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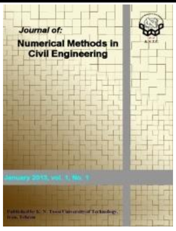

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Assessment of the seismic performance of structures designed based on uniform ductility pattern

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Abstract:

In seismic design procedure, the idea of considering uniform inelastic behavior for all stories displaces materials from unnecessary locations to stories needed for damage reduction and leads to a more economic design. In this paper, a parametric study was done to assess the seismic performance of structures designed based on uniform ductility pattern. For this purpose, three artificial records whose response spectrums were matched to the codified design spectrum, were considered. Using an iterative procedure, the tuned strength patterns were obtained for a number of models with various natural periods, ductility ratios, behavior coefficients and stiffness distributions. It can be seen that the strength of stories corresponding to uniform ductility pattern decreases in all stories in comparison with distribution recommended by Standard-2800 especially for middle stories and the total strength of structures as a weight index decreases. Also, a new equation was developed by regression analysis to determine the coefficient of story strength. Assessment of the performance of the structures with tuned story strength distribution under real ground motions showed less dispersion for ductility pattern in comparison with structures which were designed according to Standard-2800. Also, it was seen that if the amplitude of the earthquake response spectrum is larger than the design spectrum, the dispersion of the ductility values over the stories increases significantly. The situation becomes critical for lower stories when the amplitude of the earthquake response spectrum is larger than the design spectrum at periods higher than the fundamental period of the structure.

1. Introduction

It is well known that in current seismic provisions the proposed seismic force distributions are generally based on the first mode of vibration of the elastic structure [1-3]. It is recognized that structures which are designed based on this concept experience large inelastic deformation during strong earthquakes. Also, the ductility demand is not uniform in all stories of the structure. Many researches have been carried out to study the validity of the distribution of lateral forces proposed by seismic provisions.

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Anderson et al. [4] and Gilmore and Bertero [5] evaluated the seismic performance of buildings which were designed according to seismic provisions. Chopra and Cruz [6] and Chopra [7] evaluated the ductility demands of many shear buildings subjected to a ground motion. They considered yield strength distribution specified by UBC-97 [1] and found that the strength distribution does not lead to equal ductility demand in all stories. In most cases, the first story experiences the highest ductility among the other stories. Martinelli et al. [8] and Hart [9] investigated the seismic design procedure and the response of structures that are designed based on lateral force pattern recommended by seismic design codes. Moghaddam and Esmailzadeh Hakimi [10] studied a number of shear building models. They concluded that the strength pattern suggested by UBC-97 [1] does not lead to a uniform distribution of ductility demands. Karami Mohammadi [11] suggested a procedure to find the optimum strength distribution for structures subjected to seismic excitations to reach a desirable structural performance. An expression was proposed by Lee and Goel [12] to estimate lateral force pattern based on inelastic response of structures. Subsequently, based on several nonlinear analyses on braced frames and truss moment frames, Chao and Goel [13-15] revised this expression. Park and Medina [16] suggested a lateral force distribution which was suitable for moment-resisting frame structures subjected to near fault ground motions. There are many other studies that tried to improve seismic design of the structures with the aim of achieving an optimum strength and stiffness distribution in the stories [17-19]. Among the studies, a collection of researches has been carried out by Moghaddam et al. [20-27]. They used an iterative procedure to find the optimum strength distribution based on uniform distribution of deformation. In their suggested procedure, the properties of the structure are modified so that the strength is gradually shifted from strong to weak parts of the structure. They proposed a new distribution for lateral seismic force, which is a function of the period and ductility. Also, they proposed a prescribed distribution for ductility to minimize the total weight of the structure and reach the desirable performance. Medina and Krawinkler [28] investigated the strength demand for moment resisting frames under seismic excitation. Deguchi et al. [29] amended the lateral force pattern presented by seismic design codes and proposed a new lateral force pattern based on the maximum shear induced by seismic excitations. Ganjavi et al. [30] assessed damage and drift distribution in Reinforced Concrete (RC) buildings considering uniform strength ratio. Abdollahzade and Niknafas [31] evaluated damage distribution in frames and proposed an approach to make this parameter become uniform between structural members. Golizadeh and Fattahi [32] proposed a computational method to design optimized steel structures under earthquake loading. They showed that using a developed grey wolf algorithm incorporating back propagation neural network leads to the best results. Kermani et al. [33] considered ductility in seismic design of steel structures and presented a simple approach to design steel structures for a predetermined ductility. Akbari and Sadegh Ayubirad [34] developed a computer program for optimization of low, intermediate and high rise frames. They compared the results of sequential quadratic programming method with the results of genetic algorithm technique. They concluded that sequential quadratic programming method can lead to the optimum design confidently. Heidari and Raeisi [35] used simulated annealing method to achieve optimum design of structures. They used a discrete wavelet transform to reduce computations. A number of space structures were designed and optimized for minimum weight by this method. Sarcheshmehpour et al. [36] provided a methodology for the optimal design of steel structures considering building codes recommendations. They evaluated the applicability of the proposed approach for 20, 40 and 60-story buildings.

In order to investigate the influence of ground motion's characteristics, Praveen et al. [37] studied the effects of ground motions on performance of RC buildings with a soft story at ground level through incremental dynamic analyses. Ganjavi et al. [38] evaluated scaling methods of ground motions on drift of energy-based plastic designed steel frames.

These studies showed that the design procedure in seismic provisions will not lead to a predictable and desirable seismic response for structures under strong earthquakes. It is clear that one of the main elements of seismic design of structures is to use realistic lateral strength distribution which is based on the inelastic response of structures. In order to reach this goal, it is important to consider inelastic response of systems in design procedure. Many expressions have been proposed to estimate optimum lateral seismic load distribution. Most of them suggest the lateral force as a function of the period and ductility of the structure. However, in design procedure of the structures recommended by seismic design codes, the base shear is determined based on the behavior coefficient(R_u).

In this paper, a number of buildings with different number of stories have been designed based on Standard-2800 [3]. Then, the tuned strength distribution is determined by an iterative procedure to achieve uniform ductility pattern. Considering a new prospective, the structures are subjected to three artificial records which are matched with the design spectrum. Subsequently, the effects of variation of different parameters such as the natural period of the structure, ductility, behavior coefficient and stiffness distribution are evaluated on the seismic performance of structures with tuned strength distribution pattern.

Since the amplitude and frequency content of the records have considerable influence on the response of structures, the seismic performance of structures with tuned strength distribution pattern is evaluated under real ground motions in accordance with the characteristics of records.

2. Model buildings

As shown in Fig. 1, shear buildings with 5, 10 and 15 stories are considered in this research. The story mass is assumed to be identical for all stories. Two distributions are assumed for stiffness over the height of the structures. In the first type, uniform stiffness with identical stiffness for all stories is considered. For the second type, it is assumed that the stiffness of each story is proportional to its shear strength. As a result, different values are assigned to story stiffness values in order to reach a target natural period for the structure. In both types of stiffness distribution, the stiffness values of each story are estimated by trial and error to set periods of 5, 10 and 15-story models to be 0.5 sec, 1 sec and 1.5 sec, respectively.

All models, considered as multi degree of freedom shear buildings, are constructed in OpenSees program [39]. Lumped mass is assigned to all stories. Each story is connected to the lower story with uniaxial spring which acts in horizontal direction. A bilinear behavior (Steel01) is considered for the springs. The yield strength of springs is considered equal to the strength of each story. Rayleigh damping of 5 percent is assumed, considering the first and the second modes of vibration of the structures.

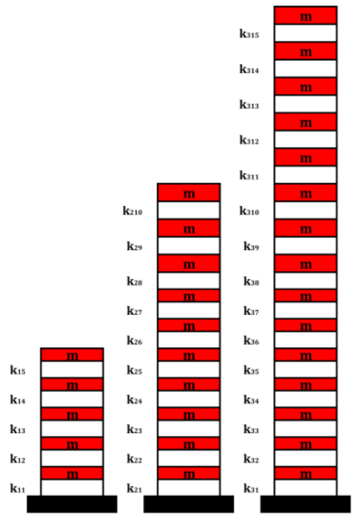


Fig. 1: 5, 10 and 15 story model buildings

3. Methodology

The models are designed based on Standard-2800 [3] and then subjected to different ground motions for seismic performance evaluation. For this purpose a design spectrum for very high seismicity zones with base acceleration of A=0.35g and soil type II with shear wave velocity of $375\,m/s < V_s < 7500\,m/s$ is assumed [3]. Also, various behavior coefficients ($R_u = 4{,}5$ and 6) are considered for design of structures in order to have different levels of nonlinearity in the structure. The value of design base shear is equal to $V_u = ABIW/R_u$; where A is the base acceleration, B is the reflection coefficient, I is the importance factor, R_u is the behavior coefficient and W is the seismic weight of the structure. Standard-2800 [3] suggests an expression for lateral seismic force pattern as below:

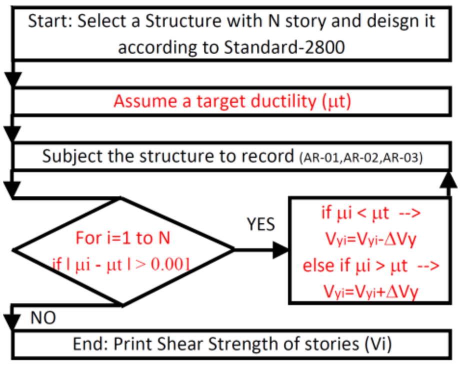
$$F_{ui} = \frac{W_i h_i^k}{\sum_{j=1}^{n} W_i h_i^k} V_u \tag{1}$$

In which F_{ui} is the lateral force at i-th story level, W_i is the weight of the story, h_i is the story height measured from the base and N is the number of stories. k is a coefficient which can be determined in accordance with the fundamental period of the structure (T) as below:

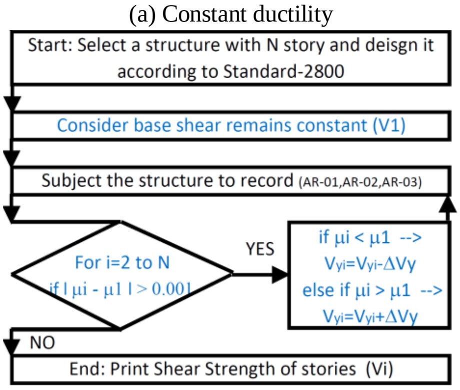
$$k = 0.5T + 0.75 \qquad 0.5 \le T \le 2.5\,Sec \tag{2}$$

where k is equal to 1 for periods smaller than 0.5 sec and equals to 2 for periods greater than 2.5 sec.

As mentioned previously, the seismic performance of structures which are designed based on uniform ductility at all stories is assessed in this research. Story ductility (μ_i) is defined as the ratio of the maximum relative displacement of the story to yield displacement of the story. To achieve this goal, two procedures are considered as shown in Fig. 2. In the first one (Fig. 2(a)), the distribution of strength over the height of the structure is determined to reach a predetermined uniform ductility in all stories while subjected to the artificial records. The response spectrums of the artificial records are matched to the design spectrum using Seismomatch program [40]. In this procedure, a value for target ductility (μ_t) is assumed. Then at each cycle of analysis, the ductility of each story is compared with μ_t and then it is decided to tune the strength of the story with step ΔV in order to reach μ_t. In another procedure (Fig. 2(b)), the base shear at the first story is determined in accordance with Standard-2800 [3] and kept constant in all cycles of iterations. Then, at each cycle of analysis, the ductility of each story is compared with ductility of the first story (μ_1) and then, it is decided to tune the strength of the story with step ΔV in order to reach μ_1 , while μ_1 varies in each cycle.



(a) Constant ductility



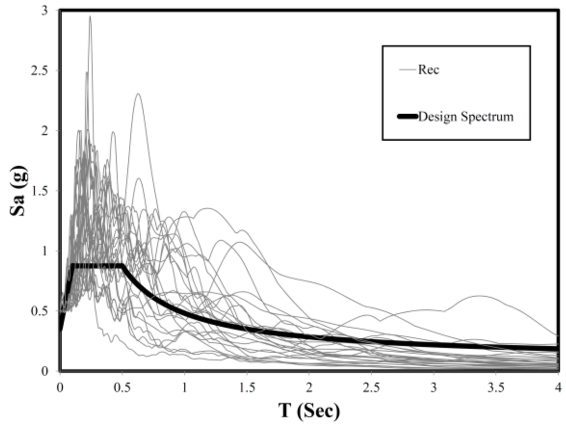
(b) Constant base shear

Fig. 2: Targeted iterative approach

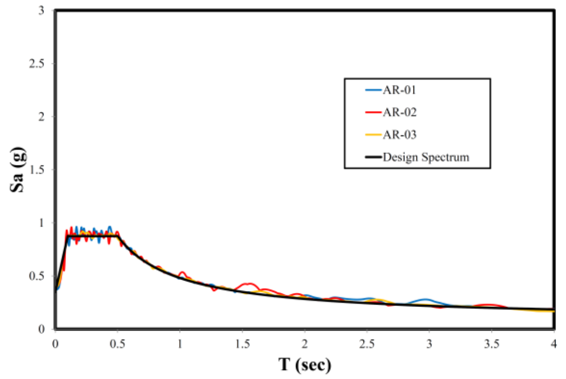
Three artificial records are considered to find the tuned strength distributions to achieve uniform ductility pattern. The ductility demand of the structures with tuned strength distribution is compared with their corresponding models which were designed based on Standard-2800 [3] strength distribution. Furthermore, 24 real ground motions are considered for seismic performance evaluation of the structures. The properties of the real ground motions are mentioned in Table 1 and the response spectrums of all records are shown in Fig. 3.

3. Assessment of structures with tuned strength distribution under artificial records

The procedures introduced in Fig. 2 are performed for 5, 10 and 15-story models. In Fig. 4 the ratio of the required strength for each story to reach the expected ductility is calculated relative to the total seismic weight. It can be seen that by increasing the expected ductility, the required strength for all stories decreases and the distribution pattern of the story strength becomes linear over the height of the structure. Also, by increasing the target ductility, the slope of graphs in Fig. 4 increases which means that the difference between strength of the stories decreases. For ductility values over 5, the system is very sensitive to the reduction of the strength and the reduction in story strength is not significant by considering higher ductility values.



(a) 24 Real ground motions

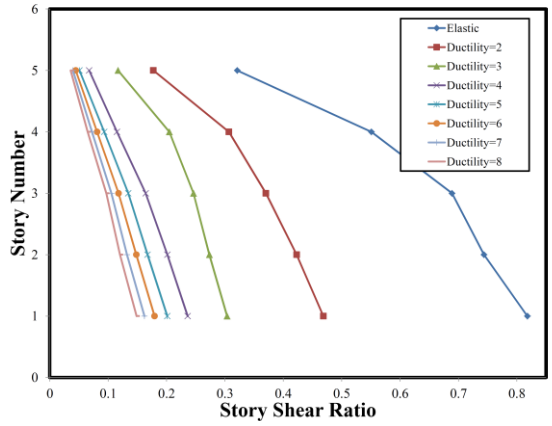


(b) Two artificial records

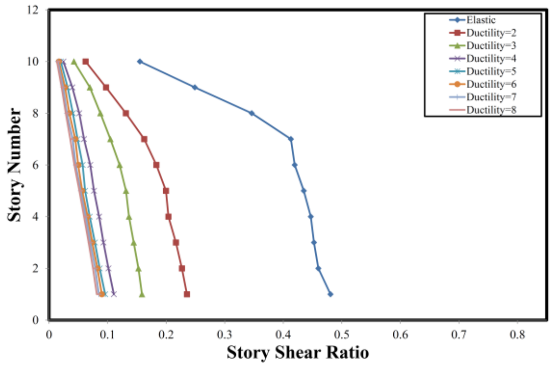
Fig. 3: Design spectrum and response spectrums of the ground motions

Table 1. Selected ground motions' characteristics [41,42]

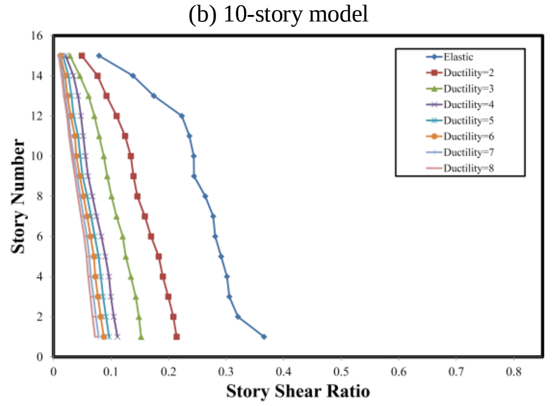
Record Number	Date	Earthquake Name	Magnitude (Ms)	Station Name	Station Number	Component (deg)	PGA (cm/s2)
01	10/15/1979	Imperial Valley	6.8	El Centro, Parachute Test Facility	5051	315	200.2
02	2/9/1971	San Fernando	6.5	Pasadena, CIT Athenaeum	80053	90	107.9
03	2/9/1971	San Fernando	6.5	Pearblossom Pump	269	21	133.4
04	6/28/1992	Landers	7.5	Yermo, Fire Station	12149	0	167.8
05	10/17/1989	Loma Prieta	7.1	APEEL 7, Pulgas	58378	0	153
06	10/17/1989	Loma Prieta	7.1	Gilroy #6, San Ysidro Microwave site	57383	90	166.9
07	10/17/1989	Loma Prieta	7.1	Saratoga, Aloha Ave.	58065	0	494.5
08	10/17/1989	Loma Prieta	7.1	Gilroy, Gavilon College Phys Sch Bldg	47006	67	349.1
09	10/17/1989	Loma Prieta	7.1	Santa Cruz, University of California	58135	360	43.1
10	10/17/1989	Loma Prieta	7.1	San Francisco, Diamond Heights	58130	90	110.8
11	10/17/1989	Loma Prieta	7.1	Fremont, Mission San Jose	57064	0	121.6
12	10/17/1989	Loma Prieta	7.1	Monterey, City Hall	47377	0	71.6
13	10/17/1989	Loma Prieta	7.1	Yerba Buena Island	58163	90	66.7
14	10/17/1989	Loma Prieta	7.1	Anderson Dam, Downstream	1652	270	239.4
15	4/24/1984	Morgan Hill	6.1	Gilroy, Gavilon College Phys Sci Bldg	47006	67	95
16	4/24/1984	Morgan Hill	6.1	Gilroy #6, San Ysidro Microwave Site	57383	90	280.4
17	7/8/1986	Palmsprings	6	Fun Valley	5069	45	129
18	1/17/1994	Northridge	6.8	Littlerock, Brainard Canyon	23595	90	70.6
19	1/17/1994	Northridge	6.8	Castaic, Old Ridge Route	24278	360	504.2
20	1/17/1994	Northridge	6.8	Lake Hughes #1, Fire station #78	24271	0	84.9
21	10/17/1989	Loma Prieta	7.1	Emeryville, 636 Christie Ave.	1662	350	210.3
22	9/16/1978	Tabas	7.35	Bajestan	RSN137	0	89.2
23	6/20/1990	Manjil	7.37	Abhar	RSN163	N33W	205
24	12/26/2003	Bam	6.6	Bam	RSN404	0	792.4



(a) 5-story model



(b) 10-story model



(c) 15-story model

Fig. 4: Story shear ratio for structures with tuned strength distribution considering identical target ductility for all stories under AR-01

In order to design a structure, the minimum required base shear is determined based on Standard-2800 [3] or other seismic provisions. Thus, in the procedure of Fig. 2(b), the base shear is considered to be equal to the value recommended by Standard-2800 [3] and the strength of other stories are changed to reach the same ductility in all stories. In Fig. 5, the distribution of the story shear is shown for 10-story model considering $R_u = 4, 5$ and 6. It can be seen that the strength of the story decreases in all stories, especially the middle stories. Also, the tuned distribution pattern of strength has become linear.

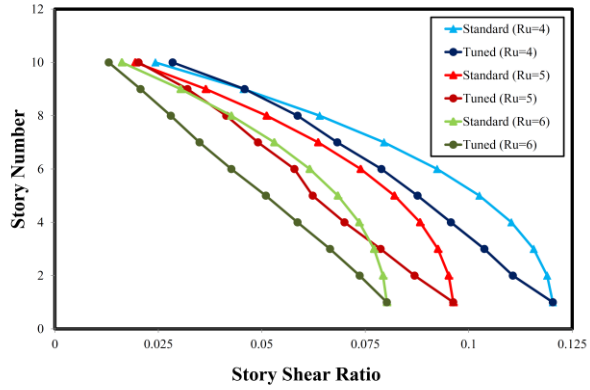


Fig. 5: Strength distribution for 10-story model considering various R_u under AR-01

Fig. 6 shows the variation of ductility pattern for structures designed based on Standard-2800 [3] strength distribution and tuned strength distribution. It can be seen that the ductility of the upper and the lower stories decreases but the middle stories experience higher ductility demands by tuning the strength of the stories. Also, for systems with higher values of behavior coefficient ($R_u = 6$), the uniform ductility of the structures with tuned strength distribution becomes larger than the average ductility for corresponding structures with Standard-2800 [3] strength distribution.

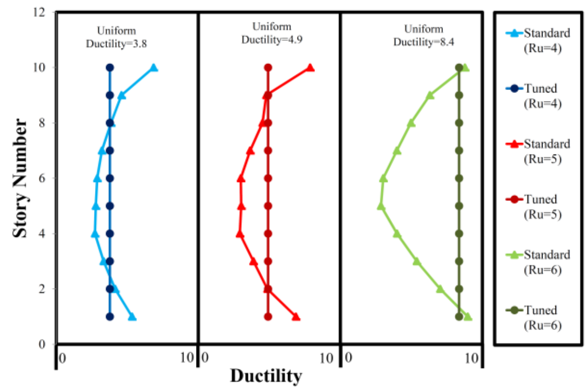


Fig. 6: Ductility distribution for various R_u under AR-01

The sum of the story strength in each building ($\sum_{i=1}^{N} V_{yi}$) is considered as a weight index to evaluate the amount of required material for construction. The ratio of the total strength of structure with tuned strength distribution relative to the total strength of structure with Standard-2800 [3] distribution is calculated. In Fig. 7, it is shown that the total strength of model buildings with tuned strength distribution decreases more for larger R_u. The value of reduction reaches 20% for the structure with 15 stories.

In Fig. 8, the effects of stiffness distribution over the stories are illustrated. The tuned strength distribution achieved for structures with uniform stiffness distribution is compared with its corresponding values for structures in which the stiffness of each story is proportional to its strength. It can be seen that the variation is not significant for 10 and 15-

story models. The strength distribution pattern for the structures with stiffness distribution proportional to strength is linear.

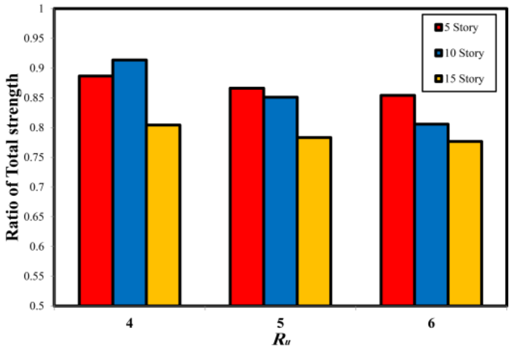
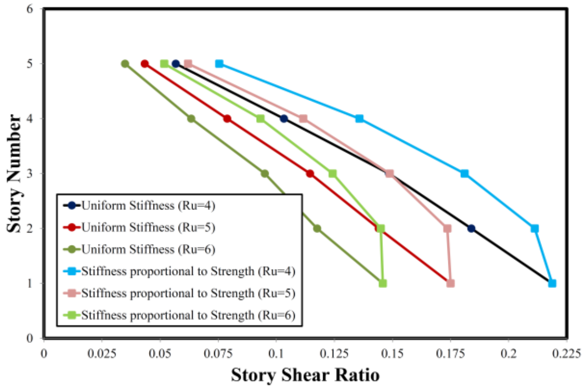
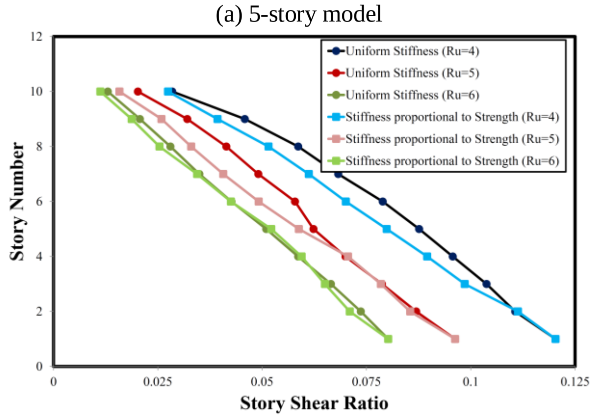


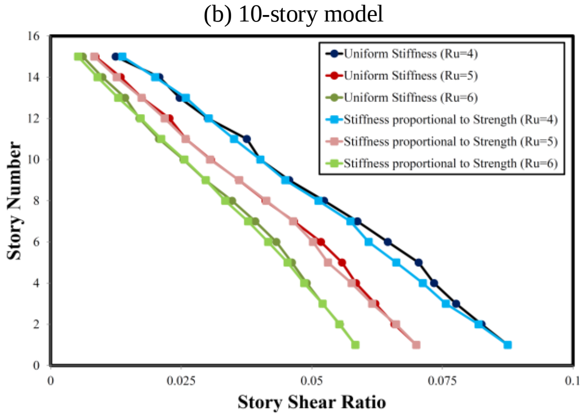
Fig. 7: Ratio of total strength for different R_u under AR-01



(a) 5-story model



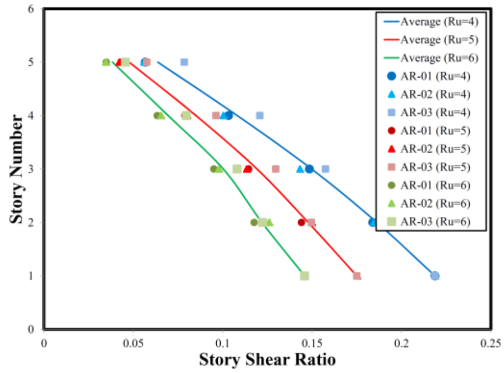
(b) 10-story model



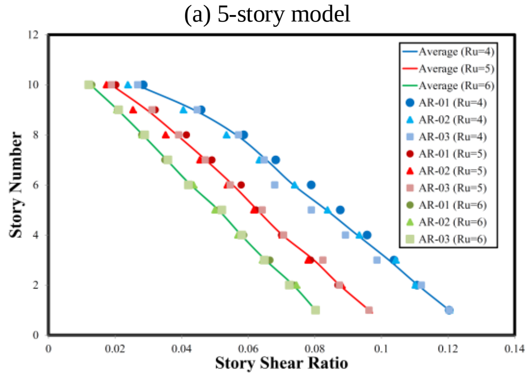
(c) 15-story model

Fig. 8: Comparison of strength distribution for various R_u considering different stiffness distribution under AR-01

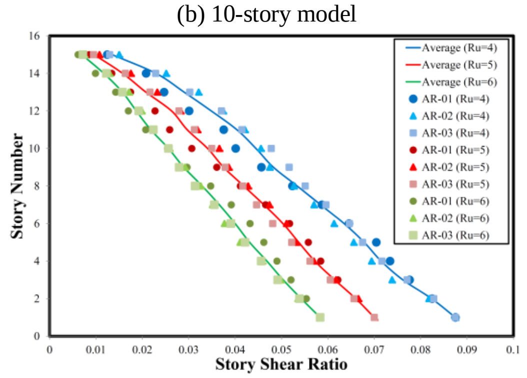
In Fig. 9, the average of tuned strength distribution is obtained by applying AR-01, AR-02 and AR-03 as excitation in iterative procedure. Comparing the results achieved by these records showed that the difference between the three patterns is not significant. Thus, for ground motions with similar response spectrum, it is foreseeable to achieve identical tuned strength distribution to reach uniform ductility over all stories.



(a) 5-story model



(b) 10-story model



(c) 15-story model

Fig. 9: Comparison of tuned strength distribution for various R_u under AR-01, AR-02 and AR-03

3.1. Analytical Expression for tuned strength distribution

Considering the results of the analyses obtained from iterative procedure under three artificial records, an expression is found by nonlinear regression analysis to estimate the ratio of the story shear for the structures with tuned strength distribution. Equation 3(a) is proposed to calculate the story shear coefficient:

$$C_i = C - m(N-1) \tag{3a}$$

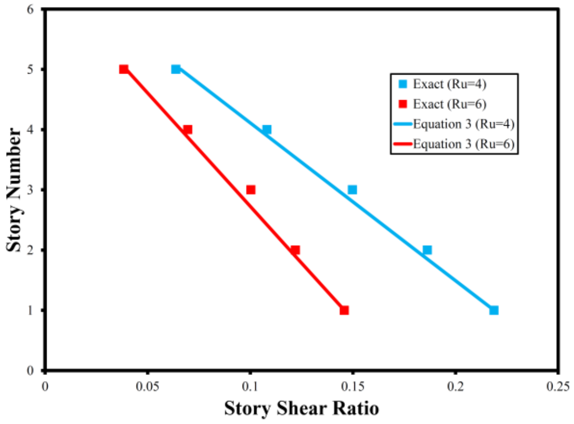
where:

$$m = \frac{\alpha}{10^4 T^{\beta}} \tag{3b}$$

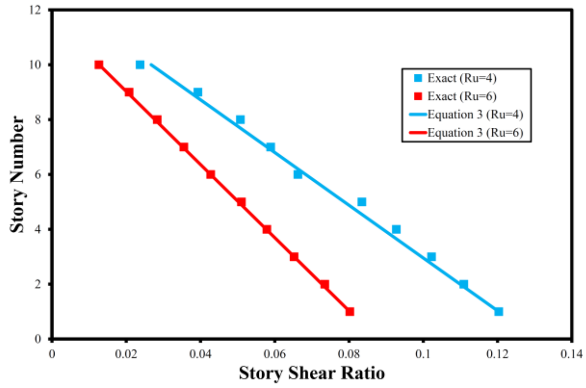
$$\alpha = 3R_u^2 - 40R_u + 222 \tag{3c}$$

$$\beta = -0.024R_u^2 + 0.218R_u + 1.395 \tag{3d}$$

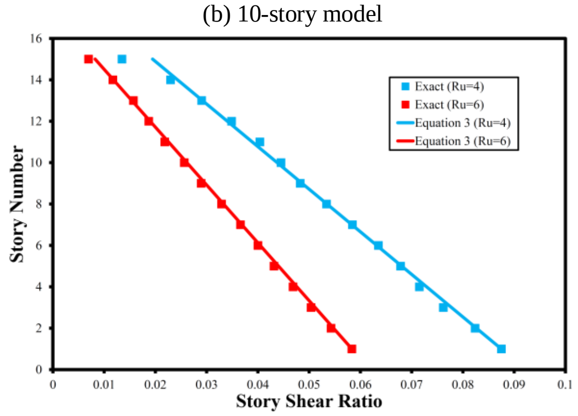
In Equation 3, C is the base shear coefficient, C_i is the story shear coefficient, N is number of stories, R_u is behavior coefficient and T is the natural period of the structure. In Fig. 10, the exact values of story shear ratio are compared with their corresponding values estimated by Equation 3(a). The results show good agreement.



(b) 5-story model



(b) 10-story model



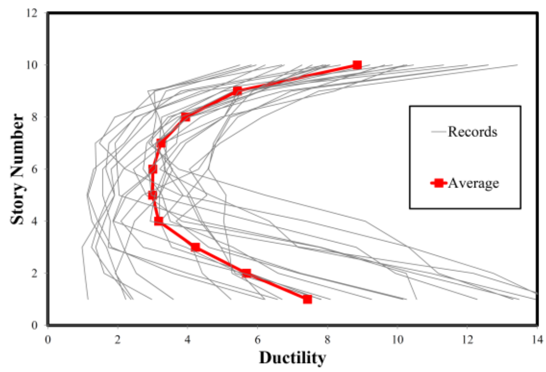
(c) 15-story model

Fig. 10: Comparison of tuned strength distribution estimated by Equation 3 with exact values

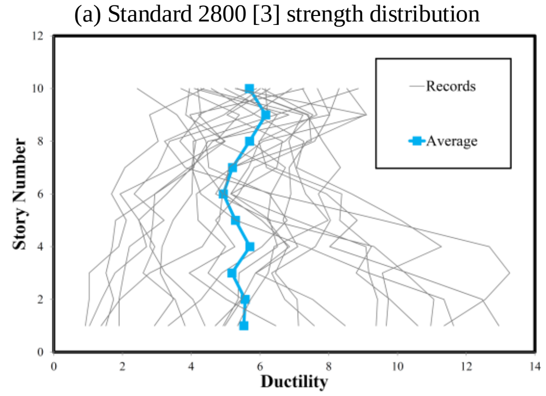
4. Assessment of structures with tuned strength distribution under real ground motions

All 24 ground motions of Table 1 are scaled, employing the procedure proposed by Standard-2800 [3]. The ductility demand patterns for 10-story model subjected to the ground motions are illustrated in Fig. 11. Fig. 11(a) shows that the structure with Standard-2800 [3] strength distribution experiences great values of ductility, at the upper and the lower stories. However, the average of ductility pattern in the structure with tuned strength distribution is approximately uniform as shown in Fig. 11(b).

In Fig. 12, it can be seen that the Coefficient of Variation (COV) of ductility values over the height of the structure and the maximum ductility of stories are significantly reduced for the structure with tuned strength distribution in comparison with Standard-2800 [3] strength distribution. However, it is obvious that the ductility demand pattern over the height of structure is highly dependent on the characteristics of the ground motions. In other words, if the response spectrum of the record is not compatible with the design spectrum, the tuned strength distribution will no longer lead to uniform ductility over all stories. This issue is investigated in Fig. 13 for the structure with tuned strength distribution. The results are assessed by classifying ground motions in accordance with the amplitude of the response spectrum and frequency content of the applied ground motions.



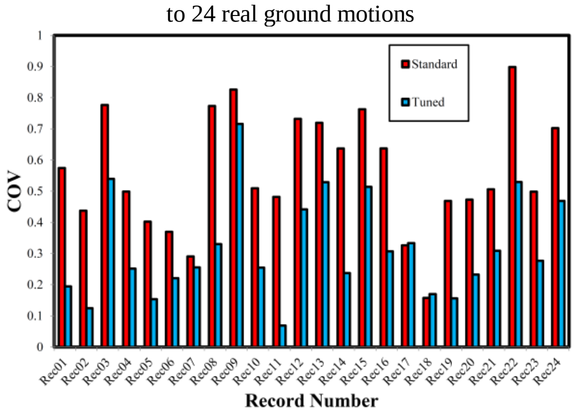
(a) Standard 2800 [3] strength distribution



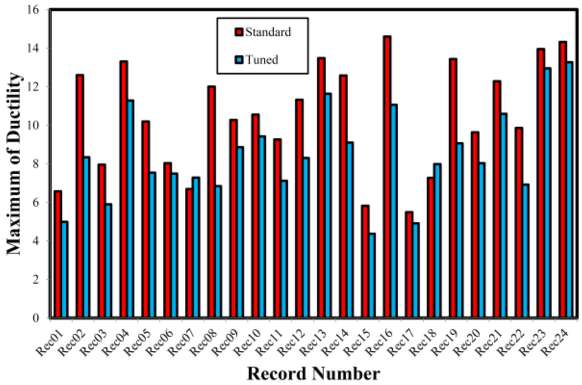
(b) Tuned strength distribution

Fig. 11: Ductility patterns of 10-story model ($R_u = 5$) subjected

to 24 real ground motions



(a) COV of ductility values over height of structure

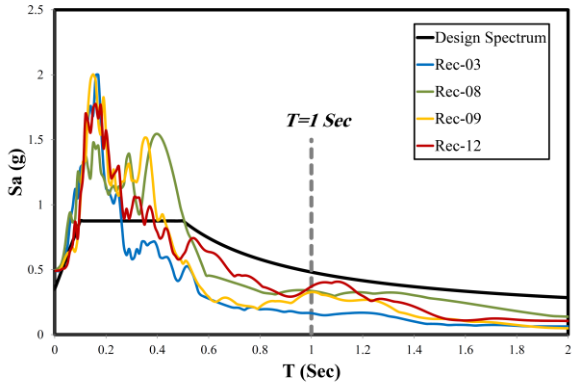


(b) Maximum of ductility of stories

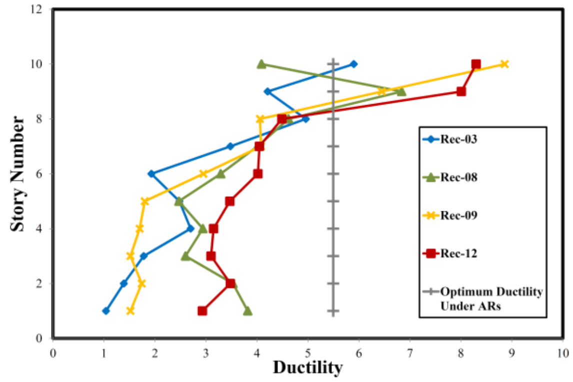
Fig. 12: COV of ductility values and maximum ductility of 10-story model ($R_u = 5$) subjected to 24 real ground motions

In Fig. 13(a), a number of records whose spectral amplitudes at low periods are higher than that in the design spectrum are selected (periods less than the period of the structure ($T = 1$sec)). In Fig. 13(b) the ductility patterns for the 10-story model are shown corresponding to the records of Fig. 13(a). In this condition, the structure experiences greater ductility demands at the upper stories in comparison with the lower stories. The higher modes of vibration of the structures are excited because of large amplitude of the response spectrum at low periods. It should be noted that the ductility demand at the lower stories is smaller than the average uniform ductility achieved under artificial records. Also, the values of ductility in the upper stories are not significantly larger than the average uniform ductility.

In Fig. 14(a), the records whose spectral amplitudes at high periods are greater than the design spectrum are selected (periods larger than the period of the structure ($T = 1$sec)). In Fig. 14(b) the ductility patterns for the 10-story model are shown corresponding to the records of Fig. 14(a). The results showed that, the structure experiences larger ductility demands at the lower stories in comparison with the upper stories. Although the spectral amplitudes at low periods are larger than that in the design spectrum (like the situation that was seen in Fig. 13), lower stories isolate upper stories from excitation by high inelastic behavior. It should be considered that ductility demands at lower stories are much larger than the average uniform ductility achieved under artificial records.

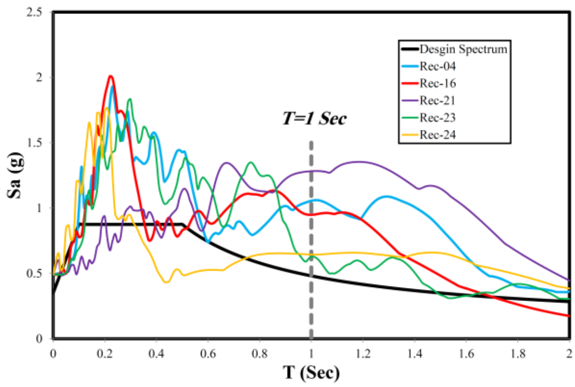


(a) Response spectrum of records

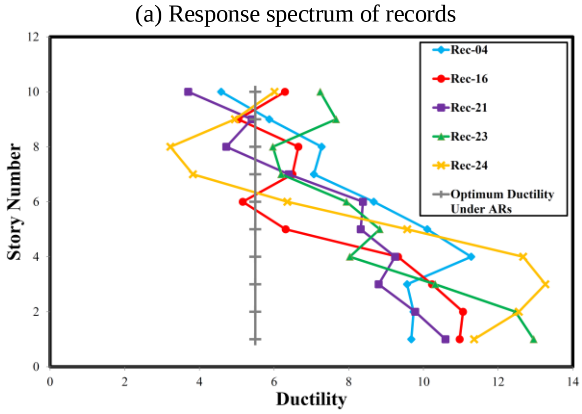


(b) Ductility demand pattern of stories

Fig. 13: Ground motions with high amplitude at low periods



(a) Response spectrum of records



(b) Ductility pattern of stories

Fig. 14: Ground motions with large amplitude at high periods

According to the results of Fig. 13 and Fig. 14, if the structure is subjected to the Maximum Credible Earthquake (MCE) while the tuned strength distribution is determined based on the Design-based Earthquake (DBE), some precautions should be taken. This situation is shown in Fig. 15 for artificial records. These three records are scaled by a factor of 1.5 to be considered as MCE.

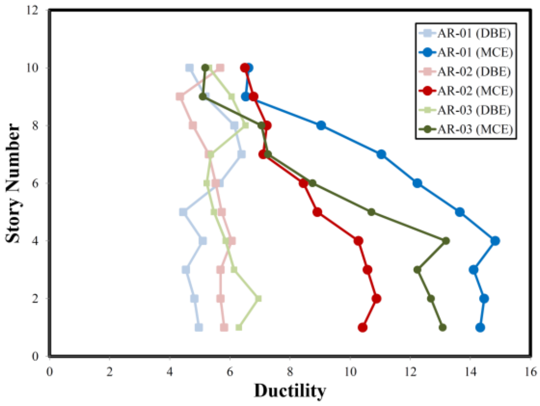


Fig. 15: Ductility demand distribution for 10-story model subjected to DBE and MCE

In Fig. 15, it can be seen that the ductility patterns show low dispersion when the structure is subjected to DBE level of artificial records. Nonetheless, ductility values are significantly larger at the lower stories in comparison with the upper stories for MCE level of artificial records. In this situation, since the structure is vulnerable, some preparations should be considered. It may be suggested that the lower stories of the structure with tuned strength distribution should be strengthened. Also, the problem can be fixed by choosing appropriate artificial records for tuning the strength of the stories during iterative procedure. In other words, the characteristics of the selected records must match the situation with more precision.

5. Conclusions

A parametric study was conducted to investigate the seismic performance of structures designed based on uniform ductility demand. For this purpose, three artificial records whose response spectrums matched the design spectrum, were considered. Using an iterative procedure, the tuned strength patterns were obtained for models with different properties. Assessment of the seismic performance of the models leads to the results mentioned below:

- Structures designed based on strength distribution recommended by Standard-2800 [3] can experience 3 times larger ductility values especially at the lower and the upper stories, in comparison with the middle stories.
- If the value of the base shear (story shear at first story) is calculated in accordance with Standard-2800 [3] and kept unchanged during iterative procedure, then it can be seen that the strength of all stories (especially the middle stories) decreases up to 50% for large values of R_u in comparison with Standard-2800 [3] distribution.
- The weight index of the structure with tuned strength distribution decreases up to 20 % in comparison with structures with Standard-2800 [3] strength pattern.
- The results showed that when the stiffness of the stories are set proportional to the strength of the story, it does not have significant influence on the strength distribution in comparison with the structure with uniform stiffness distribution.
- While the structures with tuned strength distribution are subjected to real ground motions, the COV of ductility over the stories decreases in comparison with the structures designed based on Standard-2800 [3] strength distribution for more than 90% of cases.
- It was shown that if the amplitude of the earthquake response spectrum is larger than the design spectrum at periods lower than the fundamental period of the structure, the ductility demands of the upper stories are larger than that of the other stories.
- It was shown that if the amplitude of the earthquake response spectrum is larger than that of the design spectrum at periods greater than the fundamental period of the structure, the ductility demands of the lower stories are significantly higher than the other stories. For instant, the ductility at the first and the second stories can be twice that of the other stories.

References

[1] Uniform Building Code (UBC-97), (1997), “Structural engineering design provisions”, International Conference of Building Officials, Whittier.

[2] American Society of Civil Engineering/Structural Engineering Institute (ASCE/SEI 7-10), (2010), “Minimum Design Loads for Buildings and Other Structures”, American Society of Civil Engineering, Reston, Virginia.

[3] Standard-2800, (2015), “Iranian Code of Practice for Seismic Resistant Design of Buildings”, 4th edition, Building and Housing Research Center, Tehran, Iran.

[4] Anderson, J.C., Miranda, E. and Bertero, V.V., (1991), “Evaluation of the Seismic Performance of a Thirty-story RC Building”, Report: UCB/EERC-91/16, Earthquake Engineering Research Center, University of California, Berkeley.

[5] Gilmore, T.A. and Bertero, V.V., (1993), “Seismic Performance of a 30-story Building Located on Soft Soil and Designed According to UBC 1991”, Report: UCB/EERC-93/04, Earthquake Engineering Research Center, University of California, Berkeley.

[6] Chopra, A. K. and Cruz, E. F., (1986), "Evaluation of building code formulas for earthquake forces", Journal of Structural Engineering, Vol. 112, pp. 1881–1899.

[7] Chopra, A. K., (2000), "Dynamics of Structures—Theory and Applications to Earthquake Engineering", Second Edition, Prentice Hall, Englewood Cliffs, NJ.

[8] Martinelli, L., Perotti, F. and Bozzi, A., (2000), "Seismic design and response of a 14-story concentrically braced steel building", Behavior of Steel Structures in Seismic Areas, pp. 327-355.

[9] Hart, G.C., (2000), "Earthquake forces for the lateral force code", The Structural Design of Tall Buildings, Vol. 9, No. 1, pp. 49-64.

[10] Moghaddam, H. and Esmailzadeh Hakimi, B., (1999), "On the optimum seismic loading of multistory structures." Proceedings, 3rd International Conference of Seismology and Earthquake Engineering, International Institute of Earthquake Engineering, Tehran, Iran, (May 17-19, 1999).

[11] Karami Mohammadi, R., (2001), "Effects of shear strength distribution on the reduction of seismic damage of structures." Ph.D. Thesis, Sharif University of Technology, Tehran, Iran.

[12] Lee, S.-S. and Goel, S. C., (2001), "Performance-based Design of Steel Moment Frames Using Target Drift and Yield Mechanism", Report No. UMCEE 01-17, Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI, USA.

[13] Chao, S.-H. and Goel, S. C., (2005), "Performance-based Seismic Design of EBF Using Target Drift and Yield Mechanism as Performance Criteria", Report No. UMCEE 05-05, Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI, USA.

[14] Chao, S.-H. and Goel, S.C., (2006), "Performance-based Plastic Design of Seismic Resistant Special Truss Moment Mrames", Report No. UMCEE 06-03, Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI, USA.

[15] Chao, S. H. and Goel, S. C., (2007), "A seismic design lateral force distribution based on inelastic state of structures", Earthquake Spectra, Vol. 23, No. 3, 547-569.

[16] Park, K. and Medina, R. A., (2006), "Lateral load patterns for conceptual seismic design of frames exposed to near-fault ground motions", Proceedings, 8th U.S. National Conference on Earthquake Engineering, San Francisco, California, (April 18–22, 2006).

[17] Sabelli, R., (2000), "Research on Improving the Design and Analysis of Earthquake Resistant Steel Braced Frames", FEMA/EERI Report, Earthquake Engineering Research Institute, Oakland, California.

[18] Gantes, C.J., Vayas, I. and Spiliopoulos, A., (2000), "Optimum bending and shear stiffness distribution for performance based design of rigid and braced multi-story steel frames", Behavior of Steel Structures in Seismic Areas, 585-592.

[19] Gong, Y., Grierson, D.E. and Xu, L., (2003), "Optimal design of steel building frameworks under seismic loading", Response of Structures to Extreme Loading (XL2003), Canada, Toronto.

[20] Moghaddam, H. and Hajirasouliha, I., (2004), "A new approach for optimum design of structures under dynamo excitation", Asian Journal of Civil Engineering (Building and Housing), Vol. 5, NOS 1-2, 69-84.

[21] Mohammadi, R.K., El Naggar, M. and Moghaddam, H., (2004), "Optimum strength distribution for seismic resistant shear buildings", International Journal of Solids and Structures, No.41, 6597-6612.

[22] Moghadam, H. and Hajirasouliha, I., (2005), "Fundamentals of optimum performance based design for dynamic excitation", Scientia Iranica, Vol. 12, No. 4, 368-378.

[23] Moghadam, H., Hajirasouliha, I. and Doostan, A., (2005), "Optimum seismic design of concentrically braced steel frames: concepts and design procedures", Journal of Constructional Steel Research, Vol. 61, 151-166.

[24] Moghadam, H. and KaramiMohammadi, R., (2006), "More efficient seismic loading for multi degrees of freedom structures", Journal of structural Engineering, ASCE, Vol. 132, No. 10, 1673-1677.

[25] Moghaddam, H. and Hajirasouliha, I., (2006), "Toward more rational criteria for determination of design earthquake forces", International Journal of Solids and Structures, No. 9, 43, 2631-45.

[26] Hajirasouliha, I. and Moghaddam, H., (2009), "New lateral force distribution for seismic design of structures", Journal of Structural Engineering, Vol. 135, No. 8, 135, 906-915.

[27] Moghaddam, H., Hosseini Gelekolai, S. M., Hajirasouliha, I. and Tajali, F., (2012), "Evaluation of various proposed lateral load patterns for seismic design of steel moment resisting frames", 15th World Conference on Earthquake Engineering, Lisbon, Portugal, (September 24-28, 2012).

[28] Medina, R. A. and Krawinkler, H., (2005), "Strength demand issues relevant for the seismic design of moment-resisting frames", Earthquake Spectra, 21, 415–439.

[29] Deguchi, Y., Kawashima, T., Yamanari, M. and Ogawa, K., (2008), "Seismic design load distribution in steel frames", 14th World Conference on Earthquake Engineering, Beijing, China.

[30] Ganjavi, B., Vaseghi Amiri, J., Ghodrati Amiri, G., Yahyazadeh Ahmadi, Q., (2008), "Distribution of drift, hysteretic energy and damage in reinforced concrete buildings with uniform strength ratio", The 14th World Conference on Earthquake Engineering, Beijing, China, (Oct. 12-18, 2008).

[31] Abdollahzadeh, Gh. and Niknafs, S., (2012), "Evaluation of damage distribution in elements of dual frames", International Journal of Engineering, Vol. 25, No. 4, 279-288.

[32] Golizadeh S. and Fattahi F., (2015), "Optimum design of steel structures for earthquake loading by grey wolf algorithm", Asian Journal of Civil Engineering Vol. 16, No. 5, 663-679.

[33] Kermani, H., Behnamfar, F. and Morsali, V., (2016), "Seismic design of steel structures based on ductility", International Journal of Engineering, Vol. 29, No. 1, 23-30.
[34] Akbari J. and Sadegh Ayubirad M., (2017), "Seismic optimum design of steel structures using gradient-based and genetic algorithm methods", International Journal of Civil Engineering, Vol. 15, 135-148.
[35] Heidari A., Raeisi J., (2018), "Optimum design of structures for seismic loading by simulated annealing using wavelet transform", Journal of Soft Computing in Civil Engineering, Vol. 2, No 4, 23-33.
[36] Sarcheshmehpour M., Estekanchi H. E. and Moosavian H., (2020), "Optimum seismic design of steel framed-tube and tube-in-tube tall buildings", The Structural Design of Tall and Special Buildings, Vol. 29(14).
[37] Praveen, O., Pithadiya, M. and Gopikrishina, K., (2019), "Influence of real ground motion records in performance assessment of RC Buildings", International Journal of Engineering, Vol. 32, No. 12, 1745-1752.
[38] Ganjavi, B., Hadinejad, A. and Jafarieh A.H., (2019), "Evaluation of ground motion scaling methods on drift demands of energy-based plastic designed steel frames under near-fault pulse type earthquakes", Steel and Composite Structures, Vol. 32 No. 1, 91-110.
[39] OpenSees (Open System for Earthquake Engineering Simulation platform), Version 2.5.0, developed by the Pacific Earthquake Engineering Research Center (PEER), at the University of California, Berkeley. Available at: http://opensees.berkeley.edu/
[40] SeismoSoft Seismo Match, (2011), A computer program for adjusting earthquake records to match a specific target response spectrum.
[41] Federal Emergency Management Agency (FEMA-440), (2005), "Improvement of Nonlinear Static Seismic Analysis Procedures", Department of Homeland Security, Federal Emergency Management Agency, Washington, D.C., USA.
[42] Pacific Earthquake Engineering Research Center Ground Motion Database, https://ngawest2.berkeley.edu/.