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THE STUDY OF X-BRACING ON LIMIT STATE BEHAVIOR OF BUCKLING RESTRAINED BRACE (BRB) IN STEEL FRAMES USING PUSHOVER ANALYSIS

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Abstract. *Using energy dampers in structures is highly considered for the dissipation and absorption of earthquake energy. The main advantage of using energy dampers is absorbing the earthquake energy in some sections apart from the structure. Among different types of dampers, hysteresis dampers are of special place because of low cost, high reliability and the lack of mechanical parts. In this paper, a special kind of hysteresis damper is considered under the name of buckling brace, which is provided with the aim of the study and investigation of X-brace in the seismic behavior of the steel framed buildings and for pipe and equipment racks that are extensively used in the oil and gas industry. In this paper, 62 models of steel frames with X-brace and buckling type damper are processed with different bays and heights. The frames' plasticity index, behavior coefficient, distribution type and the number of plastic hinges formed were calculated. Furthermore, suitable locations of braces for improving nonlinear behavior and suitable distribution of plastic hinges were presented and it was determined that for some models, the behavior coefficient of structure will increase to 1.5 times.*

1 INTRODUCTION

One of the simple ways for static non-linear analysis of complex structures is gradual increase of lateral load statically. The presented methods are part of a seismic design and structure evaluation, which are based on three-dimensional mathematical model of the structure in nonlinear range. Most of behavioral defects of common converged braces are the result of difference between compressive and tensile capacity of these braces and decline of their resistance under cyclic loading. Therefore, many researches are devoted to optimize these braces in order to make them show an ideal elast-o-plastic behavior. To achieve this goal, it is required to prevent the compressive buckling of braces using a suitable mechanism and provide the steel compressive yield. The method considered was encapsulating a ductile metallic core among a mass of concrete, covered with a metal membrane.

The basics of this damper's function are preventing the buckling of the steel core in order to produce the compressive yield phenomenon in it and as a result absorb the energy in this member of the structure. It is possible through covering the whole length of steel core by a steel pipe filled with concrete or mortar. In this system, there is a need to provide a sliding surface or discontinuity layer between metal core and confining concrete. The main aim of this process is to make the bracing force be tolerated just through the steel core. The sliding layer materials and geometry should be in such a way that provides a relative movement between steel core and concrete, which are created because of shear and Poisson effect and as a result provides its yield in compressive loading mode besides preventing local buckling of the core. Concrete and steel tubular casings provide the required stiffness and bending resistance to prevent general buckling of braces and provide the conditions of load tolerance by the steel core up to yield limit without decreasing the stiffness and resistance of braces during loading cycles. In addition, concrete and steel casings prevent the local buckling of the core.

During the systematic multiplier analysis, showing the distribution of the plastic joints creation method is possible in steel structures. Non-linear static analysis by gradual increase of lateral load or location change on top of the structure is part of the new methods, which present a good and simple estimation of nonlinear function of the structure. Most of the researches show that the multiplier nonlinear static analysis methods properly match with nonlinear dynamic analysis results in evaluating the structures (e.g. [1]). Pushover analysis can provide good information about the structure's resistance-capacity, deformation demand, and discontinuity in the distribution of resistance and the areas with energy absorption potential in the structure [2]. In this study, pushover nonlinear static method is used for seismic evaluation and determination of plasticity index, behavior and resistance coefficient, plastic joints distribution mode, and studying the location of the braces.

2 MODEL SELECTION, MODEL'S LOADING AND SECTIONS

Here, there is a close match among the geometric dimensions of the sections in models and oil and gas industrial frames and structural frames of ordinary building in Iran. For created models, the bays distance is considered 5 metres and the height stories are 3 metres. The aim of this study is modeling and analyzing the structures with different heights and bays by using buckling braces to provide the possibility of studying and observing the effects of the type of braces and the number of braces spans. So the steel frames with 3, 5 and 7 bays and the height of 6, 12 and 18 stories are used. In order to determine the effect of buckling braces location on boundary behavior of braced framed, it has tried to create bracing in different bays. Therefore, in three-bay frames, the braced spans were created as one-bay and two-bays together. In addition, in five-bay frames, the braced spans are used as two-bays, the location of which is different among models. For seven-bay frames the braced spans are used as two-bays and three-bays, where the side by side symmetric form is used for two-bays and single, double and triple forms are used for three bays next to each other.

In naming the braced frames, a special trend is used. Therefore, in the frame considered, numbering of the bays is from left to right in such a way that the first braced span on the left receives number 1 and the last one on the left receives number 7 for those frames with highest number of bays. Thus, the naming trend for braced frames is as *WS*(X, Y, Z). *W* is the number of the bays in regarded frame and *S* is for bay. X, Y and Z are the number of the first, second and third braced spans, respectively. For instance, 7S (1, 4, 7) means a seven-bay frame where the first, fourth and seventh bay of it is braced from the left, respectively. In Figure 1, a frame sample is shown, which is named in the form of 7S (1, 4, 7).

The composite roof details are used to determine the gravity dead load. Lateral loading of frames is calculated based on the regulations of seismic design with the design basis acceleration of 0.35 for South Pars region [3] and soil period of 0.5 second for soil type II. The design of steel structures was according to AISC89-ASD. The connections between beams and braces are simple joint and columns' connections to the foundation are simple support. The effective length of braces for out of plane buckling is considered equal to 0.67; this value for in plane is 0.5 for IPE sections for beams and IPB section for columns. Also double L sections were employed for braces. Material properties assumed compatible with ST-37 steel grade.

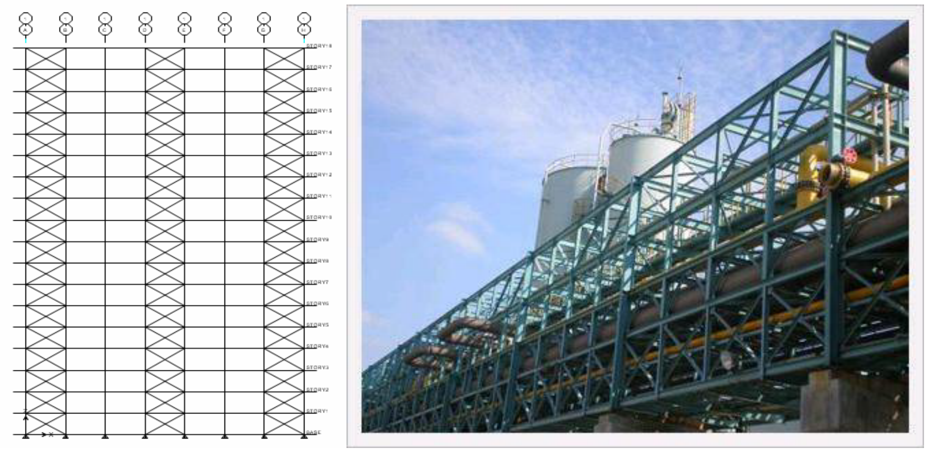

Fig. 1 7S (1,4,7) Steel Framed Building and a 4 Story Pipe Rack Structure

3 BASICS OF INELASTIC CYCLIC BEHAVIOR OF BUCKLING BRACES

Buckling-Restrained Braced Frames (BRBFs), as can be shown in Figure 2, are a relatively new type of concentrically braced system characterized by the use of braces that yield inelastically both in tension and compression at their adjusted strengths [4]. Despite their being a relatively new system, BRBFs in the United States have, to date, been subjected to numerous analytical and experimental studies that have demonstrated their robustness when subjected to code-type ground motions (e.g. [5], [6], [7]).

The brace component of BRBFs is known as the Buckling Restrained Brace (BRB). BRBs have full, balanced hysteresis loops as illustrated in Figure 3, with compression-yielding similar to tension-yielding behavior. They achieve this through the decoupling of the stress-resisting and flexural buckling resisting aspects of compression strength. Axial stresses are resisted by a shaped steel core. Buckling resistance is provided to that core by a casing, which may be of steel, concrete, composite, or other construction. Because the steel core is restrained from buckling, it develops almost uniform axial strains. Plastic hinges associated with buckling do not form in properly designed and detailed BRBs.

Fig. 2 Buckling Brace in Stories' Height and Details of Bracing

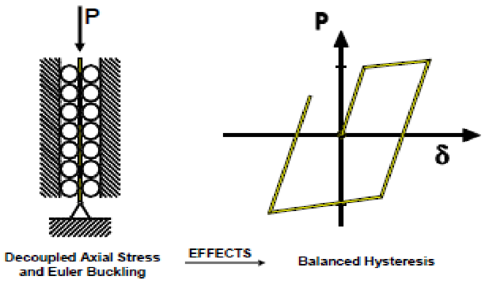

Fig. 3 Mechanics of a Buckling-Restrained Brace

The inelastic cyclic behavior of these braces is studied through many experiences (e.g [8], [9] and [10]). These experiences, matching with finite element studies, showed that unlike common braces, the stable hysteresis cycles can be obtained in tension and pressure, therefore a high capacity of earthquake energy absorption is obtained in the structure. The behavior of the frames with buckling braces shows considerable difference with common coaxial bracing frames despite apparent similarities. In buckling–restrained braces, the hysteresis loops are stable and no resistance or curve decline is observed in the system during loading and unloading cycles.

In this study, after determining the loads applied on the structure and analyzing the frame under them, the force created in braces can be calculated and shown as P'_{br} . Therefore, the section required for yielding area of the buckling equals:

$$A'_{br} = \frac{P'_{br}}{1.25 \times 0.6 F_y} \alpha \tag{1}$$

In which α is considered between one and final resistance relative to the maximum load resulted from analysis in members to which the load of brace is transferred (such as columns). Higher values of this coefficient increase the stiffness and energy absorption capacity of the system. *Fy* equals the steel core yield resistance of bracing. Coefficient 1.25 is for considering the strain hardening of steel. Because the cross section of the central core is considerably smaller than the cross section of the final area of the connection, most of the elastic and even plastic displacements happen in this area. With regard to this fact, the axial stiffness of each buckling brace equals:

$$K_{br} = \frac{EA'_{br}}{L'_{br}} \tag{2}$$

In which L'_{br} is the length of the central core and E is the elasticity module of the core steel materials. Furthermore, the axial strain of yielding area is:

$$\varepsilon_{br} = \frac{\delta_{br}}{L'_{br}} \tag{3}$$

In which δ_{br} is the axial deformation of the brace. By reducing L'_{br}, the brace's stiffness increases and as a result, the relative displacement of the story decreases. As the above relation shows, this is independent from the brace resistance.

In order to prevent buckling in pressure, the metal core is placed inside a metal sheath filled with concrete or mortar. Before filling the sheath with concrete, a few separating material or vacuum is placed between metal core and mortar to prevent the axial force transfer from metal core to concrete covering or at least to minimize it. The effect of Poisson coefficient also causes the metal core to expand in pressure and this requires a distance to be created (Figure 4).

Fig. 4 Components of Buckling –Restrained Brace

When these braces designed properly with details, the steel sheath should not bear any axial force. To prevent the buckling of BRBs, the metal sheath should be designed for the following stiffness of bending:

$$\frac{P_e}{P_y} \geq 1.0 \tag{4}$$

In which P_y is the flowing resistance of the flowing confined part and P_e is the elastic buckling resistance of the metal sheath.

$$P_e = \frac{\pi^2 EI_{sc}}{L^2{}_{sc}} \tag{5}$$

E is Yang module, EI_{sc} is the inertia momentum of steel sheath section and L_{sc} is the length of the sheath. In using these equations, it should be noted that the effects of steel strain stiffness is omitted under cyclic loading. In this case, steel strain stiffness increases the pressure resistance of the brace up to 30% and a resistance coefficient of $\varphi = 0.85$ is used in numerator.

$$\frac{\varphi P_e}{1.3 \times P_y} \geq 1.0 \longrightarrow \frac{P_e}{P_y} \geq 1.5 \tag{6}$$

In designing process, it has been tried to change the dimensions and thickness of BRB sections to have a more uniform energy absorption in height. The characteristics of plastic joints of BRB are the same as tensile section of the braces in pressure section (Figure 5).

Point	Force/SF	Disp/SF
E-	-0.8	-14
D-	-0.8	-11
C-	-1.33	-11
B-	-1	0.
A	0	0.
B	1	0.
C	1.33	11
D	0.8	11
E	0.8	14

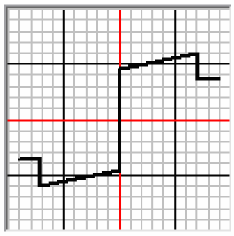

Fig. 5 The Plastic Joints Characteristics of BRB in Pressure and Tensile Section of the Brace

4 RESULTS FROM NONLINER STATIC ANALYSIS

After the two dimensional nonlinear static analysis of each one of the models, the results from base shear–roof displacement for lateral push expressed through a curve. The incremental load curve includes horizontal and vertical axes, which show roof displacement and base shear resulted from lateral push respectively. Information retrievable from these diagrams is yield displacement *Dy*, yield base shear *Fy*, final displacement *Du* and final base shear *Fu*. Displacement and yield base shear are a point on pushover diagram in which the linear an elastic behavior of the structure has terminated and the structure enters the nonlinear area. Displacement and final base shear are a point on this diagram in which the structure's resistance has extensively decreased and in fact this is the result of the structure's destruction, decreases in the structure's stiffness and the lack of tolerance of the loads applied to it.

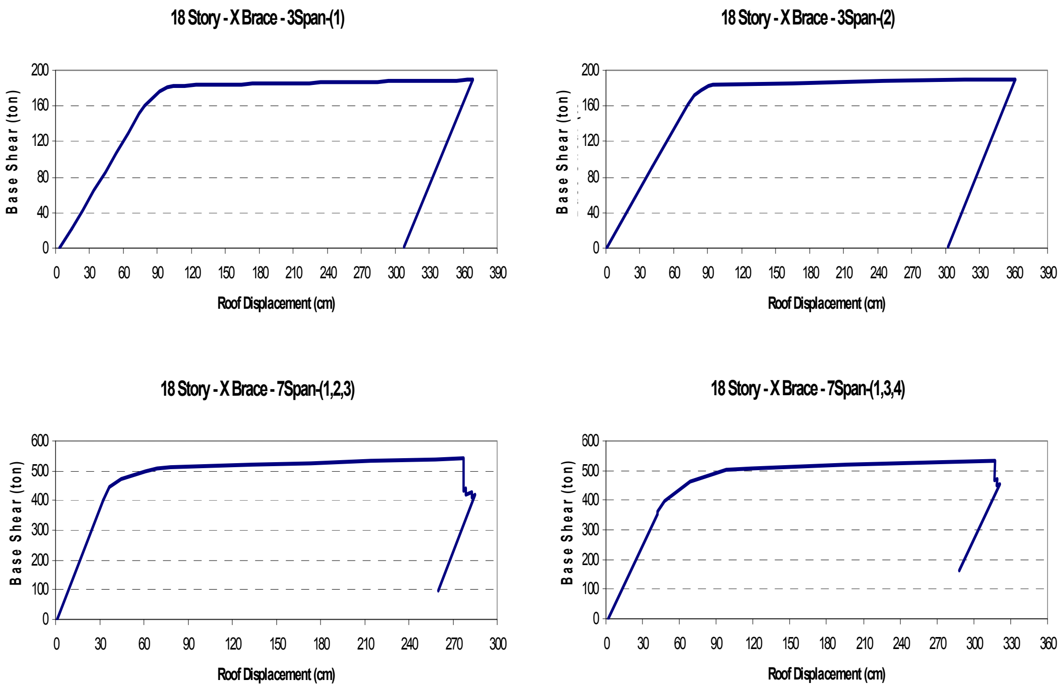

Fig. 6 Roof Story Displacement for 18 Stories Frames for Example for Models 3S(1), 3S(2), 7S(1,2,3) and 7S(1,3,4)

In this paper, computation of R can be carried out using the following method but there are some essential values to be derived first. These values include: yield and ultimate displacements; also yield force and elastic strength demand force. R can be performed by defining two factors: strength demand reduction factor R_d and overstrength factor Ω. Figure 7 shows parameter derived for evaluation of R-values. The results from all models are illustrated in Figure 8, 9 and listed in Table I, II.

$$R_d = \frac{Elastic\ \ Strength\ \ Demand}{Real\ \ Strength} \qquad (7)$$

$$\Omega = \frac{Real\ \ Strength}{Design\ \ Strength} \qquad (8)$$

$$R = R_d . \Omega \qquad (9)$$

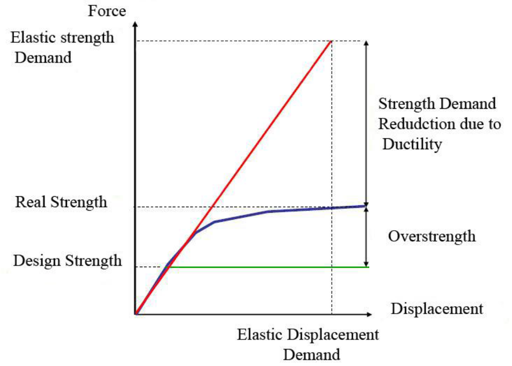

Fig. 7 Parameters Employed in Determined Behavior Coefficient

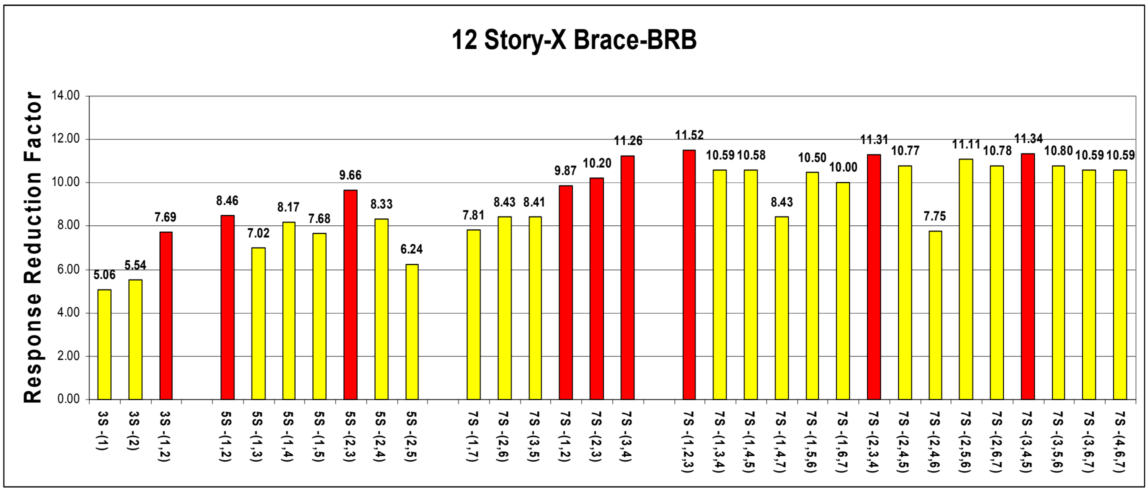

Fig. 8 Computed R-Values for 12-Story Frame and Different Braced Bays

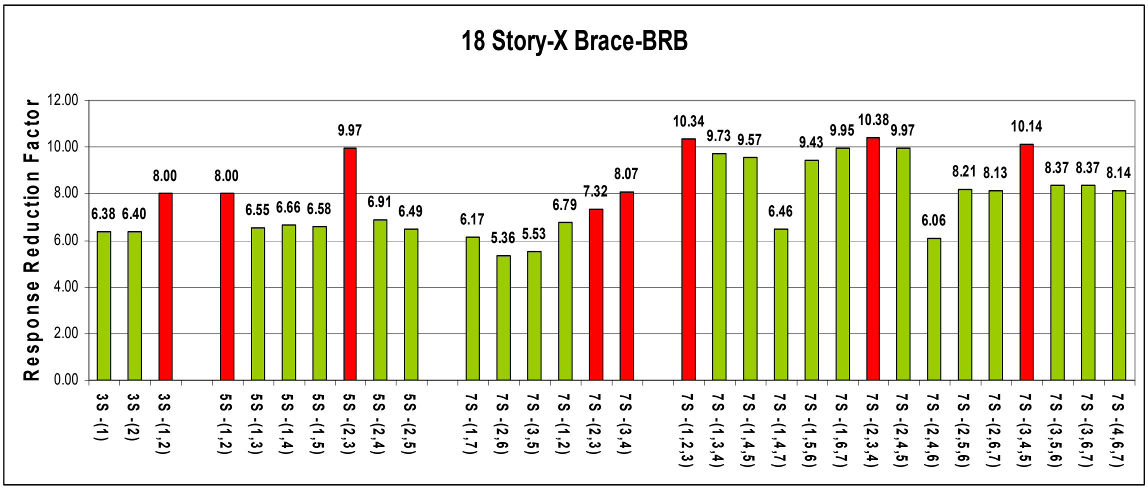

Fig. 9 Computed R-Values for 18-Story Frame and Different Braced Bays

TABLE I
BEHAVIOR COEFFICIENT AND RESISTANCE COEFFICIENT COMPUTATION FOR 6, STORIES FRAMES
UNIT: TON,CM

6 storey - X Brace - BRB			
Span	Initial Stiffness	R	O.S
3S -(1)	11.97	8.20	1.29
3S -(2)	12.26	8.23	1.29
3S -(1,2)	26.80	8.46	1.32
5S -(1,2)	27.53	9.50	1.44
5S -(1,3)	20.53	7.56	1.44
5S -(1,4)	20.25	7.48	1.45
5S -(1,5)	20.25	8.77	1.72
5S -(2,3)	26.34	9.76	1.46
5S -(2,4)	21.34	7.87	1.46
5S -(2,5)	22.52	8.69	1.50
7S -(1,7)	19.75	8.89	1.47
7S -(2,6)	20.72	9.00	1.50
7S -(3,5)	22.69	9.84	1.49
7S -(1,2)	26.00	11.37	1.50
7S -(2,3)	27.48	11.47	1.52
7S -(3,4)	26.96	11.56	1.53
7S -(1,2,3)	43.23	10.24	1.50
7S -(1,3,4)	37.09	8.67	1.43
7S -(1,4,5)	35.17	8.31	1.44
7S -(1,4,7)	28.86	7.34	1.50
7S -(1,5,6)	35.74	8.62	1.47
7S -(1,6,7)	33.77	10.49	1.59
7S -(2,3,4)	40.48	11.86	1.54
7S -(2,4,5)	37.15	11.00	1.59
7S -(2,4,6)	32.86	9.79	1.64
7S -(2,5,6)	36.54	11.10	1.60
7S -(2,6,7)	36.93	10.36	1.60
7S -(3,4,5)	43.73	11.44	1.55
7S -(3,5,6)	38.67	9.84	1.63
7S -(3,6,7)	34.15	8.15	1.47
7S -(4,6,7)	36.89	8.66	1.46

TABLE II
BEHAVIOR COEFFICIENT AND RESISTANCE COEFFICIENT COMPUTATION FOR 12, STORIES FRAMES
UNIT: TON,CM

12 storey - X Brace - BRB			
Span	Initial Stiffness	R	O.S
3S -(1)	4.32	5.06	1.26
3S -(2)	4.64	5.54	1.29
3S -(1,2)	11.05	7.69	1.34
5S -(1,2)	10.84	8.46	1.39
5S -(1,3)	8.31	7.02	1.39
5S -(1,4)	8.43	8.17	1.62
5S -(1,5)	7.96	7.68	1.61
5S -(2,3)	10.88	9.66	1.40
5S -(2,4)	8.56	8.33	1.40
5S -(2,5)	7.98	6.24	1.29
7S -(1,7)	7.79	7.81	1.41
7S -(2,6)	7.73	8.43	1.56
7S -(3,5)	8.36	8.41	1.43
7S -(1,2)	10.72	9.87	1.40
7S -(2,3)	11.89	10.20	1.37
7S -(3,4)	12.98	11.26	1.37
7S -(1,2,3)	18.77	11.52	1.55
7S -(1,3,4)	15.84	10.59	1.55
7S -(1,4,5)	15.82	10.58	1.55
7S -(1,4,7)	11.67	8.43	1.55
7S -(1,5,6)	15.74	10.50	1.57
7S -(1,6,7)	14.99	10.00	1.55
7S -(2,3,4)	18.82	11.31	1.52
7S -(2,4,5)	16.56	10.77	1.51
7S -(2,4,6)	11.72	7.75	1.40
7S -(2,5,6)	16.57	11.11	1.56
7S -(2,6,7)	16.51	10.78	1.52
7S -(3,4,5)	18.83	11.34	1.52
7S -(3,5,6)	16.56	10.80	1.51
7S -(3,6,7)	16.18	10.59	1.52
7S -(4,6,7)	16.22	10.59	1.53

5 CONCLUSION

In conducting this research, many results are obtained. The mail results are as follows:
1- Yield displacement of frames braced by buckling-retrained X-brace is decreased when the bracing spans are approaching each other

2- Final displacement of braced frames is minimized when the bracing spans are approaching each other in all bays and heights.

3- The yield base shear and final force increases when the bracing spans are approaching each other in all bays and heights. Therefore, the lateral loading increases and maximum capacity of the sections can be employed to bear the lateral loads.

4- Primary stiffness decreases with an increase in the number of stories. But by creating the stiff spans in the bays, which are located next to each other, the primary stiffness also increases.

5- By increasing the number of the stories' dispersion, behavior coefficient values increases. Therefore, it shows the sensitivity of behavior coefficient value to the structure height and the criticality of behavior coefficient effect in designing steel joint frames.

6- To improve the behavior coefficient of steel frames with buckling retrained X- bracing, the distance between bracing spans should be decreased and they should be even placed next to each other if it's possible.

7- The resistance coefficient of frames braced with buckling-retrained X-brace can be increased to 1.5 times and improved as well relative to the situation of braces.

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