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Comparing Seismic Parameters in Dual Systems Equipped with Concentric and Eccentric Braces and Side Plate Connection

[1]Z. Rahmani, [1]M. Naghipour, [1]J. Vaseghi Amiri and [2]R. Karimnezhad

[1]Faculty of Civil Engineering, Noushirvani University of Technology, Babol, Iran
[2]Department of Civil Engineering, Shomal University of Technology, Amol, Iran

Abstract: After 1994 Northridge and 1995 Cobe earthquakes and the extensive damage in moment resisting connections, side plate connection was introduced. This connection is able to hold plastic hinge far from the beam-column connection and has sufficient strength and ductility, so plastic hinges can form in beams. In this paper, specimens of dual systems are analyzed at different heights 4, 8 and 12 stories, namely moment resisting frames equipped with concentric braces (CBF), eccentric braces (EBF) and side plate connection. It is known that eccentric braced frame has more ductility than concentric braced one. Therefore, the ability to absorb and dissipate energy during an earthquake in eccentric braced system is increased. In these braces, ductility is caused due to yielding the beam between two braces or the beam between the brace and the column. This part of the beam is called the link beam. These beams are experienced very large displacement, due to nonlinear behavior of link beam sunder the applied load of diagonal braces. This inelastic ductility is the major factor in dissipation of seismic loads. In order to include ductility in structure analysis and also to use entire capacity of the structure, the conception of modification response factor (R-factor) is used in linear analysis. To investigate the ductility and R-factor of a structure, use of nonlinear analysis is inevitable. In this paper, R-factor of the mentioned structural systems are obtained using PERFORM-3D software and pushover analysis. Then application of Uang method, ductility, over strength and R-factor of the models were determined and obtained results were compared. On the basis of present study, the EBF increases ductility but the CBF increases lateral strength. Also the R-factor for the EBF was higher than the CBF due to high difference in ductility.

Key words: Side plate connection · Ductility · R-Factor · Brace · Pushover analysis

INTRODUCTION

Providing strength, stability and ductility are major purposes of seismic design. Nevertheless many fractions occurred in connections of moment resisting frames by Northridge earthquake. The main reason of these fractures is attributed to the access holes created in the web beside the beam's flange, which is performed to penetration weld between beam's and column's flanges. These access holes cause high stress concentration due to sudden change in the geometry of the section in the vicinity of the welding zone. On the other hand, improper performance of welding operation, residual stress caused by welding, existence of welding remnant and lack of adequate control on welding process caused unknown welding zone. Thus, due to increase of stress in this zone, brittle fracture occurs in the zone of access holes.

The idea of full-depth side plate connection was first proposed by Houghton [1, 2]. Side plate connection is a recorded technology in the U.S.A. and New Zealand which is now owned by a cooperation with the same name "Side Plate Systems, INC". In this connection the beams plastic hinge informed far from the column side. Considering the geometry of the connection; many problems including cutting out of the column's flange, triaxial stresses of the weld of the beam's flange to the column's flange and buckling of the panel zone are eliminated [3].

Corresponding Author: J. Vaseghi Amiri, Faculty of Civil Engineering, Noushirvani University of Technology, Babol, Iran.

One of the important parameters in reducing the design forces against earthquake is the R-factor [4]. The proposed factors in design codes, which are experimentally obtained, are evaluated by investigating on the performance of structures in real earthquakes based on terms of building codes [5]. Also, in the recent decades many theoretical studies have been carried out on R-factor. Based on these investigations, ductility and over strength factors are the major factors affecting on R-factor value which is affected by various parameters.

R-factor which was first reported by ATC-3-Oб, in 1978, tentative provisions for the development of seismic regulations for buildings [6], was actually based on investigation on performance of building through previous earthquakes and the calculations performed on damping and over strength.

Investing the behavior of reinforced concrete frames equipped with steel X-bracing, Maheri and Akbari [4] have demonstrated that in short dual systems equipped with knee-bracing, the values of ductility and behavior is larger than those frames that equipped with X-bracing [4]. Balendra and Huang [7] have realized that moment resisting frames equipped with X and chevron (Inverted-V) bracing roughly have the same over strength and ductility. Freeman [8] has investigated the effect of the indeterminacy degree and found that increasing indeterminacy degree resulted in increasing of lateral resistance capacity and R-factor. It was also found that increasing the number of braces in the braced frames resulted in increasing the lateral rigidity and decreasing the ductility and R-factor [3, 8-11]. Asgarian [12] has concluded that increasing the number of stories result in decreasing ductility and R-factor in BRBF (buckling restrained braced frames). Kim and Choi [11] have investigated on R-factor of ordinary moment resistance frame (MRF) and special moment resistance frame (SMRF). Several investigators have found that increasing the span length (6-10 m) resulted in an increase in ductility and R-factor [3-5, 13].

Side Plate Connection: After Northridge earthquake, to improve the performance of bending connections, various connections were proposed. One of the recommended connections was the side plate connection which is shown in Figure 1. As it is illustrated in this figure, there is a gap between beam and column. Full-depth side plates are placed on sides of column. The bending moment from beam to column is transferred by link plates and shear force of beam is transferred by vertical shear plates between beam's web and side plates. Continuity plates are placed between the column's web and side plates. All of the connections elements are welded by fillet weld [3].

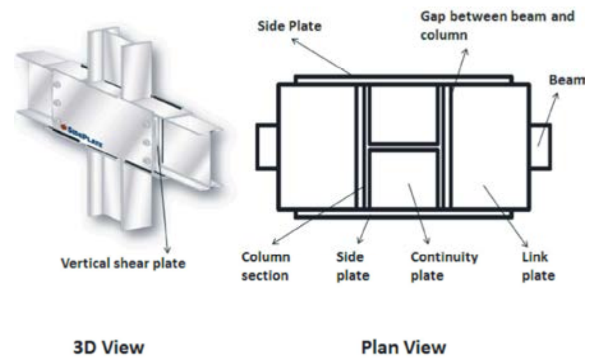


Fig. 1: Side plate connection

Braces: Sever damage of CBFs in recent earthquakes such as Mexico [14] and Northridge [15, 16] which occurred due to lack of an adequate ductility improvement necessity of EBFs are demanded. On the other hand, due to proper ductility of EBFs and increasing trend to apply seems to be necessary to compare the EBFs and CBFs seismic behavior. EBF has simultaneously both the properties of ductility and stiffness [17]. Ductility is the major property of MRFs; in addition stiffness is the major property of CBFs. EBFs were supposed to resist against seismic forces with significant plastic displacement of link beams. When diagonal braces, columns and the beam segments are placed out of the link zone; they are designed based on maximum force of link beam yielded; therefore, they must remain in elastic zone.

Response Modification Factor: General structure response curve is shown in Figure 2. If a structure is supposed to have linear behavior under a severe earthquake, it must be designed based on a huge base shear like V_{eu} that it is not an economic design. According to equation 1, base shear in linear zone is decreased to V_w by a factor called response modification factor (R) [18]:

$$V_w = \frac{V_{eu}}{R} \qquad (1)$$

Ductility Factor (μ): Ductility factor is absorptivity, energy loss and load tolerance capability while affecting by hysteretic nonlinear displacement due to earthquake

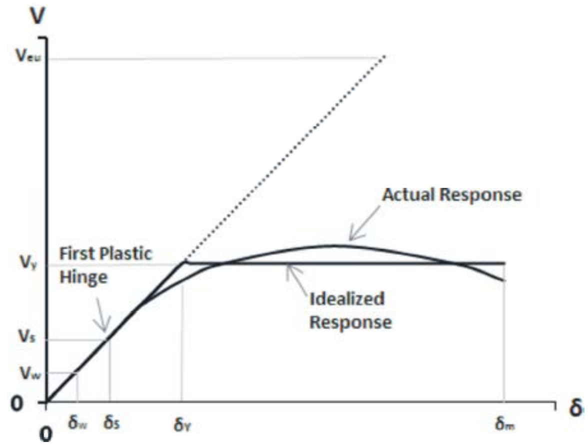


Fig. 2: General structure response

[19]. According to Figure 2, ductility factor of structure is the ratio of maximum displacement (δ_m to the yield displacement (δ_y):

$$\mu = \frac{\delta_m}{\delta_y} \tag{2}$$

Uang Method: Using idealized bilinear response curve, Uang demonstrated that R-factor which is combination of these following parameters [20]:

Reduction Factor Due to Ductility (R_μ): R_μ is the ratio of maximum base shear in elastic zone V_{eu}, to maximum base shear at yield limit while collapse mechanism is happening V_y.

$$R_\mu = \frac{V_{eu}}{V_y} \tag{3}$$

This factor which used to consider the structural yield ductility, absorptivity and energy dissipation, is corresponded to both system characteristics and earth vibrations. Rμ is a function of structural period of vibration, type of hysteretic behavior, linear deformation limit of structure and ductility factor. Extensive researches about this factor have conducted by Newmark-Hall, Nasar, Krawinkler and the others [7, 9, 13, 16, 17]. In this paper, Newmark-Hall method is used as follows:

$$\begin{aligned} &T \le 0.03s \rightarrow R_\mu = 1 \\ &0.12 \le T \le 0.5 \rightarrow R_\mu = \sqrt{2\mu - 1} \\ &T \ge 1s \rightarrow R_\mu = \mu \end{aligned} \tag{4}$$

where T is the functional period and μ is the structural ductility factor.

Over Strength Factor (R_s): Considering the actual lateral strength of a structure is more than the designing lateral strength of that structure, the value of this factor is defined by the following equation [14]:

$$R_{s_s} = \frac{V_y}{V_s} \tag{5}$$

$$R_s = R_{s_o} f_1 f_2 f_3 \tag{6}$$

f_1 accounts for the difference between actual and nominal static yield strengths. Based on statistical analysis, for structural steel, the value of f_1 may be selected as 1.05. During an earthquake, parameter f_2 is used to know the yield stress under the strain rate effect. For that purpose, to account for the strain rate effect, a value of 1.1 (an increase of 10%) desired to be used. The parameter f_3 is defined as nonstructural elements effectiveness.

Allowable Stress Factor (Y): To design for allowable stress method, the design codes decrease design loads from V_s to V_w. This decrease is done by allowable stress factor which is defined in equation 7 [21]:

$$Y = \frac{V_s}{V_w} \tag{7}$$

Thus, the R-factor value is defined as follows:

$$R = \frac{V_{eu}}{V_w} = \frac{V_{eu}}{V_y} \cdot \frac{V_y}{V_s} \cdot \frac{V_s}{V_w} = R_\mu . R_s . y \tag{8}$$

Structural Models: In this research a few dual frames consisting of EBF and CBF with intermediate ductility in 3 different height levels and different lateral load patterns under non-linear static analysis were designed and analyzed. The initial design is modeled by ETABS software according to the building code UBC-97 [22] without considering seismic requirements. Then, according to Iranian national building code (part 10) the seismic controls were manually carried out to intermediate frames, panel zones and braces. Moreover, IPE, IPB and 2UNP (as a box) sections were used as beams, columns and braces, respectively.

After design, according to Uang's method, nonlinear static analysis on models under two lateral load patterns (Triangular and rectangular) was carried out. The chosen models of present study were intermediate dual systems.

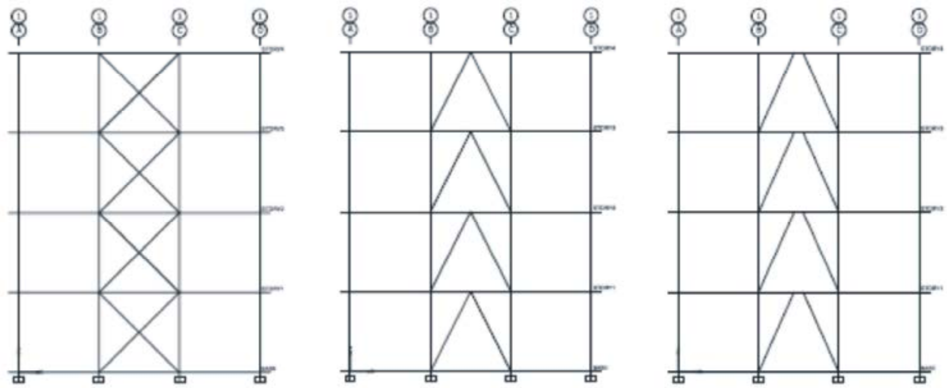


Fig. 3: Configuration of model structure

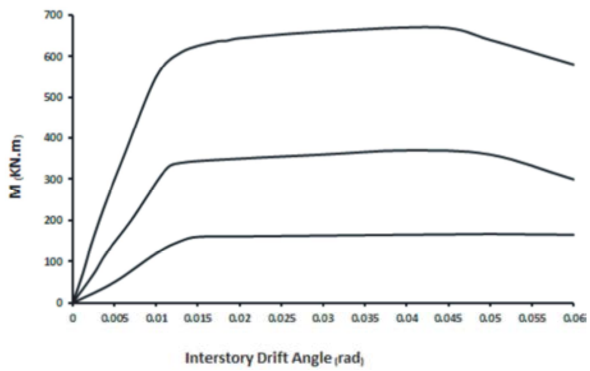


Fig. 4: Moment- rotation hysteresis diagram envelops of side plate connection

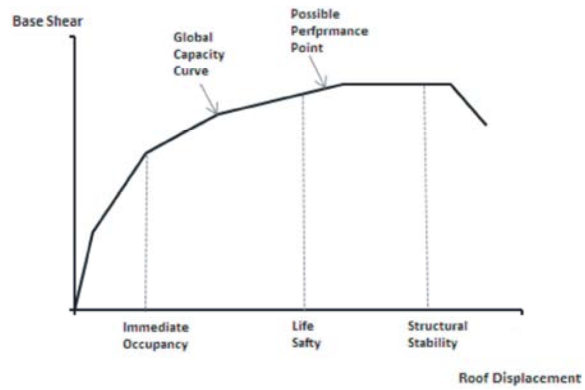


Fig. 5: Structure's capacity curve

This system is studied at chevron (Invert-V), X braces and EBFs with side plate connection. The current work has used steel type ST37 (δ_y = 2400 kg/cm^2) for all structural members. Figure 3 depicts the typical configuration of the used four-story models.

To assess the R-factor, systems with 4, 8 and 12 stories as well as a bay of 5 meter long were selected. In all structural models, height of the base story and the other stories were 2.80 and 3.20, respectively. The selected frame is the middle one and the type of floor system is one way slab. The dead loads of 600 and 520 kg/m^2 are used to gravity loads of the stories and roof, respectively. According to Iranian national building code, part 6, the live loads of 200 and 150 kg/m^2 are used to gravity loads of the stories and roof, respectively. The importance factor of I = 1.0, preliminary response modification factor of R = 7.0 and seismic zone factor of A = 0.3 are considered to frame design. The soil is identified as type III.

Static Analysis: Linear static analysis is done using ETABS software and the nonlinear static analysis was carried out using PERFORM_3D software based on Iranian 2800 code (third edition), Iranian National Building Code (part6 and 10) and FEMA356. In order to introduce the behavior of side plate connections, PERFORM-3D, nonlinear behavior of beams, columns and braces is defined through Force-deformation (F-D) curves. The program uses the connections moment rotation hysteresis diagram envelops provided by Deylami and Gholipour [23], Deylami and Salami [24], Latour [25], Taranath [26] and Nateghi-A [27]. A sample of hysteresis envelope diagrams used for this research is depicted in Figure 4.

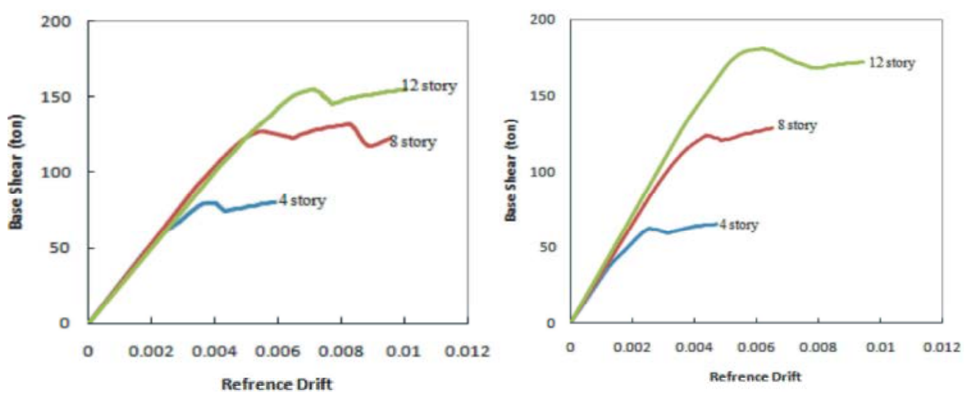
In recent years, pushover analysis (nonlinear static analysis) has gained significant attention of many researchers; especially in performance-based seismic engineering. The method is based on a nonlinear mathematical model of a structure is exposed to lateral load pattern and this lateral load increases at a constant rate until the structure reaches to a predefined target displacement. This target displacement is measured at a control point. and According to nonlinear behavior curves which have been predefined in the literature [28], in each step during the increment in lateral load, the strength and stiffness of the structure was modified. The major outcome of this method is the base shear versus roof displacement diagram which is known as the structure's capacity curve. Each point on this diagram represents a certain degree of damage to the building (Figure 5).

In this research FEMA's regulations were implemented. In order to carry out the nonlinear static analysis, lateral load patterns, triangular and rectangular are chosen and applied on the model.

RESULTS AND DISCUSSION

After the design process, in order to carry out the nonlinear analysis the frames were exposed to lateral loads. Using the result of nonlinear analysis, base shear-displacement curve was obtained. The curve should be idealized. Considering the idealized curve, ductility, over strength factor and R-factor values were obtained. The new R-factor was compared to the initial one. If the difference of these two factors were more than defined deviation, then the structure must be redesigned by new R-factor. This process was repeated to obtain the minimum difference between nonlinear zone R-factor and the current design R-factor.

Base shear-displacement diagrams of the models are shown in Figures 6, 7 and 8. The horizontal axis represents the reference drift which is the ratio of lateral displacement of the target point that is usually the roof to the height of that point. The vertical axis is the base shear. Tables 1, 2 and 3 summarized the values of seismic parameters (R-factor, ductility, Reduction factor due to ductility and over strength factor). Table 4 shows the average values of seismic parameters.



a. Load pattern triangular b. Load pattern rectangular

Fig. 6: Base shear- displacement curve, X bracing

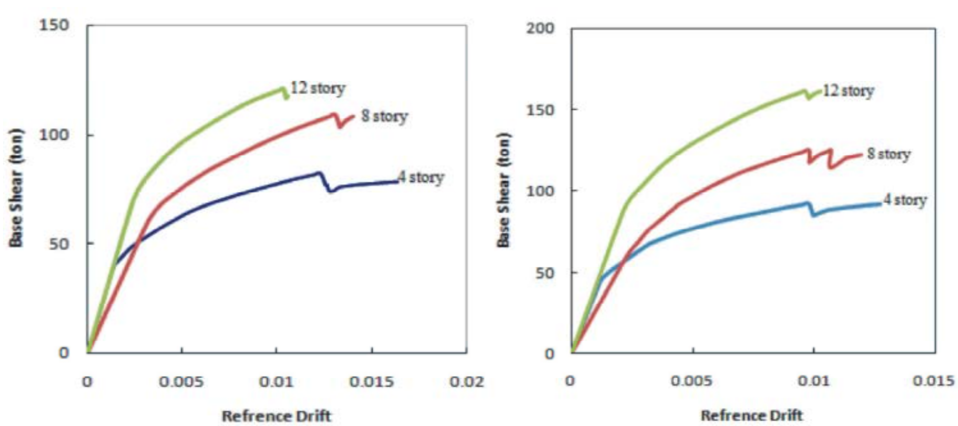


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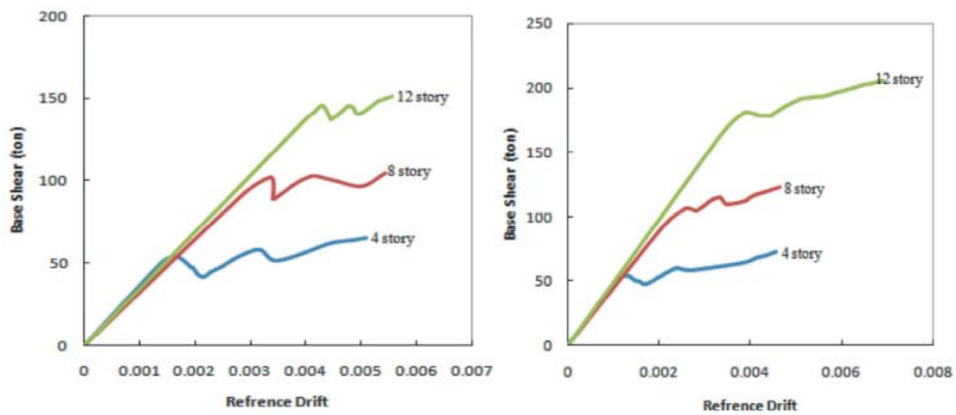
Fig. 7: Base shear- displacement curve, EBF



a. Load pattern triangular b. Load pattern rectangular

Fig. 8: Base shear- displacement curve, chevron (inverted-v) bracing

Table 1: R-factor parameters, X bracing

No. Story	Lateral Loading	μ	R_μ	R_s	γ	R
4	Triangular	2.21	1.85	1.77	2.41	7.89
	Rectangular	2.56	2.03	1.96	2.37	9.43
8	Triangular	2	1.9	1.6	1.81	5.52
	Rectangular	2.09	1.98	1.62	1.99	6.35
12	Triangular	1.74	1.74	1.56	1.77	4.8
	Rectangular	2.09	2.09	1.57	2.14	7.02

Table 2: R-factor parameters, EBF

No. Story	Lateral Loading	μ	R_μ	R_s	γ	R
4	Triangular	7.55	3.75	1.85	1.38	9.7
	Rectangular	6.92	3.58	1.8	1.45	9.02
8	Triangular	3.37	3.37	1.52	1.34	6.84
	Rectangular	3.21	3.21	1.87	1.23	7.39
12	Triangular	3.33	3.33	1.57	1.18	6.17
	Rectangular	3.63	3.63	1.58	1.22	6.97

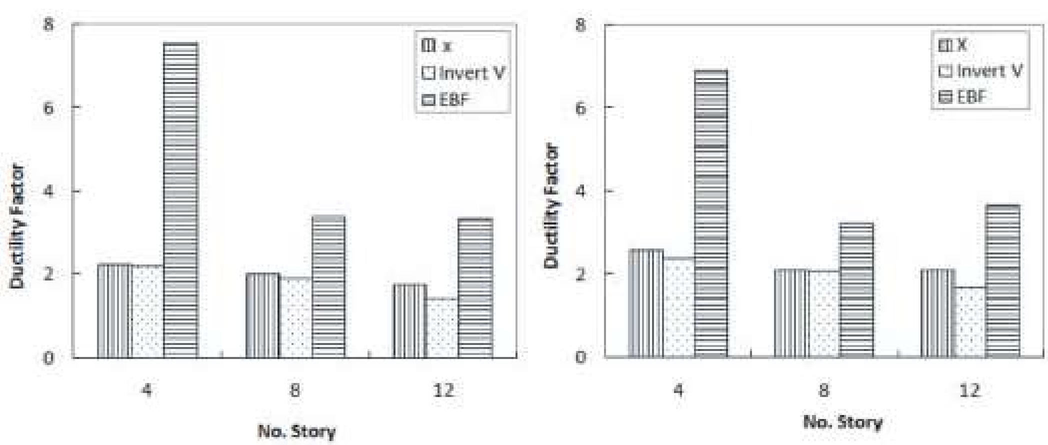
Table 3: R-factor parameters, Chevron Invert-V

No. Story	Lateral Loading	μ	R_μ	R_s	γ	R
4	Triangular	2.19	1.84	1.19	2.34	5.12
	Rectangular	2.36	1.93	1.2	2.5	5.79
8	Triangular	1.87	1.76	1.17	2.32	4.76
	Rectangular	2.05	1.91	1.26	2.33	5.59
12	Triangular	1.4	1.4	1.16	2.23	3.63
	Rectangular	1.64	1.64	1.25	2.47	5.1

Table 4: The average values of seismic parameters

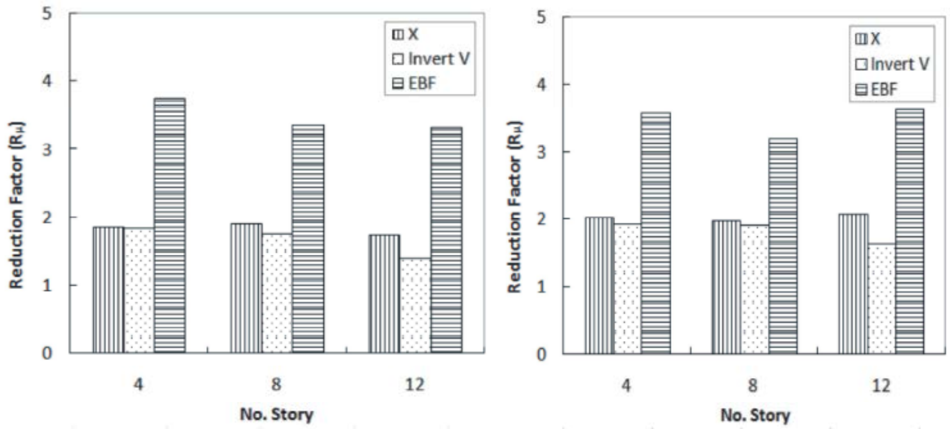
Model	μ	R_μ	$R_s\gamma$*	R
X	2.11	1.93	3.53	6.81
EBF	4.67	3.48	2.21	7.69
Chevron Invert-V	1.92	1.77	2.85	5

Figures 9 to 12 show the seismic parameters changes for the various types of braces (X, inverted V, EBF). In Figure 11, the lateral strength is equal to over strength factor multiple allowable stress factors.



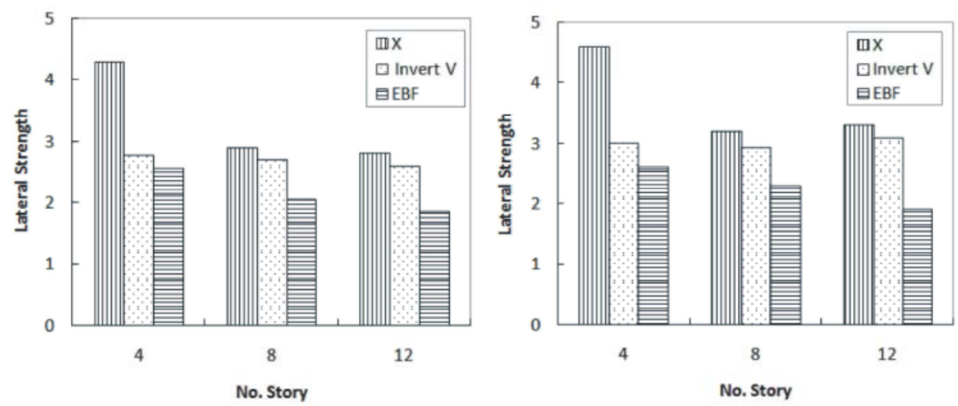
a. Load pattern triangular b. Load pattern rectangular

Fig. 9: Ductility factor



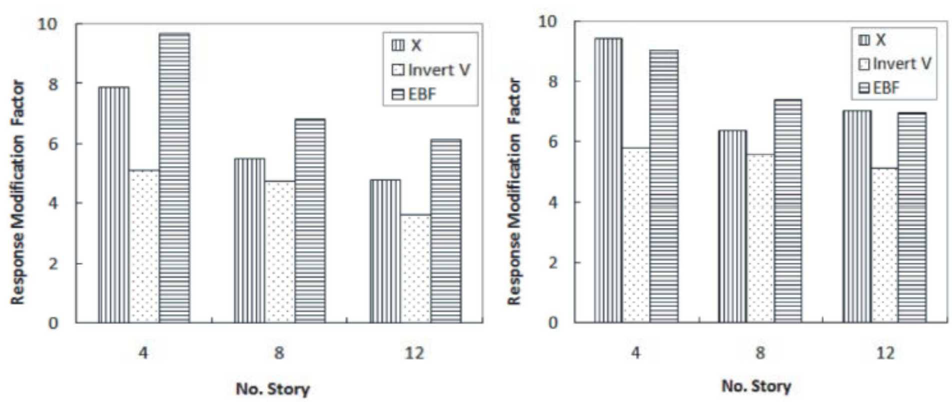
a. Load pattern triangular b. Load pattern rectangular

Fig. 10: Reduction factor due to ductility



a. Load pattern triangular b. Load pattern rectangular

Fig. 11: Lateral strength



a. Load pattern triangular b. Load pattern rectangular

Fig. 12. R-factor

In Figure 9a, it was found that ductility in EBFs is maximum due to the inelastic deformation is limited to the link beam. The braces must be designed considering not to buckle even under the severe lateral loads. According to Figure 10, it was also found that there is a little difference of reduction ductility factor value between EBFs and CBFs. This matter was due to high ductility in EBFs. In triangular load pattern, ductility factor value and reduction factor due to ductility were decreased as the number of stories is increased; while in rectangular load pattern, there is no specific pattern. According to Figure 11, it was observed that in the both patterns of loading, lateral strength value is the lowest in EBFs and the highest in X-braced frames. This matter is because of the CBFs have a great strength and stiffness but low inelastic behavior and energy absorptivity due to braces buckling. According to Figure 12, it can be seen that in the triangular load pattern, R-factor value is the lowest in Inverted V-braced and the highest in EBFs while in rectangular load pattern, there is no specific pattern. In rectangular load pattern, the value of R-factor is decreased as the number of stories is increased. The average values of seismic parameters for different braces are calculated as follows:

- The value of ductility factor for EBF, X and inverted V braces is 4.67, 2.11 and 1.92, respectively.
- The value of reduction factor due to ductility for EBF, X and inverted V braces is 3.48, 1.93 and 1.77, respectively.
- The value of lateral strength for EBF, X and inverted V braces is 2.21, 3.53 and 2.85, respectively.
- The value of R-factor for EBF, X and inverted V braces is 7.69, 6.81 and 5.00, respectively.

Considering the above results, X-braced frames have the highest R-factor while invert V-braced frames has the lowest R-factor. According to Iranian national building code (part 10), this can be justified that the braces section would increase. Also, in any hinge wouldn't form along the beam, because of the beam placed on braced bay can resist against the gravity forces and earthquake forces combined to gravity forces, without braces. Therefore, considering that there is no significant differences between inverted V-brace and X-brace sections, then the inverted V-brace buckles sooner than the others. Accordingly, the R-factor of inverted V-brace would be lower than the others. According to the obtained results, it was found that in CBFs, the lateral strength is the main parameter in determination of R-factor but in EBFs, ductility is the main.

CONCLUSION

In this research, seismic parameters were obtained for 3 types of bracing. The main objectives were to investigate and conduct analysis of seismic parameters on 4, 8 and 12 story frames based on nonlinear static analysis methods. The beam-column connection is side plate connection and the following results were concluded in present work. Ductility has the maximum value in EBF but there were no significant differences between inverted-V and X braced frames. There was great differences between reduction factor value due to ductility of EBF and CBF but this value was almost close in two X and inverted-V braces.

- In triangular loading, ductility and reduction factor due to ductility decreased as the height increased, while in rectangular loading it did not follow a specific pattern.
- In the both patterns of loading, lateral strength value was the lowest in EBFs and in X-braced frames the highest value.
- In the triangular load pattern, R-factor value was the lowest in inverted V-braced and the highest in EBFs while in rectangular load pattern, there was no specific pattern.
- In rectangular load pattern, the value of R-factor decreased as the number of stories increased.
- The values of R-factor for EBF, X and inverted V braces were 7.69, 6.81 and 5.00, respectively. These values are just as criteria to comparison not to determine the exact values of these parameters in this specific frame.
- In CBFs, over strength factor and lateral strength are important parameters in determining the R-factor but in EBFs, ductility is the determining parameter.
- A factor as the R-factor is considered to design the EBFs and CBFs systems without considering the over strength and ductility values in building codes. This can't guaranty the structure stability in the probable earthquakes.

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