Effect of Material Strength and Reinforcement Detailing on Displacement Capacity of Existing RC Buildings

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SUMMARY
This study aims to evaluate effect of material strength and lateral reinforcement detailing on displacement capacity of existing low and mid-rise RC building stock by nonlinear static analysis. Models reflecting the existing RC building stock are established according to an inventory study. Different cases of considered parameters are evaluated per Turkish Earthquake Code-2007. The parameters are: number of story, seismic code as modern and pre-modern and infill-wall contribution. Displacement capacities for Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) are determined. The observations are made based on 864 capacity curves and 2592 performance evaluation instances. It is found that effect of material strength and lateral reinforcement detailing is not significant for IO level but may reduce displacement capacity by 50% for LS and 58% for CP level under considered circumstances. The effect increases with increasing number of story and excursion in the plastic zone.

Keywords: Concrete, displacement capacity, lateral reinforcement, nonlinear analysis, performance level.

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. 1992 Erzincan, 1999 Kocaeli, 1999 Duzce, 2003 Bingol) has emphasized inadequate seismic performance of these buildings, most of which are less than eight stories in height. Insufficient concrete strength and improper detailing are one of the important reasons of these poor performances (Sezen et al., 2003; Ozcebe 2004; Akkar et al., 2005; Inel et al., 2008).

This study aims to evaluate effect of material strength and detailing on displacement capacity of existing low and mid-rise RC building stock by nonlinear static analysis.

After a detailed investigation of existing buildings in Turkey (for approximately 500 buildings) general characteristics of the stock are determined. The building characteristics are thought to be in resemblance with other developing countries as the building codes are similar with other earthquake prone regions. Using this data building models representing the existing stock are established. The parameters for the investigation are number of stories (2, 4 and 7 story), design code as pre-modern and modern, compliance to the code, material quality, existence of load bearing infill walls. Four hundred and thirty two, 3D building models reflecting different cases are analyzed to take into consideration of all the parameters.

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. For the effect of transverse steel detailing two different cases are considered as code-conforming and transverse reinforcement with only peripheral stirrups with 200 mm spacing to reflect ductile and non-ductile detailing, respectively.

Capacity curves of the models are obtained using nonlinear static analyses which are performed using SAP2000. Beam and column elements are modeled as nonlinear frame elements with lumped plasticity by defining plastic hinges at both ends of beams and columns. Effect of infill walls is modeled through diagonal struts as suggested in FEMA-356. Shear hinges take into account possible shear failures in existing reinforced concrete buildings. Displacement capacities are determined at different performance levels Immediate Occupancy, Life Safety and Collapse Prevention) according to 2007 Turkish Earthquake Code.

Evaluations based on the capacity curves, displacement capacities and observed behaviour of the buildings are made. The findings of the study are useful for understanding effect of material strength and transverse reinforcement detailing on displacement capacity of existing low and mid-rise RC buildings. The outcomes may be valuable for seismic risk assessment studies.

2. DESCRIPTION OF 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 buildings are given in Figure 2.1. The load carrying infill-walls are shown in figure by shaded areas.

The outcomes of detailed field and archive investigation including 475 real residential RC buildings, 40351 column and 3123 beam elements established building models (Inel et al., 2009). Values of more than 30 key parameters like 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 and section dimensions and reinforcement detailing for member level are taken into consideration.

The selected reference buildings are designed according to pre-modern and modern Turkish Earthquake Codes (TEC-75 and TEC-98), considering both gravity and seismic loads (a design ground acceleration of 0.4 g and soil class Z3 that is similar to class C soil of FEMA-356 is assumed). 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. Two different spacing are considered as code-conforming and transverse reinforcement with only peripheral stirrups with 200 mm spacing to reflect ductile and non-ductile detailing, respectively. The parameters and corresponding cases investigated in scope of the study are given in Table 2.1.

Note that existence of infill-wall means that the infill-walls (not all of them) satisfying TEC-2007 criteria are modeled 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 loads are taken into account. The infill-wall amount satisfying TEC-2007 criteria in the principal directions are determined by inventory study and not an arbitrary amount. Design code is only assumed for dimensioning members and longitudinal reinforcement. Lateral reinforcement detailing is taken as a separate case.

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. Then using the outcome member size and reinforcements, structures are modeled 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 modeled as given in the design.

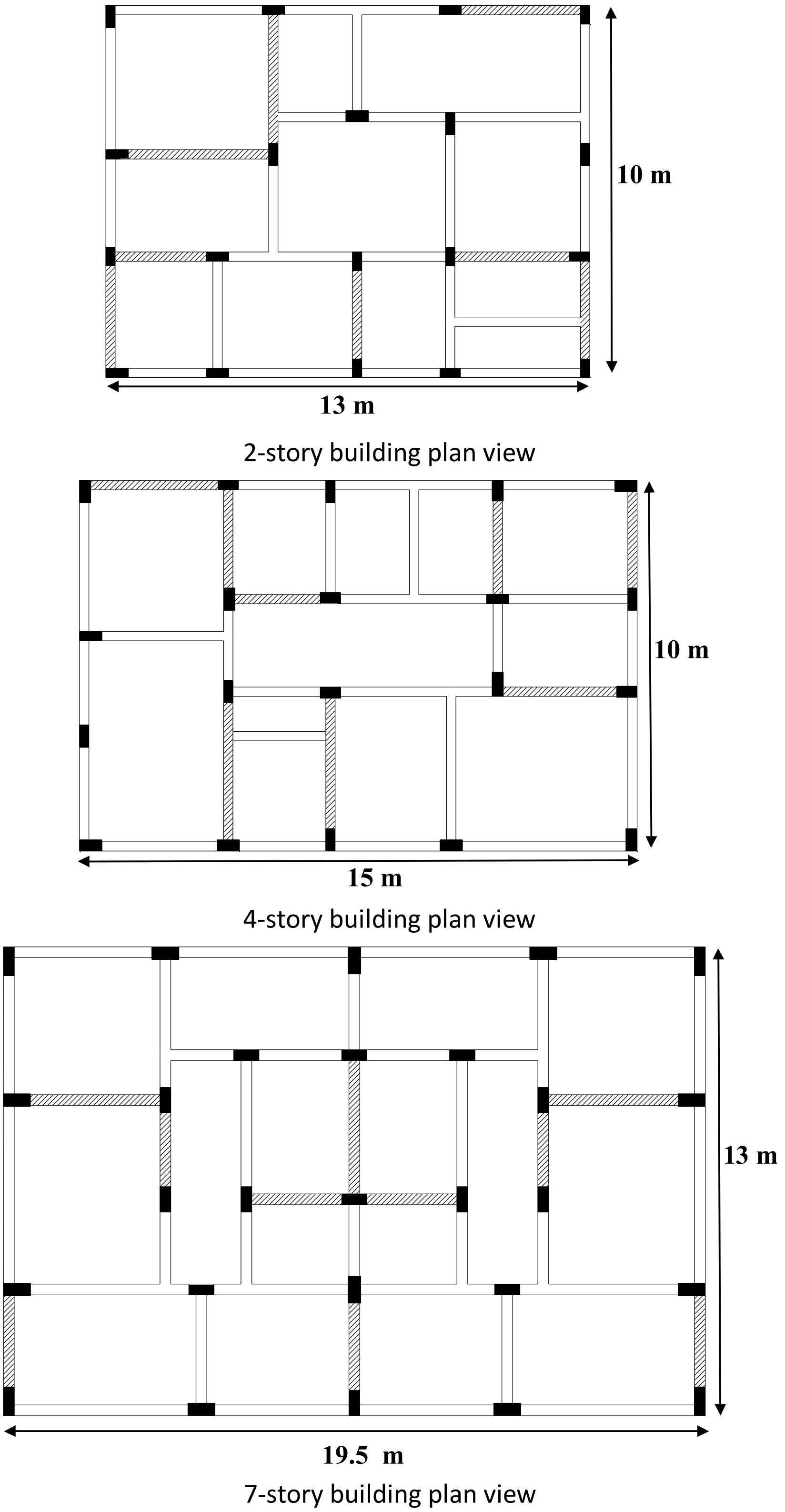


Figure 2.1. Plan view of the considered buildings (load carrying infill-walls are shaded)

Nonlinear static analyses have been performed using SAP2000 Nonlinear that is a general-purpose structural analysis program (SAP2000). Three-dimensional model of each structure is created in SAP2000 to carry out nonlinear static analysis. Beam and column elements are modelled as nonlinear frame elements with lumped plasticity by defining plastic hinges at both ends of beams and columns.

Table 2.1. Parameters investigated in scope of the study

Parameter	Story #	Design Code	Load carrying infill-wall	Concrete Strenght	Lateral Reinforcement
Cases	2	TEC-75	Exist	C10 (TEC-75)	Conforming TEC-75
	4	TEC-98	Non	C16 (Both codes)	Conforming TEC-98
	7			C25 (TEC-98)	200 mm spacing without hooks

As shown in Figure 2.2, five points labeled A, B, C, D, and E define force-deformation behavior of a plastic hinge. The values assigned to each of these points vary depending on type of element, material properties, longitudinal and transverse steel content, and axial load level on the element. The definition of user-defined 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 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 assumed to be half of the section depth as recommended in 2007 Turkish Earthquake Code. Also, effective stiffness values are obtained per the code; 0.4EI for beams and values between 0.4 and 0.8EI depending on axial load level for columns.

In 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.

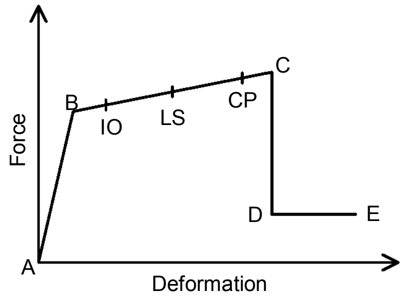


Figure 2.2. Force-Deformation relationship of a typical plastic hinge

Effect of infill walls are modeled through diagonal struts as suggested in TEC-2007 and FEMA-356. Nonlinear behavior 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.

Table 2.2. Range of some important properties of the building models

Parameter	Minimum	Maximum	Mean
Seismic Weight (kN)	2440	19677	9213
Period (s)	0.22	0.92	0.52
Lateral Strength Ratio	0.13	0.79	0.38

Range of some important properties of the building models is given in Table 2.2. "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 two story buildings constructed according to TEC-98 and attributable to higher overstrength ratio because of minimum requirements of code and infill-wall contributions.

3. PUSHOVER ANALYSIS

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 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.

4. DISPLACEMENT CAPACITIES

Performance evaluations are performed using TEC-2007. Three performance levels, Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) are considered as specified in this code and several other international guidelines such as FEMA-356 and ATC-40. Criteria given in the code for three performance levels are listed in Table 4.1. The most critical of the given criteria are taken for the IO level.

Table 4.1. Performance levels and criteria provided in Turkish Earthquake Code-2007

Performance Level	**Performance Criteria**
Immediate Occupancy (IO) (post-earthquake damage state that remains safe to occupy, essentially retains the pre-earthquake design strength and stiffness of the structure)	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) (the post-earthquake damage state that includes damage to structural components but retains a margin against onset of partial or total collapse)	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) (post-earthquake damage state that includes damage to structural components such that the structure continues to support gravity loads but retains no margin against collapse)	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.

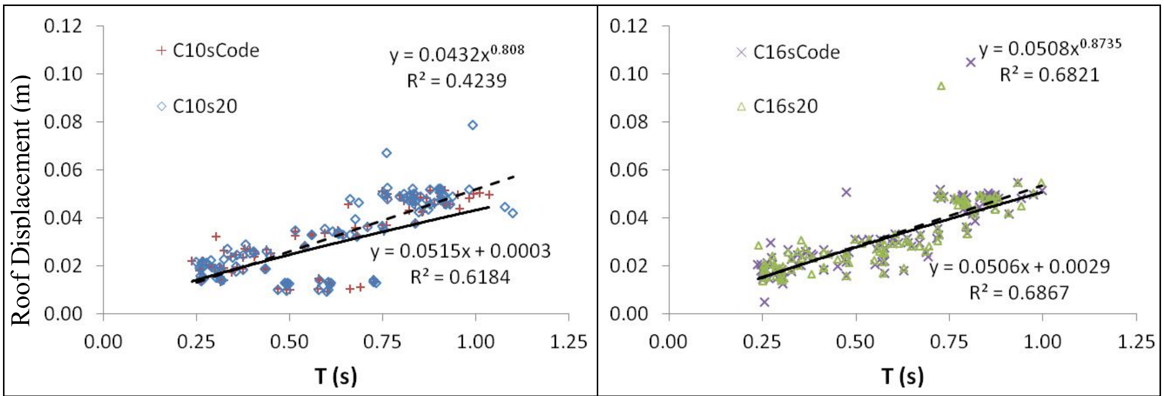
However, as the criteria number 3 for LS and CP levels (same) is related to the yielding of the members, it is not taken into consideration for the scope of the study. As the yielding is more related with the flexural strength capacities of the members it may take very different values for different models changing with redistribution of forces among structural elements. As the strength has a very flat plateau after yielding this criteria is very unstable and may take very different values with small changes. In addition, in many models due to strong column-weak beam this condition does not occur at all.

As the criteria number 4 for LS, may even become valid with only one element it is not thought to be representative for the building system. Therefore, it is also ignored and evaluations are based on criteria number 2 for LS. With same considerations criteria number 2 of is also selected for evaluations for CP.

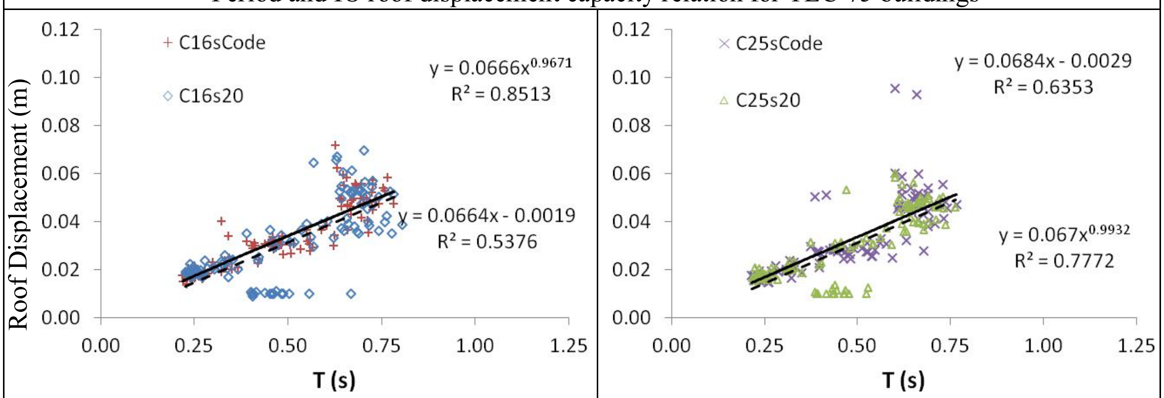
Pushover analysis data and criteria of TEC-2007 were used to determine global displacement drift (defined as lateral displacement at roof level) of each building corresponding to the considered performance levels. Building period and roof displacement capacities are given in Figures 4.1-4.3 for different cases and performance levels.

Mean values of the different cases of buildings are also examined and evaluated (Table 4.2-4.3). It should be noted that code conforming lateral reinforcement is different for the TEC-75 and TEC-98 buildings. The lateral reinforcement for TEC-75 buildings conforms TEC-75 code and, the lateral reinforcement for TEC-98 buildings is per TEC-98.

The mean values for IO level is not given as the values are very close to each other and comparison is not meaningful. The "Ratio" in the tables is the ratio of the displacement capacity to the best case. The "sCode" in the tables and figures stands for the case with lateral reinforcement conforming to the corresponding code and "s20" is for the case with 200 mm spacing lateral reinforcement and without hooks. The number after "C" refers the compressive concrete strength of the building.

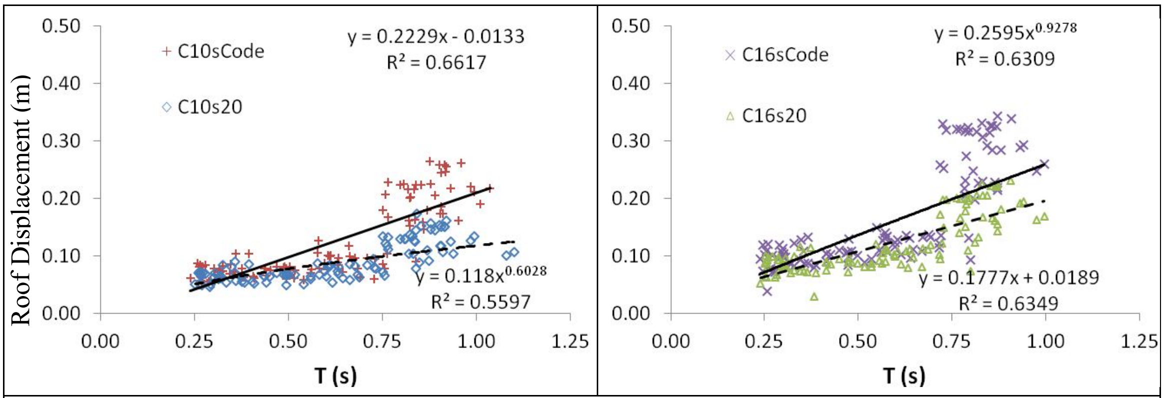


Period and IO roof displacement capacity relation for TEC-75 buildings

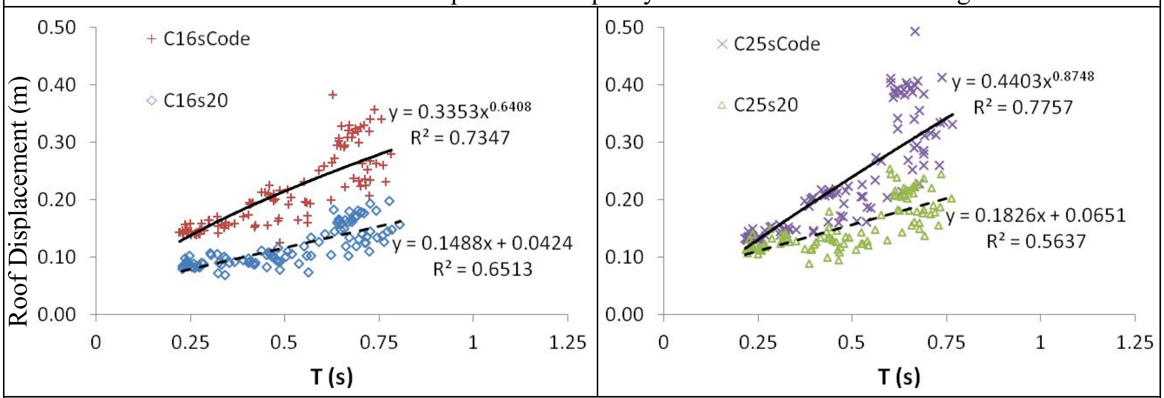


Period and IO roof displacement capacity relation for TEC-98 buildings

Figure 4.1. Period and IO roof displacement capacity relation for TEC-75 and TEC-98 buildings

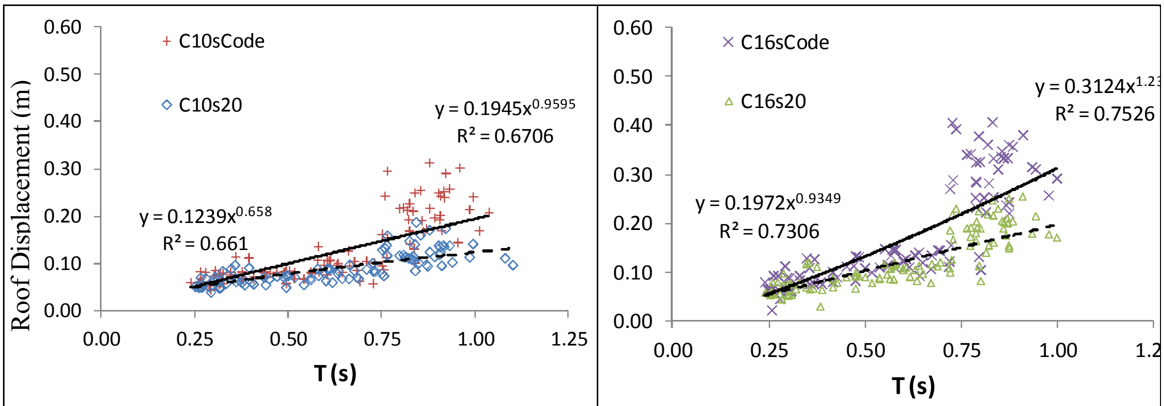


Period and LS roof displacement capacity relation for TEC-75 buildings

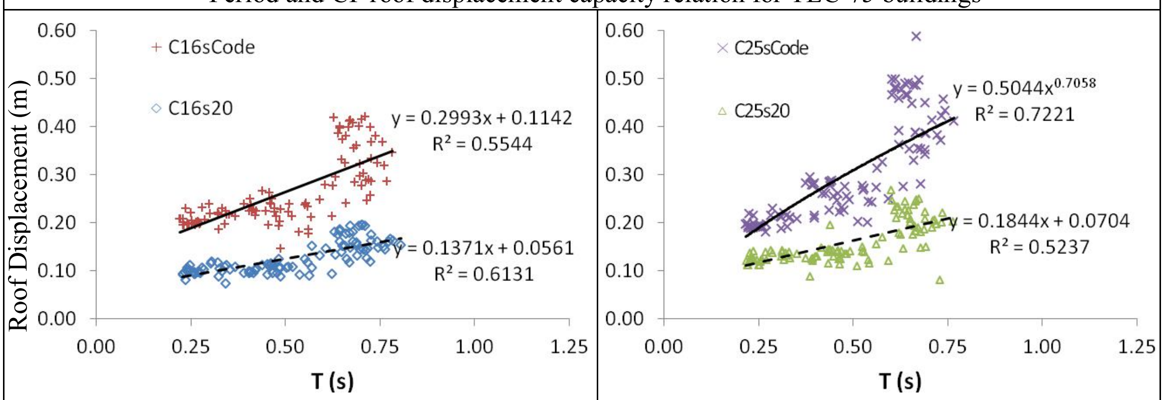


Period and LS roof displacement capacity relation for TEC-98 buildings

Figure 4.2. Period and LS roof displacement capacity relation for TEC-75 and TEC-98 buildings



Period and CP roof displacement capacity relation for TEC-75 buildings



Period and CP roof displacement capacity relation for TEC-98 buildings

Figure 4.3. Period and CP roof displacement capacity relation for TEC-75 and TEC-98 buildings

Table 4.2. The LS level mean roof displacement demands for different cases of the buildings

	C10s20	Ratio	C16s20	Ratio	C10sYon	Ratio	C16sYon	Ratio
TEC-75	0.088	0.54	0.122	0.74	0.122	0.74	0.165	1.00
	C16s20	Ratio	C25s20	Ratio	C16sYon	Ratio	C25sYon	Ratio
TEC-98	0.116	0.50	0.151	0.65	0.213	0.92	0.232	1.00
	Mean				Ratio			
TEC-75	0.125				0.70			
TEC-98	0.178				1.00			

Table 4.3. The CP level mean roof displacement demands for different cases of the buildings

	C10s20	Ratio	C16s20	Ratio	C10sYon	Ratio	C16sYon	Ratio
TEC-75	0.090	0.52	0.122	0.71	0.127	0.74	0.172	1.00
	C16s20	Ratio	C25s20	Ratio	C16sYon	Ratio	C25sYon	Ratio
TEC-98	0.124	0.42	0.158	0.53	0.262	0.88	0.299	1.00
	Mean				Ratio			
TEC-75	0.128				0.61			
TEC-98	0.211				1.00			

4.1 Decreasing Capacity with Increasing Concrete Strength or Lateral Reinforcement Amount

One of the interesting result of the study, is the observation of the displacement capacity of some of the buildings being higher than the ones with greater concrete strength and/or higher amount of lateral reinforcement. It should be noted that, the number of these cases are limited. When it is first noticed these values are checked for possible errors. After they are confirmed, the physical reason is examined.

The displacement capacity of the buildings are controlled by the amount of members in damage states according to the strain values of the concrete in compression and longitudinal reinforcement in tension. Certain strain limits are determined in TEC-2007 for these. When the compressive strength of the concrete is increased or its properties get better due to better confinement with higher amount of lateral reinforcement, the depth of concrete block is decreased. Because the same amount of force can be supplied with smaller concrete area. The decrease in the depth of neutral axis increases the strain in longitudinal tension reinforcement. As the neutral axis depth is small when compared to the depth of the section small changes in the neutral axis depth may result in significant strain differences in longitudinal tension reinforcement.

Therefore, when the section damage state is controlled by the strain in longitudinal tension reinforcement, increase in concrete strength or amount of lateral reinforcement may decrease the displacement capacity of the building. For the strain in longitudinal tension reinforcement to be critical, of course compression forces on the section should be low. This is valid for columns with low level of axial load and beams. Consequently, this phenomenon is more significant for the buildings with less number of stories and more apparent for lower damage states.

5. SUMMARY AND CONCLUSIONS

The effect of concrete strength and amount of lateral reinforcement on displacement capacity of low and mid-rise RC buildings are investigated in this paper. Models reflecting the existing RC building stock are established according to the inventory study and 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. Differences in displacement capacities are examined. Based on 864 capacity curves and 2592 performance evaluation instances following observations are made:

- The effect of concrete strength and lateral reinforcement amount is least pronounced for the IO performance level. It is evident from the closer trendlines and mean values of displacement capacities for the different cases. It is an expected conclusion because the IO level is more related with the yielding of members that is not much affected by aforementioned parameters.
- For some cases, especially for low story buildings and performance criteria related with the beam damage, increase in concrete strength or amount of lateral reinforcement may decrease the displacement capacity. The reason for that is explained above. The performance level where these instances are mostly occurred is IO level. This is attributable to the fact that as the IO level is closer to the yielding, greater changes in the depth of neutral axis may occur around this point.
- Since the LS level is in further stages of the plastic displacements, the effect of concrete strength and amount of lateral reinforcement is more emphasized. It is evident from the trendlines in the figures and mean values of displacement capacities for the different cases in the table.
- When the Table 4.2 is examined for both TEC-75 and TEC-98 models the displacement capacities may reduce approximately 50% for the worst case (low concrete strength and low amount of lateral reinforcement) when compared to the code conforming lateral reinforcement with higher strength concrete. The displacement capacities significantly increase when concrete strength or lateral reinforcement get better values.
- Another interesting point is the limited effect of the lower concrete strength for the TEC-98 buildings (8%) if the lateral reinforcement is code conforming. However it should be kept in mind that the mean values get closer mostly due to lower story buildings.
- For high number of story buildings the differences in displacement capacities are more noticeable for LS level. This is clear from Figure 4.2 as the trendlines get apart with increasing period (number of story).
- Regardless of the concrete strength and lateral reinforcement case, on the average the TEC-75 buildings have 30% less displacement capacity, for the LS displacement level, when compared to the TEC-98 buildings. This is attributable to the more advanced and strict provisions of TEC-98. Of course, due to lower stiffness and strength, the displacement demands for TEC-75 buildings will be higher, resulting in a more severe condition.
- When CP displacement capacities are examined, it is seen that they are not much different than the ones for LS level, especially for TEC-75 buildings. This is incompliance with some other researchers' conclusion that for Turkish buildings displacement capacities for low and high damage levels are not distant (Booth et al., 2004; Ay and Erberik, 2008).
- The CP performance level is a more advanced plastic displacement point level when compared to LS. Compliant with this, the effect of concrete strength and lateral reinforcement case is more evident on the displacement capacity of the buildings as the ratios between best and the other cases are smaller compared to LS (Table 4.2-3).
- The change in concrete strength and lateral reinforcement amount may reduce CP displacement capacity up to 58% according to the considered circumstances. Changes in TEC-98 buildings are more significant. This is attributable to the higher displacement capacities of them and greater excursion of the buildings in the plastic zone.
- Regardless of the concrete strength and lateral reinforcement case, on the average the TEC-75 buildings have 39% less displacement capacity, for the CP displacement level, when compared to the TEC-98 buildings. This effect is also greater than the one for LS level may be credited to being a more advanced plastic displacement point.

- The change in displacement capacity for CP level with increasing number of story (period) is more obvious when compared to LS level as the trendlines are more apart.
- Like for all other performance levels, especially for some of the low story TEC-98 ones, buildings with lower concrete strength and/or lower amount of lateral reinforcement may have greater displacement capacities. Since this is a result not fully conforming with previous knowledge and expectations, it should be further investigated, especially with experimental studies, to have a more consistent code provisions.

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REFERENCES

Akkar, S., Sucuoglu, H., Yakut, A., (2005). Displacement based fragility functions for low- and mid-rise ordinary concrete buildings, *Earthquake Spectra* **21:4**, 901-927.
ATC-40 (1996). Seismic Evaluation and Retrofit of Concrete Buildings, Applied Technology Council, Vol 1. Washington, DC. USA.
Ay B. O. and Erberik, M. A., (2008). Vulnerability of Turkish low-rise and mid-rise reinforced concrete frame structures, *Journal of Earthquake Engineering*, **12**(S2), 2-11.
Booth, E., Spence, R. and Bird, J., **(**2004). Building vulnerability assessment using push-over methods-A Turkish case study, Proceedings of an international workshop on performance based seismic design concepts and implementation, Bled, Slovenia, 397-408.
FEMA-356 (2000). Prestandard and Commentary for Seismic Rehabilitation of Buildings, Report No. FEMA-356, Federal Emergency Management Agency, Washington, D.C..
Inel M, Ozmen HB, Bilgin H, (2008) Re-evaluation of building damages during recent earthquakes in Turkey, *Engineering Structures* **30**: 412-427.
Inel M., Ozmen H.B., Şenel Ş.M. ve Kayhan A.H. (2009). Mevcut Betonarme Binaların Yapısal Özelliklerinin Belirlenmesi, *Uluslararası Sakarya Sempozyumu*, 1-2 Ekim 2009, Sakarya, Türkiye.
Ozcebe G. (2004) Seismic assessment and rehabilitation of existing buildings, Tubitak research Report no: ICTAG YMAU I574, Ankara.
Ozmen H.B., M. İnel and H. Bilgin (2007). Betonarme Elemanların Doğrusal Ötesi Davranışlarının Modellenmesi, **6. Ulusal Deprem Mühendisliği Konferansı**, **Cilt II**:207-216, 16-20 Ekim 2007, İstanbul.
SAP2000, Integrated Finite Element Analysis and Design of Structures Basic Analysis Reference Manual, Computers and Structures, Inc., Berkeley, California, USA.
Sezen H, Whittaker AS, Elwood KJ, Mosalam KW. (2003). Performance of reinforced concrete buildings during the August 17, 1999 Kocaeli, Turkey earthquake, and the seismic design and construction practice in Turkey, *Engineering Structures* **25**, pp. 103–14
TS500 (2000), Design and Construction Specifications for Reinforced Concrete Structures, Turkish Standards Institute, Ankara, Turkey.
Turkish Earthquake Code (TEC-75) (1975). Specifications for buildings to be built in seismic areas. Ministry of Public Works and Settlement. Ankara, Turkey.
Turkish Earthquake Code (TEC-98) (1998). Specifications for buildings to be built in seismic areas. Ministry of Public Works and Settlement. Ankara, Turkey.
Turkish Earthquake Code (TEC-2007) (2007). Specifications for buildings to be built in seismic areas. Ministry of Public Works and Settlement. Ankara, Turkey.