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An Investigation on Overstrength Factor (Ω) of Reinforced Concrete Buildings in Turkish Earthquake Draft Code (TEC-2016)

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Abstract**—**Overstrength factor is an important parameter of load reduction factor. In this research, the overstrength factor (Ω) of reinforced concrete (RC) buildings and the parameters of Ω in TEC-2016 draft version have been explored. For this aim, 48 RC buildings have been modeled according to the current seismic code TEC-2007 and Turkish Building Code-500-2000 criteria. After modelling step, nonlinear static pushover analyses have been applied to these buildings by using TEC-2007 Section 7. After the nonlinear pushover analyses, capacity curves (lateral load-lateral top displacement curves) have been plotted for 48 RC buildings. Using capacity curves, overstrength factors (Ω) have been derived for each building. The obtained overstrength factor (Ω) values have been compared with TEC-2016 values for related building types, and the results have been interpreted. According to the obtained values from the study, overstrength factor (Ω) given in TEC-2016 draft code is found quite suitable.

Keywords**—**Reinforced concrete buildings, overstrength factor, earthquake, static pushover analysis.

I. INTRODUCTION

UNDER the name of design basis earthquake in the regulations, an earthquake effect is defined based on the intended purpose and the load-bearing system of the building, and the static-dynamic parameters of the load-bearing system. The aim of the design is to absorb the generated earthquake energy with the ultraelastic behavior of the buildings, rather than to help the buildings endure massive earthquakes without damage. In the other words, the aim of designing earthquake-resistant buildings is to create buildings that will show a ductile behavior under the effect of earthquakes. Therefore, as a load of design basis earthquakes, the nonlinear load-bearing capacities of the buildings are used instead of their linear elastic capacities.

Under the effect of design basis earthquake, elastic earthquake effect which is calculated by predicting the nonlinear behavior of the load-bearing system is reduced with a particular factor called the earthquake load reduction factor (Ra). There are various studies in the literature to determine and formulate the R_a factor for different types of buildings [1], [2].

The earthquake regulations in Turkey have gone through very radical changes in 1975, 1998, and 2007. Moreover, in 2016, within the scope of new earthquake regulation template, a new regulation to cover much newer principles that will bring light to the next 10 years is being prepared. One of the changes in 2016 earthquake regulation (TEC-2016) [3] is about R_a and its parameters. In TEC-2016, overstrength factor (Ω) is mentioned as a parameter in R_a calculation. In this study, 48 residential concrete reinforced buildings are designed according to the TEC–2007 [4] principles and then subjected to static pushover analysis. As a result of the static pushover analysis, overstrength factors are determined for each structure. Earthquake load reduction factors associated with the determined factors are analyzed based on the parameters of the chosen buildings. The results are evaluated by comparing the Ω in TEC-2016 with the analyzed data.

II. DUCTILITY AND ITS EFFECT ON EARTHQUAKE LOAD REDUCTION FACTOR

In RC structures, system ductility is expressed in terms of displacement ductility. System ductility is described as the ratio of maximum lateral shift of the structure at a certain point in the limit state to its lateral drift when the load-bearing system starts to yield (Fig. 1) (1):

$$\mu_\Delta=(\Delta_{max}/\Delta_y) \tag{1}$$

In RC buildings, since the transition of the capacity curve from elastic area to the plastic area is not linear as in the moment-curve change of the singular elements, the yield displacement (Δ_y) of the system is not clearly visible on this curve. There are different approaches to the yield point in the literature. When it reaches to a certain amount of the nominal strength of an elastic-plastic system, the transition of the system from the elastic area to the plastic area can be accepted. Although an exact numerical value is not given for this ratio, the nominal strength is accepted to be 70-80% [5].

RC load-bearing system cannot stay in the linear elastic state under a strong design basis earthquake. Among the concrete reinforced load-bearing elements, first the concrete cracks and then the reinforcement bars yield under the gradually increasing load of the earthquake. The elastic system leaves to be linear elastic and starts showing elastoplastic behavior from time to time. The load-bearing system has to be ductile in order to consume the earthquake energy loaded on the structure (Fig. 1). However, the earthquake load in a ductile structure can be reduced by a certain factor. This factor which is called Structure Behavior Factor (R) is generally

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formulated as below. Here, R_μ is referred as a ductility related factor or a strength reduction factor, and Ω is referred as a overstrength factor or simply Ω.

The experimental and analytic studies have shown that strength reduction factor R_μ can be considered as equal to structural ductility (μ_Δ) factor in the systems with periods bigger than 0.5 seconds.

$$R=R_\mu \times \Omega \tag{2}$$

$$R_\mu=V_e/V_y\ ,\ \Omega=V_y/V_d \tag{3}$$

$$R_\mu \approx \mu_\Delta \tag{4}$$

In TEC-2016 [3], taking V_e elastic earthquake load, the ultraelastic behavior of the load-bearing system, and Ω into consideration, the reduced earthquake load V_d is calculated after a reduction with the "Earthquake Load Reduction Factor" Ra.

$$R_a=\Omega + (R/I-\Omega)\ (T/T_B),\ T\leq T_B \tag{5}$$

$$R_a=R/I,\ T>T_B \tag{6}$$

In Fig. 1, Ω shows the relationship between "Real Strength" and "Design Basis Strength". Although TEC-2007 [4] predicts the relevant factor as 1.5, it is obvious that this factor cannot be a constant value for each structure. Therefore, Ω which is considered as a parameter of the load-bearing system conduct factor will vary depending on the features of the building such as material and size.

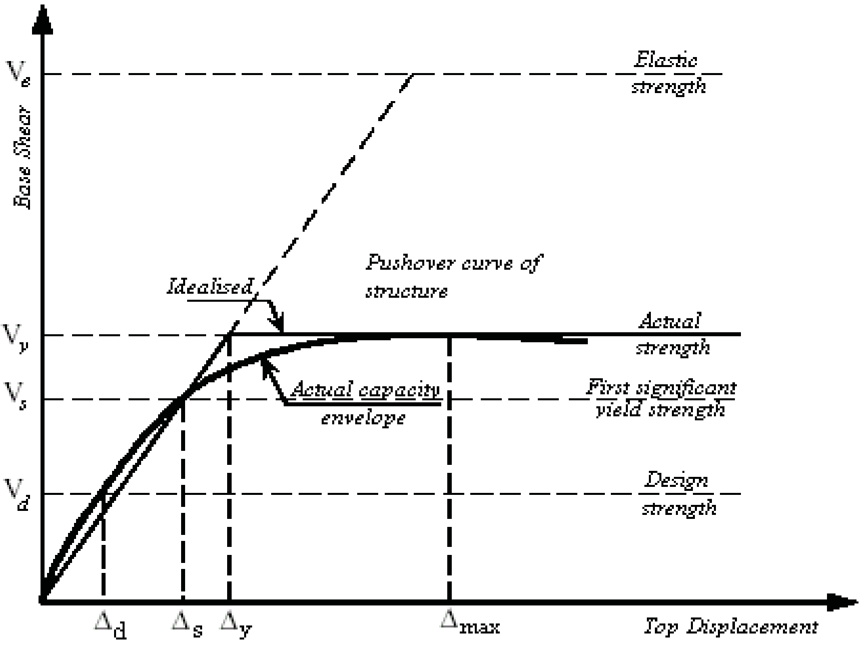

Fig. 1 An Example for Load-Displacement Curve

The strength consumption load of the load-bearing system is higher than the design load because of the following reasons: a) minimum conditions stated in the regulations, b) significantly increased loads, c) using materials with similarly reduced strength in designs, d) concrete and steel manufacturers aiming higher strength values than normal during the production of materials, e) positive impact of confinement bars used in sections on pressure strength of the concrete, f) absence of the predicted live load on the structure load during the earthquake.

III. NUMERICAL APPLICATION

Motivated by the hypothesis that Ω will vary based on the building being designed, this study includes modeling of 48 different RC buildings according to TEC-2007 [4]. The selected and structurally analyzed buildings are all from residential types of buildings, and the parameters used are a number of floors, soil class, and the earthquake region. Change intervals for these parameters are shown in Table I.

TABLE I
SELECTED PARAMETERS AND DATA RANGES

	Data Range			
Number of Floor (NF)	4	6	8	
Soil Class (SC)	Z_1	Z_2	Z_3	Z_4
Seismic Region (SR)	1st	2nd	3rd	4th

Modeling and RC calculations of the structures in the present study are carried out by using STA4-CAD program [7] (Figs. 2-4) in accordance with the TEC-2007 [4] and TS-500-2000 [6] principles. As the calculation results showed that building heights were lower than 25 meters and that structural irregularities were within the limits of regulation, an equivalent earthquake load method is used. Ductility level of the buildings is considered high, and structure conduct factor is accepted as 7. Buildings are sized so that there will be 48 alternatives in total for three different parameters as shown in Table I. These 48 buildings whose reinforcement is calculated, are later subjected to pushover analysis with the nonlinear incremental equivalent earthquake load, and the capacity curves are obtained. In these procedures, the length of plastic hinges defined for columns, beams, and curtain ends are accepted as 0,5 H; and flexural rigidity of beams are selected as 0,4 EI, and for columns and curtains within the range of 0,4 EI and 0,8 EI.

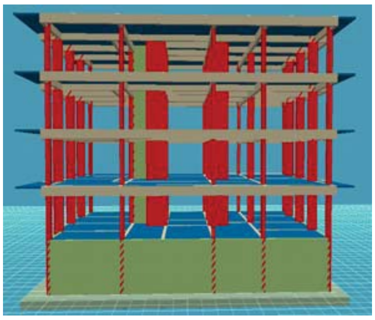

Fig. 2 4-story RC structure model

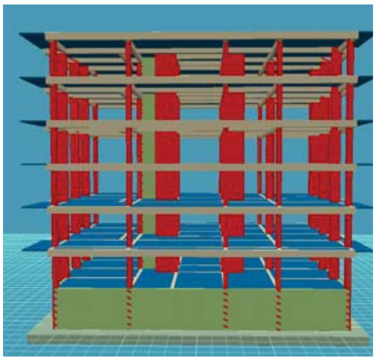

Fig. 3 6-story RC structure model

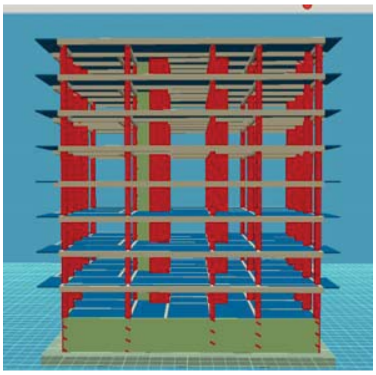

Fig. 4 8-story RC structure model

IV. COMPARISONS

Data obtained from the analyses conducted within the study are given below in three different groups. The first group evaluates the results from 4-story, second group from 6-story and the third group from 8-story buildings. The horizontal load – top displacement curves obtained as a result of the analyses are given separately. In order to interpret the charts more easily, the vertical axis (horizontal load) is divided by the weight of the building, and the horizontal axis is divided to total height for non-dimensionalization. Also, design basis earthquake force calculated according to the TEC-2007 [1] norms is shown in the charts as a horizontal dashed line. The horizontal load – top displacement curves from 4-story RC buildings are shown in Figs. 5-8 based on soil and earthquake parameters. The calculated Ω values based on the charts are shown in Table II collectively. When we look at the results from 4-story RC buildings, we see that earthquake risk is decreased regardless of the soil class with a significant increase in the value of Ω. This increase is maximum in the Z_4 type of soil and minimum in Z_1. In addition, the results showed that Ω value increased with the improvement of soil class regardless of the earthquake area. Ω value is calculated between 1.16 and 5.29 for 4-story buildings (Figs. 5-8).

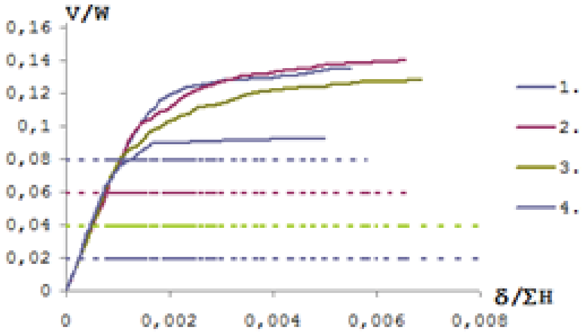

Fig. 5 Load-Displacement curves for 4-story buildings for Z1

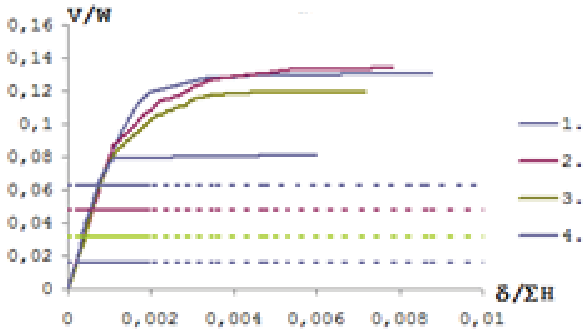

Fig. 6 Load-Displacement curves for 4-story buildings for Z2

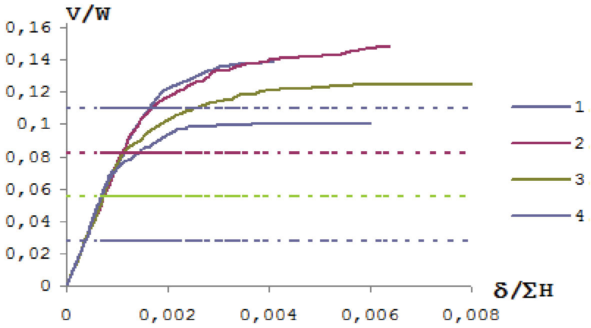

Fig. 7 Load-Displacement curves for 4-story buildings for Z3

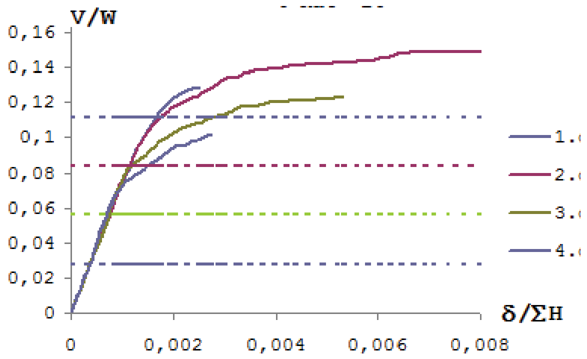

Fig. 8 Load-Displacement Curves for 4-story buildings for Z4

TABLE II
CHANGING OVERSTRENGTH (Ω) VALUES ACCORDING TO THE SELECTED PARAMETERS IN 4-STORY BUILDINGS

	1^{st}	2^{nd}	3^{rd}	4^{th}
Z1	2.16	2.85	3.79	5.29
Z2	1.71	2.35	3.22	4.76
Z3	1.25	1.79	2.23	3.63
Z4	1.16	1.75	2.19	3.62
Average	1.57	2.19	2.86	4.33
General Average	2.74			

The horizontal load – top displacement curves from 6-story RC buildings are shown in Figs. 9-12, and Ω values are shown in Table III. When we look at the results from 6-story RC buildings, we see that earthquake risk is decreased regardless of the soil class with a significant increase in the value of Ω. However, this increase is not as high as in 4-story buildings. This increase is maximum in the Z4 type of soil and minimum in Z1. In addition, the results showed that Ω value increased with the improvement of soil class regardless of the earthquake area. Ω value is calculated between 1.47 and 4.91 for 6-story buildings.

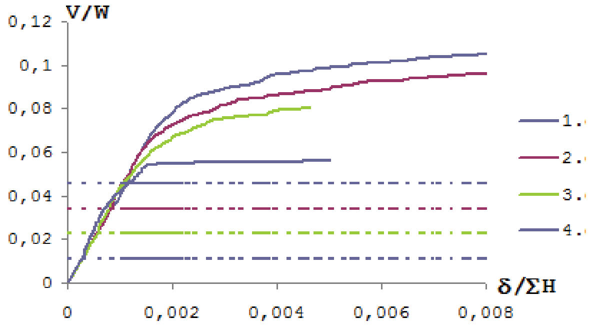

Fig. 9 Load-Displacement curves for 6-story buildings for Z1

TABLE III
CHANGING OVERSTRENGTH (Ω) VALUES ACCORDING TO THE SELECTED PARAMETERS IN 6-STORY BUILDINGS

	1^{st}	2^{nd}	3^{rd}	4^{th}
Z1	2.31	2.81	3.56	4.91
Z2	1.96	2.33	3.13	4.64
Z3	1.79	2.02	2.53	3.74
Z4	1.47	1.59	1.89	2.98
Average	1.88	2.19	2.78	4.07
General Average	2.73			

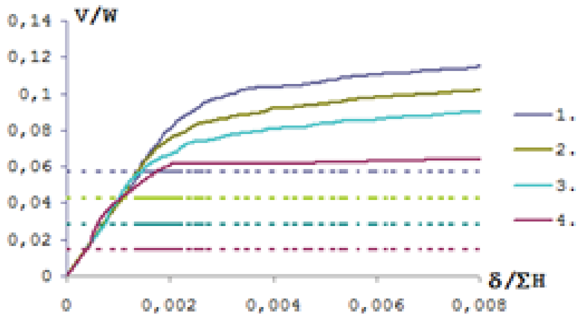

Fig. 10 Load-Displacement curves for 6-story buildings for Z2

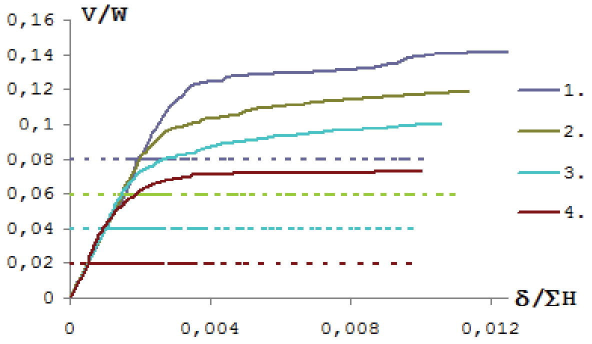

Fig. 11. Load-Displacement Curves for 6-story buildings for Z3

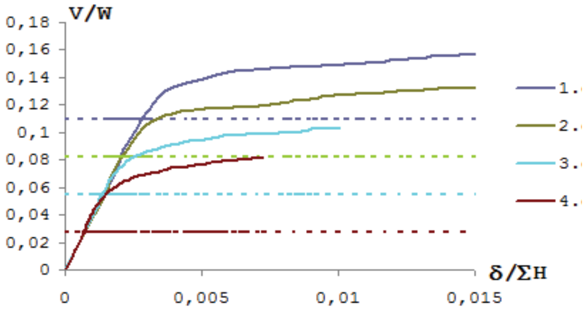

Fig. 12 Load-Displacement curves for 6-story buildings for Z4

The values obtained from 8-story RC buildings are shown in Figs. 13-16 and Table IV. These values obtained from 8-story buildings are in compliance with the values from 4 and 6-story buildings. The results showed a decrease in earthquake risk regardless of the soil type and an increase in Ω value. In addition, the results revealed that Ω value increased with the improvement of soil class irrespective of the earthquake area. Ω value is calculated between 1.54 and 5.16 for 6-story buildings.

TABLE IV
CHANGING OVERSTRENGTH (Ω) VALUES ACCORDING TO THE SELECTED PARAMETERS IN 8-STORY BUILDINGS

	1^{st}	2^{nd}	3^{rd}	4^{th}
Z1	2.47	2.80	3.64	5.16
Z2	2.14	2.44	3.22	4.31
Z3	1.76	2.04	2.58	3.65
Z4	1.54	1.68	2.14	3.23
Average	1.98	2.24	2.89	4.09
General Average	2.80			

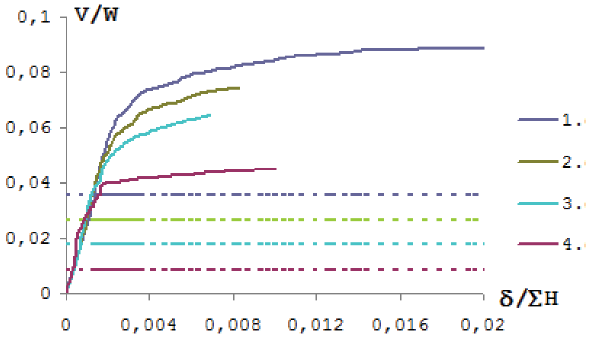

Fig. 13 Load-Displacement curves for 8-story buildings for Z1

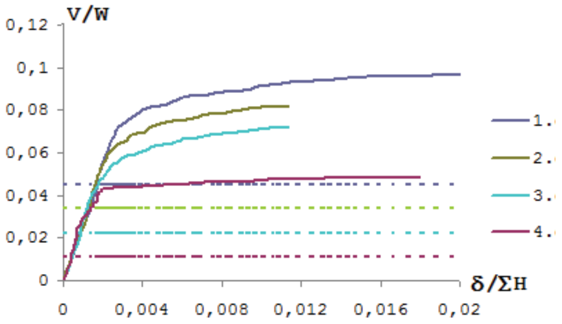

Fig. 14 Load-Displacement curves for 8-story buildings for Z2

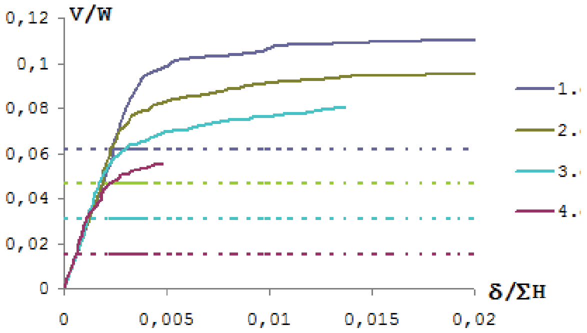

Fig. 15 Load-Displacement curves for 8-story buildings for Z3

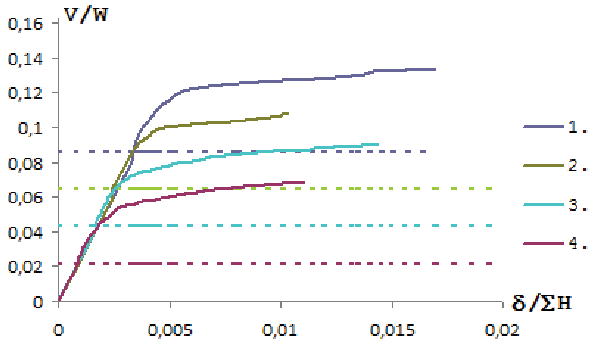

Fig. 16 Load-Displacement curves for 8-story buildings for Z4

V. RESULTS AND FINDINGS

This study evaluating the earthquake load reduction factor of multi-storey RC buildings carries out the nonlinear pushover analyses of RC buildings with different structural features. Based on the pushover analyses, different interpretations of Ω are made as a component of earthquake load reduction factor. Especially in Zone 3 and 4 where earthquakes are not very influential, load-bearing systems are analyzed based on vertical loads. Therefore, overstrength factors in Zone 3 and Zone 4 earthquake regions are found very high based on the regulation's prediction. The average calculated factor in these regions is 3.39. Overstrength factors in Zone 1 and Zone 2 earthquake regions are 2.01. Ω value is highly affected particularly by the earthquake region. In Zone 3 and 4 earthquake regions, buildings with lower height are found to have higher Ω factor than multi-story buildings. Also, when we look at the average values, overstrength factor can be accepted between 2.73~2.80 for all the buildings. According to the formulation found in TEC-2007, Ω value is accepted as 1.5. However, based on the TEC-2016 template text, Ω value is given as 2.5. This revision is considered suitable and expected to be more economical in terms of design.

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