Comparative Analysis of High-Rise Reinforced Concrete Structures According to International Seismic Design Codes

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Abstract: The field of earthquake engineering and seismology is of great importance to structural engineers around the world. The location, size and consequences of an earthquake are variable depending on several conditions. Surface conditions, boundary/fault type, distance from the boundary and hypocenter are all elements that dictate the outcome of a seismic event. The paper presents a comparison of seismic provisions of two seismic design codes—EC8 (Eurocode 8) and IBC (International Building Code) 2006, to a high-rise reinforced concrete building. The building is irregular and composes of 20 floors. The equivalent lateral force analysis was performed using the well-known structure program—ETABS (Extended 3D Analysis of Building Systems). Based on the analysis results (inter-storey index, global damage index, storey displacement, inter-storey drift ratio and base shear), EC8 was found to be conservative when compared with IBC 2006. The conclusion is that for the design and analysis of high-rise reinforced concrete buildings with certain irregularity, EC8 provisions were considered to be conservative.

Key words: High-rise building, seismic load, building codes.

1. Introduction

The primary purpose of all kinds of structural systems used in the building type of structures is to support gravity loads. The most common loads resulting from the effect of gravity are dead load, live load and snow load. Besides these vertical loads, buildings are also subjected to lateral loads caused by wind, blasting or earthquake. Lateral loads can develop high stresses, produce sway movement or cause vibration.

Therefore, it is very important for the structure to have sufficient strength against vertical loads together with adequate stiffness to resist lateral forces. In Turkey, a considerable number of buildings have reinforced concrete structural systems. This is due to economic reasons. Reinforced concrete building structures can be classified as follows [1]:

(1) structural frame systems: The structural system consists of frames, floor slabs, beams and columns, which are the basic elements of the structural system. Such frames can carry gravity loads while providing adequate stiffness;

(2) structural wall systems: In this type of structures, all the vertical members are made of structural walls, generally called shear walls;

(3) shear wall-frame systems (dual systems): The system consists of reinforced concrete frames interacting with reinforced concrete shear walls. Most of the residential reinforced concrete structures in Turkey have shear wall-frame systems.

In the last years, earthquake design of structures becomes an important phenomena due to the disastrous earthquakes which cause a big human tragedy all around the world. These earthquakes show that the buildings have low seismic performance due to the usage of low quality material, low quality of workmanship and inadequacy of the design codes.

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Since then, many new codes detailing requirements have been introduced to ensure seismic resistance.

This paper, firstly, presents a review of the EC8 (Eurocode 8) and IBC (International Building Code). Secondly, a comparative analysis was performed in terms of inter-storey index, global damage index, storey displacement, inter-storey drift ratio and base shear for the irregular RC (reinforced concrete) structure.

2. Seismic Standard Evolution

2.1 Eurocode

In Europe, Eurocodes started in 1975, as a result of the decision of the Commission of the European Community to embark on an action programme in the field of construction based on Article 95 of the Treaty of Rome. The objective of the programme was to eliminate the technical obstacles to trade and the harmonisation of technical specifications by means of technical rules which, in the first stage, would serve as an alternative to turn the national rules in force in the member states and, ultimately, would replace them [2].

In 2006, the publication of EN (European Norm) Eurocodes was concluded. The implementation of programme enters the coexistence period, during which the EN Eurocodes are used in parallel with National Standards that have the same scope. Finally in 2010, a full implementation of the code was enforced by withdrawing all conflicting National Standards. It is also mandatory that the member states accept designs to the EN Eurocodes. Since the National Standards' implementing, the EN Eurocodes become the standard technical specification in all contracts for public works and public services. Specifically, Eurocode 2 and Eurocode 8 are devoted for concrete and earthquake provisions. Eurocode 2 covers the design of buildings and civil engineering works constructed in plain, reinforced, pre-stressed and precast concrete while Eurocode 8 explains how to design and analyze building and civil engineering structures resistant to earthquakes [2].

The vast majority of buildings, in earthquake prone areas in Europe, constructed before the 1980s are seismic deficient in terms of our current understanding and knowledge. Furthermore, before the 1970s, a significant number of existing RC building structures were constructed with plain reinforcing bars, prior to the enforcement of the modern seismic oriented design philosophies [3]. In fact, in some European countries until the 1960s, no specific seismic design provisions were included in building codes and, from that period on, only seismic equivalent lateral loading was considered in building design. Provisions for the design and detailing of members and structures resembling those of modern codes only appeared in European national codes in the 1980s (e.g., Portuguese design code—RSA; European design code—Eurocode 8) [4].

The recent earthquakes in Europe (e.g., Bucharest, Romania, 1977; Montenegro, Yugoslavia, 1979; Azores, Portugal, 1980; Campania, Italy, 1980; Kalamata, Greece, 1986; Umbria/Marche, Italy, 1997; Azores, Portugal, 1998; Kocaeli, Turkey, 1999; Athens, Greece, 1999; Molise, Italy, 2002 and 2009; Spain, 2011) confirm and highlight that also Europe may suffer from the vulnerability of the existing building stock [5]. Majority of the countries mention adopted and implemented European Standards in the design and analysis of their structures.

2.2 International Building Code

The earliest model code in the United States was the National Building Code recommended by the National Board of Fire Underwriters, published in 1905 in response to fire insurance losses in the Great Baltimore Fire of 1904. Furthermore in 1927, the Pacific Coast Building Officials promulgated the Pacific Coast Building Code, which later became the UBC (Uniform Building Code). The organization of this code differed from that of the National Building Code in that it ranked occupancies by life risk and linked fire safety criteria to specific occupancies. The code included provisions for existing and control of material finishing.

In addition, this code contained numerous structural provisions organized by building material type [6].

The Uniform Building Code was widely used west of the Mississippi River until the adoption of the International Building Code in 2000. The National Building Code was promulgated by the insurance industry. It was the basis for most local and state codes until late in the last century [7]. To date, UBC is also the model or reference code for many developing countries around the world.

The Southern Building Code, later the Southern SBC (Standard Building Code), was first published by the Southern Building Code Congress in 1945. The Basic Building Code, published by the Building Officials of America (now the BOCA (Building Officials and Code Administrators International)), was first published in 1950. It served the Midwest and New England regions. BOCA later obtained the right to use the title National Building Code. Some editions of the Code are called the BOCA/National Building Code. These organizations that published the three model codes were membership organizations with members from the building industry, the building regulatory community and the public. The model building codes were updated on a three-year cycle [7].

Beginning in the late 1980s, efforts were made to improve consistency and uniformity among the three

model codes. By 1990, agreement was reached on consistent chapter organization in the codes, on reasonably consistent occupancy definitions, and on construction types. The three model codes, namely, BOCA, SBCCI (Southern Building Code Congress International), and the ICBO (International Conference of Building Officials) agreed to form the International Code Council and to publish one national model code. This resulted in the publication of the 2000 edition of the International Building Code. The IBC (International Building Code) is updated on a three-year cycle and the latest publication was IBC 2012 [8].

3. Modelling of High-Rise Reinforced Concrete Structures

3.1 Brief Description of the High-Rise Reinforced Concrete Structure

A high-rise RC building has been considered for comparison, as shown in Figs. 1-3:

- 20 stories building;
- irregular plan shape;
- 1st~12th stories with 1,750-m² area;
- 13th~20th stories with 1,225-m² area.

The RC building has a storey height of 3 m. Dead-load and live-load are 2.5 kN/m² and 1.5 kN/m²,

Fig. 1 Typical floor plan from 13th till 20th story.

Fig. 2 Typical floor plan from 1st till 12th story.

Fig. 3 Tri-dimensional model.

respectively. The material properties used are: $f'_c = 20$ MPa for concrete and $f_y = 400$ MPa for reinforcement. The member sizes were: 500 mm $\times$ 500 mm column, 300 mm $\times$ 500 mm (typical beam section), 170 mm (slab thickness) and 250 mm (wall thickness). 3D finite element model of the structure has been used. The structural software ETABS (Extended 3D Analysis of Building Systems) 9 was utilized for this purpose [9]. Beams and columns are modeled with frame element while shear wall and slabs are modeled with shell element.

The building was analyzed in terms of the following: Inter-storey index, global damage index, storey displacement, inter-storey drift ratio and base shear.

3.2 Seismic Parameters

The RC building has a standard occupancy with the following site characteristics:

- Importance factor: $I_E = 1$; Site class: D; Seismic design category: D;
- Design parameters: $S_S = 0.32$, $S_1 = 0.22$, $F_a = 1.544$, $F_v = 1.96$, $S_{DS} = 0.3294$, $S_{D1} = 0.2875$;
- Response modification factor: $R_x = 6.5$, $R_y = 6.5$, $T_x = 1.4$ s, $T_y = 1.4$ s;
- Eccentricity ratio: 0.05.

Shear wall-frame system (dual system) was used. Shear walls resist 75% of the lateral force and the frames resist 25% of the lateral force.

Five percent elastic damping was assumed.

4. Seismic Performance Evaluation

The seismic responses of two seismic design codes, Eurocode 8 and IBC 2006, have been compared using the well-known computer program ETABS [9].

4.1 Inter-storey Index

The maximum inter-storey drift (δ_{max}) divided by the storey height (h) is defined as the maximum inter-storey index. This index is a good indication of the damages experienced by the structural members. Fig. 4 shows the comparison of the maximum inter-storey index of the structure obtained from two seismic design codes Eurocode 8 and IBC 2006. From Fig. 4, it was noticed that utilization of EC8 provides significant reduction in the inter-storey drift ratios of structure.

4.2 Global Damage Index

Global damage indices can be identified in terms of a comprehensive parameter. For example, ductility factors related to storey displacements, such as the one based on roof displacement [10] or softening indices [11] in order to state the level of damage in the structure [12]. Furthermore, for estimating seismic demands of buildings due to an earthquake ground motion, the peak (target) roof displacement is required to be estimated in an attempt to quantify the global seismic demand. Therefore, in this study, the ratio of

Fig. 4 Maximum inter-storey index obtained from Eurocode 8 and IBC 2006.

Fig. 5 Global damage index obtained from Eurocode 8 and IBC 2006.

Fig. 6 Base shear obtained from Eurocode 8 and IBC 2006.

the roof displacement (D) over the total height of the building (H) denoted as the global damage index was used as a response parameter.

Fig. 5 compares the global damage index for the two seismic design codes Eurocode 8 and IBC 2006. Comparison of global damage index of the models revealed that the global damage index for IBC 2006 model was considerably greater than that of EC8 model.

4.3 Total Base Shear

It is known that seismic zone, earthquake type and

support conditions are very influential on the variation of base shear forces. In the current study, the base shear at target displacement was evaluated. Fig. 6 shows the base shear values obtained from the two seismic codes Eurocode 8 and IBC 2006. It was observed that the calculation of base shear using EC8 is 6,267 kN while using IBC 2006 is 6,144 kN. The conclusion is that for the design and analysis of high-rise reinforced concrete buildings with certain irregularity, EC8 provisions were considered to be safer.

Fig. 7 Storey displacement obtained from Eurocode 8 and IBC 2006.

Fig. 8 Variation of inter-storey drift ratio obtained from Eurocode 8 and IBC 2006.

4.4 Storey Displacement

Fig. 7 shows the variation in storey displacements of the structure obtained from the two seismic design codes Eurocode 8 and IBC 2006. As seen from Fig. 7, the use of EC8 decreased the value of storey displacements compared to IBC 2006.

4.5 Inter-storey Drift Ratio

In addition to the variation of storey displacements mentioned above, in order to obtain a generalized response that can be representative of damage states of a structure, inter-storey drift ratio of the structures were evaluated in this section. Therefore, inter-storey drift

demands over height in the model are given in Fig. 8.

5. Conclusions

A comparison of EC8 and IBC2006 standard has been presented focusing on the inter-storey index, global damage index, storey displacement, inter-storey drift ratio and base shear. The structural model for the high-rise RC building was analyzed in ETABS. The results for the analysis were compared and obtained using equivalent lateral force analysis function and the corresponding seismic parameters.

It can also be noted that the base shear calculated using EC8 is more than IBC 2006 where EC8 gives 6,267 kN and IBC 2006 gives 6,144 kN. The

conclusion is that for the design and analysis of high-rise reinforced concrete buildings with certain irregularity, EC8 provisions were considered to be safer.

The study presented in this paper increases the understanding of an important earthquake engineering issues concerning the different seismic design codes.

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