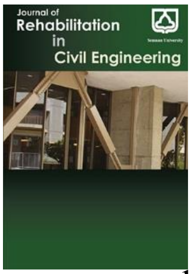
Journal of Rehabilitation in Civil Engineering 7-1 (2019) 141-158



journal homepage: http://civiljournal.semnan.ac.ir/

New Lateral Force Distribution for Seismic Design of Structures Based on Seismic Demand Ratio

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ARTICLE INFO

Article history:
Received: 09 November 2017
Accepted: 05 February 2018

Keywords:
Ductility,
Seismic Design,
Lateral Force Distribution,
Demand to Capacity Ratio,
Plastic Rotation.

ABSTRACT

The design of earthquake-resistant buildings starts with defining the maximum lateral earthquake forces or their resultant. The amount of these forces depends on various factors, including coefficient of system behavior which depends on over strength and its ductility. In this study, a method is proposed in order to design an earthquake-resistant system in which the distribution of lateral forces is adjusted based on equal distribution of the seismic demand ratio in structural elements for the optimum use of seismic capability of the structure. To this end, three types of 4-, 7-, and 10-story structures are Applied. Firstly, the above-mentioned structures are designed based on gravity loads and consequently analyzed based on linear and nonlinear dynamic analyses, applying the accelerograms of some major earthquakes. Pursuant to that, the average loading ratio to the allowed capacity of the elements of each story in linear analysis and the average ratios of plastic rotations to the allowed capacity of elements in nonlinear analysis are applied as the modified shear ratio in the Iranian National Seismic Code. On that account, the new lateral loading distribution is measured and identified. Based on this new distribution, the above-mentioned structures are designed and their seismic behaviors are identified, applying linear and nonlinear dynamic analyses of the same accelerograms. The findings indicate an ameliorated seismic behavior of the beams and the columns. Moreover, the distribution of the seismic demand ratios attains more uniformity along the height of the structures.

1. Introduction

The method of seismic design, which is the basis of the majority of earthquake provisions, is called force-based design. The experience of past earthquakes points out that force-based design methods require evolution and modification [1,2]. Owing to the fact that the nature of earthquake forces is mainly displacement, consequently, the

DOI: 10.22075/JRCE.2018.13041.1235

resistance-based design cannot meet the needs of structure in case of an earthquake by itself. Force-based design methods do not contemplated the uniform distribution of stiffness and resistance in the height of structures; thus, in the case of an earthquake, damage might be more concentrated in some stories than other stories. Conclusively, It is essential ro consider design methods which lead to the uniform distribution of resistance and ductility ratios in different stories [3]. Essential parameters such as ductility and resistance have been inspected in many research reviews. In 1992, Fajfar [4] proposed an equivalent ductility coefficient to contemplate the cyclic effects of earthquake, which is a damage controller in structures.

In 2017, Mezgebo and Lui [5] proposed a procedure whereby input and hysteretic energy spectra developed for single-degree-of-freedom (SDOF) systems are applied to multi-degree-of-freedom (MDOF) steel moment resisting frames. A comparison of this proposed hysteretic equation with the actual hysteretic energy distribution from a pushover analysis revealed that the proposed equation gave rather good results. In 2012, Barrera et al. [6] came to the conclusion that by inspecting the reinforced concrete columns under bending and axial loads, that the ductility of slender columns under the axial load is not always reduced. In 2015, Bazzaz et al. [7, 8] indicated that because of the cyclic behavior of earthquake, X-braces do not have a suitable performance, and as a result, more ductile braces with the ability to absorb energy are required. They applied an off-center braced system with ductile elements. The results of the numerical analysis revealed that the proposed system, because of its high capacity to absorb energy, has a proper seismic performance. One of the ratios representing the damage resulting from an earthquake is the ratio of ductility, which is also known as damage index. Concerning the ratios, there is another ratio which is the damage criterion in the case of progressive failure and is called DCR or the ratio of needed force to capacity [9]. If the potential of damage distribution in the height of structure is uniform, consequently the seismic performance of the structure is ameliorated without an increase in costs. In this regard, by choosing eligible sections for elements, suitable distribution should be created for resistance and ductility [10]. In 2006 and 2009, Moghadam et al. [11, 12] proposed equations for lateral load distribution on the basis of uniform distribution of deformation, which were a function of ductility and structure period. Applying these methods reported to be very effective in enhancing the dynamic performance of the structure, but the loading distribution could not cause uniform distribution of damage in the height of the structure. In 2007, Moghadam et al. [13] revealed that the design based on optimum performance of moment steel frames under earthquake would be based on the uniform distribution of plastic torsion in the members. Hence, in this study, the order of beams and columns in the steel moment frames is determined to achieve the uniform distribution of ductility and DCR in stories. In this study, regular steel frames of 4-, 7-, and 10-stories are utilized to evaluate the proposed method. First, according to the Iranian National Seismic Code [14], the frames are designed, and DCR values and ductility ratios for all members are calculated according to the hypothetical accelerograms. Subsequently, based on the multi-distribution of lateral forces, new structures with the same number of spans and stories are designed, and DCR values and ductility ratios of the members in all of these structures are computed by contemplating the previous accelerograms. The results acquired represent an improvement in the seismic performance of the new structures compared with the previous ones designed based on the Iranian National Seismic Code, while no significant increase in the structure weight is reported

2. Design of Structural Models

In the present study, 4-, 7-, and 10-story steel (ST34) frames are applied. The frames are of the moment frame type. Each frame has 4 spans, a length of 4 meters, and a fixed height of 3 meters in the stories. The plan of the building is square, including five frames in each direction.

2.1. Loading and Design of Frames Based on Gravity Loads

To compute the gravity-based loading of frames, the 6th chapter of Iran's National Building Regulations [15] is applied. In gravity loading, it is assumed that structures have a residential use, the weight of all stories is equal, and the roof system is two-way slab. Dead load and live load of each story are assumed 600 and 200 kg/m^2, respectively; moreover, those of the roof are 650 and 150 kg/m2, respectively. Considering the fact that the initial structural design in the proposed method is conducted only under the gravity loads, the above-mentioned structures are analyzed and designed under gravity loads by means of SAP2000 software [16]. Based on gravity loading, the sections of columns designed are box sections with different dimensions and thicknesses, and those of beams are IPE180 profiles. In this case, there is no prejudice against the distribution of lateral forces in the structure design phase. Figure 1 illustrates 4-, 7-, and 10-story frames along with the sections used. This category of structures is called group I of the structures.

2.2. Loading and Lateral Design of Frames

Group II of the structures consisting of 4-, 7-, and 10-story frames is designed under gravity and seismic load combinations in order to compare the seismic behavior with the frames which would be designed later based on the method proposed in this paper.

Lateral loading is performed in consonance to the Iranian National Seismic Code [14]. Furthermore, the analysis of lateral loading is conducted on the basis of equivalent staticloading of the Iranian National Seismic Code. Design base acceleration ratio (A), the soil type, and the reduction factor of structure (R), by assuming the special moment frames, are 0.35, 3, and 10, respectively. The provision employed for the steel design is the 10th chapter of Iran's National Building Regulations [17].

3. Seismic Design with Requirement of Uniform Ductility

In this section, the structures designed based on sections 2.1. and 2.2. are inspected by linear time history and nonlinear dynamic analysis methods. Moreover, the seismic demands of members are computed.

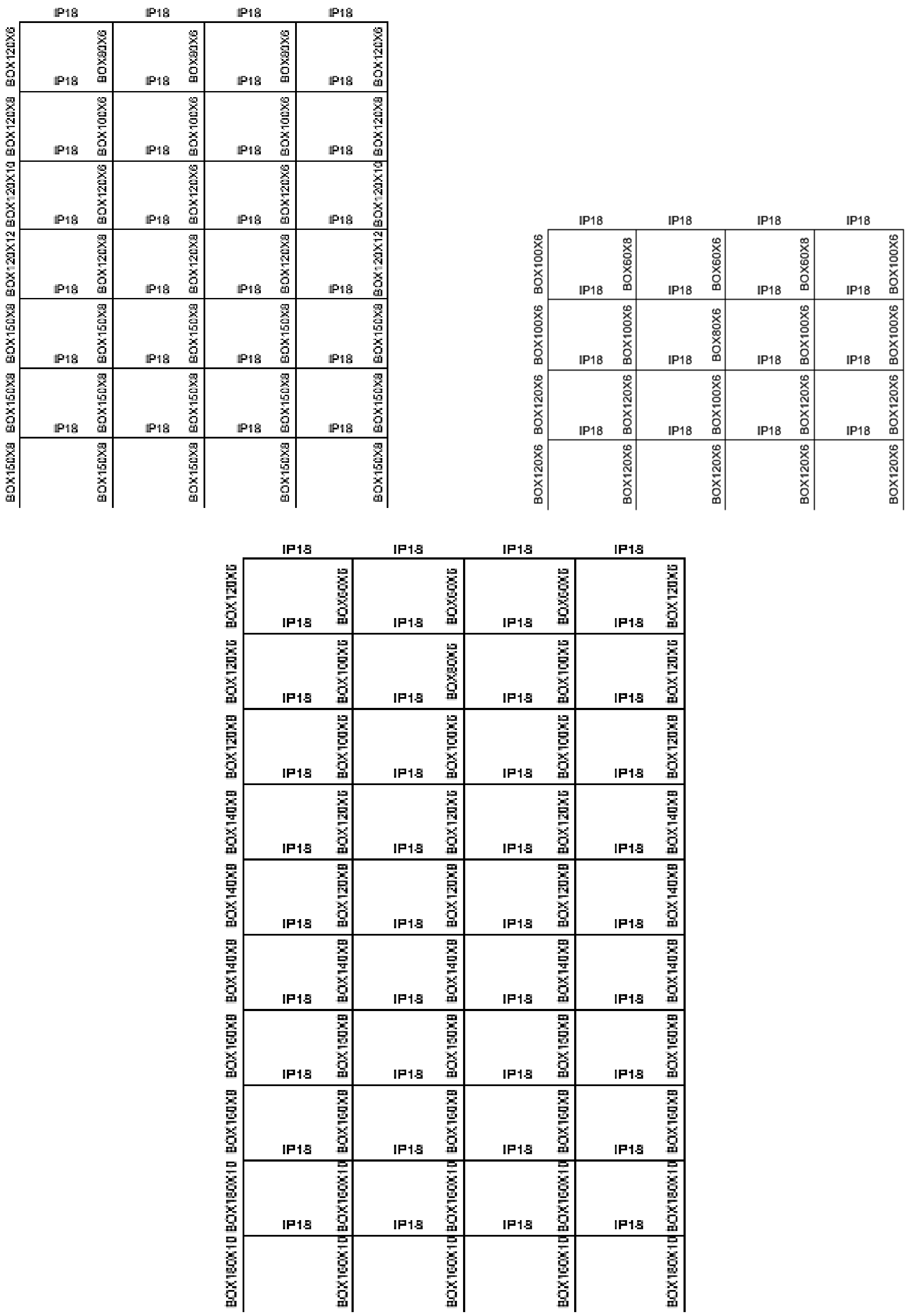


Fig. 1. Structures Designed only under gravity loads.

3.1. Earthquake Records Used

For dynamic time history analysis, the earthquake records are presented in Table 1 which is applied in here.

To provide the earthquake records, the database from PEER Berkeley is used [18].

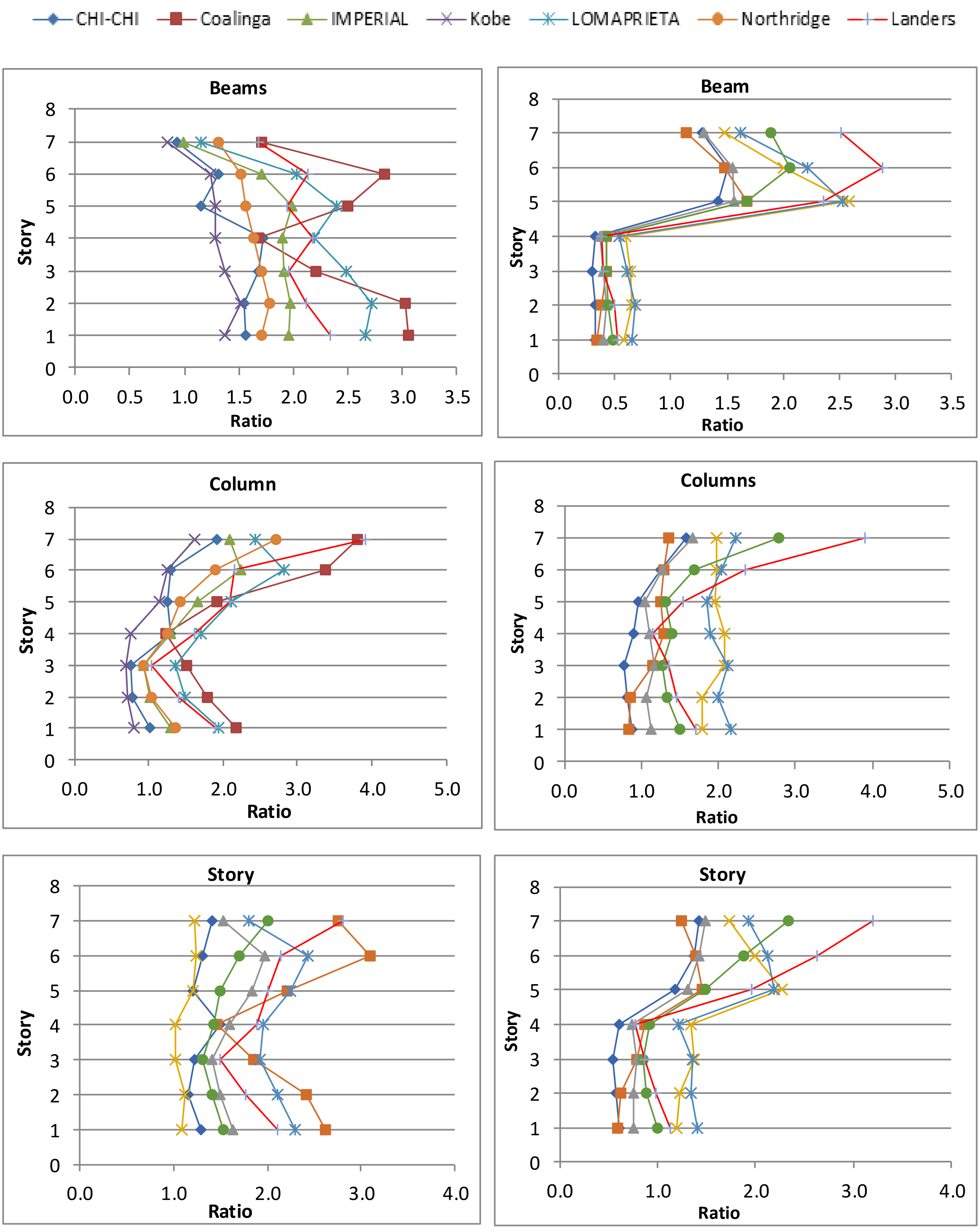
Table 1. Earthquake records selected [18]

Record	Station	*Year*	*Max. horizontal ground acceleration* (g)	*Magnitude*
Chi-Chi, Taiwan	*CWB 99999 TCU065*	*1999*	*0.282*	*6.2*
Coalinga	*CDMG 36456 Parkfield - Fault Zone 14*	*1983*	*0.282*	*6.36*
Imperial Valley	*USGS 5061 Calipatria Fire Station*	*1979*	*0.13*	*6.53*
Kobe, Japan	*CUE 99999 Kakogawa*	*1995*	*0.345*	*6.9*
Loma Prieta	CDMG 57425 Gilroy Array #7	1989	0.323	6.93
Northridge	*USC 90091 LA - Saturn St*	*1994*	*0.435*	*6.69*
Landers	SCE 23 Coolwater	*1992*	*0.417*	*7.28*

The magnitude of earthquakes ranges from 6 to 8 on the Richter scale. The earthquakes are similar in distance from the fault, and those away from fault are applied. Hence, the earthquakes selected in this study are more than 20 km away from the fault. Since the structures surveyed in this work are of soil type 3 with shear wave velocity ranging from 175 to 375 meters per second, the quakes selected occurred in the earth with shear wave velocity of the same range. As the analysis is two-dimensional, consequently, the horizontal components of each quake with larger maximum acceleration is selected. Scaling of the earthquakes is manifested by means of ASCE-2010 [19]. Pursuant to the aforesaid regulation, accelerograms should be scaled in such a way that an average of response spectra with 5% damping within the distance of 0.2T-1.5T (T: Natural Period of Structure) should not be less than the design response spectrum of the code.

3.2. Linear Dynamic Analysis

Considering the importance of resistance factor in improving the seismic behavior of structures, linear dynamic analysis for both groups of structures, which are designed based on sections 2.1 and 2.2, is performed by means of OpenSees [20] under the earthquakes introduced in Table 1; moreover, the ratio of force to capacity (DCR) is computed for all components of the force in all members. Regarding the Feman356 [9], the DCR ratio can be contemplated as QUD/QCE. In this relation, QUD and QCE are the force calculated as a result to the gravity and earthquake loads and expected strength of the component or element, respectively. These values include axial, shear, and bending efforts. The maximum values of DCR for each earthquake and the average value of all 7 earthquakes are calculated. Due to the large number of figures, these values for beams, columns, and story average for a 7-story structure are depicted in Fig. 2.



a. DCR values of beams, columns and story for a 7-story structure of group I;

b. DCR values of beams, columns and story for a 7-story structure of group II;

Fig. 2. DCR values of beams, columns and story for 7-story structures of groups I and II.

Graphs acquired from linear analysis of structures in group I indicate that DCR values of beams in lower stories and DCR values of columns in upper stories are greater than those of other stories. Therefore, in order to compensate for this weakness, the shear force value of these stories should increase, and the process of this increase will be described in the following sections. According to the figures obtained by linear structural analysis of group II, DCR values in the 4-story model are uniformly distributed in beams; however, DCR values for columns of upper stories are greater than those of other stories. In the 7-story model, values related to the beams are well uniform in lower stories, notwithstanding that they have increased in upper stories significantly. Regarding the DCR values in columns, different requirements are observed in dissimilar earthquakes, however these values have increased in upper stories. In the 10-story model, large disparities in DCR values of beams and columns can be noticed, particularly in upper stories of the structure. This non-uniformity can be observed in the mean DCR of the stories as well. This issue reflects the shear weakness of the upper stories of the structure. In agreement to that, it is necessary to increase shear force in upper stories while distributing the lateral force of the stories in the height of the structure.

3.3 Nonlinear Dynamic Analysis

It is noteworthy to mention that one cannot consider the earthquake behavior just as a force such as dead and live loads. The nature of loads resulting from an earthquake is mainly conventional and creditable and is of the displacement type. Thus, it is not appropriate to contemplate the structural resistance as the only factor improving the seismic behavior. To investigate structural deformation, both groups of structures are designed according to sections 2.1 and 2.2; moreover, nonlinear dynamic analysis is performed by applying OpenSees software to the earthquakes introduced in Table 1. In the nonlinear dynamic analysis, the concentrated plasticity with rotational springs is applied. This model utilizes Rayleigh damping which formulates the damping matrix as a linear combination of the mass matrix and stiffness matrix. At last, the ductility ratio, which is the ratio of maximum rotation to the yielding rotation, is computed for all members. The maximum rotation is the maximum spin which plastic hinges in elements experience during a specific earthquake. If a member enters the plastic zone, the maximum rotation is obtained from Eq. 1:

$$\theta_{max} = \theta_{Plastic} + \theta_y \tag{1}$$

In consonance to FEMA356, yielding rotate of the beams and columns are obtained from Eq. 2 and 3:

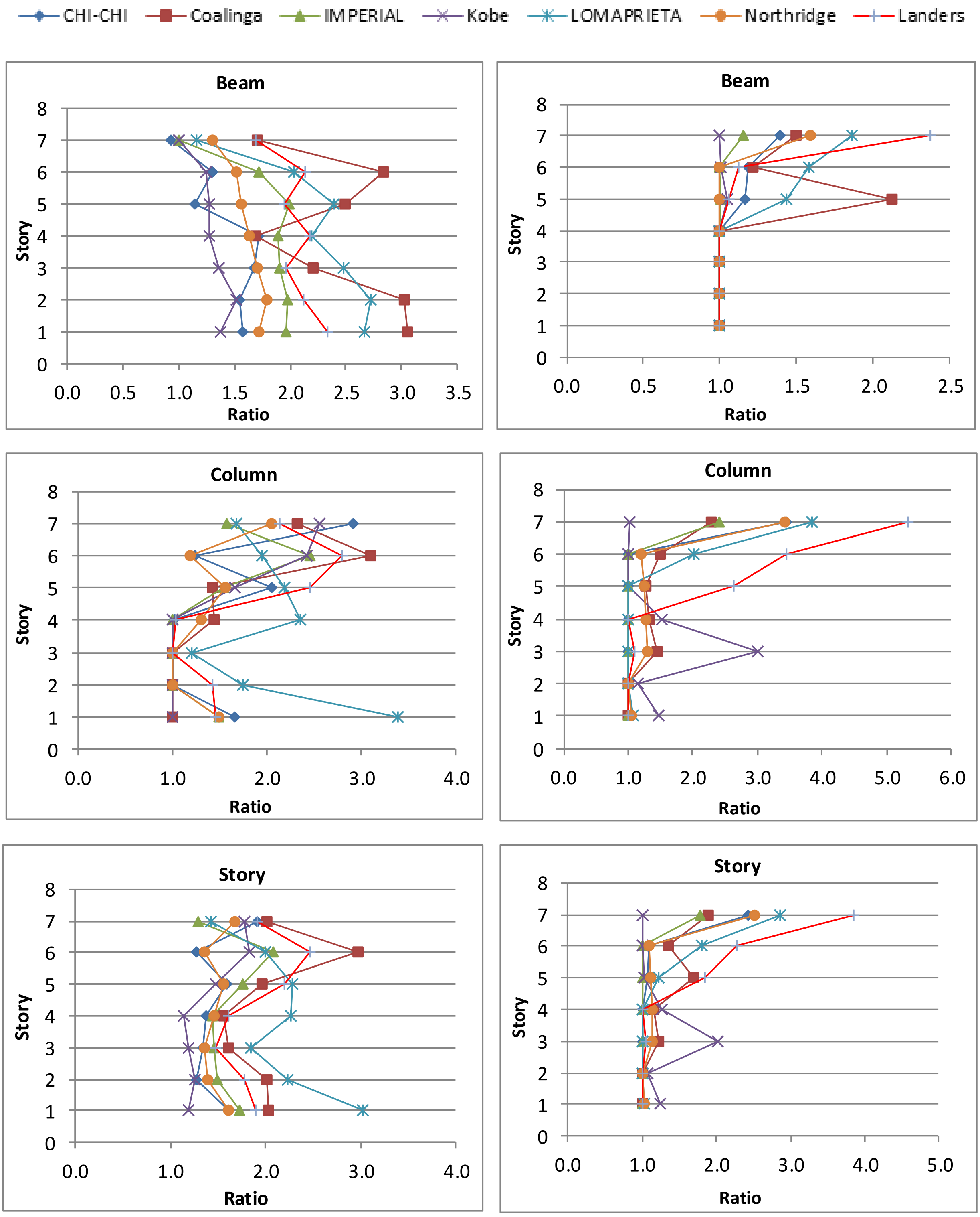
$$\theta y = \frac{Z F_{ye} L_b}{6 E I_b}, F_{ye} = Ry \times Fy, Ry = 1.2 \tag{2}$$

$$\theta y = \frac{Z F_{ye} L_C}{6 E I_C}(1 - \frac{P}{P_{ye}}) \tag{3}$$

The terms introduced in Eq. 1 and 2, Z, F_{ye}, E, I and P, indicate section plastic modulus, yield stress of materials, modulus of elasticity, moment of inertia and member axial force, respectively. $P_{ye}= A_y F_{ye}$, is member axial force, where Ay is the member cross-section. Therefore, the ductility value is calculated by:

$$\mu\theta = \frac{\theta \max}{\theta y} = 1 + \frac{\theta_{Plastic}}{\theta y} \tag{4}$$

Ductility ratios for the first and second group are calculated and shown in charts. As a result to the large number of figures, the ductility ratios of beams, columns and average of story just for a 7-story structure are portrayed in Fig. 3.



a. Ductility ratios of beams, columns and story for a 7-story structure of group I;

b. Ductility ratios of beams, columns and story for a 7-story structure of group II;

Fig. 3. Ductility ratios of beams, columns, and story for 7-story buildings of groups I and II.

Based on the nonlinear analysis of the structures in group I, different ductility ratios are observed for different earthquakes. Ductility demand is not the same in different stories. According to the proposed method, which is described in the following sections, the aim is to ameliorate the distribution of code lateral forces to satisfy ductility demands. Pursuant the results of nonlinear analysis of the structures in group II, it is found that in the 4-story model, the ductility distribution of columns is uniform in lower stories. However, these ratios have increased in upper stories.

As presented in Fig. 3.b, ductility ratios of beams increased in upper stories of the 7-story model, and ductility ratios of columns change in some earthquakes in lower stories. Additinally, the majority of earthquakes show more evident changes of ratios in upper stories. In the 10-story model, great values of ductility ratios for beams are observed in lower stories, but the same values for columns increase in upper stories.

4. Calculating New Lateral Forces and Redesigning Structures

After evaluating DCR values and ductility ratios of beams and columns acquired from time history analysis of structures in group I, it is observed that beams and columns have dissimilar ductility requirements and that it is essential to apply different lateral loadings to redesign them.

By examining the structures designed based on the distribution of regulation loads undergoing different earthquakes, it is found that DCR and ductility ratios are not uniformly distributed in elements and many members have entered the plastic area, while there is no plastic deformation in some other members, meaning that the total capacity of elements is not applied optimally.

In this study, for the sake of optimal use of sections, distribution of loads is presented to dispense the damage control factors such as ductility and strength-to-capacity ratio uniformly in the height of structure.

In order to achieve uniform distribution of DCR and ductility ratio in the height of structure, which is a criterion for an optimal design [9, 21], shear distributions based on regulation in stories are modified.

In this regard, by applying the following 4 methods, correction coefficients (α_i and β_i) of story shear are computed and multiplied in the story shear obtained from Iranian National Seismic Code for each story. Finally, by using this modified shear, the new distribution of lateral forces is obtained.

a. The coefficient $\alpha_{i,story}$ to design all members of the story:

$$\alpha_{i.\ story} = \left(\frac{\sum_{j=1}^{N}\left(D_j\right)}{N} + \frac{\sum_{j=1}^{M}\left(D_j\right)}{M}\right)/2 \quad (5)$$

b. The coefficient $\alpha_{i,\ beam}$ to design beams and the coefficient $\alpha_{i,\ column}$ to design columns:

$$\alpha_{i.\ beam} = \frac{\sum_{j=1}^{Nn}(D_j)}{N}\ .\ \alpha_{i.\ column} = \frac{\sum_{j=1}^{M}(D_j)}{M} \quad (6)$$

c. The coefficient $\beta_{i,story}$ to design all members of the story:

$$\beta_{i.\ story} = \left(\frac{\sum_{j=1}^{N}\left(R_j\right)}{N} + \frac{\sum_{j=1}^{M}\left(R_j\right)}{M}\right)/2 \quad (7)$$

d. The coefficient $\beta_{i,beam}$ to design beams and the coefficient $\beta_{i,column}$ to design column:

$$\beta_{i.\ beam} = \frac{\sum_{j=1}^{N}(R_j)}{N}\ .\ \beta_{i.\ column} = \frac{\sum_{j=1}^{M}(R_j)}{M} \quad (8)$$

The terms used in equations 5-8 are as follows:

N: the number of beams,

M: the number of columns on the i_{th} floor,

$D = DCR / m$, $R = \theta_{Plastic} / m$, and

m: Allowable plastic rotation, obtained from FEMA356 [9].

Fig. 4 shows the new distribution of lateral forces obtained by methods a, b, c, and d only for the 7-story model.

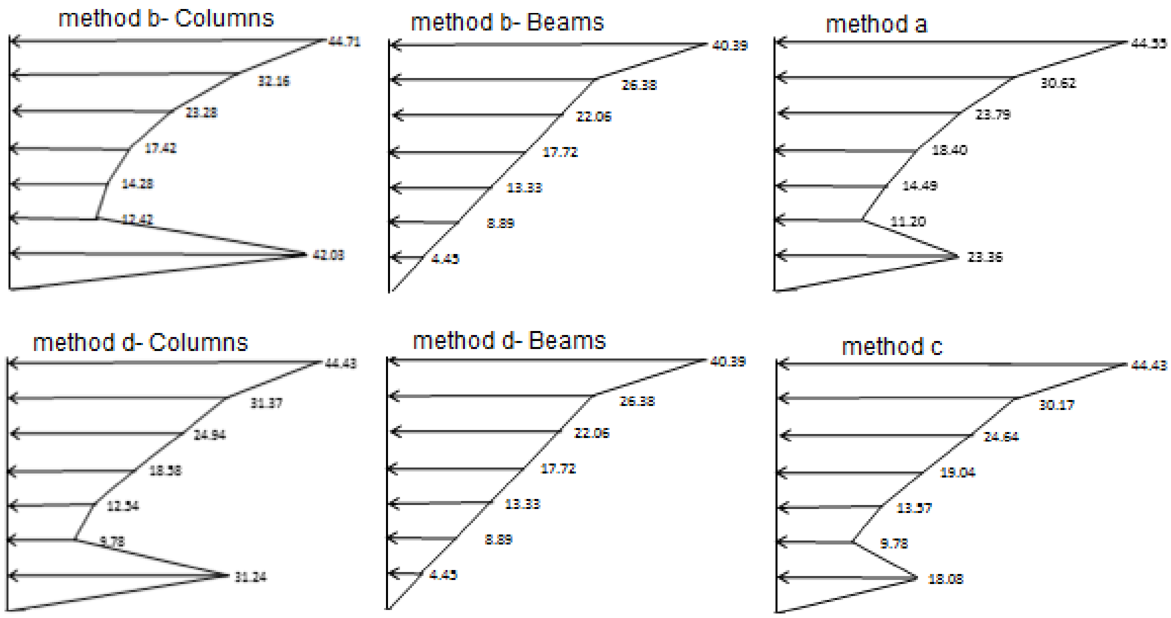
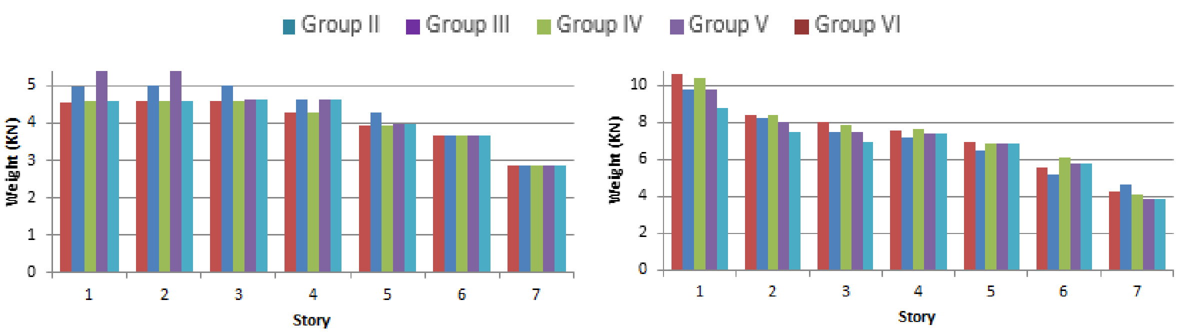


Fig. 4. New distribution of lateral forces in height of structure obtained by methods a, b, c, and d in the 7-story model (kN)

After obtaining the design forces for 4-, 7-, and 10-story models, new sections of beams and columns are acquired which are differing from the sections of group II. Structures designed according to methods a, b, c, and d are called III, IV, V, and VI groups, respectively, and the total weight of all story members of all models is calculated and compared. Hence, owing to the large number of figures, weight of columns and beams in the 7-story model in groups II-VI is illustrated in Fig. 5. Fig. 6 compares total weight changes of new structures with those of the other structures of group II, and Fig. 7 indicates the period of structures.



a. Weight changes of beams; b. Weight changes of columns;

Fig. 5. Total weight changes of columns and beams in the 7-story model in groups II-VI

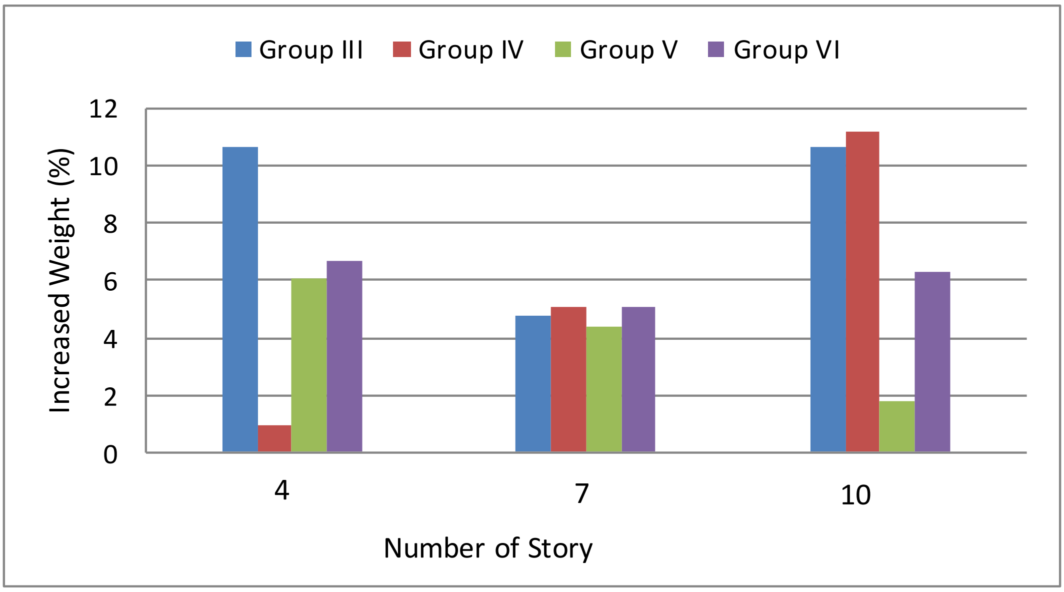


Fig. 6. Total weight changes of all new structures compared to the total weight of group II model

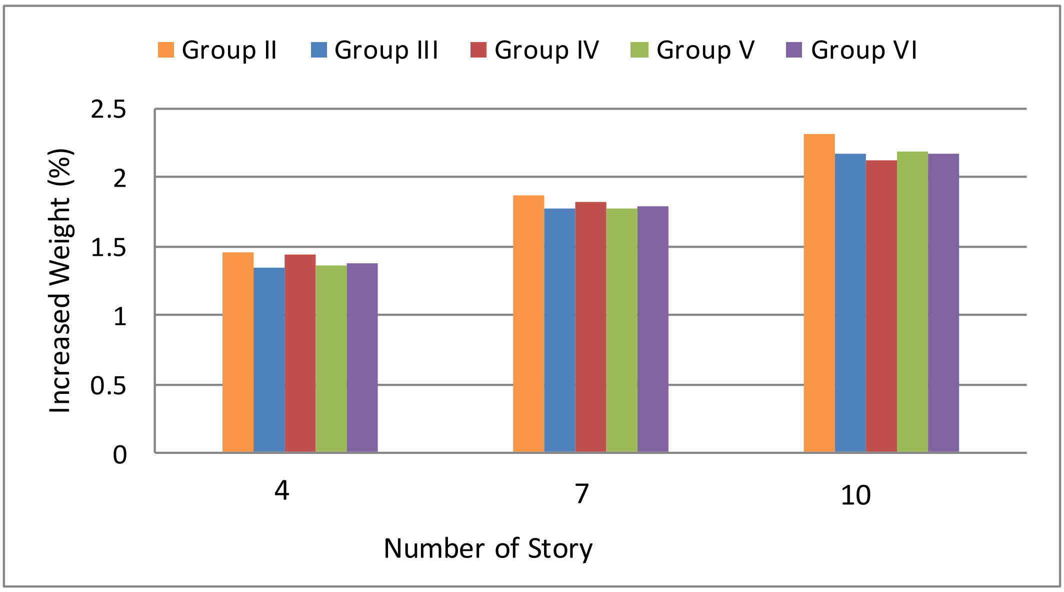
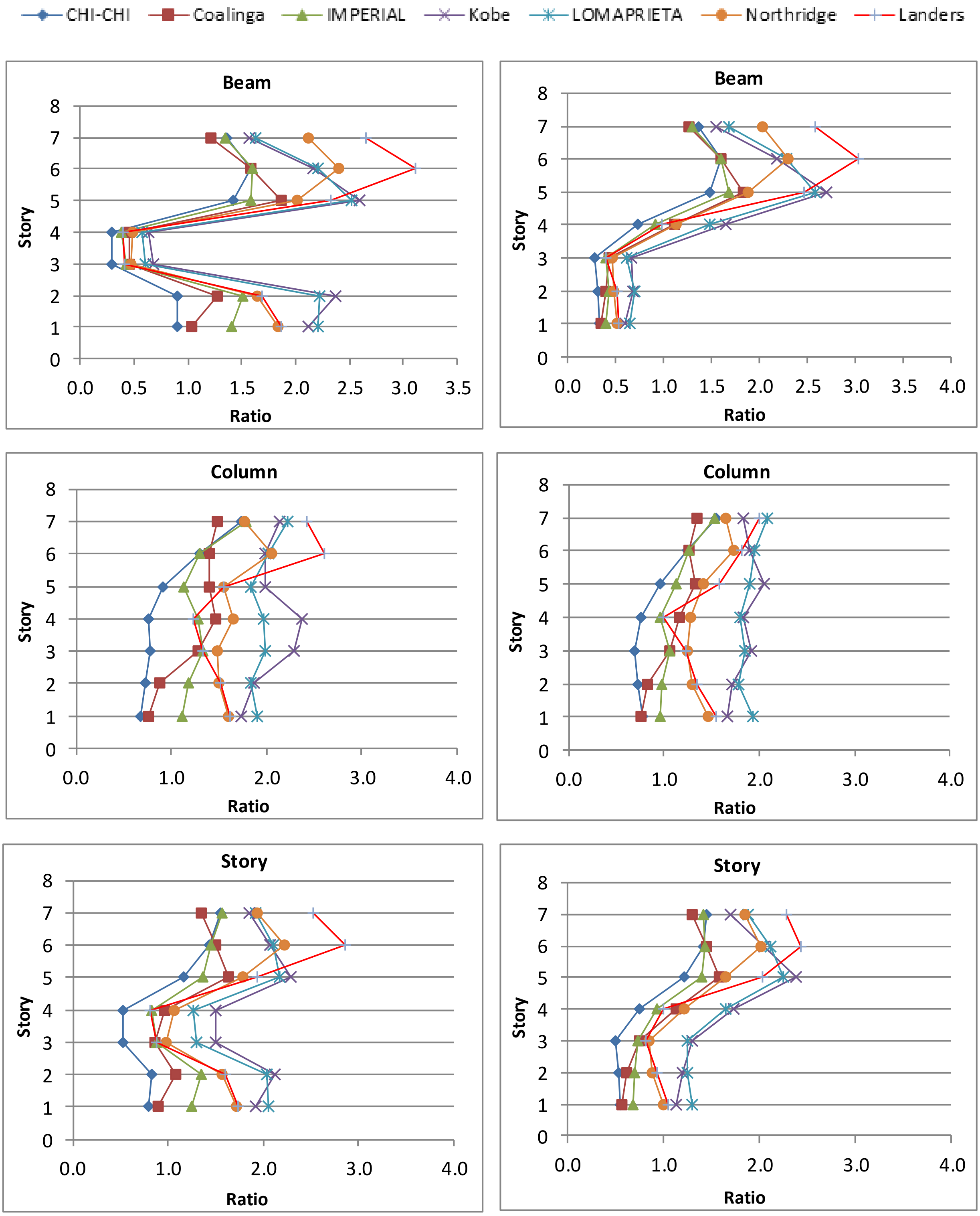


Fig. 7. Period values of models in groups II-VI

Fig. 5 displays that the weight of beams and columns in different stories of new models increases or decreases compared to structures in group II. Similar changes are observed in 4- and 10-story structures as well. However, pursuant to Fig. 6, slight increment is noticed in the total weight of new structures compared to group II models; furthermore, according to Fig. 7, a reduction in period in all new structures is observed.

5. Linear and Nonlinear Dynamic Analysis of Redesigned Structures

Linear and nonlinear time-history analyses are employed for 4-, 7-, and 10-story models designed based on new sections for the earthquakes represented in Table 1. DCR values and ductility ratios of members and stories are computed. Fig. 8 and 9 represent these values in beams, columns, and average of story for a 7-story structure. Furthermore, for the sake of comparison, the mean of the above-mentioned values of structures from groups II, III, IV, V and VI for 7 earthquakes for a 7-story structure is exhibited in Figure 10.



a. DCR values of beams, columns and story for a 7-story structure of group III;

b. DCR values of beams, columns and story for a 7-story structure of group IV;

Fig. 8. DCR values of beams, columns, and story for 7-story structures of groups III and IV.

According to the results of linear analysis of 4-story structures in groups III and IV, it is found that DCR values of beams and columns on the top story of group III are high and require strengthening. However, for the same structure of group IV, the average DCR values of beams and columns decrease on the one hand and are more uniform on the other hand. Furthermore, DCR distribution in height is more uniform.

Considering the fact that the closer the mean of DCR values and the ductility ratios in stories, the more uniform the distribution of these values is, this uniformity indicates the optimal application of sections of beams and columns.

As Fig. 8.a reveals, DCR distribution of middle stories in beams of the 7-story structure in group III is highly non-uniform, whilst more uniform distribution is observed in columns of the same structure in group II. Contemplating the above-mentioned structure in group IV, Fig. 8.b exhibits uniform distribution in lower stories similar to those in group II; DCR distribution in columns is more uniform than structures in groups II and III.

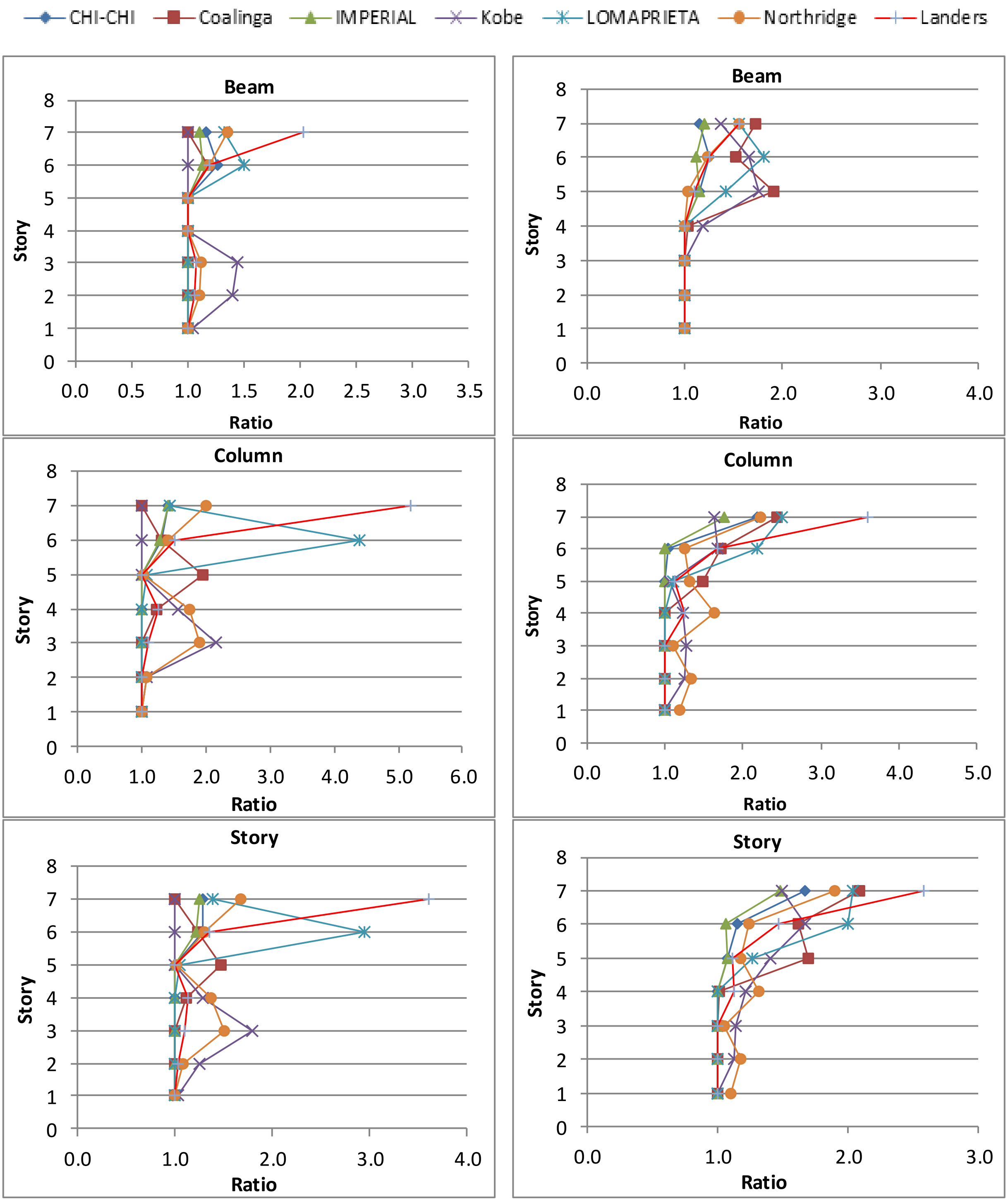
In the 10-story structure of group III, DCR distribution in beams is more appropriate than other methods and DCR distribution in columns is almost uniform. In addition to this, inspectingthe same structures of group IV implies non-uniform distribution in beams and more uniform distribution in columns compared to groups II and III.

A close look at the results of nonlinear analysis of the 4-story structure in group V reveals that ductility distribution in beams is the same as that in group II, while ductility distribution in columns is more uniform. Moreover, columns and beams of the 4-story structure indicate a better performance in group VI than groups II and V, indicating uniform distribution in height and compensating for shear weakness of structure in lower stories.

Focusing on beams and columns of the 7-story structures, Fig. 9.a reveals perfectmonotony of ductility distribution in lower stories of group V in all earthquakes, except for Kobe and Northridge earthquakes.

Based on Fig. 9.b, uniform ductility distribution can be observed in beams and columns of lower stories in all earthquakes, and this distribution is particularly more uniform in upper stories. Furthermore, ductility distribution values have decreased compared to structures in group II.

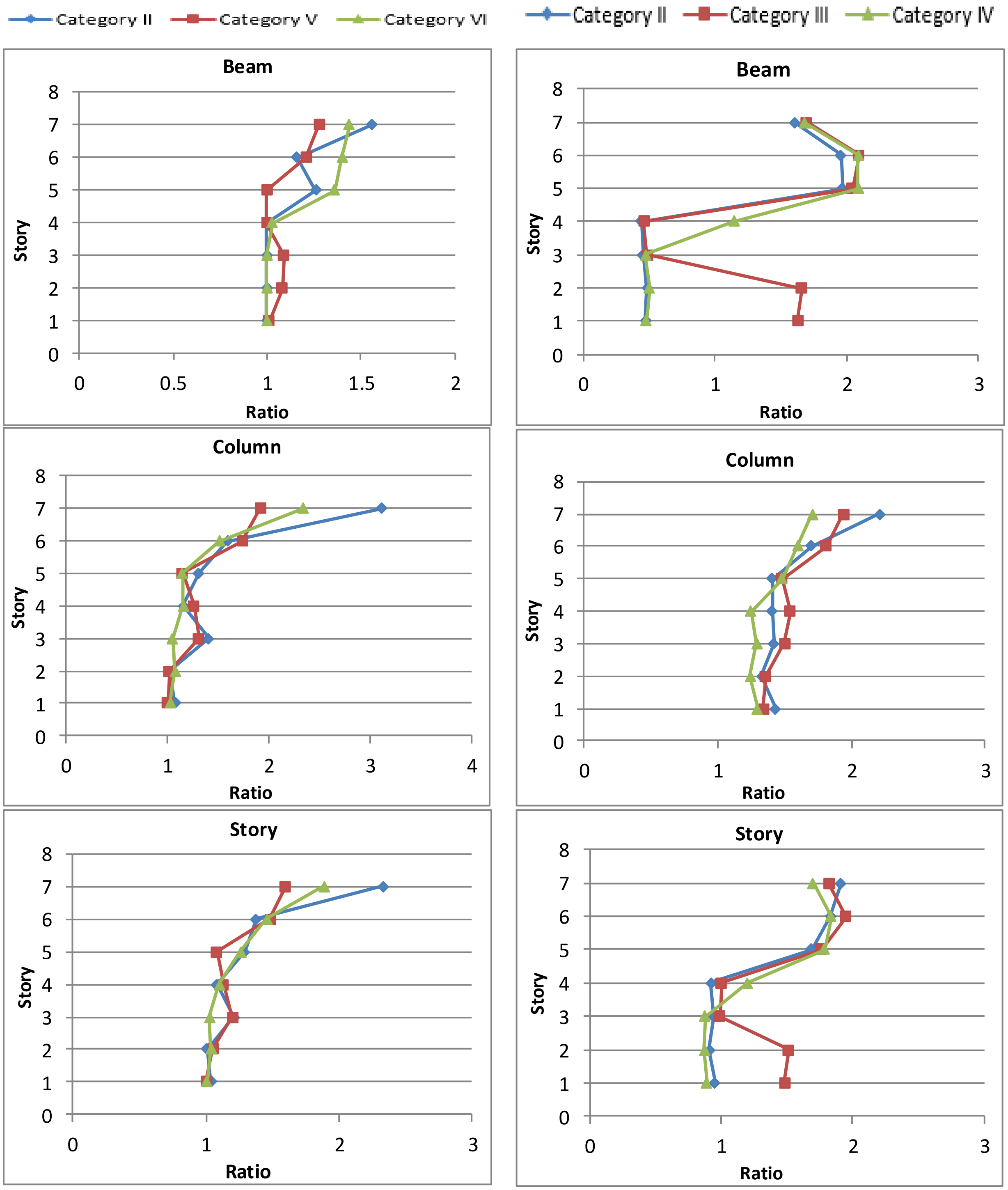
Distribution in columns and beams of the 10-story structure in group V is somewhat similar to that in group II, but with smaller values. In the 10-story structure in group VI, the performance of the columns is much better and the ductility distribution is more uniform although the values are lower. In point of fact, we can conclude method d has been more successful than method c and the Iranian National Seismic Code in controlling ductility distribution.



a. Ductility ratios of beams, columns and story for a 7-story structure of group V;

b. Ductility ratios of beams, columns and story for a 7-story structure of group VI;

Fig. 9. Ductility ratios of beams, columns, and story for 7-story structures of groups V and VI.



a. Comparison of the average ductility ratios in beams, columns and story of 7-story structure in categories II, V and VI;

b. Comparison of the average values of DCR in beams, columns and story of 7-story structure in categories II, III and IV;

Fig. 10. Comparison of ductility ratios and average DCR values in beams, columns and stories of the 7-story structure in groups II–VI

Pursuant to the results of ductility ratios (e.g. Fig. 10.a), the outstanding performance of method d, compared to Iranian National Seismic Code and method c, in controlling ductility ratios as well as the uniform distribution of these ratios in the height of structure are clearly observed. Moreover, the method that is mentioned above performs well in the 4-story structure, reducing ductility ratios and distributing them uniformly. In agreement to the results of DCR ratios (e.g. Fig. 10.b), DCR distribution of beams and columns in the 4-story structure of group IV is more uniform than that in groups II and III, while these values have decreased to some extent. This is accounted for by the fact that in short structures, the requirement for columns and beams is well-satisfied and shear weakness observed in the structure designed on the basis of Iranian National Seismic Code is well compensated for. In 7- and 10-story structures of groups III and IV, distribution of DCR values in beams is generally the same as that in structures of group II. Furthermore, the above-mentioned values are distributed in the height of columns in structures of group IV better than groups II and III, knowing that distribution in structures of group III is better comparing to group II.

It is noteworthy to mention that groups VI and II have similar distribution of ductility ratios in beams of the 7- and 10-story structures. This similarity can be accounted for by the fact that the allowable value, which is defined by FEMA356 for DCR and ductility ratios, is generally close to 1 in models with higher stories of structure. However, depending on the size of sections, different values other than 1 are acquired for force improvement in columns, leading to more significant modifications in the sections of columns. That explains the reason why method d performs better in improving column performance compared to Iranian National Seismic Code and method c.

6. Conclusion

In this study, some methods were introduced that led to the uniform distribution of DCR values and ductility ratios in structure in case of an earthquake. DCR values and ductility ratios are both major factors in expressing the structural damage. In structures designed based on Iranian National Seismic Code, it was found that DCR values and ductility ratios are not uniformly dissipated in the height of structure when an earthquake occurs. This non-uniformity of distribution results from the non-optimal application of the structural sections. Based on the seismic demand obtained by the value allowed for each member, the new distribution of lateral forces was proposed. Due to these new loadings, the original structures were redesigned and evaluated under linear and nonlinear dynamic analysis, and the behavior of all structures was investigated. The results indicated an improvement in seismic performance while achieving uniform distribution of DCR values and ductility ratios in the height of structure. Moreover, it was observed that the structures redesigned, in addition to their good seismic performance, did not gain much weight compared to the structures designed based on regulations, showing the optimal application of the capacity of sections in structure.

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