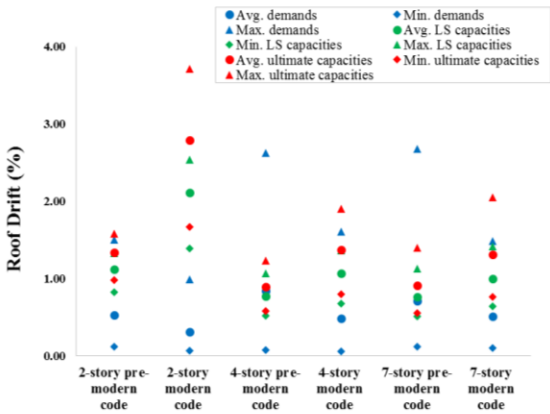
$$C_{R1} = \frac{1+(R_{y1}-1)\cdot T_B / T}{R_{y1}} \tag{1}$$

$$R_{y1} = \frac{S_{ae1}}{a_{y1}} \tag{2}$$

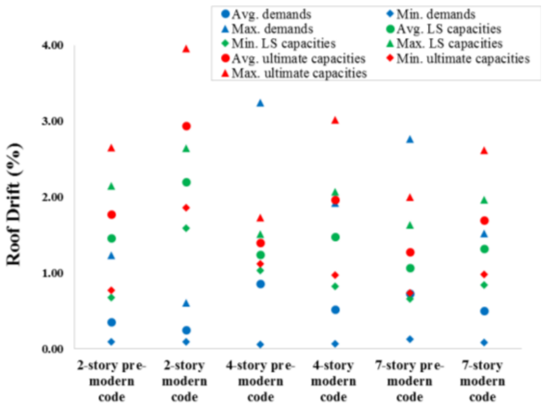
In Eqs. (1) and (2), C_{R1} is the ratio between inelastic and elastic displacements, R_{y1} is the



Roof drift demands and capacities of REF buildings



Roof drift demands and capacities of SS buildings



Roof drift demands and capacities of HO buildings

Fig. 8 Comparisons of average, minimum and maximum roof drift demands and capacities of 2-,4- and 7-story buildings strength reduction factor, T is the building period, S_{ae1} is the spectral acceleration, a_{y1} is the acceleration at the yield point of the building, in other words lateral strength at yielding point divided by seismic weight of building.

The ESDOF system inelastic displacement demands of response history and code were multiplied by the first mode participation factor to determine global displacement drift ratio (defined as lateral displacement at roof level divided by building elevation) of each building model. The obtained inelastic displacement demands were compared to the displacement capacities corresponding to the considered performance levels. In a previous study, nonlinear displacement demand values were compared with the values obtained by FEMA-356 (2000), FEMA 440 (2005) and TEC (2007) methods using the first mode participation factor for 144 mid-rise building models which included structural irregularities such as soft story and heavy overhangs by authors (Inel *et al*. 2010). However, it should be kept in mind that all buildings have higher values of the first mode mass participation factors than nonlinear static analysis requirement similar to the current building set.

The performance levels of buildings subjected to 20 ground motions were also determined and evaluated in average sense instead of each individual record to compare the performance levels obtained for the code demands. Since the average spectrum of 20 ground motions is about 80-85% of code spectrum, performance levels of the records are expected to be better than the performance levels of the code.

7. Discussion of results

Tables 8 and 9 list the percentage of satisfying LS and exceeding LS performance level of the pre-modern and modern code buildings for 20 ground motion records. The tables show variations in the building performances due to ground motion records, improvements in building performances due to code and the effect of number of stories on performance. Since the 2-story buildings have better over-strength values and the infill wall contribution is better than the buildings with higher number of stories, the best performance is observed in 2-story buildings as expected. The good seismic performances of low-rise buildings are also indicated by previous studies (Ozcebe 2004, Akkar *et al.* 2005). All modern code 2-story buildings satisfy LS performance level for the selected 20 records. However, there are few pre-modern code 2-story buildings exceeding LS performance level for 5 records of 1992 Erzincan and 1999 Duzce earthquakes.

The significant number of pre-modern code 4-story buildings exceeds LS performance level while the modern code 4-story buildings have better performances. The pre-modern code buildings are exceeding LS level for 14 records while the modern code 4-story buildings exceed LS level only for 5 records. Similar observations are valid for the 7-story buildings. Although the performance of modern code 7-story buildings is better than that of pre-modern code 7-story buildings, there are quite significant portion of buildings exceeding LS level for 6 of 20 records.

The tables obviously indicate the existence of destructive earthquakes especially for 4- and 7-story buildings. 1999 Duzce and 1992 Erzincan earthquakes seem to be destructive for the pre-modern code 2-story buildings. Except 2002 Afyon-Sultandagi earthquake, there are pre-modern code 4-story buildings exceeding LS level for all earthquakes. DZ99BOLU.360, DZ99BOLU.090, DZ99DUZC.180, DZ99DUZC.270, ER92ERZN.360 and ER92ERZN.090 records are the most destructive records, having 83.33% or higher percentage of buildings exceeding LS performance level. Both records of Erzincan earthquake are destructive for the pre-modern code 7-story buildings; the building ratios exceeding LS level are 87.5% and 100% for ER92ERZN.360 and ER92ERZN.090 records, respectively. DZ99BOLU.090 record is also destructive for these buildings. Another interesting observation is that DN95DINA.180 is a damaging record for the pre-modern 4- and 7-story buildings while no damage is observed for the pre-modern 2-story buildings. Two third of the 7-story buildings are damaged for DN95DINA.180 record. This can be explained with characteristic of the record.

Significant improvements in the performance of the modern code buildings are obvious when Tables 8 and 9 are compared. The earthquakes occurred during last several decades seem to be destructive especially for the pre-modern code 4- and 7-story buildings. The modern code buildings show better performance due to improvements in stiffness and material quality. There are findings in the literature similar to this observation (Ozmen *et al.* 2010, Ozmen *et al.* 2014). The overall building stock performance is evaluated for all records and demand spectrum provided in 2007 Turkish Earthquake Code for design earthquake with 10% probability of exceedance in 50

Table 8 Performance evaluation of pre-modern code (designed per 1975 Turkish Earthquake Code) residential buildings subjected to the selected ground motion records (%)

Record ID	PSA (g) 1 Hz	PSA (g) 5 Hz	2-story		4-story		7-story	
			V_y/W range					
			0.39-0.53		0.17-0.25		0.11-0.15	
			Satisfying LS	Exceeding LS	Satisfying LS	Exceeding LS	Satisfying LS	Exceeding LS
AF02AFYO.360	0.223	0.203	100.00	0.00	100.00	0.00	100.00	0.00
AF02AFYO.090	0.224	0.203	100.00	0.00	100.00	0.00	100.00	0.00
BN03BING.360	0.205	1.043	100.00	0.00	70.83	29.17	95.83	4.17
BN03BING.090	0.171	0.764	100.00	0.00	100.00	0.00	100.00	0.00
AD98CEYH.090	0.338	0.602	100.00	0.00	91.67	8.33	100.00	0.00
AD98CEYH.180	0.399	0.365	100.00	0.00	100.00	0.00	95.83	4.17
DN95DINA.090	0.608	0.714	100.00	0.00	100.00	0.00	91.67	8.33
DN95DINA.180	0.356	0.752	100.00	0.00	54.17	45.83	33.33	66.67
DZ99BOLU.360	0.719	1.551	95.83	4.17	16.67	83.33	58.33	41.67
DZ99BOLU.090	1.157	0.923	75.00	25.00	0.00	100.00	29.17	70.83
DZ99DUZC.180	0.534	0.558	100.00	0.00	16.67	83.33	100.00	0.00
DZ99DUZC.270	0.757	1.301	87.50	12.50	4.17	95.83	54.17	45.83
ER92ERZN.360	0.848	0.817	95.83	4.17	12.50	87.50	12.50	87.50
ER92ERZN.090	0.590	1.321	95.83	4.17	4.17	95.83	0.00	100.00
KC99DUZC.180	0.435	0.525	100.00	0.00	87.50	12.50	100.00	0.00
KC99DUZC.270	0.609	0.648	100.00	0.00	79.17	20.83	66.67	33.33
KC99GEBZ.180	0.229	0.478	100.00	0.00	91.67	8.33	100.00	0.00
KC99IZMT.090	0.279	0.620	100.00	0.00	100.00	0.00	100.00	0.00
KC99YARM.060	0.326	0.458	100.00	0.00	87.50	12.50	62.50	37.50
KC99YARM.330	0.378	0.521	100.00	0.00	91.67	8.33	66.67	33.33

years. It should be kept in mind that the average spectrum of the selected records is about 80-85% of code spectrum. Table 10 provides the percentage of buildings satisfying LS performance level for all records and the code demand. Although the modern code buildings have similar performances for both demands, the pre-modern code 4- and 7-story buildings have demand compatible performances; the higher ratio of buildings is exceeding LS performance level for the code demands. This emphasizes the vulnerability of existing pre-modern code buildings, especially for building having 3 to 8 stories. Almost one third of pre-modern code buildings is exceeding LS level during records in the past earthquakes. This observation also supports the building damages experienced in the past earthquake events in Turkey (Inel *et al.* 2008, Bayraktar *et al.* 2013b).

The buildings set in the current study includes structural irregularities such as soft story and heavy overhangs. The effect of such irregularities on LS performance level is shown in Table 11. The building ratios satisfying LS and exceeding LS levels obviously indicate that the soft story irregularity has more negative effect on seismic performance of existing buildings, especially on the pre-modern code buildings (Inel and Ozmen 2008, Meral 2010).

Table 9 Performance evaluation of modern code (designed per 1998 Turkish Earthquake Code) residential buildings subjected to the selected ground motion records (%)

Record ID	PSA (g) 1 Hz	PSA (g) 5 Hz	2-story		4-story		7-story	
			V_y/W range					
			0.50-0.72		0.26-0.39		0.22-0.26	
			Satisfying LS	Exceeding LS	Satisfying LS	Exceeding LS	Satisfying LS	Exceeding LS
AF02AFYO.360	0.223	0.203	100.00	0.00	100.00	0.00	100.00	0.00
AF02AFYO.090	0.224	0.203	100.00	0.00	100.00	0.00	100.00	0.00
BN03BING.360	0.205	1.043	100.00	0.00	100.00	0.00	100.00	0.00
BN03BING.090	0.171	0.764	100.00	0.00	100.00	0.00	100.00	0.00
AD98CEYH.090	0.338	0.602	100.00	0.00	100.00	0.00	100.00	0.00
AD98CEYH.180	0.399	0.365	100.00	0.00	100.00	0.00	100.00	0.00
DN95DINA.090	0.608	0.714	100.00	0.00	100.00	0.00	100.00	0.00
DN95DINA.180	0.356	0.752	100.00	0.00	100.00	0.00	100.00	0.00
DZ99BOLU.360	0.719	1.551	100.00	0.00	87.50	12.50	95.83	4.17
DZ99BOLU.090	1.157	0.923	100.00	0.00	33.33	66.67	54.17	45.83
DZ99DUZC.180	0.534	0.558	100.00	0.00	87.50	12.50	83.33	16.67
DZ99DUZC.270	0.757	1.301	100.00	0.00	87.50	12.50	87.50	12.50
ER92ERZN.360	0.848	0.817	100.00	0.00	100.00	0.00	83.33	16.67
ER92ERZN.090	0.590	1.321	100.00	0.00	87.50	12.50	54.17	45.83
KC99DUZC.180	0.435	0.525	100.00	0.00	100.00	0.00	100.00	0.00
KC99DUZC.270	0.609	0.648	100.00	0.00	100.00	0.00	100.00	0.00
KC99GEBZ.180	0.229	0.478	100.00	0.00	100.00	0.00	100.00	0.00
KC99IZMT.090	0.279	0.620	100.00	0.00	100.00	0.00	100.00	0.00
KC99YARM.060	0.326	0.458	100.00	0.00	100.00	0.00	100.00	0.00
KC99YARM.330	0.378	0.521	100.00	0.00	100.00	0.00	100.00	0.00

Table 10 Performance evaluation of pre-modern and modern code (designed per 1998 Turkish Earthquake Code) residential buildings for all ground motion records and demand spectrum given in TEC (2007) (%)

Number of story	Earthquake Demand	Pre-modern code buildings		Modern code buildings	
		Satisfying LS	Exceeding LS	Satisfying LS	Exceeding LS
2-story	All records	97.50	2.50	100.00	0.00
	TEC (2007)	100.00	0.00	100.00	0.00
4-story	All records	65.42	34.58	94.17	5.83
	TEC (2007)	54.17	45.83	95.83	4.17
7-story	All records	73.33	26.67	92.92	7.08
	TEC (2007)	58.33	41.67	91.67	8.33

Table 11 The effect of structural irregularity on performance of existing buildings (in terms of percentage of buildings, %)

Building irregularity	Number of story	Pre-modern code buildings		Modern code buildings	
		Satisfying LS	Exceeding LS	Satisfying LS	Exceeding LS
Reference (REF)	2-story	100.00	0.00	100.00	0.00
	4-story	67.50	32.50	97.50	2.50
	7-story	78.75	21.25	97.50	2.50
Soft Story (SS)	2-story	93.13	6.88	100.00	0.00
	4-story	54.38	45.63	90.00	10.00
	7-story	62.50	37.50	86.25	13.75
Heavy Overhangs (HO)	2-story	99.38	0.63	100.00	0.00
	4-story	74.38	25.63	95.00	5.00
	7-story	78.75	21.25	95.00	5.00

8. Conclusions

This study aims to evaluate seismic performance of existing low and mid-rise reinforced concrete buildings by comparing their displacement capacities and displacement demands under selected ground motions experienced in Turkey as well as demand spectrum provided in 2007 Turkish Earthquake Code for design earthquake with 10% probability of exceedance in 50 years for soil class Z3. It should be noted that typical residential buildings are designed according to demand spectrum of 10% probability of exceedance in 50 years.

Three RC building sets as 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. The outcomes of detailed field and archive investigation including approximately 500 real residential RC buildings established building models to reflect existing building stock. The reference buildings reflect the existing building stock with different parameters such as plan dimensions, story height, total column area per unit area, total load carrying infill-wall (satisfying TEC (2007) criteria) area per unit area for building level. Section dimensions and reinforcement detailing for member level are taken into consideration. Existing structural irregularities are reflected in building models as soft story and heavy overhangs.

Soft story usually occurs due to insufficient lateral resistance and lack of rigidity of first story. For this reason, buildings with soft story were created by increasing the first story height of reference buildings. Heavy overhang increases mass of structure and internal forces due to separation of mass and rigidity centers under earthquake loading. The statistical data obtained from detailed field and archive investigation including approximately 500 real residential RC buildings are reflected in modeling of soft story and heavy overhangs. This study considers 72 3-D building models to include the effects of some properties such as structural irregularities, concrete strength, seismic codes, structural deficiencies, transverse reinforcement detailing, and number of story on seismic performance of low and mid-rise RC buildings. The residential buildings are designed for Life Safety performance level under the design earthquake with 10% probability of exceedance in 50 years. The performance of buildings are evaluated for LS performance level.

Capacity curves of building sets are obtained by nonlinear static analyses conducted in two principal directions, resulting in 144 models. The inelastic dynamic characteristics are represented by “equivalent” Single-Degree-of- Freedom (ESDOF) systems using obtained capacity curves of buildings. Nonlinear time history analysis is used to estimate displacement demands of representative building models idealized with (ESDOF) systems subjected to the selected ground motion records from past earthquakes in Turkey. The findings and observations are summarized as:

• The positive effects of higher concrete strength, transverse reinforcement detailing for ductile design and design code are obvious for the displacement capacities of the RC residential buildings. Although there is no significant differences in displacement capacities of 16 MPa and 25 MPa concrete, the differences are quite obvious for 10 MPa and 16 MPa concrete. Moreover, the differences between conforming and nonconforming transverse reinforcement detailing are evident in the displacement capacities.

• All modern code 2-story buildings satisfy LS performance level for the selected 20 records. However, there are few pre-modern code 2-story buildings exceeding LS performance level for 5 records of 1992 Erzincan and 1999 Duzce earthquakes.

• The significant number of pre-modern code 4- and 7-story buildings exceeds LS performance level while the modern code 4- and 7-story buildings have better performances. The findings obviously indicate the existence of destructive earthquakes especially for 4- and 7-story buildings. Except 2002 Afyon-Sultandagi earthquake, there are pre-modern code 4-story buildings exceeding LS level for all earthquakes. DZ99BOLU.360, DZ99BOLU.090, DZ99DUZC.180, DZ99DUZC.270, ER92ERZN.360 and ER92ERZN.090 records are the most destructive records, having 83.33% or higher percentage of buildings exceeding LS performance level.

• Both records of Erzincan earthquake are destructive for the pre-modern code 7-story buildings; the building ratios exceeding LS level are 87.5% and 100% for ER92ERZN.360 and ER92ERZN.090 records, respectively. DZ99BOLU.090 record is also destructive for these buildings. Another interesting observation is that DN95DINA.180 is a damaging record for the pre-modern 4- and 7-story buildings while no damage is observed for the pre-modern 2-story buildings. Two third of the 7-story buildings are damaged for DN95DINA.180 record. This can be explained with characteristic of the record.

• Significant improvements in the performance of the modern code buildings are obvious. The earthquakes occurred during last several decades seem to be destructive especially for the pre-modern code 4- and 7-story buildings. The modern code buildings show better performance due to improvements in stiffness and material quality.

• Almost one third of pre-modern code buildings is exceeding LS level during records in the past earthquakes. This observation also supports the building damages experienced in the past earthquake events in Turkey.

• The building ratios satisfying LS and exceeding LS levels obviously indicate that the soft story irregularity has more negative effect on seismic performance of existing buildings, especially on the pre-modern code buildings.

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