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Earthquake performance investigation of R/C residential buildings in Turkey

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Abstract. The aim of this study is to determine the earthquake performances of reinforced concrete (R/C) residential buildings in Turkey and to analyze the parameters that affect the performance. The performance of Turkish residential buildings, determined by their levels of damage, directly relates to their structural systems. Damage parameters observed from previous earthquakes define structural parameters selected to be used in the present study. Five different types of frame R/C buildings were modeled. For the analysis, the model buildings vary according to the number of stories, column sizes, and reinforcement and concrete strength parameters. The analyses consider gravity forces and earthquake loads through 1975 and 2007 Turkish design codes. In a total of 720 different R/C buildings were investigated for the analysis to obtain capacity curves. A performance evaluation was employed by considering the Turkish design code (TDC-2007). The current study ignores irregularities such as soft stories or short columns. The study's analysis considers a comparison of the parameters' influence on the structural performance of the model buildings.

Keywords: earthquake performance evaluation; Turkish R/C residential buildings; Turkish Design Codes; pushover analyses; performance estimation

1. Introduction

Turkey is frequently the victim of destructive earthquakes. In 1999 Marmara and 2011 Van earthquakes in Turkey, majority of the existing buildings either sustained severe damage or collapsed. Similar types of damages, observed to a lesser extent in many earthquakes in Turkey, is similar to the Erzincan event during the 1939 (Mw=8) earthquake in which, 30,000 people died. The same Anatolian fault is also responsible for the Marmara earthquake (Bruneau 2002).

The metropolitan cities in Turkey such as Istanbul and Izmir are under high seismic risk. Population in these cities constantly increases over the last three decades due to migration from less developed regions of the country. During this population boom, most of the buildings that are typically low to mid rise reinforced concrete structures with infill walls, were generally not designed according to the current seismic design code, which was 1975 version of the Turkish

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Design Code (TDC, 1975). Also, the supervision in the construction phase of these buildings was not adequate (Erberik and Cullu 2006). Therefore, the majority of this building stock is generally composed of low-engineered buildings (Erberik 2008).

Observed structural damage after earthquakes in Turkey have of significant interest to many researchers (Sezen *et al.* 2003, Bal *et al.* 2007, Elnashai 1999, Inel *et al.* 2008, Yakut *et al.* 2005 and Dogangun 2004), and according to existing research recent earthquakes particularly affected three to seven story frame structures. These buildings are the ones generally designed for residential purposes. Most of them, complying with the 1975 Turkish design code or only considered the gravity loads. However, more recent construction of low- to mid-rise buildings complies with the 2007 Turkish design code.

A summary of the reasons for damage includes: poor concrete quality, incorrect detailing, inadequate cross sectioning, large spacing of stirrups, soft and weak story phenomenon, short column problems, incorrect arrangement of non-structural walls, insufficient shear walls, poor construction quality control. After the 1999 Marmara and Duzce earthquakes, the poor construction of buildings became quite apparent (Irtem *et al.* 2007, Arslan 2010 and Korkmaz 2009). Understanding the characteristics of damage and the reasons for the collapse of existing buildings in recent earthquakes will help to identify potential avenues for preventing damage and collapse of similar buildings in other parts of the world.

The present study aims to investigate the effects of parameters such as concrete and reinforcement strengths, column dimensions, and numbers of stories that directly relate to the safety of buildings in the presence of seismic events. The study also evaluates the 1975 and 2007 Turkish design codes to compare the differences between these two codes. Five different types of frame, R/C buildings with different openings constitute the models for evaluation. The analyses of these model buildings involve varying the numbers of stories, column sizes, and concrete reinforcement and concrete strength parameters. The analyses consider gravity forces (using 1975 and 2007 Turkish design codes) and earthquake loads. The dataset includes 720 different R/C model buildings and the capacity curves are the result of pushover analysis for each model. The investigation compares results from each model and determines earthquake resistance.

2. Development of Turkish design codes

The first Turkish design code for buildings, published in 1940, is similar to the Italian seismic code of that time. The base shear was a calculation of the product of a lateral force coefficient, and the weight of the building. The set coefficient value was equal to 0.10 regardless of geographic location. The base shear force, distributed over the height of the building, used a uniform load pattern. Calculation of earthquake loads for buildings employed a seismic code similar to U.S. practice in which calculation of earthquake loads were according to the Uniform Building Code (UBC 1997). Subsequent to 1940, published variations editions of the code extended through 1997.

In 1975, the Turkish design code proposed a spectrum coefficient, which is mostly dependent on the natural period of the building, a strict relationship between the dimension parallel to earthquake loads and structural height, and soil conditions. In comparison to the previous design codes, the 1975 code is modern in concept in that the code introduced the concept of ductile design with specifications for stirrups construction in earthquake prone areas.

In 1997, an updated Turkish design code gained attention for being revolutionary from the seismic design aspects for structures. This code incorporated earthquake resistant building design concepts for rigidity, stability, and strength and specified irregular types of buildings which had have seismic design faults both in plan and in vertical direction. The new code also included changes for calculating earthquakes' horizontal forces that act upon buildings during seismic events. The code changed the coefficients related to the importance of the buildings were changed.

An update of Turkish design code occurred most recently in 2007, and the Turkish design code 2007 (TDC-2007) evaluated existing RC buildings according to the principles that relate to their performance in an earthquake. With TDC-2007, determination of structural systems' performance during an earthquake and the resulting damage to RC buildings used linear or nonlinear analysis methods (Arslan 2010 and TDC 2007).

Currently, two codes in Turkey: TS- 500, building code requirements for reinforced concrete (the "building code",) and specification for structures to be built in disaster areas, (the "seismic design code") guide design and construction of reinforced concrete buildings. The building codes define requirements for proportioning and detailing reinforced concrete components, and they are partially similar to ACI-318 (ACI 1999).

The published design codes in most earthquake prone countries coincide with the date ranges and are similar in specifications. When the design codes for these countries are examined, the initial design codes dates back to 1940s. Modern earthquake calculations, from the subsequent 50 years have advanced details. Notably, contemporary design codes' revisions contain major changes after several important earthquakes.

3. Structural performance evaluation

During the last decade, pushover analysis has become a practical tool for estimating seismic demands of inelastic structures (ATC 40, FEMA 356, Eurocode-8, Otani et al., 2000). Conventional pushover analysis applies an invariant lateral force pattern, incrementally, to the structural model until achieving a predetermined target displacement This procedure accurately estimates low-rise buildings' global seismic response in which the first mode dominates (Saiidi and Sozen 1981, Fajfar and Gašperšič 1996, Gupta and Krawinkler 2000 and Shakeri *et al.* 2010).

Since conventional approaches underestimate structural performance of ductile frame systems, development of new approaches allow estimation of structural performance: Priestley and Kowalsky (1998) developed a new concept for defining structural design capacity. Yüksel and Polat (2005) proposed the first significant member yield, a global yield approach for RC frame structures. Miranda (2005) conceived of methods for evaluating seismic performance of existing reinforced concrete and emphasized simplified methods for identification of existing buildings based on the parameters that control structures' seismic demands. Miranda and Reyes (2002) approximated a method to estimate the maximum lateral drift demands in multistory buildings with non-uniform lateral stiffness which primarily in responds in the fundamental mode. Villarde (2007) presented a comprehensive review of the currently available analytical methods for assessing existing buildings' capacities to resist earthquake-induced collapse, identified limitations of these methods, described prior experiments which tested examples reaching collapse, and identified the requirements for accurate evaluation of a structure's seismic collapse capacity and the safety margin necessary to avoid such a collapse. García and Miranda (2010) suggested implementation of a probabilistic approach to estimate residual drift demands (e.g. residual roof, residual drift at specific stories, and maximum residual drift over all stories) during seismic performance-based assessment of existing multi-story buildings. Inel *et al.* (2008) evaluated seismic performance of the most common Turkish reinforced concrete building stock and considered nonlinear behavior of the components. To reflect existing construction practices, the current research selects a sample building set.

For the present study, the structural parameters used for the model buildings described earlier. are the result of observations performed after the earthquakes in Turkey. These parameters are: story number, concrete and steel strength, column size and number of spans. All model buildings' designs follow three different codes from different time periods. The model frame structures represent selection of five different types of spans as seen in Figs. 1-5 (Yenice 2010). The varied parameters for the models that result in 720 combinations are: 2-, 3-, 4- and 5-story frames, 30/30 and 40/40 column sizes, C10, C16 and C20 concrete strengths, and S220 and S420 steel classes. The analyses resulted in sketches of the capacity curves for each structure and determination of performance levels.

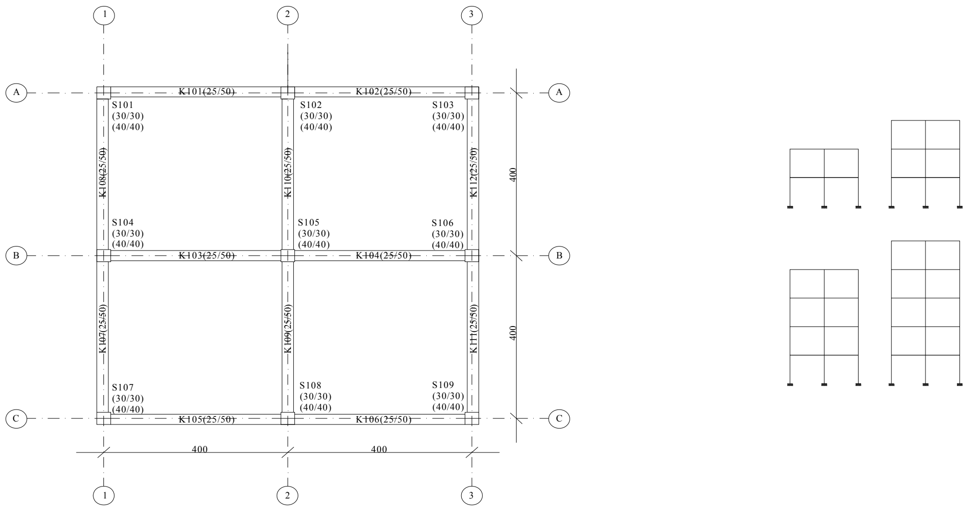


Fig. 1 Plan and elevation view for Type 1

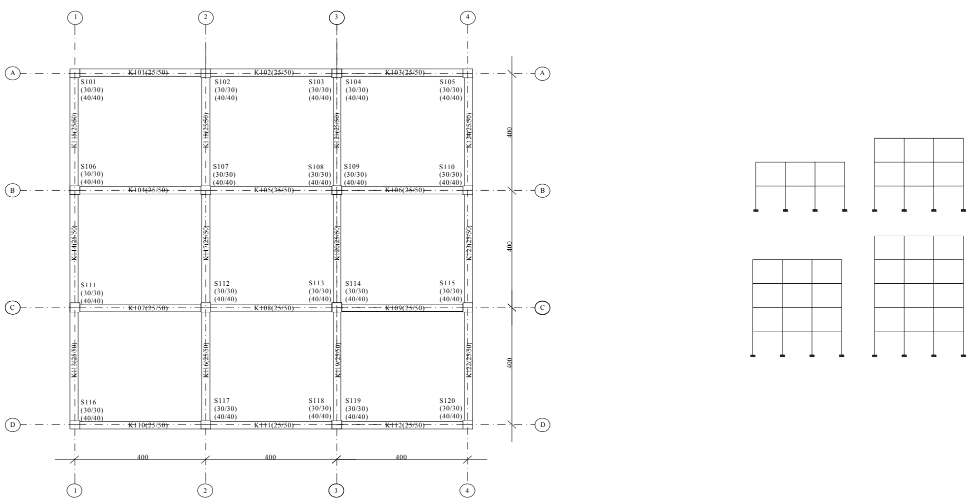


Fig. 2 Plan and elevation view for Type 2

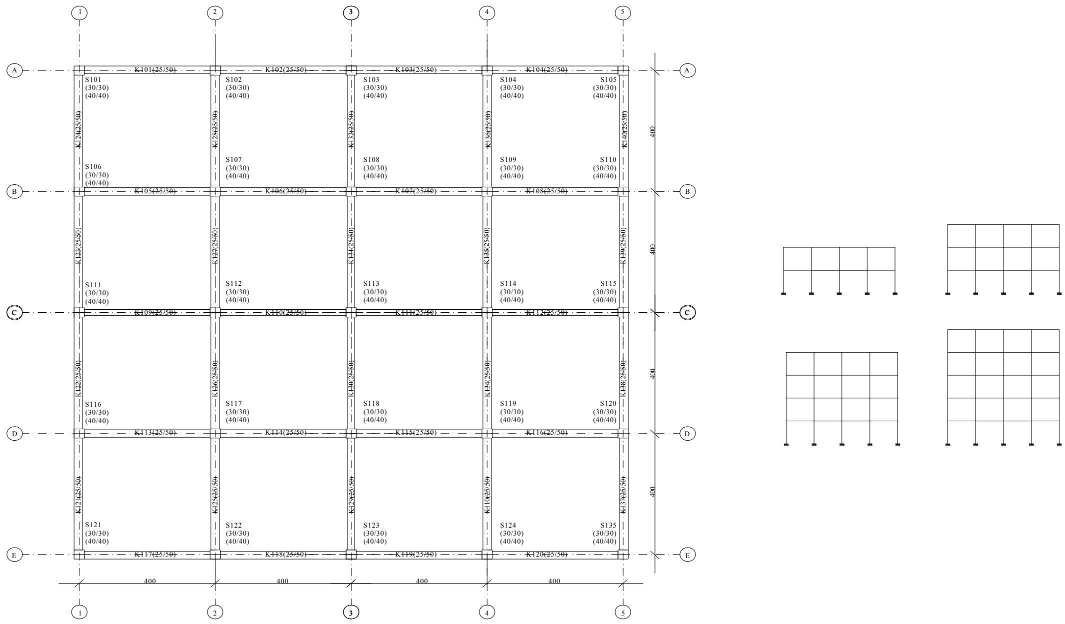


Fig. 3 Plan and elevation view for Type 3

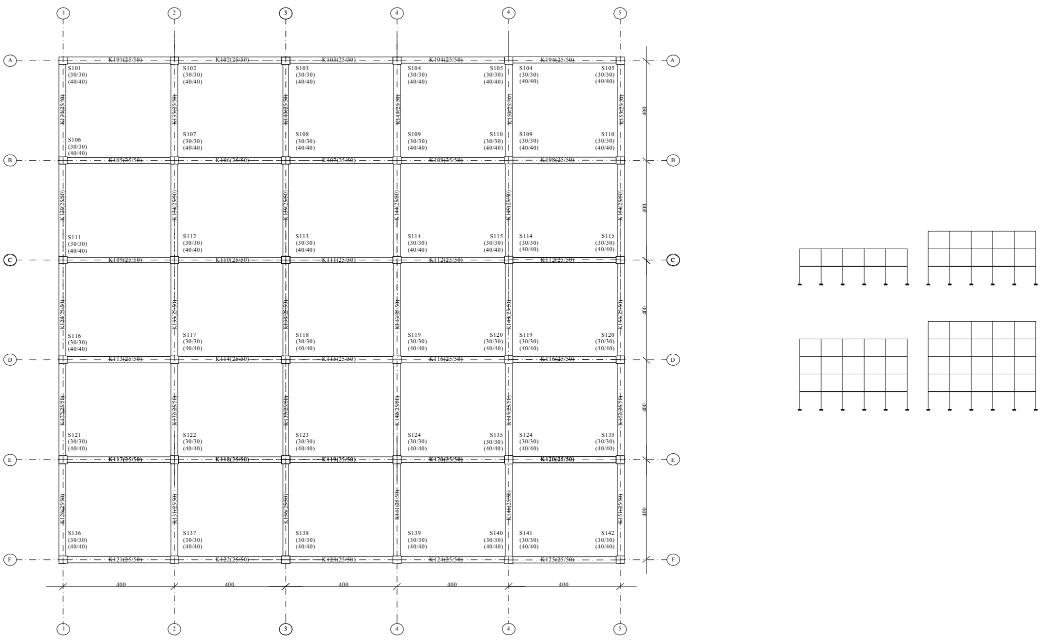


Fig. 4 Plan and elevation view for Type 4

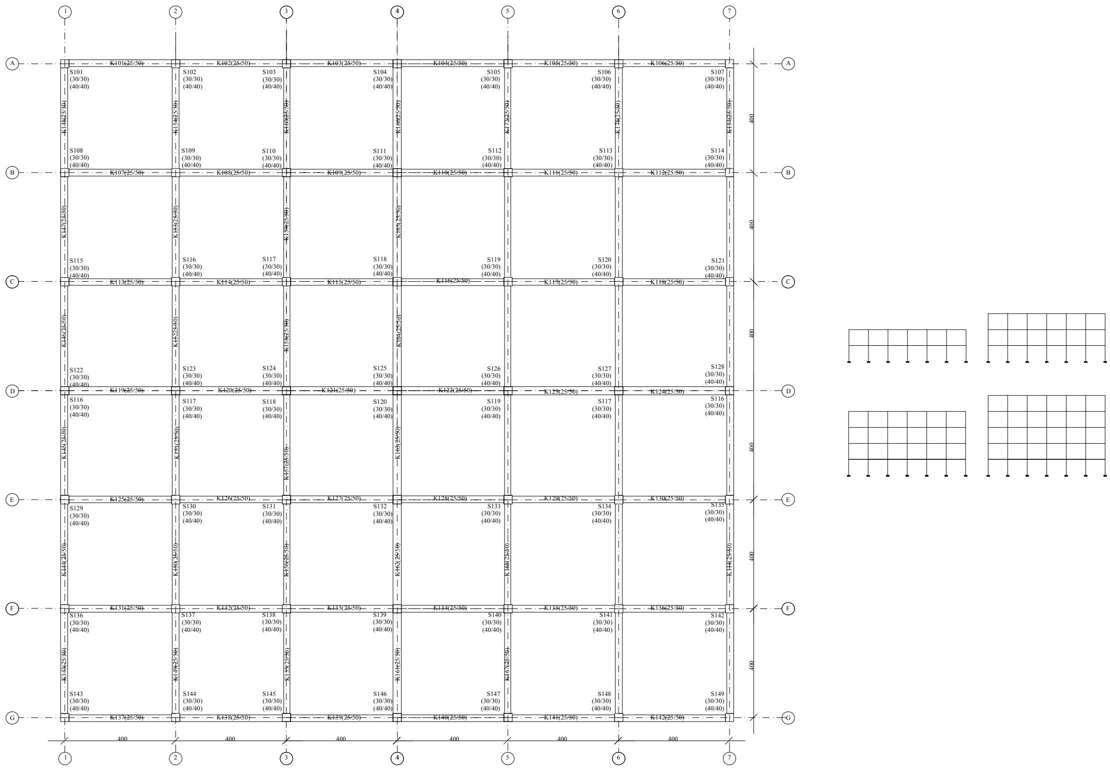


Fig. 5 Plan and elevation view for Type 5

Plastic hinge theory is used to define nonlinear behavior of structural materials. In this theory, plastic deformations are lumped at plastic hinges. At other sections between plastic hinges, material behavior is accepted as linear elastic. It is assumed that, plastic behavior is assigned with one-dimension bending moment for beams, two-dimension bending moment and axial force interaction for columns. Therefore, M3 hinges are used for beams and PMM hinges are used for columns and they are assigned at both ends of beams and columns.

Moment-plastic rotation relation of beams and columns are assumed as strengthening rigid plastic. Plastic hinge information of members as plastic rotations, -plastic moments (force-deformation behavior of plastic hinges) are taken from ATC 40 (ATC, 1996). Cracked section rigidity of beams, columns and shear walls are taken as recommended in FEMA 356 (FEMA, 2000). Shear capacity of structural members are checked to avoid brittle failure in the analyses.

Building models' nonlinear analyses as pushover analyses are realized with SAP2000 nonlinear analysis program (Wilson and Habibullah 1998). Since the building is symmetrical, pushover curves at X and Y directions are same. In pushover analysis, the behavior of building is characterized by a pushover curve that represents the relationship between the base shear force and the lateral displacement of the roof. This is a general trend in practice (Korkmaz and Karahan 2011).

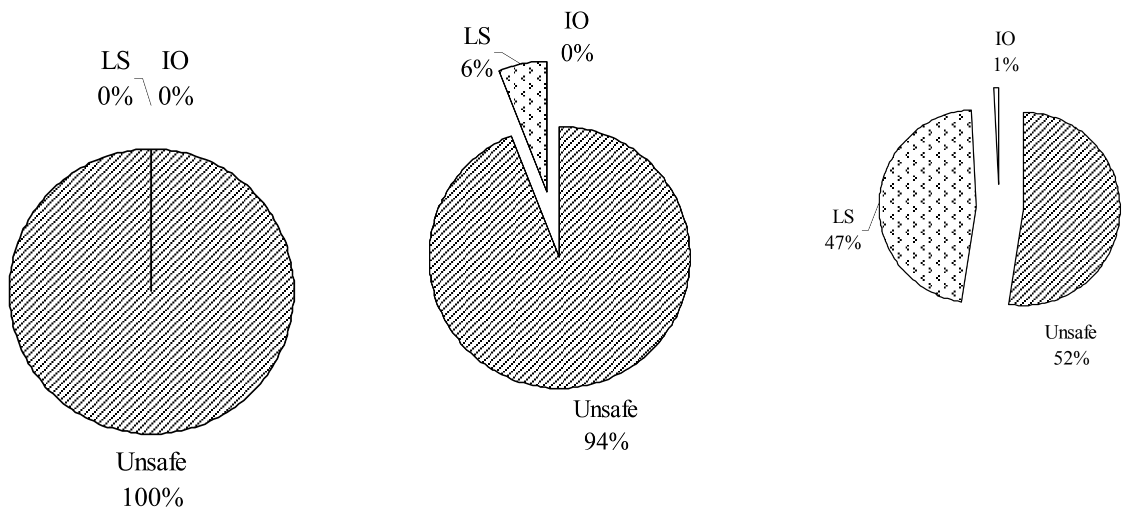
4. Analysis results

According to Turkish Design Code 2007, to determine the level of performance of reinforced concrete buildings, a set of analyses was carried out. According to the these analyses, which did not consider earthquake loads, none of the model buildings demonstrated the required performance of the model buildings designed according to the 1975 code, 6% provided the required level of performance, and of the buildings designed according to the 2007, 48% provided the required level of performance (See Fig. 6).

The parameters that affect a structure's earthquake performances appear in Figs. 7 through 10: Reinforcement in Fig. 7, concrete strength in Fig. 8, column size in Fig. 9, and number of stories in Fig. 10.

While maintaining all other parameters constant, just increasing reinforcement strength from S220 to S420 for 25% of the model buildings, results in a performance increase (See Fig. 7). On the other hand, if concrete strength increases from C10 to C20, 40% of the model buildings demonstrate a performance increase (See Fig. 8). When the column sizes increase, performance increases 20% (See Fig. 9).

When the story number increases, buildings' structural performances increase to approximately 20% as Figure 10 shows. Based on the TDC 2007, capacity curves for model buildings with 4 openings and C10 and S220 class materials for different stories have been constructed (See Fig. 11). Building weight increases with building height; however, base shear does not change in same proportion with the height. In other words, with building height increase, base shear Vt increases but Vt/W ratio decreases. Capacity curves for 5-story buildings according to three different approaches appear in Fig. 12. TDC 2007 has positive effects on building behavior.



(a) gravity force (b) 1975 (c) 2007

Fig. 6 Performance levels of structures designed according to (a) Gravity force, (b) 1975 code and (c) 2007 design code

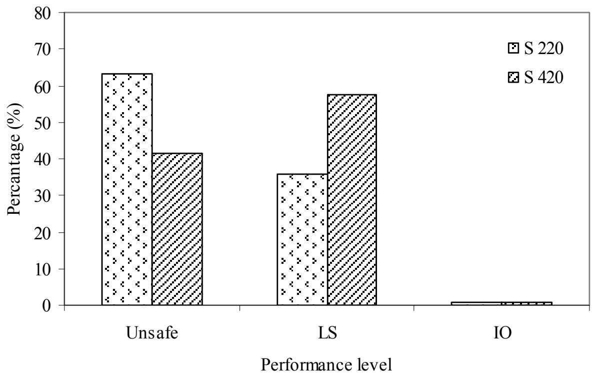


Fig. 7 The effect of reinforcement class change on the level of performance

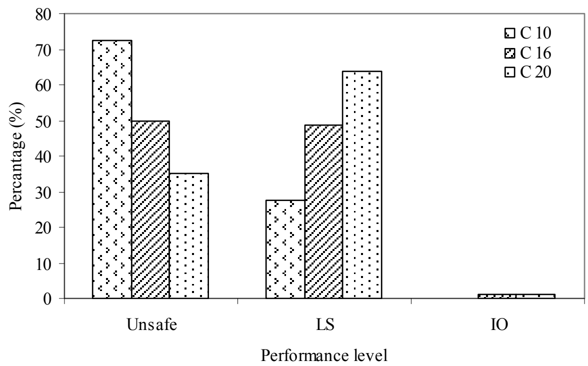


Fig. 8 The effect of concrete strength change on level of performance

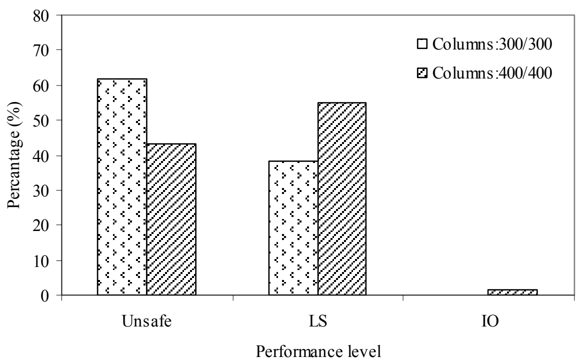


Fig. 9 The effect of column size on the level of performance

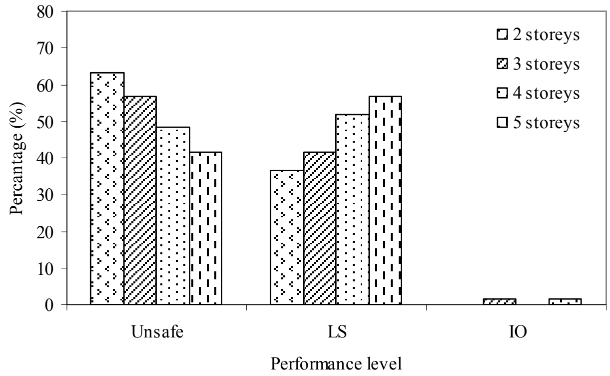


Fig. 10 The effect of the change in number of stories on the performance

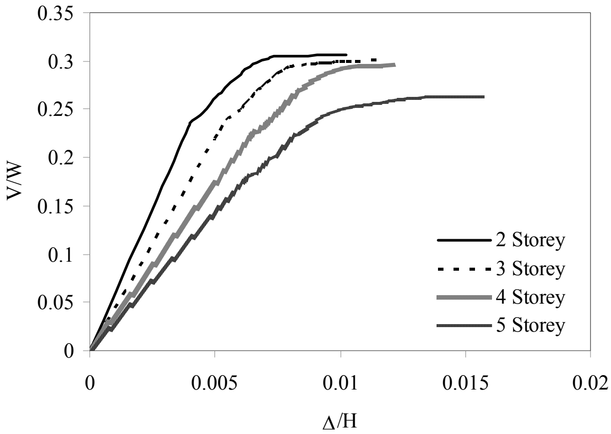


Fig.11 For Type 3, C10, S220 change in the number of stories according TDC 2007 code

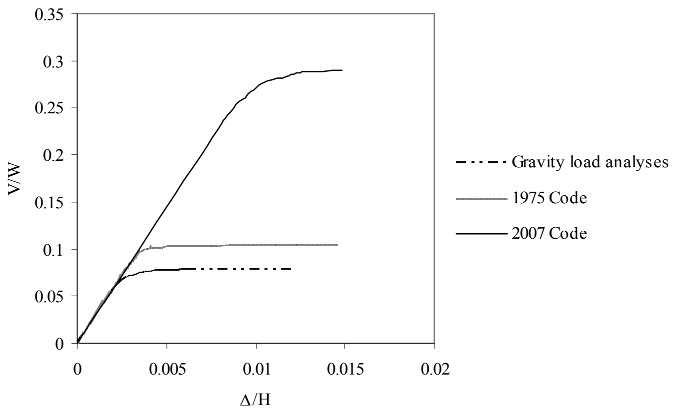


Fig.12 Capacity curves for Type 3 -C20-S420-5 story building

5. Conclusions

In Turkey, significant design codes changes occurred between1940 and 2007 design codes. The modern design codes of TDC 2007 represent effective standards. When a building's maximum base shear effect is examined over a period of years, observations indicate that, the base shear

Table 1 Structure performance based on damage in Turkish design code (TDC, 2007)

Performance level	Performance criteria
Immediate Occupancy (IO)	• The ratio of beams in Slight Damage (SD) and Moderate Damage (MD) shall not exceed 10% in any story. • There must not be any columns beyond Slight Damage (SD). • There must not be any beams beyond Heavy Damage (HD).
Life Safety (LS)	• The ratio of beams in Moderate Damage (MD) and Heavy Damage (HD) shall not exceed 30% in any story. • In any story, the shear force carried by columns in Heavy Damage (HD) shall not exceed 30% of story shear.
Collapse Prevention (CP)	• The ratio of beams in Heavy Damage (HD) must not exceed 20% in any story. • In any story, the shear force carried by column that passed Slight Damage (SD) must not exceed 30% of story shear force.
Collapse (C)	• If the failure cannot be prevented, it is under failure condition.

Table 2 Performance levels of structures designed according to Gravity forces (Column size 400/400 and 2 storey) (Yenice 2010)

Material	Number of stories	Sa (g)	Sd (mm)	Level of performance		
C10 S220	2	0.208	12.7	incidence of loss of beam in collapse	%76.2>20	C (unsafe)
C16 S220	2	0.230	16.91		%81>20	C (unsafe)
C20 S220	2	0.222	15.38		%81>20	C (unsafe)
C10 S420	2	0.287	19.82		%23.8>20	C (unsafe)
C16 S4	2	0.314	24.93		%23.8>20	C (unsafe)
C20 S420	2	0.311	72.60		%23.8>20	C (unsafe)

Table 3 Performance levels of structures designed according to Turkish Desing code (Column size 400/400 and 2 storey) (Yenice 2010)

Material	Number of stories	Sa (g)	Sd (mm)	Level of performance		
C10 S220	2	0.298	77.14	The ratio of beams in moderate damage and heavy damage shall not exceed 30% in any story. In any story, the shear force carried by columns in heavy damage shall not exceed 30% of story shear.	64%>30%	C (unsafe)
C16 S220	2	0.304	15.12		53.1%>30%	C (unsafe)
C20 S220	2	0.315	45.25		52.7%>30%	C (unsafe)
C10 S420	2	0.372	75.24		2.3%<30%	LS (Life safety)
C16 S4	2	0.386	17.15		0%<30%	LS (Life safety)
C20 S420	2	0.395	17.50		0%<30%	LS (Life safety)

effects of buildings constructed according to the Turkish design code of 2007 are relatively higher when compared to buildings designed according to the 1975 code and gravity forces. For instance, just 6% of the buildings designed according to 1975 Turkish code satisfied the LS (Life Safety) performance level, while 48% of buildings constructed according to the 2007 Turkish design code reach this performance level. (See Tables 1-3).

When reinforcement increases from S220 to S420, the numbers of buildings satisfying the LS performance level increases around 25%. When C10 increases to C20, the increase in buildings reaching the desired performance level is approximately 40%. Also, when column size increases, the performance level increases approximately 20%. Finally, when the number of stories increases, Vt base shear increases and the Vt/W ratio decreases.

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