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Evaluation of the main parameters affecting seismic performance of the RC buildings

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Abstract. Low and mid-rise reinforced concrete (RC) buildings consist of an important portion of the building stock in many earthquake prone countries. Therefore understanding their seismic behaviour is important for mitigation studies. This study aims to evaluate how much and when; seismic code, number of stories, concrete strength, amount of transverse reinforcement and infill-wall contribution parameters are important for seismic performances of RC buildings. Seismic performances of the models reflecting different cases are determined for different performance levels and seismic loading conditions. Based on the considered values of the parameters, it is concluded that: modern code specifications and higher transverse reinforcement 50%, the concrete strength up to 66%, infill-walls 15% and number of story 55% increase the seismic performance for life safety level. Evaluations on the effect of the considered parameters for different performance levels and seismic loadings in relation with other parameters are also given in this paper.

Keywords. Existing building; infill wall; nonlinear analysis; number of story; seismic code; transverse reinforcement.

1. Introduction

Low and mid-rise reinforced concrete (RC) buildings consist of an important portion of the building stock in many earthquake prone countries. Remarkable number of casualties and heavily damaged or collapsed buildings after past earthquakes (i.e., Manila-Philippines 1990; Uttar Pradesh-India 1991; Erzincan-Turkey 1992; Kobe-Japan 1995; Kocaeli-Turkey 1999; Bingol-Turkey 2003) has emphasized inadequate seismic performance of these buildings, most of which are less than eight stories in height (Otani 1997; Sezen *et al* 2003; Inel *et al* 2008a; Tama 2012). The number of buildings and their portion in the building stock underlines the importance of understanding their seismic behaviour (Building Census 2000 2001).

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This study aims to evaluate the main parameters affecting seismic performance of existing low and mid-rise RC building stock by nonlinear static analysis. Outcomes of a detailed field and archive investigation is used to establish the building models reflecting the existing building stock in Turkey or other earthquake prone countries with similar construction practice (Ozmen *et al* 2014). The current study considers forty eight (48) 3-D RC building models to reflect the existing low and mid-rise building stock with different parameters as number of stories, design code as pre-modern and modern, compliance to the code, material quality, and existence of load bearing infill walls. The degree of importance of these parameters and under which circumstances they are important or negligible, is examined throughout the study.

The outcomes and findings of the study may be useful for seismic behaviour assessment of low and mid-rise RC building stock and contribute to understand the effect of accounted parameters on seismic performance of existing buildings. Although this study focuses on Turkish building stock, it may resemble the cases of other developing countries in earthquake prone regions.

2. Description of the structures and modelling approach

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. Plan views of the buildings are given in figure 1. The load carrying infill-walls are shown in figure by shaded areas.

According to 2007 Turkish Earthquake Code (TEC-2007) an infill wall may be taken as load carrying element if it is totally surrounded by columns and beams; and does not have any opening with more than 10% of wall area or along the diagonal lines of the wall. These criteria are used to identify the load carrying infill walls. The outcomes of detailed field and archive investigation including 475 real residential RC buildings, 40351 column and 3123 beam elements from the selected buildings established building models (Ozmen *et al* 2014). Values of more than 30 key parameters like plan dimensions, story height, total column area per unit area, total load carrying infill-wall area per unit area and section dimensions and reinforcement detailing for member level are taken into consideration.

The selected reference buildings are designed according to the pre-modern (TEC-1975) and modern (TEC-1998) Turkish Earthquake Codes, considering both gravity and seismic loads. There has been a more recent code change in Turkey in 2007. However, changes in new code are greatly related to the assessment of existing buildings and the differences in design of new buildings are limited between TEC-1998 and TEC-2007. Therefore, the code considered as modern is TEC-1998. Design ground acceleration of 0.4 g (complying with high seismicity region for Turkey) and soil class Z3 that is similar to class C soil of FEMA-356 2000 is assumed. Two different concrete compressive strength values are considered for each code sets; 10 and 16 MPa for the pre-modern code and 16 and 25 MPa for the modern code based on the values in existing building stock (Inel *et al* 2008b). 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. Two different transverse reinforcement cases are considered as code-conforming and only peripheral stirrups with 200 mm spacing to reflect ductile and non-ductile detailing, respectively. It should be noted that code conforming transverse reinforcement is different for the TEC-1975 and TEC-1998 buildings. The transverse reinforcement for each case is consistent with the corresponding code. The parameters and corresponding cases investigated in scope of the study are given in table 1.

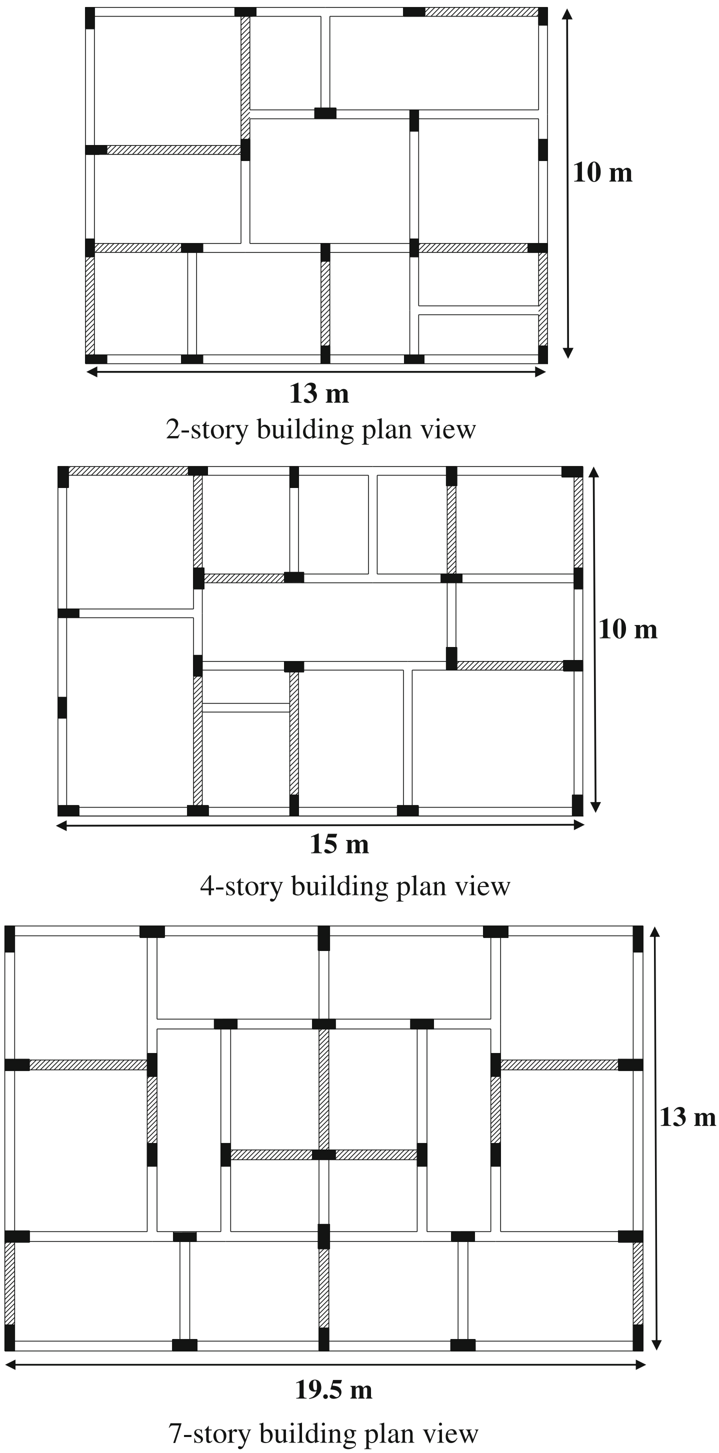

Figure 1. Plan view of the considered buildings (load carrying infill-walls are shaded).

Table 1. Parameters investigated in scope of the study.

Parameter	Story #	Design code	Load carrying infill-wall	Concrete strength	Transverse reinforcement
Cases	2	TEC-1975	Exist	10 MPa (TEC-1975)	Conforming TEC-1975
	4	TEC-1998	None	16 MPa (Both codes)	Conforming TEC-1998
	7			25 MPa (TEC-1998)	200 mm spacing without hooks

Note that existence of infill-wall means that the infill-walls (not all of them) satisfying TEC-2007 criteria are modelled as load carrying elements. In the other case, they are not assumed as load carrying. In all cases building models do have infill-walls and their own weights are taken into account. The infill-wall amount satisfying TEC-2007 criteria in the principal directions are determined by inventory study and not arbitrary amounts (Ozmen *et al* 2014). Design code is only assumed for dimensioning members and longitudinal reinforcement. Transverse reinforcement detailing is taken as a separate case.

The reference 2- 4- and 7-story buildings are represented using dimensions and parameters based on field and archive investigations and designed per 1975 and 1998 Turkish Earthquake Codes for the gravity and seismic loading. 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. SAP2000 is used in nonlinear analyses of the building models (SAP2000). Detailed information about the cases and modelling can be found at Ozmen (2011).

Table 2 lists range of some important properties for the building models. '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 80% of seismic weight are for the 2-story buildings constructed according to TEC-1998 and attributable to higher overstrength ratio because of minimum requirements of code and infill-wall contributions.

2.1 *Definition of plastic hinges*

Beam and column elements are modelled as nonlinear frame elements with lumped plasticity by defining plastic hinges at both ends of beams and columns. 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. The definition of the hinge properties requires moment–curvature analysis of each element. Moment-curvature analyses of the RC members are carried out according to TEC-2007 by using a software called

Table 2. Range of some important properties of the building models.

Building	Period range (s) (Based on cracked section properties)	Seismic weight range (kN)	Yield base shear coefficient (Vy/W)
2-story	0.21–0.31	2488–2500	0.37–0.79
4-story	0.37–0.60	6216–6474	0.19–0.47
7-story	0.60–0.88	18621–20065	0.13–0.32

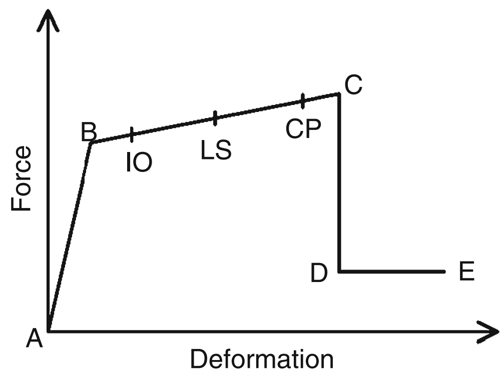

Figure 2. Force-deformation relationship of a typical plastic hinge.

SEMAp (Ozmen *et al* 2007). 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 taken as half of the section depth (Park & Paulay 1975; TEC-2007). In addition, effective stiffness values are obtained per this code; 0.4EI for beams and values between 0.4 and 0.8EI depending on axial load level for columns.

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).

Acceptance criteria for members and performance level criteria for buildings are used as given in TEC-2007. The acceptance criteria for members in TEC-2007 are given based on deformation limits of the steel and concrete materials. Limiting tension strain values for outermost tension steel and compression strain for the outermost fibre of concrete core in compression side are given in table 3.

Table 3. Limit material strains for different acceptance criteria provided in Turkish Earthquake Code-2007.

Acceptance criteria	Compressive concrete strain ε_c	Tensional steel strain ε_s
Immediate occupancy (IO)	$\varepsilon_c \leq 0.0035$	$\varepsilon_s \leq 0.01$
Life safety (LS)	$\varepsilon_c \leq 0.0035 + 0.010 \cdot (\rho_s/\rho_{sm})$ $\varepsilon_c \leq 0.0135$	$\varepsilon_s \leq 0.04$
Collapse prevention (CP)	$\varepsilon_c \leq 0.0040 + 0.014 \cdot (\rho_s/\rho_{sm})$ $\varepsilon_c \leq 0.0180$	$\varepsilon_s \leq 0.06$

*ρ_s is the volumetric ratio of the lateral steel that is present in the member confinement zone.
ρ_{sm} is the volumetric ratio of the lateral steel that is required by the code.

2.2 *Infill wall modelling*

Effect of infill walls are modelled through axial load carrying diagonal struts as suggested in TEC-2007 and FEMA-356 2000. Nonlinear behaviour of infill walls is reflected by assigned axial load hinges on diagonal struts whose characteristics are determined as given in FEMA-356 2000. 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.

3. Nonlinear static analyses and capacity curves

Capacity curves of the models are obtained using nonlinear static analyses (pushover). The pushover analysis consists of the application of gravity loads and a representative lateral load pattern. Gravity loads were in place during lateral loading. In all cases, lateral forces were applied monotonically in a step-by-step nonlinear static analysis. As the loads and displacements increase, the strength and stiffness of the members change due to the imposed deformations. When a member looses all or some of its strength, the member is unloaded consistently, resulting in redistribution of loads or possible loss of global strength. The applied lateral forces were proportional to the product of mass and the first mode shape amplitude at each storey level under consideration. P-Delta effects were taken into account.

Examples of the capacity curves of buildings reflecting different cases are given in figure 3. The lateral axis is the roof displacement normalized by building height; the vertical axis is the base shear normalized by building seismic weight. The notation in figure 3 corresponds to seismic code, concrete strength and transverse reinforcement cases. The first four numbers is the seismic code year, the two digits after 'BS' is the concrete strength in MPa, and the last figures after 's' refer to transverse reinforcement case. 's20' means the spacing of the transverse reinforcement is 200 mm with only peripheral stirrups. 'sCode' means the transverse reinforcement conforms the given code requirements. For example, 1998-BS16sCode means that the building conforming TEC-1998 requirements for member dimensions and longitudinal reinforcement with 16 MPa concrete strength and code compliant transverse reinforcement.

4. Building performance

Building performance evaluation requires calculation of demand and capacity. Displacement capacities and demands are both determined using the TEC-2007 provisions given for assessment of existing low and mid-rise RC buildings.

4.1 *Determination of displacement capacity*

Four performance levels, immediate occupancy (IO), life safety (LS), collapse prevention (CP) and collapse (CO) are considered as specified in TEC-2007 and several other international guidelines such as ATC-40 (1996) and FEMA-356 (2000). Pushover analysis data and criteria of TEC-2007 were used to determine global displacement drift ratio (defined as lateral displacement at roof level divided by building height) of each building corresponding to the performance levels considered. Criteria given in the code for three performance levels are listed in table 4. If a building cannot satisfy CP level, it is considered as CO level.

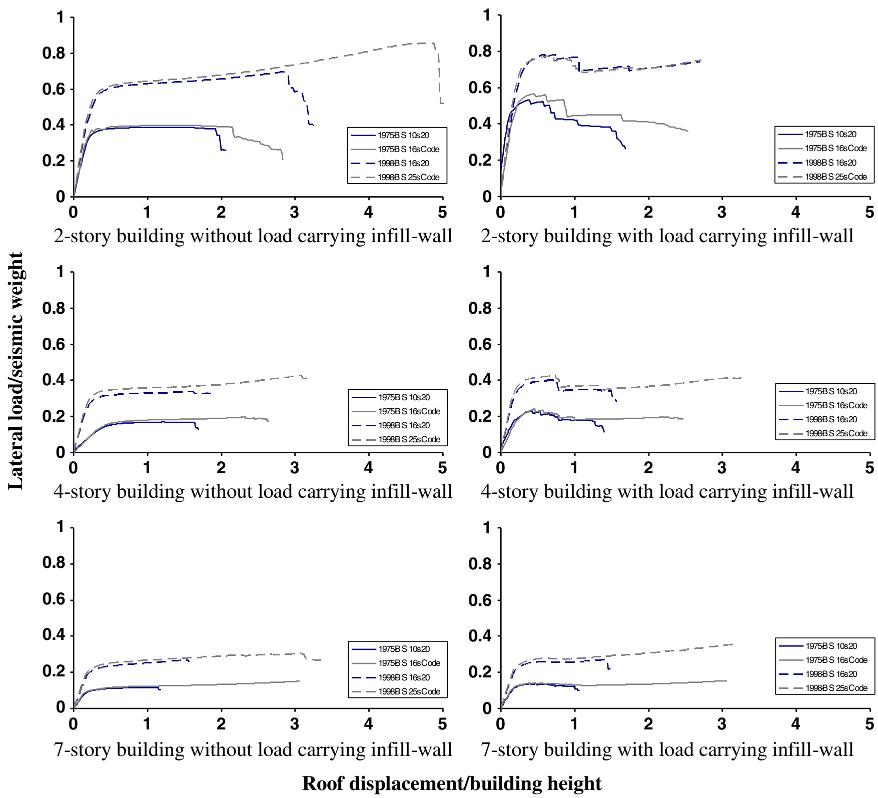

Figure 3. Typical capacity curves for representative building models.

The criteria by TEC-2007 for IO level is used as it is. However, since main goal of TEC-2007 is to establish a lower limit for seismic safety of the buildings, damage definition for the LS and CP levels may be too harsh or unstable for seismic evaluation purposes. For example, the third criterion for both LS and CP levels are the same end aims to prevent story mechanism in the buildings. Since this criterion is related with yielding of columns rather than deformation capacity, it may significantly change between models with minor differences. As the columns are close to the yielding just after the global yielding of the building, the ratio of 30% may be just at the beginning of the nonlinear response, near the collapse or does not occur at all. Therefore, the criterion number 3 for LS and CP levels are not used in evaluation. The criterion of 'no columns beyond CP' for LS (number 4) is also disregarded as it is about a single member and does not reflect global behaviour.

4.2 *Determination of displacement demands*

Displacement demand estimates for seismic loading with probability of 50%, 10% and 2% exceedance in 50 years are determined per TEC-2007 for each building. The response spectrum for the probability of 10% exceedance in 50 years is given in the code. According to TEC-2007, the ordinates of the spectrum of probability of 50% and 2% exceedance in 50 years is assumed to

Table 4. Performance levels and criteria provided in Turkish Earthquake Code-2007.

Performance level	Performance criteria
Immediate occupancy (IO)	1. There shall not be any beams beyond LS. 2. There shall not be any column or shear walls beyond 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. 2. 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. 3. 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 beyond CP.
Collapse prevention (CP)	1. The ratio of beams beyond CP region shall not exceed 20% in any story. 2. In any story, the shear carried by columns or shear walls beyond CP region shall not exceed 20% of story shear. This ratio can be taken as 40% for roof story. 3. In any story, the shear carried by columns or shear walls yielded at both ends shall not exceed 30% of story shear.

be 0.5 and 1.5 times of the spectrum with 10% exceedance in 50 years, respectively. For the highest seismic zone of Turkey, peak ground acceleration (PGA) of 0.4 g is specified. This means that 0.2 and 0.6 g as PGA for the probability of 50% and 2% exceedance in 50 years, respectively.

Soil class for buildings is assumed as Z3, as it is the most common soil type, which is similar to class C soil of FEMA-356 (2000). The elastic spectral displacement values for the buildings are determined by using the given spectrum in TEC-2007 for the corresponding seismic loading. 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. 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 the lateral strength of the building in addition to the previous parameters. The equation for C_{R1} 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 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 over building weight at yielding point.

4.3 *Determination of building performance*

Displacement demand estimates for seismic loading with probability of 50%, 10% and 2% exceedance in 50 years are compared for IO, LS and CP displacement capacities. Performance level of each building is determined for each of the seismic loading. Ratios of buildings satisfying modified TEC-2007 performance levels to all buildings, for different cases of investigated parameters and for different seismic intensities are given in table 5. The 96 capacity curves of 48 buildings are considered for 288 performance evaluation instances. Note that all the buildings reflecting the parameters given in 'Case' are included in the evaluation. For example, if the case is 'TEC-1975' all buildings irrespective of number of stories, existence of load carrying infill-walls, concrete strength or amount of transverse reinforcement, are taken in the ratios. Therefore, reader should keep in mind that, there is a wide variety of other parameters in the cases.

As the aim in the evaluations is based on analyses of the buildings, not the design, all material factors are taken as unity in the modelling and in some cases, infill-walls may significantly contribute lateral strength and rigidity. In order to focus on the given parameters solely, no irregularity exists in the models. For that reason, the models may be assumed to benefit all the overstrength factors and positive circumstances. Performances of some buildings may seem to be more than satisfactory when the given cases considered due to these assumptions.

The collapse case for 50% probability (0.2 g) and immediate occupancy (IO) for 2% probability (0.6 g) of exceedance is not given in the table as there is no building in these groups. The ratios in the table is an ascending manner since if a building satisfies the IO level, it obviously satisfy the LS level which has lower requirements.

4.4 *Observations on performance ratios*

Based on 96 capacity curves and 288 performance evaluation instances given in table 5, following observations are made.

1. Only two thirds of TEC-1975 buildings satisfy LS performance level for 10% probability of exceedance in 50 years earthquake, which is the design goal for the seismic design approach (Case 1). Buildings beyond CP level are more than 30%, which is unacceptable as the number of possible casualties considered. The situation is more severe for 0.6 g earthquake as nearly 60% of the buildings are in collapse state. This implies the weakness of the buildings designed per 1975-TEC.
2. Nearly all of the TEC-1998 buildings satisfy LS level for 0.4 g earthquake and around 17% are in collapse state for 0.6 g earthquake (Case 2). These figures when taken into account with TEC-1975 values, show great improvement with the more recent earthquake code.
3. When transverse reinforcement specifications are fully complied with TEC-1975 buildings, about 80% of them satisfy LS for 0.4 g earthquake (Case 3). However, 17% of buildings are still in collapse state. In addition, for the loadings beyond TEC-2007 design earthquake (0.6 g) more than 40% is in collapse state.
4. If transverse reinforcement specifications are fully complied with TEC-1998 buildings, they all satisfy LS level for both 0.4 g and 0.6 g earthquakes (Case 4). This emphasizes that when TEC-1998 conditions are satisfied buildings seismic performance may be very adequate even for rare earthquakes (keeping in mind that irregularity effects are not included). However, even it is not taken as a performance goal for residential buildings in TEC-2007, the buildings may be preferred to be at IO level for frequent earthquakes. Nearly half of them cannot satisfy this.
5. When cases 1–3 and 2–4 are evaluated together, it has seen that effect of transverse reinforcement detailing is less pronounced for IO performance level. That is expected as IO level is at the beginning of nonlinear zone, where the need for transverse reinforcement for confinement of RC members just arises.
6. If transverse reinforcement specifications are not satisfied for TEC-1975 buildings (Case 5) about half of the buildings are collapsed for 0.4 g and 70% for 0.6 g earthquake. It is less

Table 5. Ratio of buildings satisfying TEC-2007 criteria for the given performance level and loading.

No.	Seismic load level case	50% in 50 years (0.2 g)		10% in 50 years (0.4 g)			2% in 50 years (0.6 g)		# of instance
		IO	LS	IO	LS	CP	LS	CP	
1	TEC-1975	0.229	1.000	0.063	0.667	0.688	0.375	0.438	48
2	TEC-1998	0.521	1.000	0.021	0.979	0.979	0.833	0.833	48
3	TEC-1975 and conforming transverse reinforcement	0.250	1.000	0.000	0.792	0.834	0.458	0.583	24
4	TEC-1998 and conforming transverse reinforcement	0.542	1.000	0.000	1.000	1.000	1.000	1.000	24
5	TEC-1975 and 200 mm transverse reinforcement	0.208	1.000	0.000	0.542	0.542	0.292	0.292	24
6	TEC-1998 and 200 mm transverse reinforcement	0.500	1.000	0.000	0.958	0.958	0.667	0.667	24
7	TEC-1975 and 10 MPa concrete	0.208	1.000	0.042	0.500	0.542	0.167	0.292	24
8	TEC-1975 and 16 MPa concrete	0.250	1.000	0.083	0.833	0.833	0.583	0.583	24
9	TEC-1998 and 16 MPa concrete	0.500	1.000	0.000	0.958	0.958	0.667	0.667	24
10	TEC-1998 and 25 MPa concrete	0.500	1.000	0.000	1.000	1.000	1.000	1.000	24
11	No load carrying infill-wall	0.250	1.000	0.000	0.771	0.792	0.542	0.584	48
12	Load carrying infill-wall	0.500	1.000	0.083	0.875	0.875	0.667	0.688	48
13	2- story buildings	0.844	1.000	0.125	0.969	1.000	0.875	0.906	32
14	4- story buildings	0.188	1.000	0.000	0.625	0.625	0.438	0.438	32
15	7- story buildings	0.094	1.000	0.000	0.875	0.875	0.500	0.563	32
16	2- story buildings and TEC-1975	0.688	1.000	0.188	0.938	1.000	0.750	0.813	16
17	2- story buildings and TEC-1998	1.000	1.000	0.063	1.000	1.000	1.000	1.000	16
18	4- story buildings and TEC-1975	0.000	1.000	0.000	0.313	0.313	0.125	0.125	16
19	4- story buildings and TEC-1998	0.375	1.000	0.000	0.938	0.938	0.750	0.750	16
20	7- story buildings and TEC-1975	0.000	1.000	0.000	0.750	0.750	0.250	0.375	16
21	7- story buildings and TEC-1998	0.188	1.000	0.000	1.000	1.000	0.750	0.750	16
22	2- story buildings w/o load carrying infill wall	0.688	1.000	0.000	0.938	1.000	0.750	0.813	16
23	2- story buildings with load carrying infill wall	1.000	1.000	0.250	1.000	1.000	1.000	1.000	16
24	4- story buildings w/o load carrying infill wall	0.063	1.000	0.000	0.500	0.500	0.375	0.375	16
25	4- story buildings with load carrying infill wall	0.313	1.000	0.000	0.750	0.750	0.500	0.500	16
26	7- story buildings w/o load carrying infill wall	0.000	1.000	0.000	0.875	0.875	0.500	0.563	16
27	7- story buildings with load carrying infill wall	0.188	1.000	0.000	0.875	0.875	0.500	0.563	16

emphasized for TEC-1998 buildings (Case 6). Approximately 96% of buildings seem to be satisfying LS level for 0.4 g earthquake. Nevertheless, keep in mind that this is when all benefits of overstrength factors are accounted and without any irregularity. Also, no shear failure happens to be observed in the corresponding models, but it is a source of possible problem. Even in this case, for more severe loadings 1/3 of them are in collapse state (0.6 g earthquake).

7. Transverse reinforcement parameter seems to be more important for higher damage levels as CP and for pre-modern code buildings. Ozmen (2005) is also investigated this parameter by comparing the area under capacity curves of the pre-modern code buildings up to collapse point as an indication of dissipated energy. As the ratio is determined up to collapse point, it may be assumed as given for CP level. He gives the ratio of change between different transverse amount values as 43% for 4 story, and 67% for 7 story buildings. Although, it is evaluated in a very different way similar figures has been reported.
8. When the given values are considered, concrete strength is significant for TEC-1975 buildings seismic performance but in a lesser extent for IO level (Case 7 and 8). For TEC-1998 buildings (Case 9 and 10), it seems to be not important for IO and not significant for LS levels. Still, for more severe loadings (0.6 g) it may affect building performance noticeably.
9. Load carrying infill-walls are observed to contribute the seismic performance of buildings, as the performances of the buildings are better for Case 12 than Case 11. Note that the load carrying infill-walls in the models are located without much disturbance to the center of rigidity in plan and without discontinuity in vertical direction. If this is not the case, infill-walls may have negative effects on the building behaviour (Inel & Ozmen 2008). Their contribution is more effective for IO level and decreases with increasing seismic loading and damage level.
10. For the sake of number of stories (Cases 13–15), low-rise RC buildings have the best seismic performance. Nearly all of them satisfy LS level for 0.4 g earthquake and more than 85% of them for even 0.6 g earthquake of rare loading. Nearly 85% of them are at IO level for 0.2 g earthquake. 4-story buildings have the worst performance among them with comparable performance with 7-story buildings. This may be attributable to the given more care to the higher rise buildings during design stage and lesser drift (not displacement) demands because of their higher period. There are parallel findings in the literature both theoretical (Inel *et al* 2008c) and observational after experienced earthquakes (Inel *et al* 2013).
11. The cases from 16 to 21 evaluate the number of story for both pre-modern and modern codes. The most of buildings observed to have inadequate seismic performance are found to be TEC-1975 buildings. The poor performance of 4-story buildings is obvious. Although the performance is somewhat improved for the TEC-1998 buildings, they are still the least satisfactory result for frequent and design earthquakes. Yet, the 4-story buildings are the ones most benefitted from the code change. The 2-story TEC-1998 buildings have a very good seismic performance as pointed out by previous studies (Sezen *et al* 2003; Ozcebe 2004). Ozmen (2005) by the previously mentioned methodology gives 77% differences for seismic performances of the buildings with 4 and 7 stories. As the ratio is determined up to collapse point, this difference may be taken as similar with the CP level of the current study.
12. For the IO level, an immense difference arises in comparison of the performances between two and seven story buildings by nearly nine times. The supporting result was evident after Simav Turkey earthquake (Inel *et al* 2013). The ratio of the slightly damaged buildings (normalized values with all buildings with the same number of story) between two and seven story ones are observed to be 4.2 times. As the ratio significantly changes with the denominator, the differences seem reasonable enough to show the order of the figures.

13. If the change in effect of load carrying infill-walls is evaluated; it is clearly less emphasized as the number of stories and level of damage increases (Cases 22–27). It is seen that all values for the performance of 2-story buildings in the table (Case 22, 23) is significantly improved whereas the performance of 7-story buildings is not affected at all for design and maximum earthquakes (Cases 26, 27). The 4-story buildings seem to be between 2- and 7-story buildings (Case 24, 25). Dimension of the members in the buildings is strongly related with number of stories while dimension of infill-walls depends on architectural needs and tends to be the same in all stories. It is very understandable as the smaller members in the 2-story buildings are more susceptible to the effects of infill-walls when compared to stronger elements in the higher buildings. As the displacements become higher, the brittle infill-walls come out of the picture. This observation is also in parallel with the other previous studies in literature (Inel & Ozmen 2008).

5. Summary and conclusions

Main parameters affecting seismic performance of low and mid-rise RC buildings, such as seismic code as pre-modern and modern, amount of transverse reinforcement, concrete strength, infill-wall contribution and number of stories are investigated in this paper. Proper representation of the existing RC building stock is established according to the field and archive inventory study. Models with different cases of considered parameters are evaluated per TEC-2007. Displacement capacities for Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) are determined. Ratios of building models satisfying these criteria are given for seismic loadings with probability of exceedance of 50%, 10% and 2% in 50 years. Many readers may know if the effect of given parameters are positive or negative. Therefore giving quantitative evaluations is important.

Different performance levels at different levels of seismic loadings are considered in the study and evaluation for all of them may not be practical and easy to follow. The buildings satisfying Life Safety (LS) level under design earthquake loading (0.4 g for TEC-2007) may be taken as a basis for the quantitative evaluations as it is the main design goal. The IO level for frequent earthquake loading (0.2 g) and CP level for maximum earthquake (0.6 g) may be taken as secondary objectives. So, they can be considered to decide whether the effect is increasing or diminishing for lesser and higher seismic loads and damage states. Hence, three performance objectives are considered in the following findings and observations; IO, LS and CP performance levels under the frequent, design and maximum earthquake event loadings.

The probability of an event is equal to the number of occurrence of the event divided by the total possible cases, if the considered number of cases is high enough to represent the space. In this meaning, given numbers in the table 5 may be seen as an indicator of the probability of the buildings to be in the given performance levels under the considered seismic loadings. This sense may be kept in mind when evaluating the given conclusions.

- Modern code specifications improve the seismic behaviour for the targeted performance objectives. Statistical evaluation of all buildings per pre-modern code and those per modern code shows that the performance improvement in all considered earthquake loadings is obvious and significant. Only 23% of buildings per the pre-modern code satisfy IO performance objective while this ratio is 52% for the buildings per the modern code. Similarly, LS performance objective is satisfied in 66% and 98% of buildings per the pre-modern and modern code, respectively. These numbers are 44% and 83% in CP performance objective for the buildings per the pre-modern and modern code, respectively. Consequently, the modern code provisions improve the seismic performance by approximately 50%. For IO level the improvement increases to 125% and, for CP level to 90%.

- Amount of transverse reinforcement is more important for pre-modern code buildings. The difference is nearly 50% for LS performance objective and increases up to almost 100% for CP objective. For IO level, it is less emphasized. Modern code buildings seem to be not much affected by the amount of transverse reinforcement, except for the CP case. For CP level, 50% improvement is observed.
- Concrete strength, as an important factor for ductility, has similar results with the amount of transverse reinforcement. The seismic performance improvement is obvious for LS objective from the comparison of TEC-1975 10 MPa and TEC-1975 16 MPa buildings. The ratio of buildings satisfying LS objective increases from almost 50% to 83% by increasing concrete strength from 10 MPa to 16 MPa, pointing an increase by 66%. The concrete strength does not affect the seismic performance of modern buildings except for CP objective. In general, the effect increases with increasing damage states while it is limited for IO objective.
- Infill-walls have significant positive effect for IO performance objective while their contribution is limited for LS and CP performance objectives. The ratio of buildings satisfying IO performance objective increases from 25% to 50% when the load-carrying infill walls are considered in modelling meaning a 100% improvement. After IO objective, infill-wall contribution rapidly diminishes with increasing damage due to their brittle nature. Infill-wall contribution is also limited for high story buildings due to stronger RC members. For LS objective, the satisfaction ratio with and without infill-wall contribution is 77% and 88%, respectively implying an improvement by nearly 15%.
- Low story buildings have better seismic performance compared to the mid-rise buildings. The ratios of buildings satisfying IO performance objective are 84%, 19% and 9% for 2-, 4- and 7-story buildings, respectively, indicating the decrease in performance as the number of story increases. Similarly, LS performance objective is satisfied in 97%, 62% and 88% of 2-, 4- and 7-story buildings, respectively. These numbers are 91%, 44% and 56% in CP objective for 2-, 4- and 7-story buildings, respectively. Low story buildings has 55% percent more satisfaction ratio in LS level when compared to the higher story ones. In LS and CP performance objectives, the poor performance of 4-story buildings is obvious as pointed out in previous studies and earthquake reports related to Turkey.

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