Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 1524

# EFFECTS OF X-BRACING RESISTANT SYSTEM CONFIGURATION ON LIMIT STATE BEHAVIOR IN STEEL FRAMES USING PUSHOVER ANALYSIS

Peyman Shademan Heidari[1], Hossein Kayhani[2], Roohollah Ahmady Jazany[3]

## ABSTRACT:

Generally selection and configuration of lateral load resisting systems are dictated by architectural limitations. This study aims at evaluating the effects of different X-bracing system configurations on limit state behavior of steel frames by means of pushover analysis. First, 93 steel frame models with different bracing configuration (adjacent bays, extreme bays,…), different story heights and different bay width were designed according to AISC-ASD89 and Iranian code of practice for seismic resistant design of buildings (standard No.280,2$^{nd}$ edition). Employing pushover analyses ductility factor, Overstrength factor, Response reduction factor (R) and number and distribution of plastic hinges in the frames considered were estimated. Finally, Obtained mean of R-values was compared to suggested value proposed by 2800 standard and proper bracing configurations for suitable nonlinear response and plastic hinge distribution were identified. Results indicate that proper configuration which is usually neglected in current codes and design process, can significantly affect the response reduction factor, e.g., it maybe more than 1.5 times of suggested value but in other cases, especially medium-rise frames with fewer bays, it is nearly half of the suggested value. This research suggests that configuration of resisting system should also be incorporated in design codes if proper behavior is to be expected.

## Introduction

The ‘Response Reduction Factor’ (R) which is widely used in most of the seismic design codes all over the world, is trying to compensate the effects of ductility of the system to withstand seismic load. The ultimate capacity of each structural system depends on its structural configuration and specifications, including type of bracing and size of bracing elements in case of

[1] Faculty Staff, East Tehran branch, Islamic Azad University, Tehran, Iran
[2] PhD Candidate, Science and Research Branch, Islamic Azad University, Tehran, Iran
[3] PhD Candidate, Structural Research Centre, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran

braced frames. Consequently, the codes give various values of R depending on the lateral load bearing system of the building. For example, some codes (IBC 2003) suggest a value of 5 for the case of Ordinary Concentrically Braced Frame (OCBF), and a value of 6 for the case of Special Concentrically Braced Frame (SCBF). This value in Iranian code of practice for seismic resistant design of buildings is 6 (there are no Ordinary or Special classification). However, the R-values in codes do not depend on the number of braced bays and their relative location, or even the overall pattern of bracing while the number of braced bays in a frame is important considering their effects on redundancy. Several analytical and experimental studies have been performed on braced frames since early 70s, of which some experimental works will be briefly reviewed here.

Shaishmelashvili and Edisherashvili (1973) have done an experimental study on dynamic characteristics of large-scale models of multi-story steel frame buildings with different vertical bracings. They have tested some large-scale models of a 9-story building with 12 different bracing schemes in free and forced (resonance) vibration states.

Suzuki et al. (Feb.1975) performed an experimental study on the elasto-plastic behavior of tensile braced frames to obtain the restoring force characteristics of low-rise steel structures.

Wakabayashi and his colleagues (1980) did some experimental studies on the elasto-plastic behavior of braced frames under repeated horizontal loading. In a part of those studies, experiments of one story-one bay braced frames were conducted to investigate the hysteretic behavior of this kind of steel frames whose braces were made of built-up H-shapes and whose columns and beams were made of rolled H-shapes

Lee and Bruneau (2005) studied the energy dissipation of compression members in concentrically braced frames by reviewing the available experimental data. Design and detailing requirements of seismic provisions for CBFs were specified based on the premise that bracing members with low KL/r and b/t will have superior seismic performance. However, they claimed that relatively few tests have investigated the cyclic behavior of CBFs, and hence, it is legitimate to question whether the compression member of a CBF plays a significant role as what has been typically assumed implicitly by the design provisions.

One of the simplest methods for nonlinear analysis of complex structures is Nonlinear Static Analysis, also known as pushover analysis. Despite its limitations, Pushover analysis could provide valuable information about capacity of structures, demand deformation, discontinuity on strength distribution and potential of energy absorption. To evaluate the seismic behavior and determination of ductility factor, overstrength factor and distribution of plastic hinges in structures with different x-bracing configuration, push over analysis is used in this research.

## Numerical Analysis

### Model description and naming convention

The analytical models selected based on typical practice of frames in Iran. The bay width of models was considered as 5 meters and the heights of stories as 3 meters. Models with different number of stories and bays were employed to consider the effect of X-bracing system placement on R-factor, overstrength factor and plastic hinge distribution. In order to study these parameters, frames with 3, 5 and 7 bays and 6, 12, 18 stories were modeled. The form of WS (X, Y, Z) is used for naming the models, Where W is the number of bays, S is the abbreviation of span X,Y and Z are the number of first, second and third braced bays respectively. For example, 3s (1), means a three-bay frame in which the first bay is braced. Fig. 1 shows a sample of 12-story frame and its naming based on naming convention used in this study.

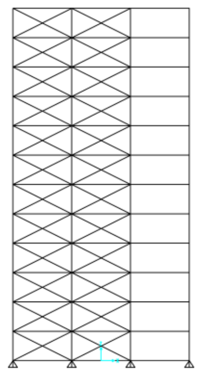

Figure 1. 12stories-3s (1, 2)

## Loading procedure on the models

Gravity loads were applied according to Iranian loading code and composite floor system was assumed, seismic loading were applied according to Iranian seismic design code (second revision) and soil type II. Computation procedure of base shear is shown in the following table; moreover, the response spectrum analysis was used for designing the models.

Table 1- Base shear and slash force computation

| 2800 Standard | 6 STORY | 12 STORY | 18 STORY |
|---|---|---|---|
| $T=0.05\times H^{3/4}$ (sec) | 0.698 | 1.176 | 1.594 |
| Soil Type 2<br>$B=2.5\times(0.5/T)^{2/3}$, $B\leq 2.5$ | 1.999 | 1.176 | 1.154 |
| C=ABI/R | 0.1166 | 0.0825 | 0.0673 |
| V=CW (ton) | 74.8 | 107.1 | 133.5 |
| $F_t=0.07TV$ (ton) | 0 | 8.82 | 14.91 |

The design of steel structures was according to AISC-DSA89. The effective length of braces for out of plane buckling is considered equal to 0.67; this value for in plane is 0.5. IPE sections were used for beams and IPB section were provided for columns and also double L sections were employed for braces. Material properties assumed compatible with ST-37 steel grade.

## Pushover Analysis: Load pattern and hinge specifications

FEMA-356 was used to conduct displacement controlled pushover analyses. The reverse triangular loading pattern or first mode compatible pattern, where applicable, was considered. During the analysis, the location of plastic hinges and the analysis termination criteria were controlled. Properties of hinges in each element were defined according to geometry, material mechanical properties and applied forces in the elements. All of these specifications were derived from FEMA-356. Axial - moment interaction hinges (P-M hinge) were used for columns and axial hinges was assigned to brace elements (P hinge).

## Numerical results

The results of two-dimensional nonlinear analyses were depicted as base shear versus roof displacement. Some information was derived from the curves that are important for computation of strength factor and response reduction factor, such as yield displacement, yield base shear, ultimate base shear and ultimate displacement. Figure 2 shows base shear versus roof displacement for 12-story frame and different configuration of X-bracing as a sample. At the end of curves, a kind of degradation is noticeable.

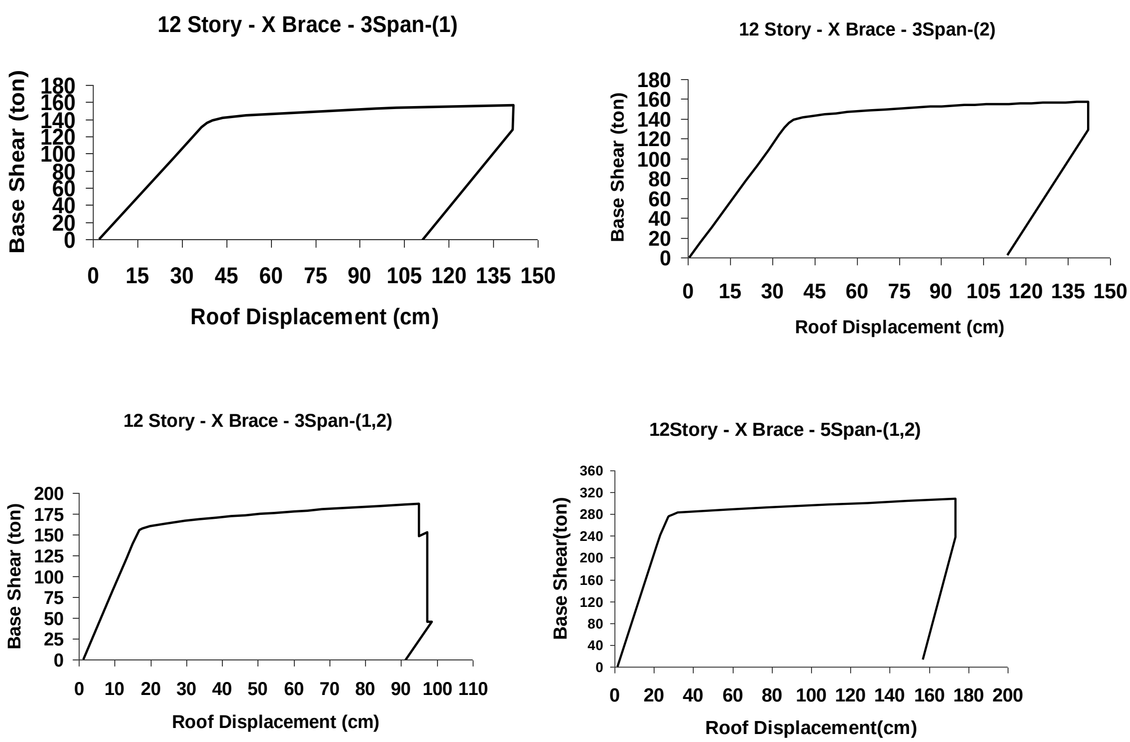


Figure 2. Base shear vs. roof displacement for 12-story frame and different configuration of X-bracing

In previous research effects of bracing configurations were not studied beyond elastic response as presented here. 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 shown respectively by $D_y$ and $D_u$; also yield force and elastic strength demand force which would be presented by $F_y$ and $F_{ed}$ notations respectively. R estimation can be performed by defining two factors: strength demand reduction factor, $R_d$ and overstrength factor, $\Omega$. Figure 3 shows parameter derived for evaluation of R-values (Uang, 1991, Behbahani, 1996,).

$$R_d = \frac{Elastic\ Strength\ Demand}{Real\ Strength} \tag{1}$$

$$\Omega = \frac{Real\ Strength}{Design\ Strength} \tag{2}$$

and then R can be computed as:

$$R = R_d.\Omega \tag{3}$$

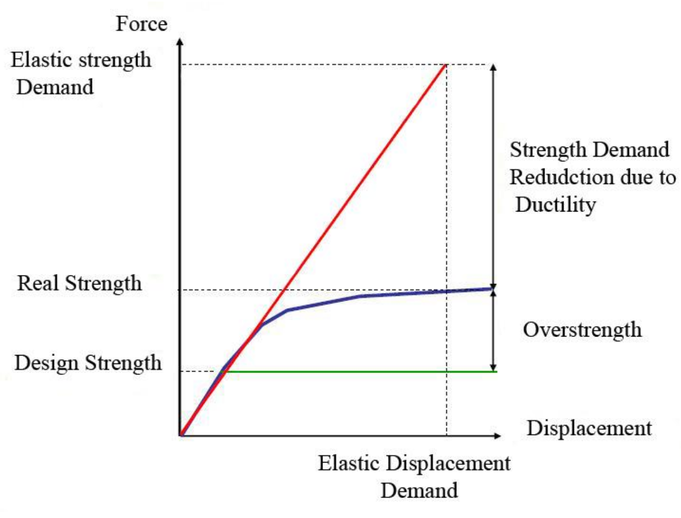


Figure 3 Parameters used in R evaluation

Effects of different bracing configuration on response reduction factors in line with overstrength factor can be summarized in table 2. Comparison of response reduction factors for the models studied in this research are displayed in figs. 4 to 6. Considering the figure better performance of adjacent braced bays behavior especially when they are placed as close as possible to the middle bays is evident.

Table 2. Computed R-values and overstrength factors for different bracing configurations

| 6 story - X Brace | | | | 12 story - X Brace | | | | 18 story - X Brace | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Span | Initial Stiffnes | R | O.S | Span | Initial Stiffnes | R | O.S | Span | Initial Stiffness | R | O.S |
| 3S -(1) | 9.98 | 6.16 | 1.19 | 3S -(1) | 3.60 | 3.81 | 1.17 | 3S -(1) | 2.12 | 4.79 | 1.16 |
| 3S -(2) | 10.22 | 6.19 | 1.19 | 3S -(2) | 3.87 | 4.17 | 1.19 | 3S -(2) | 2.24 | 4.81 | 1.10 |
| 3S -(1,2) | 22.33 | 6.36 | 1.23 | 3S -(1,2) | 9.21 | 5.78 | 1.24 | 3S -(1,2) | 4.80 | 6.02 | 1.30 |
| | | | | | | | | | | | |
| 5S -(1,2) | 25.03 | 7.14 | 1.19 | 5S -(1,2) | 9.85 | 6.36 | 1.15 | 5S -(1,2) | 5.64 | 6.02 | 1.19 |
| 5S -(1,3) | 18.66 | 5.69 | 1.19 | 5S -(1,3) | 7.56 | 5.28 | 1.15 | 5S -(1,3) | 4.24 | 4.92 | 1.15 |
| 5S -(1,4) | 18.41 | 5.63 | 1.20 | 5S -(1,4) | 7.66 | 6.15 | 1.34 | 5S -(1,4) | 4.32 | 5.00 | 1.15 |
| 5S -(1,5) | 18.41 | 7.25 | 1.42 | 5S -(1,5) | 7.24 | 5.77 | 1.33 | 5S -(1,5) | 4.42 | 4.94 | 1.18 |
| 5S -(2,3) | 23.94 | 6.87 | 1.21 | 5S -(2,3) | 9.89 | 7.27 | 1.15 | 5S -(2,3) | 6.88 | 7.50 | 1.22 |
| 5S -(2,4) | 19.40 | 5.92 | 1.21 | 5S -(2,4) | 7.78 | 6.26 | 1.16 | 5S -(2,4) | 4.47 | 5.19 | 1.16 |
| 5S -(2,5) | 20.47 | 6.53 | 1.24 | 5S -(2,5) | 7.26 | 4.69 | 1.07 | 5S -(2,5) | 4.37 | 4.88 | 1.11 |
| | | | | | | | | | | | |
| 7S -(1,7) | 17.96 | 6.69 | 1.21 | 7S -(1,7) | 7.08 | 5.87 | 1.16 | 7S -(1,7) | 4.08 | 4.64 | 1.07 |
| 7S -(2,6) | 18.84 | 6.76 | 1.24 | 7S -(2,6) | 7.03 | 6.34 | 1.29 | 7S -(2,6) | 4.41 | 4.03 | 1.11 |
| 7S -(3,5) | 20.63 | 7.40 | 1.23 | 7S -(3,5) | 7.60 | 6.32 | 1.18 | 7S -(3,5) | 4.49 | 4.16 | 1.13 |
| 7S -(1,2) | 23.63 | 8.55 | 1.24 | 7S -(1,2) | 9.75 | 7.42 | 1.16 | 7S -(1,2) | 6.81 | 5.11 | 1.09 |
| 7S -(2,3) | 24.98 | 8.62 | 1.25 | 7S -(2,3) | 10.81 | 7.67 | 1.13 | 7S -(2,3) | 7.21 | 5.50 | 1.10 |
| 7S -(3,4) | 24.50 | 8.69 | 1.26 | 7S -(3,4) | 11.80 | 8.47 | 1.13 | 7S -(3,4) | 7.38 | 6.07 | 1.15 |
| | | | | | | | | | | | |
| 7S -(1,2,3) | 39.30 | 7.70 | 1.24 | 7S -(1,2,3) | 17.06 | 8.66 | 1.28 | 7S -(1,2,3) | 11.77 | 7.78 | 1.29 |
| 7S -(1,3,4) | 33.72 | 6.52 | 1.18 | 7S -(1,3,4) | 14.40 | 7.96 | 1.28 | 7S -(1,3,4) | 9.12 | 7.32 | 1.35 |
| 7S -(1,4,5) | 31.97 | 6.25 | 1.19 | 7S -(1,4,5) | 14.38 | 7.95 | 1.28 | 7S -(1,4,5) | 8.78 | 7.20 | 1.37 |
| 7S -(1,4,7) | 26.24 | 5.52 | 1.24 | 7S -(1,4,7) | 10.61 | 6.34 | 1.28 | 7S -(1,4,7) | 6.60 | 4.85 | 1.16 |
| 7S -(1,5,6) | 32.49 | 6.48 | 1.21 | 7S -(1,5,6) | 14.31 | 7.89 | 1.30 | 7S -(1,5,6) | 8.77 | 7.09 | 1.38 |
| 7S -(1,6,7) | 30.70 | 7.89 | 1.32 | 7S -(1,6,7) | 13.63 | 7.52 | 1.28 | 7S -(1,6,7) | 8.73 | 7.48 | 1.52 |
| 7S -(2,3,4) | 36.80 | 8.92 | 1.27 | 7S -(2,3,4) | 17.11 | 8.50 | 1.26 | 7S -(2,3,4) | 12.01 | 7.81 | 1.27 |
| 7S -(2,4,5) | 33.77 | 8.71 | 1.32 | 7S -(2,4,5) | 15.06 | 8.10 | 1.25 | 7S -(2,4,5) | 9.14 | 7.50 | 1.45 |
| 7S -(2,4,6) | 29.88 | 7.36 | 1.36 | 7S -(2,4,6) | 10.65 | 5.83 | 1.16 | 7S -(2,4,6) | 6.69 | 4.56 | 1.08 |
| 7S -(2,5,6) | 33.22 | 8.60 | 1.32 | 7S -(2,5,6) | 15.06 | 8.36 | 1.29 | 7S -(2,5,6) | 9.43 | 6.18 | 1.17 |
| 7S -(2,6,7) | 33.57 | 7.79 | 1.32 | 7S -(2,6,7) | 15.01 | 8.11 | 1.26 | 7S -(2,6,7) | 9.35 | 6.11 | 1.17 |
| 7S -(3,4,5) | 39.75 | 8.56 | 1.28 | 7S -(3,4,5) | 17.12 | 8.53 | 1.26 | 7S -(3,4,5) | 12.03 | 7.62 | 1.24 |
| 7S -(3,5,6) | 35.15 | 7.40 | 1.34 | 7S -(3,5,6) | 15.05 | 8.12 | 1.25 | 7S -(3,5,6) | 9.42 | 6.29 | 1.20 |
| 7S -(3,6,7) | 31.05 | 6.13 | 1.21 | 7S -(3,6,7) | 14.71 | 7.96 | 1.26 | 7S -(3,6,7) | 9.32 | 6.29 | 1.21 |
| 7S -(4,6,7) | 33.54 | 6.51 | 1.20 | 7S -(4,6,7) | 14.74 | 7.96 | 1.27 | 7S -(4,6,7) | 9.33 | 6.12 | 1.17 |

unit: ton,cm

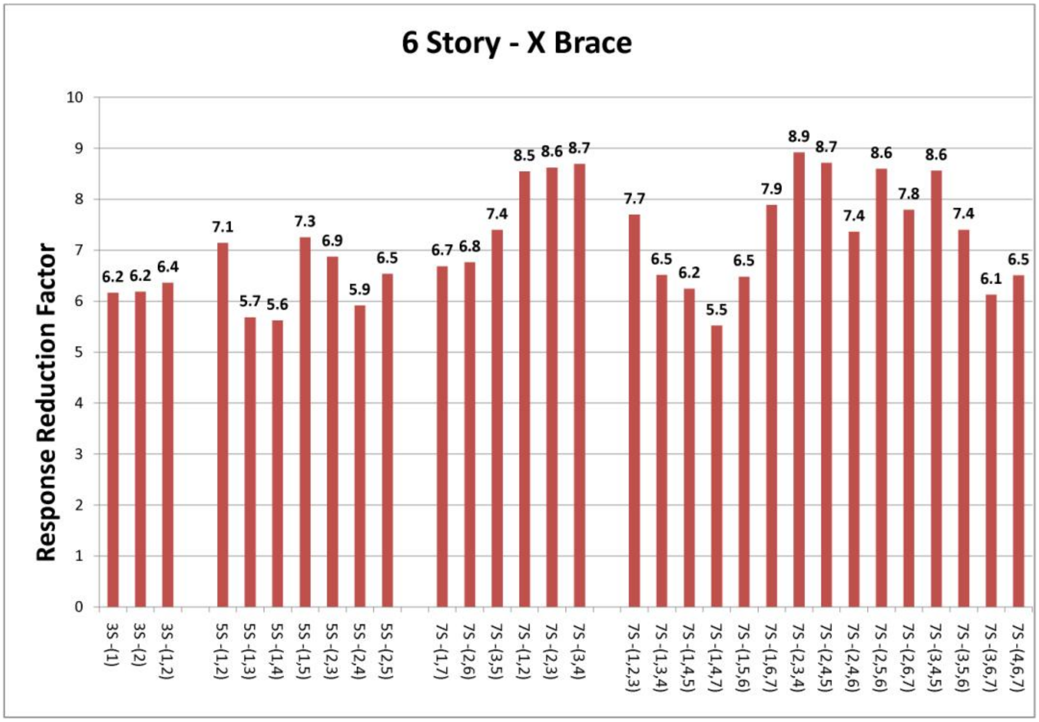


Figure 4. Computed R-Values for six-story frame and different braced bays

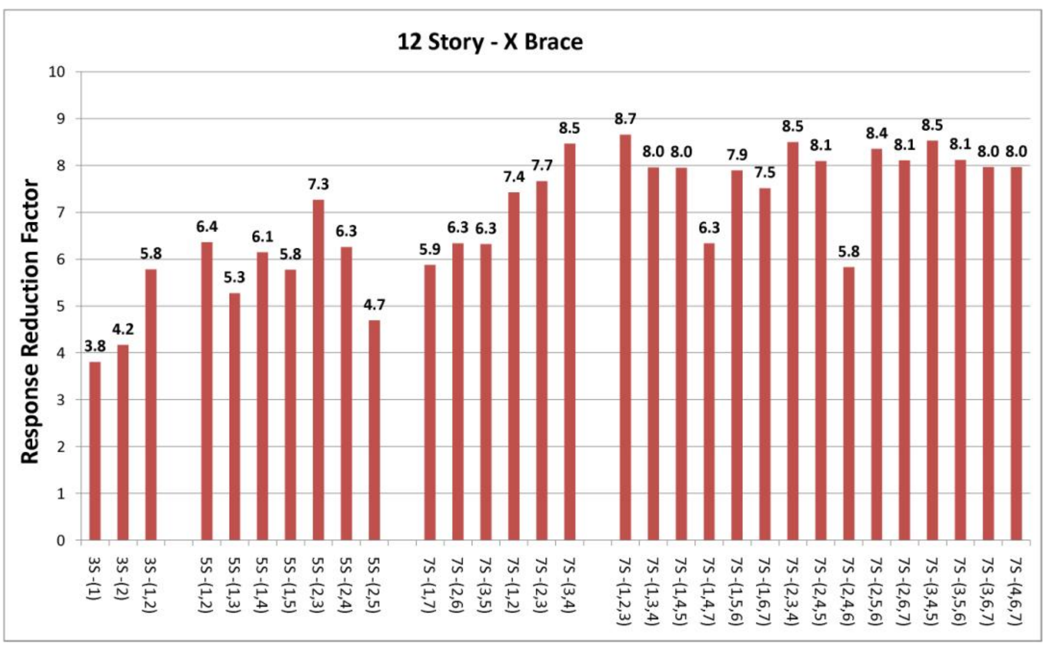


Figure 5. Computed R-Values for 12-story frame and different braced bays

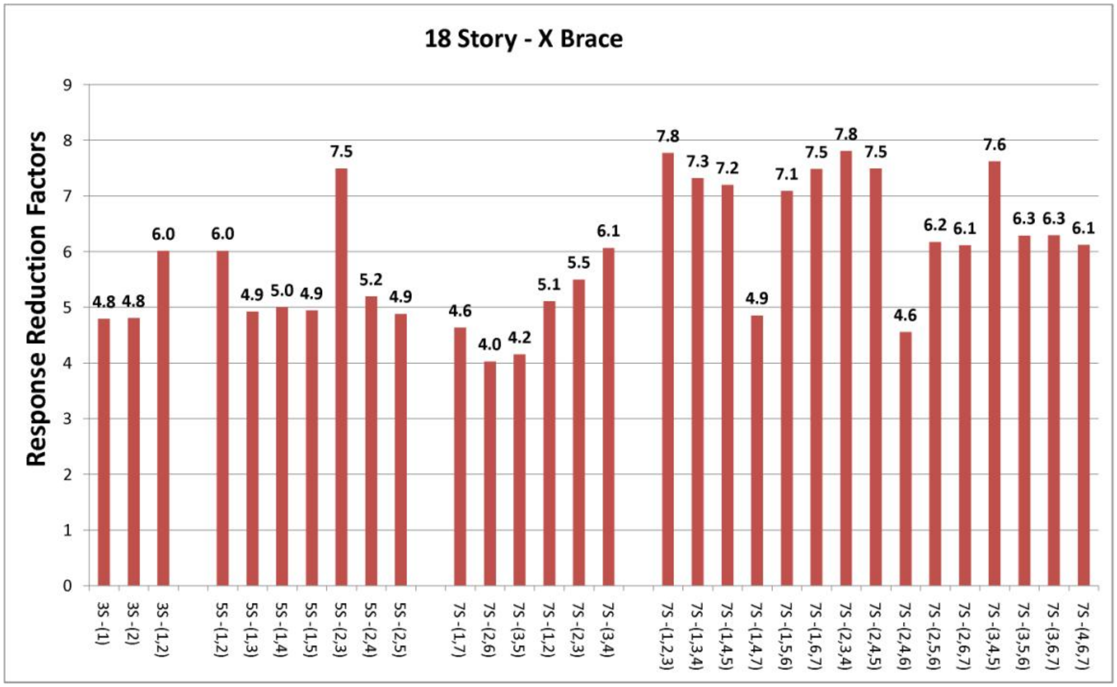


Figure 6. Computed R-Values for 18-story frame and different braced bays

## Discussion and conclusion

Considering the obtained results, it can be concluded that:

- when the number of braced bays increases, yield displacement in all models decreases due to increase of initial lateral stiffness of the model; furthermore when the braced bays are close; yield displacement in considered models would decrease. This is important when the structure behaves in its linear phase because the adjacent braced bays configuration could decrease overall lateral displacement and minimize the cracking of non load-bearing and nonstructural elements. Placing the braces in the middle bays would also decrease the yield displacement. For example, the minimum yield displacement for the six-story frame in the case of 7s(1,2,3) equals 3.7 cm. This value for the same fame but different bracing schemes like 7s(3,4,5), 7(2,3,4), 7s(2,3), 7s(3,4), 7s(1,2), 5s(2,3), 5s(1,2), 3s(1,2) would consequently be 7.8, 8.5, 8.9, 9.1, 9.4, 8.2, 8 and 8.8 cm. Moreover, when the distance between two braced bays increases, the ultimate displacement of structures would also increase, and vice versa. In addition, one can conclude, it is beneficial to put numerous adjacent braced bays in the middle bays of structures in the case of low-rise structures.

- When the braced bays are close, the initial stiffness increases, on the other hand when the number of stories increases, because of increase of top story displacement, initial stiffness decreases which in turn could affect the R-value. For example, in the case of six-story frame with 7s (3, 4, 5) configuration, R value equals 5.5. This value for 12 and 18-story frames are 6.96 and 5.93, which is lower than the average of six-story frames R factor.

- Increasing the number of stories in frames with less braced bays make the response reduction factor significantly lower than the value suggested in the building codes. For example, in the case of 12-story frame and 3s (1) configuration, this value is 3.8 and for 18-story frame and 7s (2,6) scheme, response reduction factor reaches 4. This subject indicates that using fewer braced bays in taller structures may not satisfy the requirement of seismic codes. Proposed response reduction factors could not be reached in braced frames with lots of unbraced bays between braced bays especially in high-rise structures. For example, in 18-story frame with 7s(1,4,7) configuration or 7s(2,4,6) configuration R equals 4.9 and 4.6 consequently which is lower than the code suggested value, while when adjacent bays are braced, in the middle bays, this value will be approximately 1.30 times of the Iranian code suggested value. As another example, in case of 18-story frame with 7s(2,3,4) configuration, the response reduction factor is 7.8 which is 1.3 times of Iranian code of practice for seismic resistant design of buildings (2800 standard).

- It is suggested in order to satisfy the proposed values in building codes, the braced bays should be as close as possible and it is better to place them in the middle and adjacent bays. Moreover, it is recommended to avoid unbraced bays between braced bays in high-rise buildings.

- In the case of low-rise buildings, it is apparent that by placing of braced bays as close as possible, R factor could reach nearly1.5 times of proposed values. This could lead to over design in these cases, also overstrength factor will be affect by braced bays location.

## References


Azizinamini A., 1982. Monotonic response of semi-rigid steel beam to column connection. MS thesis Columbia University of south.

Behbahani A., 1996, “Conceptual definition of earthquake resistant design criteria”, BHRC, Iran.

Broderick,B.M, Elghazouli, A.Y., Goggins,J. (Sept. 2008). Earthquake testing and response analysis of concentrically-braced sub-frames. Journal of constructional steel research,Vol.64,No. 9, pp. 997-1007.

Citipitioglu AM, Haj-Ali RM, With DW2002, Refined 3D finite element modeling of partially restraint connection including slip, Journal of constructional steel research; 8:995-1013.

Fahnestock, Larry A; Ricles, James M; Sause, Richard (2006). Experimental study of a large-scale bucklingrestrained braced frame using the pseudo-dynamic testing method, Proceedings of the 8th US National Conference on Earthquake Engineering, 100th Anniversary Earthquake Conference, San Francisco.

Hong K, Yang JG, Lee SK, 2001. Parametric study of double angle framing connection subjected to shear and tension. Journal of constructional steel and research; 57:997-1013

Inoue, K.; Murakami, M. (1978). A study on the plastic design of braced multi-story steel frames (Part 3: experimental study on the elastic plastic behavior of 3 story 3 bay braced and un-braced steel frames), Transactions of the Architectural Institute of Japan.

International Building Code2003., International Code Council, Inc. Country Club Hills, Illinois, U.S.A., Lee, Kangmin; Bruneau, Michel (Apr. 2005). Energy Dissipation of Compression Members in Concentrically Braced Frames: Review of Experimental Data, Journal of Structural Engineering (New York, N.Y.), Vol. 131, No. 4, pp. 552-559.

Shadman P., Msc thesis “Effects of X-bracing configuration on nonlinear behavior braced frames”, 2005, Islamic Azad University, Science and research complex, Tehran, Iran.

Shaishmelashvili, V. N.; Edisherashvili, N. A., 1973. Experimental studies of dynamic characteristics of multi-storey steel frame building large-scale models with different vertical bracings, Preprints of the Fifth World Conference on Earthquake Engineering; 5 pages.

Suzuki, T.; et al. (Feb. 1975). Experimental study on the elasto-plastic behavior of tensile braced frames, Transactions of the Architectural Institute of Japan, No. 228, pp. 57-64.

Uang CMU,1991. Establishing R (or Rw) and Cd factors for building seismic provisions. Journal of Structural Engineering (ASCE); 117(1):19–28.

Uniform Building Code. Vol. 2: Aug.1997 Structural Engineering Design provisions, International Conference of Building Officials, Whittier, Calif.

Wakabayashi, M.; Nakamura, T.; Yoshida, N. (Mar. 1980). Experimental studies on the elastic-plastic behavior of braced frames under repeated horizontal loading – Part 3: experiments of one story-one bay braced frames, Bulletin of the Disaster Prevention Research Institute, Vol. 29, No. 4, pp. 143-

Yang JG, Murray TM, Plaut RH, 2000. Three dimensional finite element analysis of double angle connection under tension and shear, Journal of constructional steel and research; 54:227-44