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Comparison of seismic behavior factors for reinforced concrete (RC) special moment resisting frames (SMRFs) in Iran in low-, mid-, and high-rise buildings based on Iranian seismic standard 2800 and ASCE

Samad Dehghan
Director, Education department, Construction engineering organization of east Azarbaijan province

Seyednima Naghibi Iravani
Master in structural engineering, Islamic Azad university of Sofian
Corresponding Author

ABSTRACT

Moment-resisting frames are generally preferred over shear walls in constructing reinforced concrete buildings because they architecturally provide the builder with more space, and special moment-resisting frames (SMRFs) show better earthquake performance. Applying fewer design forces will make the design of the structure more economical. In many seismic design codes, the behavior factor is used to reduce the level of elastic force to the desired force level in the design. This research will calculate the seismic design factors in RC moment-resisting frames using the answers obtained from dynamic analyzes using real-scale earthquake records. The main factors studied in this study are response behavior factor, displacement amplification factor, and overstrength factor. Then, the results obtained from the above values for the mentioned factors were compared with their corresponding values in the ASCE7 code. To investigate the above factors, four 12, 16, 20, and 24-story buildings were modeled by ETABS software according to Iranian seismic standard 2800 using the response spectrum method.

Keywords: seismic behavior factors, reinforced concrete special moment resisting frames, displacement amplification factor.

Introduction

A key issue in constructing high-rise structures is retrofitting and maintaining their stability against lateral forces, especially seismic lateral force. With the gradual increase of our knowledge about the behavior of materials in the face of applied forces, we tried to consider the economic dimension in structural design. To this end, today, designs are done using pre-collapse deformation as an energy dissipator, allowing the material to enter the plastic area. This requires that the seismic design factors be selected correctly. The codes of different countries provide the factors on which the designs are made.

Most of the damage to buildings is based on the general design of the building, the selection of the appropriate form for the building, the determination of the earthquake-resistant system, the location and initial scientific studies, and the condition of the foundation soil. Such damages are mainly general damages that may cause a building to be destroyed or useless. Insufficient shear strength of the story due to the small number of columns and walls sometimes leads to the destruction of a building [1]. Neglecting the integration of construction and creating weak connections between different building components can sometimes cause significant damage if a building has a relatively large lateral displacement δ- P effects increase the bending moment applied to the columns, especially the lower stories. This should be taken into account in preliminary structural studies. Ignoring this issue leads to damages that may lead to the destruction of the building [2].

On the other hand, the external columns of reinforced concrete buildings are sometimes exposed to high axial compressive forces due to overturning moments. The damage to these columns is often damage around the middle of the height, leading to the buckling of vertical reinforcements. Shear failure of columns is also one of the damages reported in various earthquakes. Shear failure certainly occurs if the bending moment applied to the column is greater than its flexural load-bearing capacity. According to the evidence, shear failure corresponds to the points at which the maximum bending moment is applied, i.e., the two ends of the column [3].

Connections are one of the most sensitive parts of a building. Damaged connections impair the stability of the structure and can lead to structural collapse. Insufficient ductility due to the low number of connections is often problematic with the lack of column ties in the connection area. This leads to concrete core fragmentation or diagonal cracks inside the connections [4]. Another problem with connections in reinforced concrete buildings, one of the most common damages, is the strong beam-weak column principle. In such connections, the plastic hinge usually first occurs in weak columns, undermining the stability of the building [5].

There is no precise definition for structural ductility. Ductility is an important property of earthquake-resistant concrete structures. Therefore, in the design of ductile reinforced concrete buildings, engineering judgment and correct experience are more important than the rules defined by mathematical formulas [6]. One of the main drawbacks of traditional codecs is that they use linear methods. In the case of regular structures, these methods will give acceptable results. However, in the case of irregular structures, it will be acceptable to apply linear methods and even linear dynamic methods only as long as the behavior of the remaining structure remains in the linear range [7].

Structures calculated according to common seismic codes under a severe or even moderate earthquake will have many deformations, leading to the yield of many members (stresses in these members reach the yield limit). This is what is implicitly predicted in the code. In other words, it is not economically acceptable for the members of a building (most buildings) to be large enough to react to a severe earthquake. Accordingly, ductility is an essential property of earthquake-resistant structures.

This research has tried to compare the results of design software with the conditions and factors suggested in the code. For this purpose, four structures with heights in the range required to design with high ductility have been investigated. The modeled and designed structures are highly ductile reinforced concrete moment-resisting frames. Four models of 12, 16, 20, and 24 story structures with a story height of 3 meters have been used to compare the behaviour of structures based on height and number of stories.

Methodology

This research has investigated the seismic parameters of concrete structures with reinforced concrete moment-resisting frame systems. For this purpose, four concrete structures of 12, 16, 20, and 24 stories have been modeled, and the results obtained from the study of seismic parameters have been compared. The buildings have square and symmetrical plans, in which an attempt is made to avoid torsion effects. Existing buildings are designed according to the factors listed in the Iranian code. Loading is done by considering the residential building with a one-way slab story system. Attempts have been made to perform structural loading in accordance with all code requirements in accordance with Section 6 of the National Building Regulations for a residential building. Axial and bending members are also designed according to the conditions defined in Section 9 of the National Building Regulations for a highly ductile system. The columns and beams used in these structures are square and rectangular, respectively. The dimensions of these structures after design are presented in Table 1.

Table 1: Dimensions of structural elements

No. of stories	Column dimensions (cm)		Beam dimensions (cm)
12	45	60	60-45
16	45	65	65-45
20	45	70	65-45
24	45	75	70-45

The frames are designed according to ACI 2008. Also, the loads considered in the design are dead and live gravitational loads and lateral seismic loads. According to the sixth chapter of National Building Regulations, Gravitational loading of frames has been done, and the live load applied to the structure is 200 kg force (daN) per square meter. According to calculations performed on structures, the average dead load applied is 700 kg (daN) per square meter. Also, stories and roofs have the same gravitational loads.

Concrete strength used is 28 kg/cm2. AIII steel with a minimum yield strength of 4000 kg/cm2 is considered longitudinal reinforcements. Bending frames with special ductility are used. According to code 2800, the behavior factor of this building frame system will be 7.5. The assume factor has been equal to I = 1 for buildings. The type-II ground has been used to analyze these structures based on code 2800. The relationships in Iranian seismic standard 2800 have been used to obtain the base shear value of the static and dynamic state. Rectangular and square sections are used for beams and columns, respectively. In the design, the values of the column reinforcements are predetermined, and the values of the beam reinforcements are also determined according to the software results.

In static analysis, the equivalent of earthquake-induced lateral force is applied to the structure statically reciprocal. The amount of this force is calculated from Equation 6-7-1 in Section 6 of the National Building Regulations, expressed in Equation (1):

$V = CW$ (1)

Where V is the earthquake-induced lateral force, W is the seismic weight of the structure (all dead loads plus a percentage of live loads and snow), and C is the earthquake factor, calculated based on the relationships in Section 6 of the National Building. Regulations. All the factors required for static structural analysis are given in Table 2.

Table 2: Seismic parameters of the models

No. of stories	12	16	20	24
Structure’s height (m)	36	48	60	72
Structural period	0.5196	0.8738	1.1844	1.4696

Dynamic structural analysis is performed assuming its linear behavior. For this purpose, the vibrational modes of the structure are first determined using modal analysis. Then, the maximum reflection of each mode according to the vibration period of each mode is obtained by referring to the design spectrum. In the next step, the reflection of the modes is attempted using a statistical combination.

Following structural analysis and elimination of the load combination related to equivalent static analysis, structural design is performed using the forces of dynamic analysis. When importing modal analysis parameters, paragraph 6-7-2-6-2-2 of Section 6 of National Building Regulations should be considered. This paragraph states that in each of the two building extensions, at least the first three vibrational modes must be considered, either all vibration modes with a vibration period greater than 0.4 seconds or all vibration modes with a sum of effective masses greater than 90% of the total mass of the structure. The structure is now designed and ready to enter the design phase based on performance or nonlinear static analysis.

In this study, the behavior factor is determined using the relationship presented in ATC-34, expressed in the form of Equation (2):

$R=R_{\mu}\times\Omega\times R_{r}$ (2)

where Rμ is calculated using the Newmark-Hall relation, expressed as Equation (3):

$T < 0.1 \quad R\mu = 1$

$0.1 < T < 0.5 \quad R\mu = \sqrt{(2\mu+1)}$

$0.5 < T \quad R\mu = \mu$ (3)

Findings

Target displacement is calculated according to FEMA code 356, with the results presented in Table 3.

Table 3: Calculation of target displacement by number of stories

	12-story	16-story	20-story	24-story
Fundamental vibration period of the structure (Ti)	0.5195	0.8738	1.1844	1.4696
Effective vibration period of the structure (Te)	0.5375	0.9087	1.2317	1.5238
Permissible target displacement	0.03329	0.09516	0.1991	0.2437

In this research, modeling and analysis have been performed using ETABS software. Response spectra used to determine the performance point (target) are calculated using the acceleration of the base of the Tabriz cut-off plan in three forms, namely equivalent static analysis, dynamic analysis, and nonlinear static analysis, with the results shown in Figures 1-4.

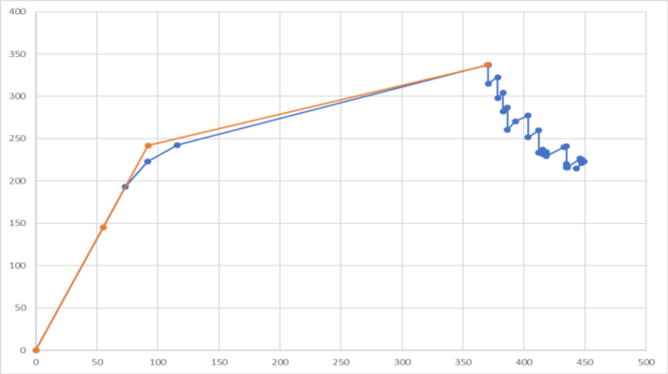

Figure 1: Pushover curve of 12-story structures

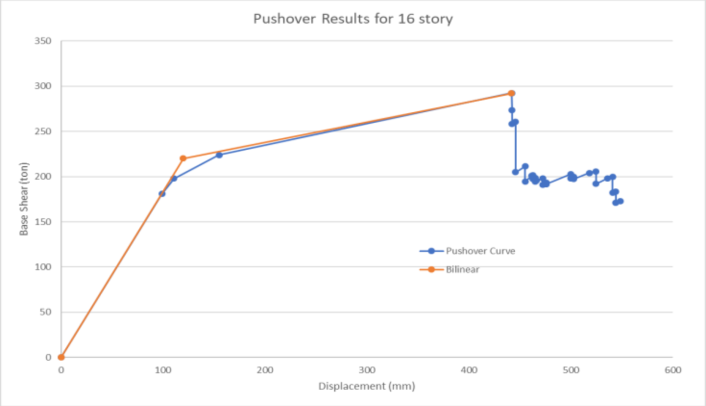

Figure 2: Pushover curve of 16-story structures

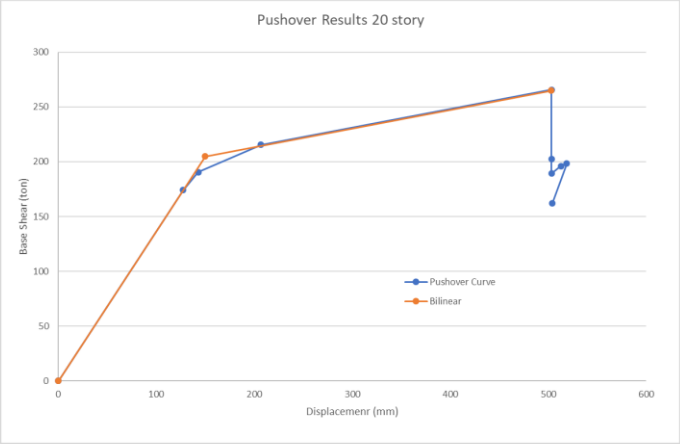

Figure 3: Pushover curve of 20-story structures

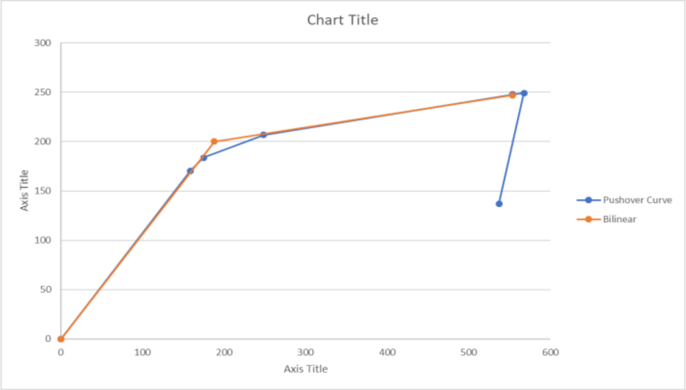

Figure 4: Pushover curve of 24-story structures

Examination of the linear part of the diagram shows that structural stiffness decreases with the increasing number of layers because the column in the raised part increases irregularity, and increasing the number of columns in the structure increases structural stiffness. Based on other results from these diagrams, dissipated energy and ductility parameters can be compared, discussed below.

Yield points for the constructed models are compared in Figure 5.

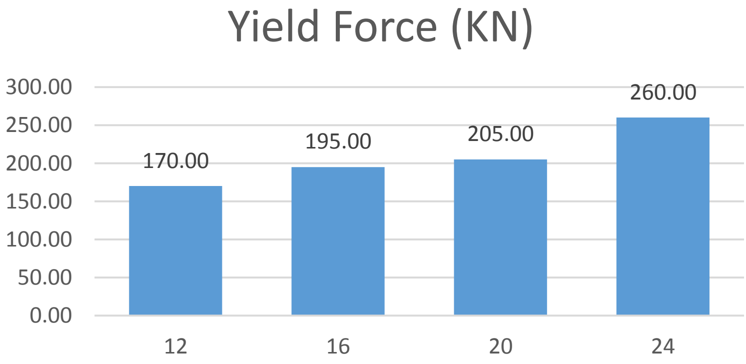

Figure 5: Yield points for fabricated models

As shown in Figure 5, this force increases with the increasing number of stories due to the increase in beam dimensions to counteract lateral displacement. According to the code, the design should be such that the beams flow faster than the columns.

In what follows, the trapezoidal integral method is used to obtain the area below the pushover diagram of the structures, as shown in Figure 6.

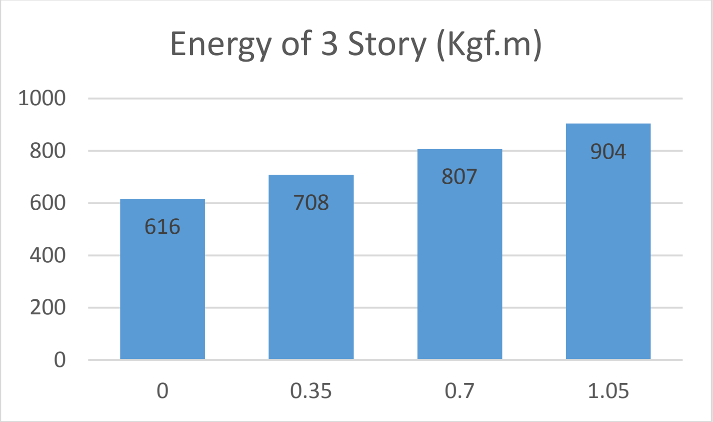

Figure 6: Dissipated energy in 3-story structures

Figure 6 shows the dissipated energy in 3-story structures. The diagram above shows that the amount of dissipated energy increases with increasing eccentricity because the maximum nonlinear displacement is located in the linear region of the diagram, and the structural stiffness increases with increasing irregularity. These results are also true for 6-story structures. However, in 16- and 20-story structures, the area under the diagram increases with increasing eccentricity. As shown in force-displacement curves, with increasing irregularity, and consequently, structural stiffness, the area below the graph decreases unless the maximum displacement of the target point is limited. In general, dissipated energy decreases with an irregular increase in the event of structural failure.

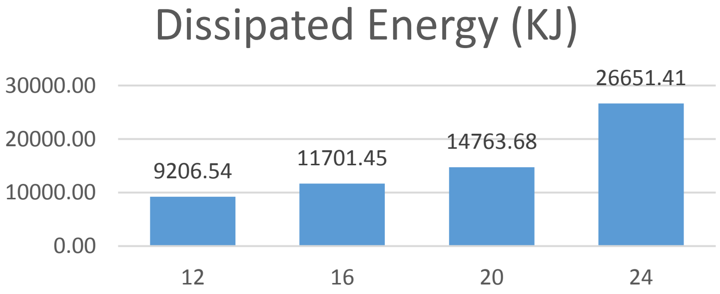

Figure 7: Comparison of dissipated energy

In the models studied in this research, hinges were formed in the beams. Also, in all models of 12 to 24 classes, the ductility parameter was examined comparatively in the following diagrams. These values are shown in Figure 8.

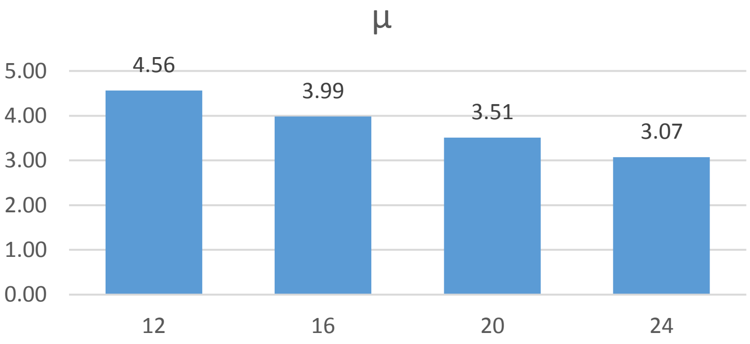

Figure 8: Ductility parameter in modeled structures

As shown in Figure 8, ductility decreases with the increasing number of stories, increasing the need for ductility in high-rise structures.

The calculated behavior factors for the constructed models are presented in Figure 9.

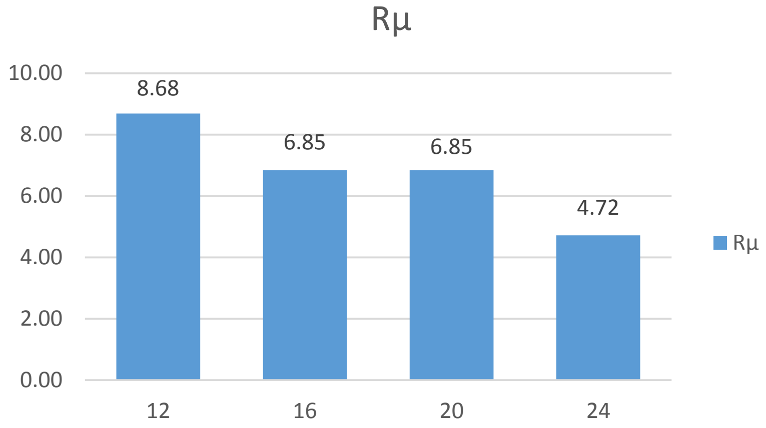

Figure 9: Behavior factors of modeled structures

Conclusion

This study investigated the seismic design factors of SMRFs or highly ductile moment-resisting frames using nonlinear static analysis. The results were then compared with the Iranian seismic standard 2800. The results showed that the code chose the factors conservatively. The amount of force that causes the yield of the first element naturally increases with the increasing number of layers. Increasing the number of layers increases the load-bearing capacity of the elements, and they flow later, i.e., absorb more energy. It also reduces ductility, i.e., the distance between yield and failure and the factor of resistance. Based on the results, it is proposed to investigate the seismic performance of special braced frames and RC SMRFs under near- and far-fault records.

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