**13th World Conference on Earthquake Engineering**
**Vancouver, B.C., Canada**
**August 1-6, 2004**
**Paper No. 1787**

# SEISMIC BEHAVIOR OF STEEL FRAMES WITH OFF-CENTER BRACING SYSTEM

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## SUMMARY

Seismic behavior of an Off-center Bracing System (OBS) has been investigated. In this system the diagonal bracing is not straight. The introduction of an off-diagonal eccentricity in this system results in a geometric nonlinear behavior. The midpoint of the diagonal member is connected to the corner joint using a brace member with a relatively low stiffness, thus forming a three member bracing system in each braced panel. An iterative method of analysis has been developed to study the non-linear load-deflection behavior of OBS. The results indicate that the load-deflection behavior of this system follows a nonlinear stiffness-hardening pattern with two yielding points, which reflect the tensile failure of different bracings. The degree of nonlinearity in the elastic range is mainly dependant on the eccentricity of the tension diagonal and the relative stiffness of bracing members. The non-linear behavior of OBS can be utilized as an effective advantage for mitigation of seismic loads.
A non-linear program has been developed to analyze seismic response of off-center bracings subjected to various collapse-level earthquakes. The results indicate that OBS behave generally like base isolated systems and that the response may be reduced remarkably by pre-adjustment of eccentricity and relative stiffness of bracings. Response of steel frames equipped with OBS has also been compared with similar x-braced frames.

## INTRODUCTION

Bracings are commonly used in steel frames in order to provide resistance to wind and seismic actions. Concentric braces are among the simplest and easiest bracing methods that have been in use. The main disadvantage of concentric braces, when considering earthquake resistance, is their relatively high stiffness to strength ratio and low deformation capacity [1-2]. Eccentric bracing systems can be considered as an improvement over concentric ones by providing higher deformation capacity, lower stiffness and higher energy dissipation through improved hysteresis loop characteristics. The basic idea behind eccentric bracing system is to provide a bending yield mechanism that allows for higher deformation and energy dissipation in the nonlinear range [3]. Various alternatives to eccentric bracing systems, such as

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knee bracings, have also been proposed to achieve better ductility and higher effective damping by using bending and shear yield mechanisms [3-4].

Another interesting innovation in seismic resistant design that can be applied to steel structures is the method of base isolation. The basic idea is to isolate the structure from the ground so that the structure is less affected by the induced ground motions. This is achieved by introducing additional flexibility at the ground-structure interface by using devices such as the elastomeric bearing pads, rollers, suspension mechanisms and various other methods [3]. Application of these mechanisms to the structure results in a marked increase in natural period of vibration of the structure that, for most ordinary low-rise structures, results in lower acceleration responses and thus reduced seismic forces [5-6].

In this paper a particular bracing system which seems to offer certain advantages as compared to conventional bracing systems in mitigating earthquake loads in buildings is investigated. The idea behind this bracing system is to use the nonlinearity introduced by geometric configuration of bracing system in order to produce a certain amount of seismic isolation. General configuration of the system is depicted in figure 1. As shown in this figure, the system is compromised of two adjacent spans in which main diagonal bracing has been diverted from straight position by certain amount, thus producing an eccentricity designated by e in figure 1(a). The bracing system is completed by connecting the diagonal braking point O to the corner joint C, thus resulting in a three member bracing system at each panel. The stiffness of the third member OC is considered to be an order of magnitude less than the main diagonal members. Now, if lateral loading is applied to the system, the initial stiffness of the system is mainly controlled by member OC that has a relatively low stiffness. As the load increases, the main diagonal members approach the straight position and the stiffness of the system will become mainly dependent on the stiffness of diagonal members. The load-deflection of the system is thus a nonlinear one in which the nonlinear behavior is resulted from geometric configuration and the stiffness proportions of members and is essentially the deformation-hardening type.

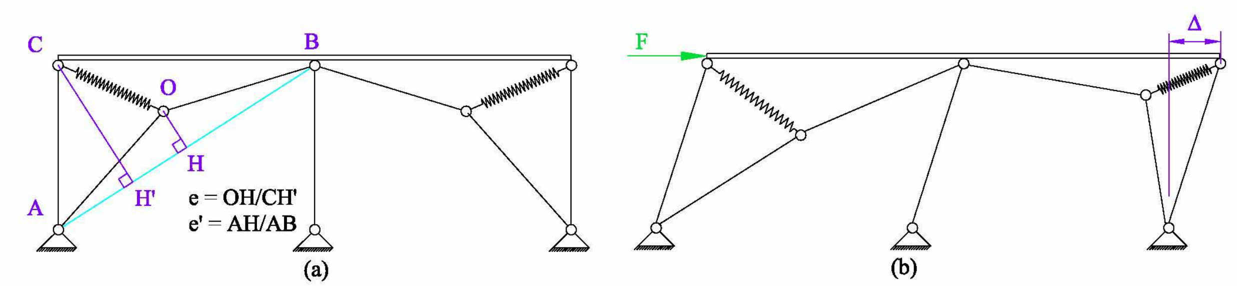


**Figure1. Schematic Off-center bracing system (a) configuration (b) deflected position**

It should be noted that depending on the direction of lateral load, the adjacent panel does not contribute to the stiffness hardening as a result of the position of the diagonal members being diverged from straight line. Out of plane displacements and buckling make this adjacent panel practically ineffective. If we consider the elastic-plastic behavior of bracing members, the schematic load deformation of the system will in general consist of two distinct yield points as shown in figure 2(a).

The first yield point occurs as the member OC reaches its plastic limit. By yielding of member OC, panel stiffness approaches zero, however there remains a considerable amount of reserved strength before the load increases to a level as to cause main members to yield. Thus an interesting feature of off-center bracing is in the ability of the designer to control the shape of load-deflection curve by changing the geometry parameters such as eccentricity and material parameters such as spring and main diagonal members' stiffness and yield point. Basic characteristics and seismic behavior of this system has been investigated by Estekanchi and Moghaddam in earlier reports [7-9]. In these early investigations, member OC was considered to be an ordinary steel profile member. However, practical considerations suggest that the use of ordinary steel profiles for member OC may not be a good proposition since this member undergoes relatively high tensile deformations. Even if the member is designed to withstand the imposed tensile strains the permanent deformations result in slaked bracings and can have undesirable effects in the hysteresis loop. In this research member OC has been designed as a coiled spring. The deformations were checked to be below yielding point of coiled springs at all levels of lateral deformation, thus the initial yield point in figure 2(a) is practically eliminated and the conceptual load defection curve resembles that of figure 2(b). The use of coil spring for member OC however results in another practical consideration about the initial stiffness of the system. A minimum stiffness is usually required in order to control the vibrations induced by low-level lateral loads such as winds. The initial stiffness provided by coil springs may be well bellow the minimum required. One alternative to increase initial stiffness is to use coiled springs with closed coils and a minimum pretension that keeps them closed at wind level loads. Another less appealing but simpler method is to add a minimum concentric bracing in the form of straight rods to provide initial stiffness. The second approach has been assumed for the purpose of this study. The additional wind bracing members have been schematically depicted in figure 3(a).

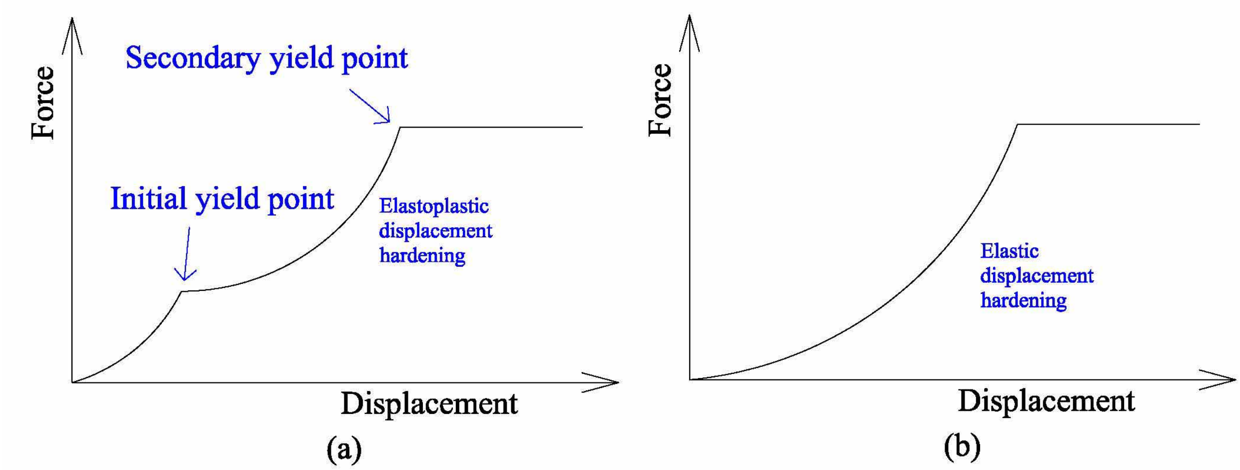


**Figure 2. Schematic load-deflection curve (a) Elastoplastic member OC (b) Elastic member OC**

By providing low initial stiffness, the certain amount of base isolation can be introduced to the system using off-center bracings. This is in effect accompanied by increased deflections and higher P-Δ forces [10]. The increased stiffness and reserved strength of off-center braces can be utilized in order to achieve best seismic performance as described in the following sections.

## MODELING AND ANALYSIS PROCEDURE

A main feature of off-center bracing system is its nonlinear geometric behavior. Bracing system at each panel consists of three members attached to a center point O in figure 1. A special purpose program has been developed for the linear and nonlinear analysis of this system which uses a combination of force method and displacement method of the structural analysis and a step by step iterative integration solution scheme to achieve optimal numerical solution efficiency. Bracing members are considered to have elastic-perfect plastic material behavior. Buckling load can be specified for members in compression which is assumed to remain constant with increased compression strains. The effect of beam and column axial deformations has been ignored in the analysis, i.e. the frames are modeled as shear buildings. The effect of P-Δ forces is also directly included in the solution algorithm which is an improvement over earlier studies. Different program modules have been developed for static analysis (NEAT), dynamic time history analysis of single story frames (HISTORY) and dynamic analysis of multistory frames (STORY). Programs output accuracy has also been verified using several test cases.

## MODEL PROPERTIES

In order to gain some practical insight on the potential of off-center bracings to be used as earthquake mitigation devices, several multistory steel frames were designed considering X-bracing and off-center bracing as lateral load resistance system. Frames were 2, 4 and 6 stories high with four bays. Typical story heights were assumed to be 3.2m and span widths were 5m. X-braced frames were designed according to UBC-97 provisions [11]. AISC-ASD provisions were used for the steel frame design. A typical four story frame is shown in figure 3.

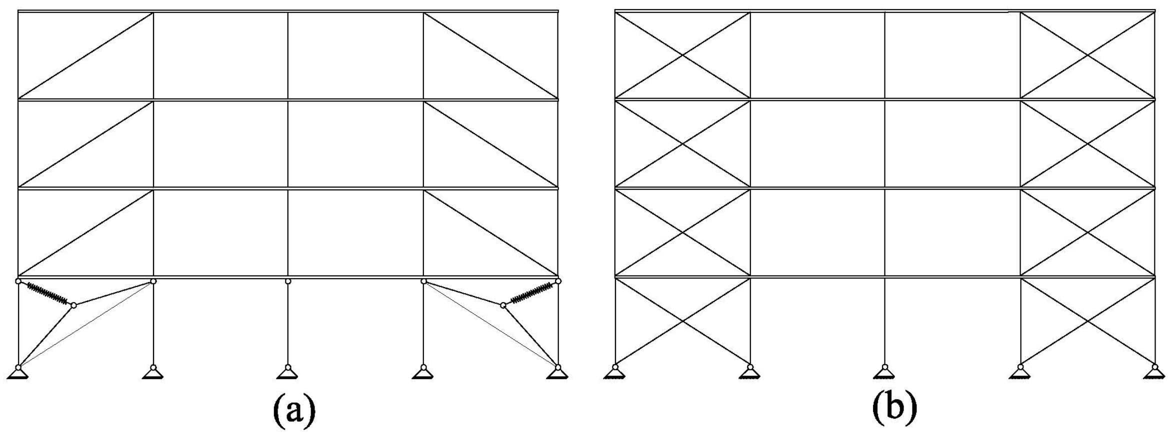


**Figure 3. Typical bracing configuration (a) Off-center bracing (b) X-bracing**

Bracing member properties for typical four story frame are shown in table 1. For off-center frames, similar member properties were assumed, except that X-braces were replaced by off-center braces in the first story and in the upper levels, one of X-bracing members was removed considering lower expected story shears in these frames. Remaining single bracings where arranged as shown figure 3(a). This arrangement produces near optimal results for single bracings [12-13]. A single diagonal member has also been added in the first story in order to provide initial stiffness required to resist wind forces as shown in figure 3(a). For main bracing members in off-center braced frames, UNP240 sections where used, considering larger lateral forces produced by the P-Δ effects. This is roughly equivalent to two UNP160s used in X-braced frames, i.e. the cross-sectional area of bracings at first level is nearly the same for off-center and X-braced frames.

**Table 1. Brace member properties for 4 story X-braced frames**

| Story | Brace Section | Cross Section Area |
|---|---|---|
| One | UNP160 | 24.0 $cm^2$ |
| Two | UNP160 | 24.0 $cm^2$ |
| Three | UNP120 | 17.0 $cm^2$ |
| Four | UNP120 | 17.0 $cm^2$ |

Three different spring stiffness was considered for off-center braced frames, namely 1.0 kN/m, 2.0 kN/m and 4.0 kN/m. These springs are designated as type 1, 2 and 3 and appear as the last digit in frame names, thus frame OBS-4-3 is a four stories off-center braced frame with the spring stiffness of 4.0 kN/m, etc.

**LOAD DEFECTION PROPERTIES OF OFF-CENTER BRACINGS**

Nonlinear static behavior of a single story off-center bracing with various eccentricity ratios has been studied in this section. Load-defection curves for a single story off-center braced frame with spring stiffness of 2kN/m are depicted in figure 4.

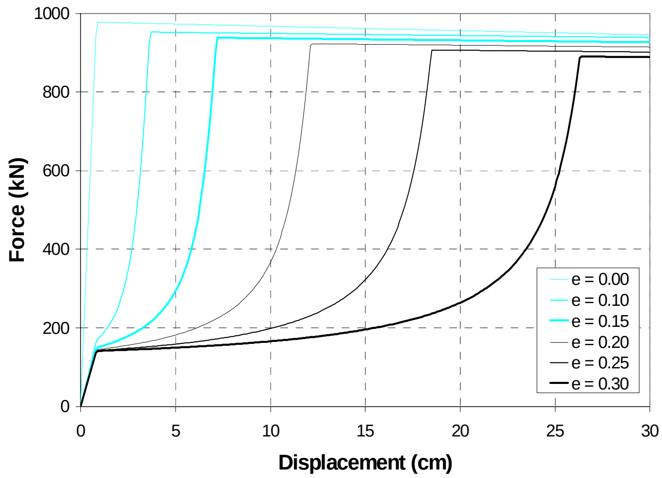


**Figure 4. Load deflection curve for Off-center braced frame with Ks=2.0kN/m**

This figure shows the typical load-defection curve for an off-center bracing. As shown in this figure, the first yield Point occurs at about 150kN where the load-deflection curve becomes nearly flat. This corresponds to the yielding of wind resisting secondary member. Initial stiffness and first yield point location can be effectively controlled using different design parameters for the spring and secondary wind resisting member. As can be seen in this figure eccentricity does not have a significant effect on the initial stiffness and yield point location. The most significant effect of eccentricity is however on the displacement at second yield. As can be seen in figure 4, yielding point of main bracing members can be adjusted to correspond to lateral displacements that vary from 1cm to 26cm while eccentricity ranges from 0.0 to 0.3. It should also be noted that maximum load is not affected considerably by eccentricity ratio. In order to study the behavior of off-center bracings when subjected to cyclic load, the same model with eccentricity ratio of 0.2 was subjected to two cycles of displacements controlled cyclic loading. The results are shown in figure 5.

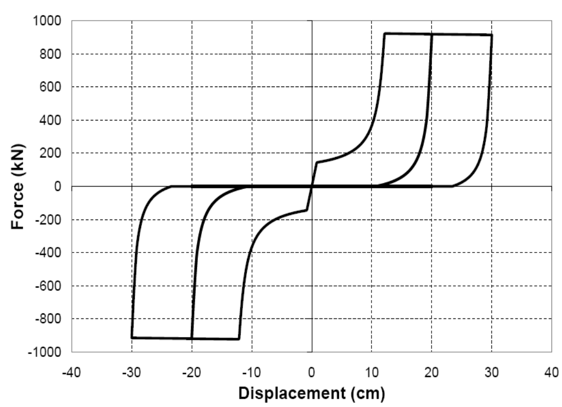


**Figure 5. Hysterisis curves for Off-center braced frame with Ks=2.0kN/m**

As can be seen in this figure the slope of load-deflection curve is relatively high at unloading and load drops to zero at unloading displacement of about 10cm. The unloading curve characteristics can be effectively controlled by using different spring design parameters. For example slope of curve at unloading can be reduced by using the spring with higher stiffness.

## STATIC PUSHOVER ANALYSIS

In this section the results of nonlinear pushover analysis of off-center braced frames are compared with those of similar X-braced frames. Frames have been considered to have ductile behavior [14]. Nonlinear static pushover analysis using response spectra method has been applied [15]. Selection of appropriate load pattern is an important issue in pushover analysis. For braced frames, uniform load pattern similar to static design load or a load pattern based on vibration modes seems to be appropriate. For off-center bracings however, considering the vibration mode, which resembles to those of base isolated structures, it seems that the constant load pattern is more appropriate. For that matter of comparison, X-braced frames were subjected to both types of the load patterns and the results are depicted in figure 6.

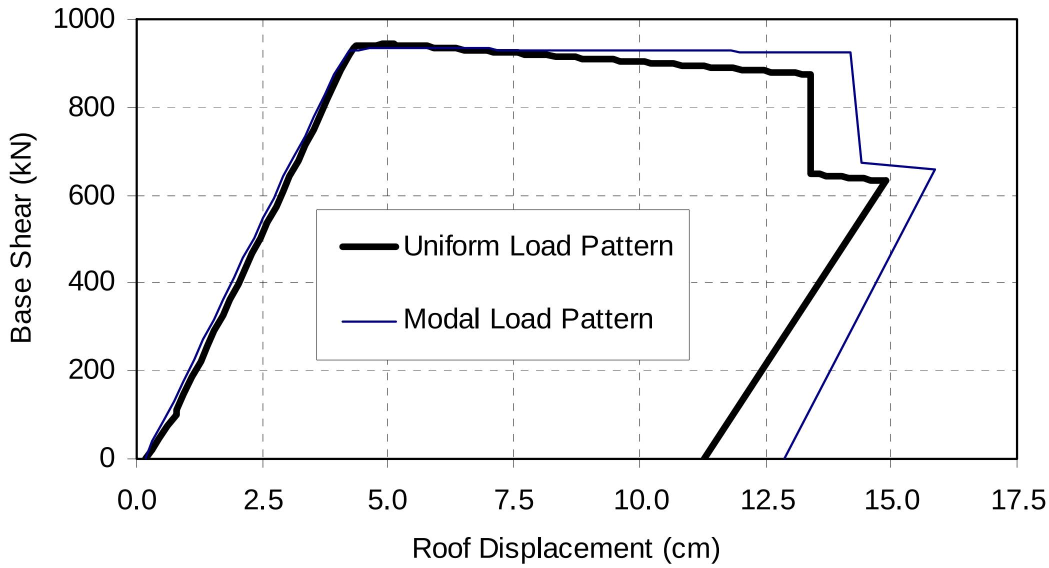


**Figure 6. Pushover curves for four story X-braced frame**

As can be seen this figure the yield point remains nearly constant. The results of pushover analysis of reference X-braced systems along with those of off-center braced frames are summarized in table 2.

**Table 2. Analysis results for four story X-braced and Off-center braced frames with e=0.2**

| Model | X-braced | | Off-center Ks=1.0kN/cm (OBS-4-1) | Off-center Ks=2.0kN/cm (OBS-4-2) | Off-center Ks=4.0kN/cm (OBS-4-3) |
|---|---|---|---|---|---|
| | Uniform load pattern | Modal Load pattern | | | |
| Max displacement | 9.2cm | 7.5cm | 18.5cm | 18.3cm | 18.2cm |
| Effective damping | 11.8% | 11.3% | 6.2% | 6.3% | 6.6% |
| Effective period | 1.17sec | 0.95% | 1.97% | 1.96% | 1.95% |

Pushover analysis of off-center bracings were conducted using the eccentricity ratio of 0.2. This value of eccentricities seems to result in the near optimal values for a story shear and drift without compromising too much the displacement requirements at first story. Off-center bracings were analyzed using modal load pattern. The results of pushover analyses for frames with different spring stiffness values are depicted in figure 7.

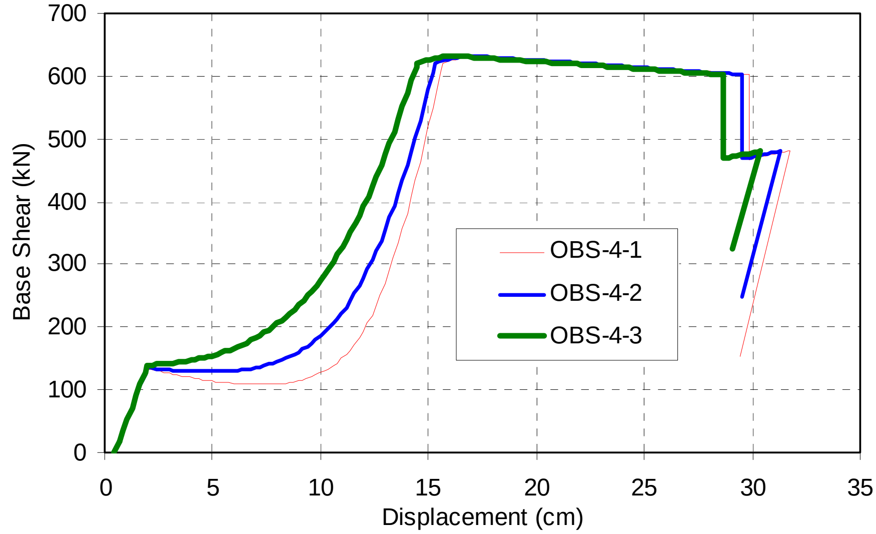


**Figure 7. Pushover curves for Off-center braced frame (e=0.2)**

As can be seen in this figure, off-center braced frames with soft spring show negative stiffness after first yield points. This is the result of the P-Δ forces being higher than the resistance provided by bracing system controlled by spring stiffness at this stage. Thus it can be concluded that in this case, the minimum practical spring stiffness should be limited to 2.0kN/m. Demand-capacity curves for four story off-center braced frame is compared to its X-braced counterpart in figure 8. As can be seen in this figure, off-center bracings are capable of undergoing higher displacements with lower stiffness resulting in overall reduction of base shears.

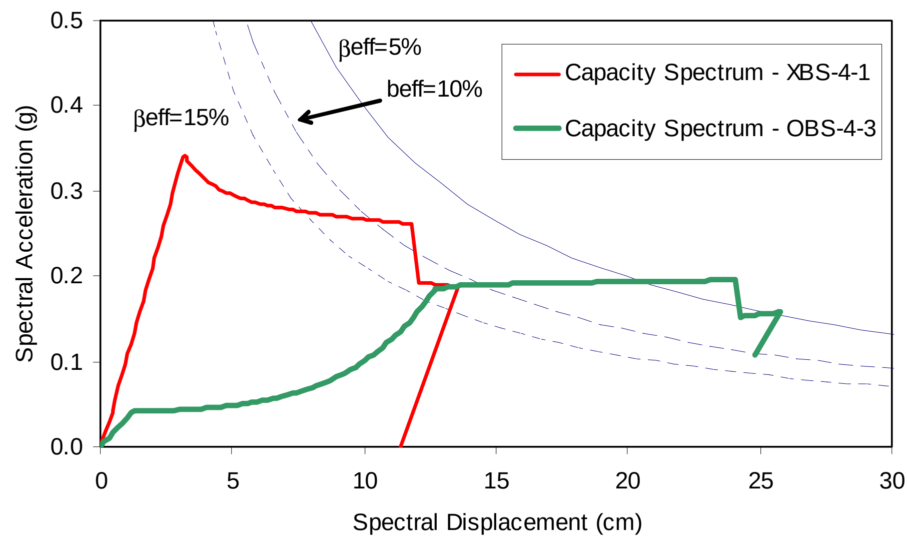


**Figure 8. Demand capacity curves for X-braced and Off-center braced frame**

Study of push-over curves seems to be a valuable tool in determining the designed requirements regarding spring stiffness for off-center braced frames. The results of pushover analysis show that effective damping of off-center braced frames is nearly half of those corresponding to X-braced frames. It should also be noted that effective damping increases with the spring stiffness. It is also interesting to note that effective period of off-center bracings are nearly two times higher than their X-braced counterparts.

## NONLINEAR DYNAMIC ANALYSIS

Three strong-motion earthquake accelerograms, namely EL-Centro, Northridge and Tabas were normalized to comply with UBC-97 design spectrum to be used for the analysis [16]. Sample response for the accelerogram obtained using El-Centro as the base accelerogram is shown in figure 9. Appropriate accelerograms should be developed for each site based on seismological considerations for time history analysis. For the purpose of this study, the accelerograms where normalized considering site factors for seismic zone factor Z=0.4 with soil profile type $S_D$. Damping ratio for X-braced frames was considered to be 0.05 as is common for ordinary steel braced frames. Four off-center braced frames, damping ratio was assumed to be 0.02 considering lower bracing strain levels for these types of frames [17].

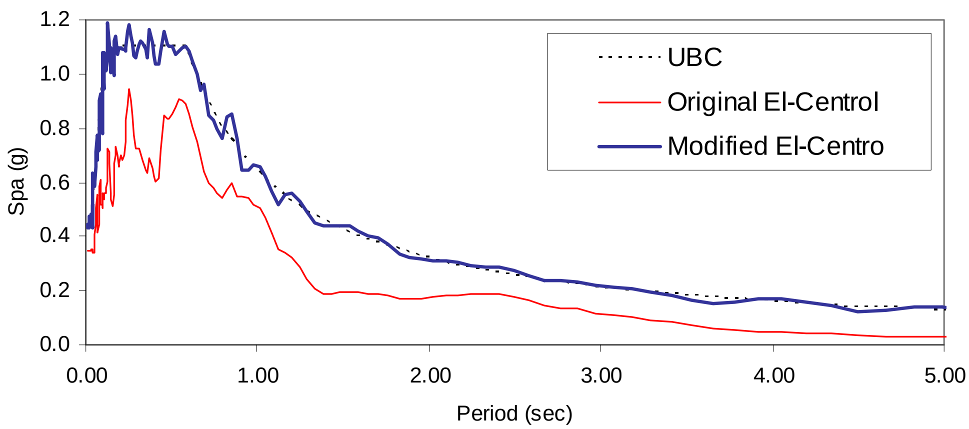


**Figure 9. Modified El-Centro accelerogram compared to UBC and original El-Centro**

In figure 10 maximum story accelerations for four story models subjected to modified-El-Centro accelerogram are compared. As expected, off-center braced frames are subjected to lower maximum story accelerations than their similar X-braced counterparts.

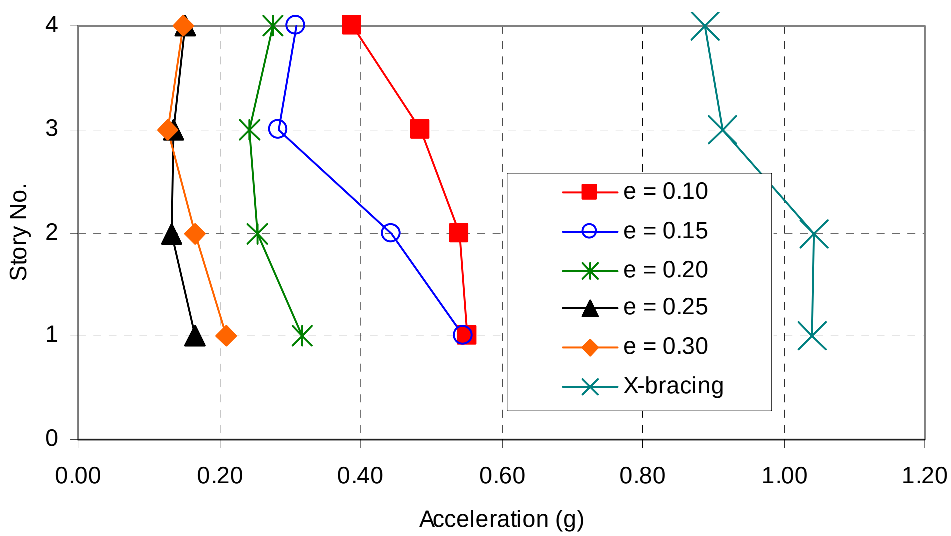


**Figure 10. Response of frames to modified El-Centro accelerogram**

Story displacements are depicted in figure 11. As expected, maximum displacements for off-center braced frames are in general higher than those with X-bracing. It is interesting to note that there seems to be an optimal value of eccentricity ratio (e) where displacement values are at their local minimum.

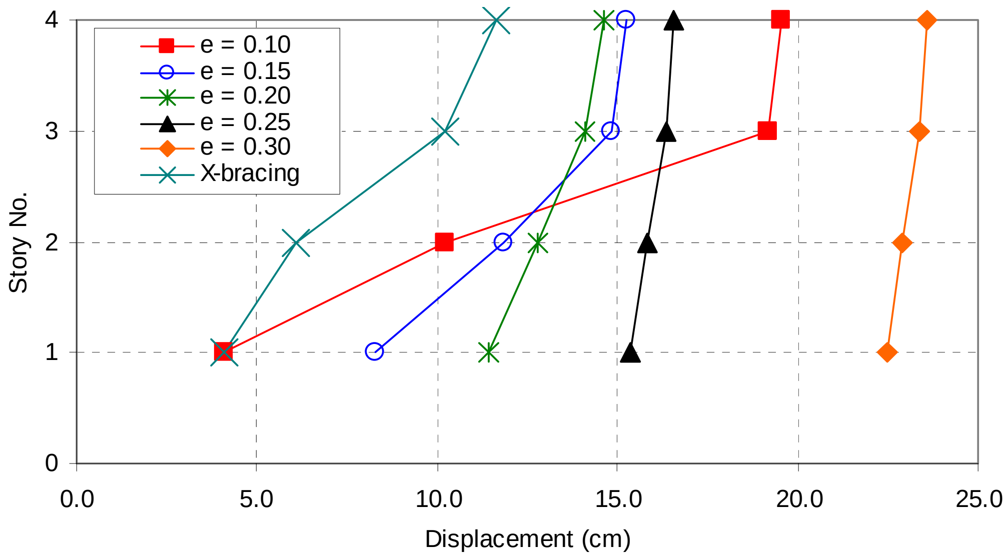


**Figure 11. Displacement response (modified El-Centro accelerogram)**

Inter story drifts have been depicted in figure 12. Maximum drifts are concentrated at lowest level in off-center bracing as expected. It should also be noted that as eccentricity increases, the story drifts seem to converge to a common value. This was the case for most combinations of the story numbers, spring stiffness and different excitations. For eccentricity ratios of higher than about 0.2, maximum story accelerations were observed to be lower than 0.44g for off-center braces in contrast to their X-braced counterparts. It is also interesting to note that for high eccentricity ratios, the drift ratio of higher stories of off-center braced frames is lower than the yield level value. The story accelerations of off-center bracing systems are in some cases more than 2.5 times lower than X-braced frames.

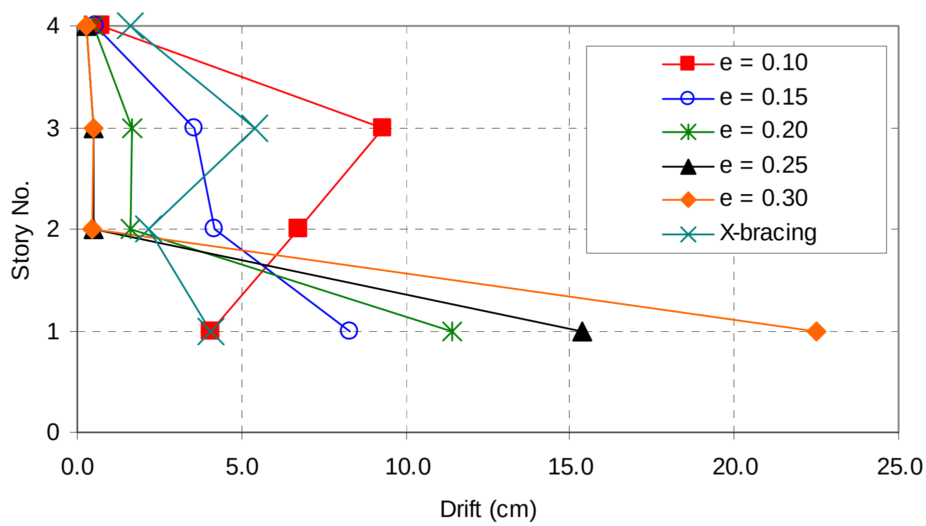


**Figure 12. Story Drifts (modified El-Centro accelerogram)**

Top story displacements for 6 story frames with various spring stiffness subjected to modified Northridge earthquake are shown in figure 13. In general, higher spring stiffness results in lower story displacements. It is observed that with increased spring stiffness, the optimal value for eccentricity ratio tends to increase. The spring stiffness in the range studied, did not have significant effect on maximum acceleration values. Lower limit for spring stiffness is controlled by P-Δ and initial stiffness requirements. A very high stiffness, on the other hand, limits the desirable level of geometric nonlinearity.

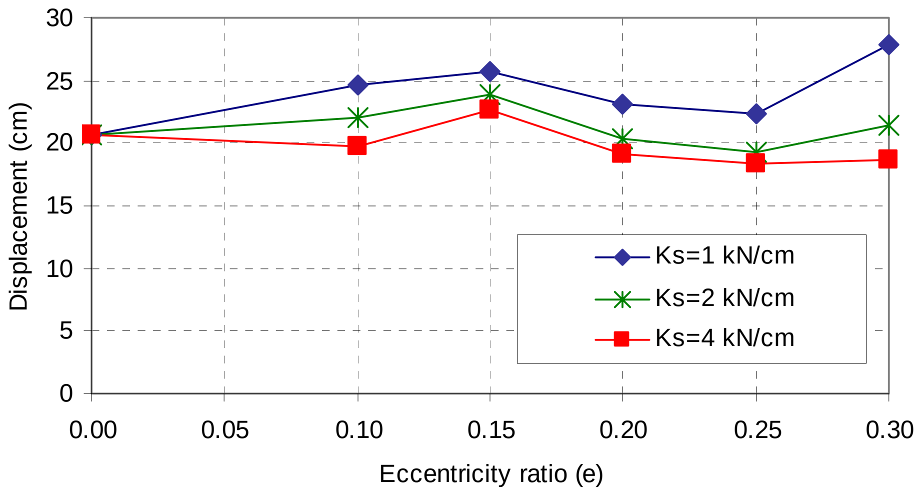


**Figure 13. Top story displacements (Modified Northridge accelerogram)**

Maximum story accelerations for different normalized earthquakes are shown in figure 14. It is observed that while the level of maximum story accelerations vary for different normalized earthquakes, in general it decreases markedly with increasing eccentricity.

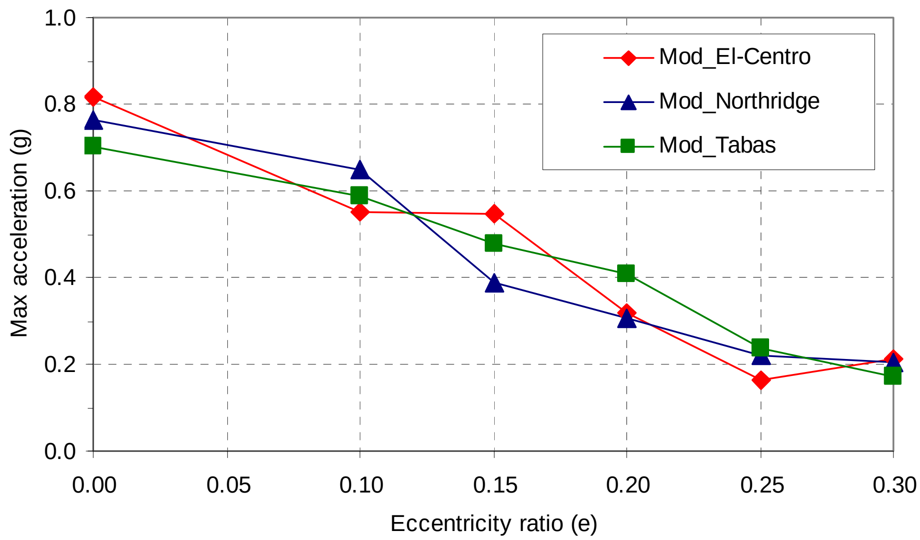


**Figure 14. Maximum story accelerations (Ks=4.0, e=.2)**

Top story displacements for 6 story buildings at various earthquakes are compared in figure 15. It was observed that in general, the optimal value of eccentricity is from 0.20 to 0.25 when considering displacements and accelerations.

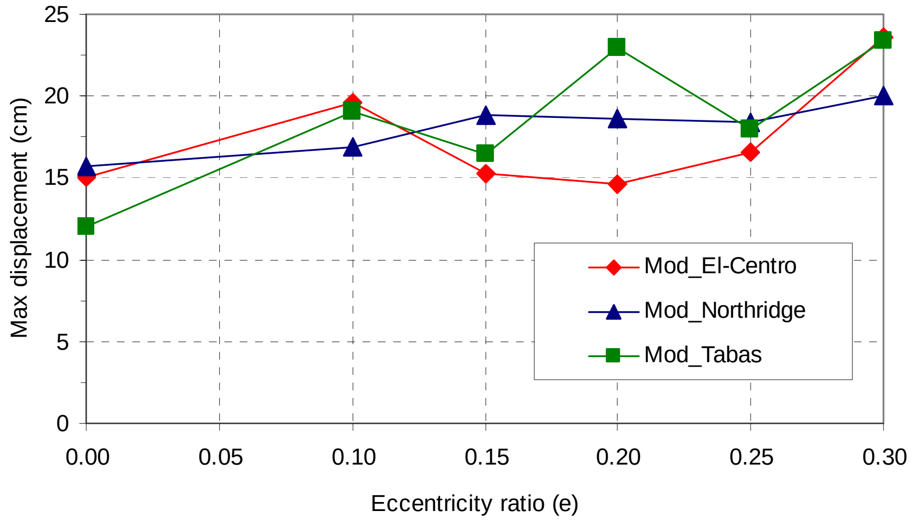


**Figure 15. Top story displacements (Ks=4.0 kN/m, e=0.2)**

A prototype model of one story off-center bracing system is shown in figure 16. This model has been used in order to demonstrate the concept of off-center bracing system. By applying a cyclic displacement to the bottom slab that presents the foundation level, the upper slab can be seen to experience reduced absolute displacements and accelerations. However, elaborate experimental procedures are required to verify the results.

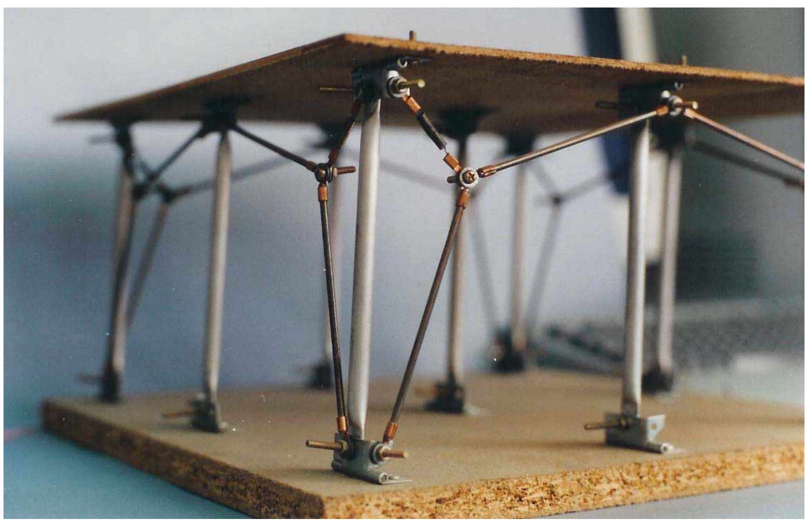

**Figure 16. Off-center bracing prototype model**

## CONCLUSIONS

Based on the results of this study, the following conclusions can be made:

1. Off-center bracing systems, when property proportioned, can be effectively used as an earthquake mitigating system.
2. General characteristics of Off-center bracings are similar to a base isolation system that acts in an entire story level at the lowest buildings level.
3. The stiffness of the spring member should be set with due consideration of the P-Δ effects.

4. In buildings equipped with off-center bracing, story drifts at lowest level are considerably higher than their X-braced counterparts while upper story drifts, accelerations and base shears are considerably lower.
5. Effective damping of off-center bracings are typically about half of their X-braced counterparts and their effective free vibration period is about two times higher.
6. By using off-center bracing systems, base shear and the story accelerations could be reduced by a factor of about 2.5 for the models investigated in this study.

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