# Journal of Applied Sciences

ISSN 1812-5654

science alert

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Journal of Applied Sciences 14 (24): 3627-3632, 2014
ISSN 1812-5654 / DOI: 10.3923/jas.2014.3627.3632


# Seismic Behavior Evaluation of Knee Braced Frames Based on Push-over and Cyclic Analyses

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**Abstract:** Knee braced steel frame is a new kind of energy dissipating frame system which combines excellent ductility and lateral stiffness. In this framing system, a special form of diagonal brace is connected to a knee element instead of beam-column joint. In this study frames with similar dimensions in three systems concentric, eccentric and knee braced frame are designed according to Iranian code of practice for seismic resistant design of building. Then based on a non-linear push over static analysis and cyclic analysis the seismic parameters such as hysteretic behavior and dissipated energy are compared. Two-dimensional frames were modeled; OpenSees finite element software package is used to perform the numerical and nonlinear analyses. Finally the inelastic performances of knee braced frames are investigated, in terms of available ductility, energy dissipation capacity and equivalent viscous damping ratio.

**Key words:** Knee bracing, seismic performance, finite element method, cyclic analysis, push-over analysis

## INTRODUCTION

Braced frames are among the most common steel structures for resisting lateral loads. In general, they are divided into three groups: Concentric Braced Frame (CBF), Eccentric Braced Frame (EBF) and Knee Braced Frame (KBF) (Fig. 1). Concentric braced systems are more desirable because of the relative good stiffness, along with their easy construction and economy aspects hence, these important criteria make this group more common than eccentrically braced frames. Although, the Moment-Resisting Frames (MRFs) are excellent energy dissipating system, its members have to be designed with uneconomically large sections to meet the drift requirement. The CBF is much stiffer than the MRF but it cannot meet the ductility requirement due to the buckling of the brace. To overcome the deficiencies of the MRF and the CBF, Roeder and Popov (1978) proposed a new structural system, named EBF. It combines sufficient stiffness and excellent ductility by setting the brace eccentrically to the beam to form a shear link. Due to the yielding of the shear link in a severe earthquake, the frame provides reliable protection from buckling (Mofid and Lotfollahi, 2006). This is because they mainly yield in bending and therefore, their hysteresis behavior is close to ideal elastic-plastic systems without significant degradation of strength and stiffness (Roeder and Popov, 1978). However, as the major part of a frame, the beam should not be severely damaged in view of the difficulties and costs required for rehabilitation of the beam.

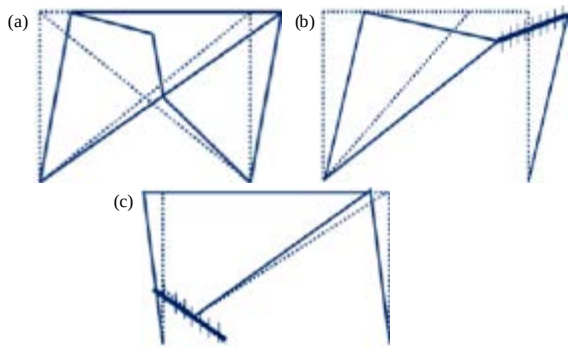


Fig. 1(a-c): Commonly used steel braced frame systems, (a) CBF, (b) EBF and (c) KBF

A new braced frame, called KBF, having all the favorable features of the above frames but without having the deficiencies, was presented by Aristizabal-Ochoa (1986) and further investigated by Balendra *et al.* (1990), Mofid and Khosravi (2000), Mofid and Lotfollahi (2006) and Wongpakdee *et al.* (2014). The KBF uses a secondary structural member (the knee member) instead of the shear link as the "Structural fuse" to ensure enough ductility but achieves excellent lateral stiffness through the setting of the diagonal brace (Mofid and Khosravi, 2000). By

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limiting the plastic hinges formed in the knee only, the major parts of the structure are safe and the rehabilitation may then be easy. To help fully understand the relations between its seismic performance and the structural parameters, static pushover and cyclic analyses of the KBF structure with finite element method were conducted in this study. Finally, general design recommendations were suggested by the analysis results.

## CHARACTERISTICS OF KBF, CBF AND EBF

There are several ways of placing the knee in a KBF. It can be placed at the bottom, top, or at both ends of the brace. When the knee element is placed at both ends of the brace, the stiffness of the frame would be reduced without any improvement in ductility (Balendra *et al*., 1990). Furthermore, as an extra knee is required with more connections, the construction costs, including the workmanship and material, would be higher. Thus, in this study, a KBF with a knee element only at one end of the brace is considered. The KBF must have sufficient stiffness to prevent structural as well as nonstructural damage during frequently occurring minor earthquakes. The elastic lateral stiffness depends on its geometry and section properties of its member. Non-dimensional analysis shows that shorter knees are preferred for higher stiffness (Balendra *et al*., 1990). A proper choice of the length of the knee element in a KBF is important, as it affects not only the lateral stiffness but also the mode of yielding (Hjelmstad and Popov, 1983). A shorter knee element will yield in shear, while a longer one will yield in bending. For the knee element to yield in shear, the longer segment ($l_k$) of the knee generated by the intersection of the diagonal brace and the knee member, should satisfy the following condition:

$$L_k = 2M^*_p/V_p \quad (1)$$

where, $M^*_p$ is the reduced plastic moment contributed by flanges only and $V_p$ the plastic shear force (Balendra *et al*., 1990). They are defined as follows:

$$M^*_p = t_f\, b_f\, (d-t_f)\, F_y \quad (2)$$

$$V_p = t_w\, (d - t_f)\, F_Y / \sqrt{3} \quad (3)$$

where, $F_y$, d, $t_f$, $b_f$ and $t_w$ are yield stress, depth, flange thickness, flange width and web thickness of knee member, respectively. To satisfy Eq. 1, it is necessary to use sections with a higher ratio of section modulus to shear area. As a comparison, among the standard sections that are produced commercially, wide flange is most suitable. It has a higher section modulus to shear area ratio than rectangular hollow sections, as it has only one web that contributes to the shear area.

The study is based on frames which are plane, orthogonal and regular described in Fig. 1. For comparison between frames, CBF, KBF and EBF were modeled with same frame sections (columns, beams and braces). The design of an EBF is based on creating a frame which will remain essentially elastic outside a well-defined link. During extreme loading it is anticipated that the link will deform inelastically with significant ductility and energy dissipation. The code provisions are intended to ensure that beams, braces, columns and their connections remain elastic and that links remain stable. In a major earthquake, permanent deformation and structural damage to the link should be expected. Considering previous study on hysteresis behavior of CBF's, many problems of this system has been specified and many suggestions are presented to achieve sustainable behavior of CBF's during severe earthquakes. Recent study shows that "Compressive strains that develop after brace buckling has occurred and plastic hinging has formed, generally decrease as the brace effective slenderness ratio is increased".

## MATERIALS AND METHODS

The one-bay single-story frames have a total span of 4.5 m and height of 3 m. The frames base was fixed at both ends by restraining the displacement in X, Y and Z translational directions and the rotation in the three directions ($R_x$, $R_y$ and $R_z$). Also, the translation in the direction perpendicular to frame plan was restrained at the intersection of the beam and column, while beams are shear connected to the columns. This assumption of pin connections between the framing members is widely accepted, although the presence of gusset plates increases the stiffness and hence decreases the inelastic deformation demands. For studying the behavior of these systems, inspecting its defaults and effective parameters, the OpenSees software is used and a typical model is shown in Fig. 2.

This software is one of the best softwares that has many characteristics making it the best for the finite element modeling. However with regards to the material characteristics of this system and using one type of steel which is more regular for constructing buildings, the input data is introduced. Afterwards, noticing the finite elements that are used in this field element, the SHELLMTC4 is used for modeling the all members. For the purpose of this modeling, a brace frame with real dimensions and real cross sectional areas are considered.

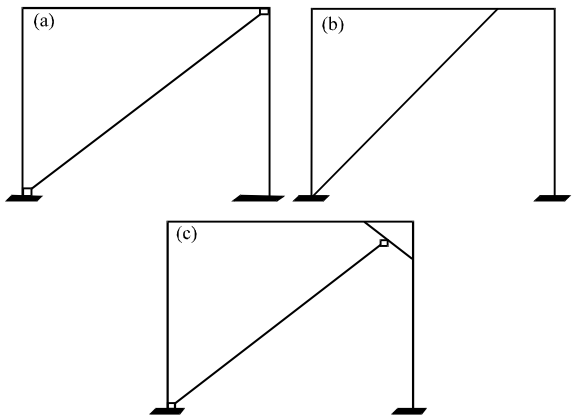


Fig. 2(a-c): Finite element model of the one-bay single-story frames in opensees software, (a) CBF, (b) EBF and (c) KBF

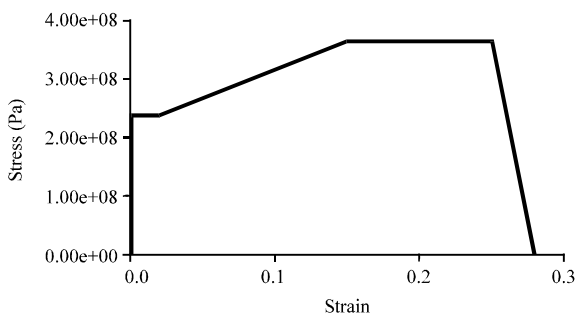


Fig. 3: Stress-strain curve

Table 1: Column, beam and brace section profiles

| Elements | Section profile |
|---|---|
| Column | H250×250 |
| Beam | H250×25 |
| Brace | C76.2×3.9 |

Mesh refinement studies were conducted to determine the level of refinement necessary to accomplish the objectives.

Standard shell elements were used in the models, the geometry of each shell model corresponded to the centerline dimensions of a link. Stiffener details were considered and the stiffener welds were not modeled explicitly. The SHELLMTC4 is suitable for analyzing thin to moderately-thick shell structures (McKenna and Fenves, 2002; Awaludin *et al*., 2012).

Elastic module E = 2.10e11 N $m^{-2}$, the yielding strength $F_Y$ = 2.4e8 N $m^{-2}$ and the specified minimum ultimate tensile strength $F_U$ = 3.6e8 N $m^{-2}$ is selected. The profiles of the structural elements are wide flange H and brace element is a tube pipe (Table 1). The stress-strain curve used in this study shows in Fig. 3.

## RESULTS AND DISCUSSION

**Correlation studies:** The numerical method has been validated using the available experimental results in the literature; therefore the specimen3 Kasai and PoPov's work, is selected and modeled in FEM software (OpenSees). This specimen is 1/2 scaled link beam with 37 cm length. Moreover, in the analysis, initial imperfection based on first buckling mode is assigned to the numerical model. The numerical hysteretic and push-over load-displacement curves from the non-linear finite element modeling are presented and compared with experimental model in Fig. 4.

The difference between obtained shear capacity in the numerical and experimental models is less than 12%. Some preliminary analyses were conducted to study the effect of mesh refinement and to determine whether reduced integration elements could be used to improve computational time without loss of significant accuracy. An element edge length of approximately 20 mm was found to adequately represent the behavior of the link through a mesh refinement study (Kasai and Popov, 1986).

The nonlinear static pushover analyses with a comparison of KBF, CBF and EBF are demonstrated in Fig. 5. Figure 5 shows the force-displacement curves of KBF frames with two different frames. The ultimate bearing capacity is reduced as the area of the EBF and CBF is reduced, in inelastic stage. It is observed that the elastic lateral stiffness of the EBF is smaller than those of the CBF and KBF. Thus, it is expected that CBF and KBF will have limited drift and hence a more desirable performance under the effect of small earthquakes. But in nonlinear range, the stiffness of KBF is more than two systems and has better performance.

The three specimens were subjected to quasi-static, cyclic loading, based on SAC (SAC is a joint venture of the Structural Engineers Association of California (SEAOC), the Applied Technology Council (ATC) and California Universities for Research in Earthquake Engineering (CUREe)). The choice of a testing program and associated loading history depends on the purpose of the experiment, type of test specimen and type of anticipated failure mode (e.g., rapid strength deterioration, slow strength deterioration, member buckling, etc.). The loading protocol for this study is shown in Fig. 6. Cyclic quasi-static tests have been conducted in the past three decades to characterize the inelastic seismic performance of steel bracing members made of rectangular or circular hollow structural shapes.

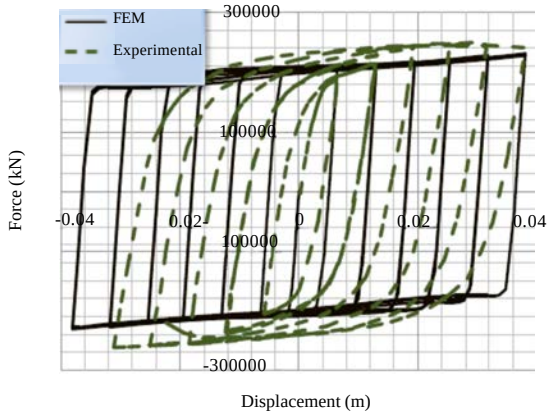


Fig. 4: Good agreement between numerical and experimental models (Kasai and Popov, 1986)

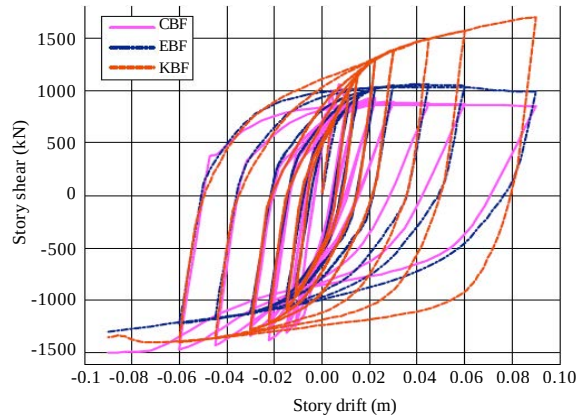


Fig. 7: Hysteretic curves of specimens and comparison between finite element results

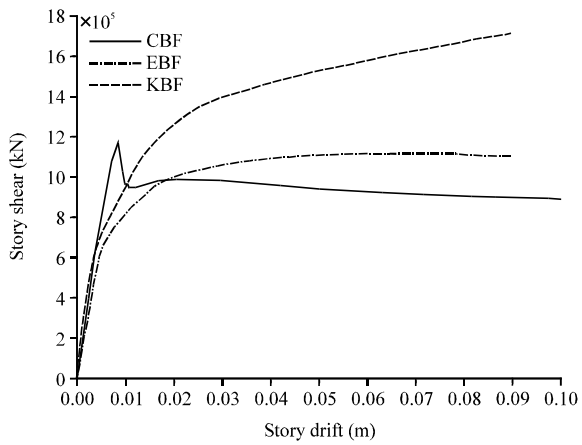


Fig. 5: Lateral performance of CBF, EBF and KBF frames

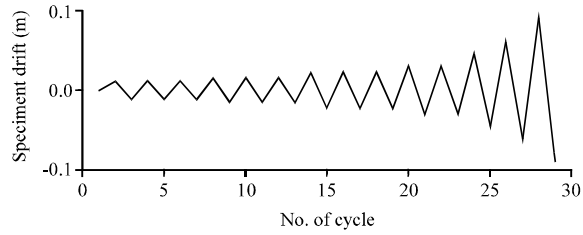


Fig. 6: Loading protocol based on SAC

By including large displacement effects in the analysis, local buckling could be captured and the post buckling behavior of the link and knee could be simulated. Figure 7, illustrates a typical shear versus inelastic displacement hysteresis for different systems.

In Fig. 8, the comparison in terms of cumulative dissipated energy of all specimens is provided. Numerical results show that KBF is able to increase cumulative dissipated energy. In Fig. 9, the comparison in terms of

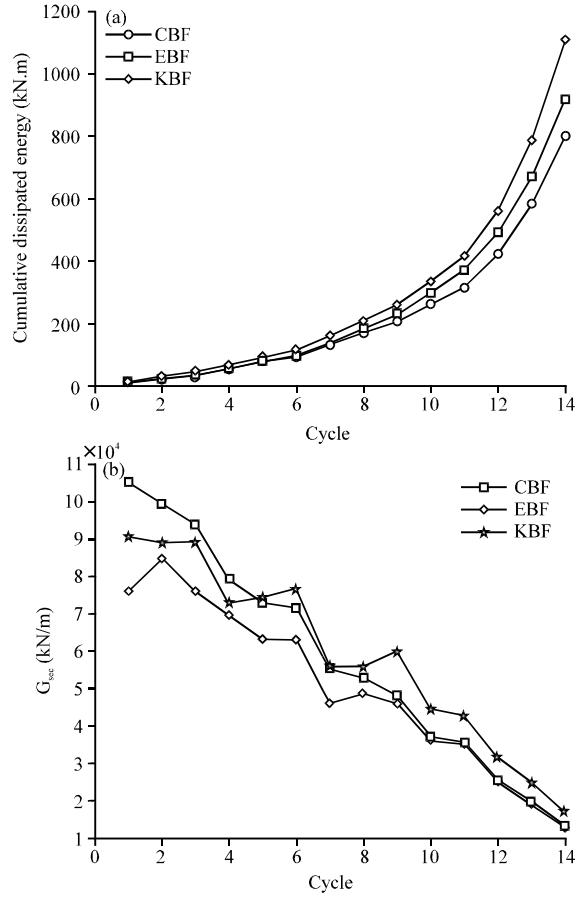


Fig. 8(a-b): (a) Cumulative dissipated energy of the specimens and (b) Secant stiffness of the specimens

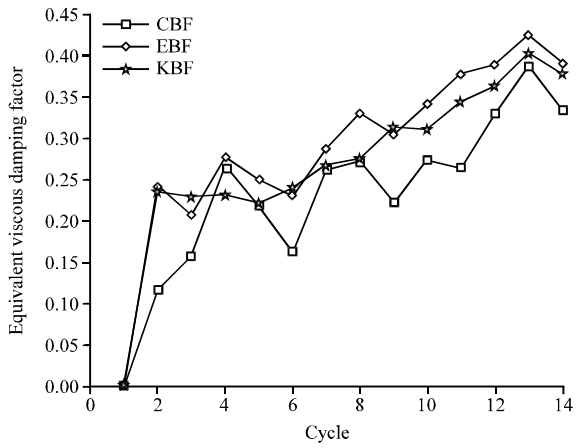


Fig. 9: Equivalent viscous damping ratio

equivalent viscous damping ratio of the all specimens is provided. Also the comparisons in terms of secant shear stiffness of all specimens are represented. Numerical results show that EBF have more than equivalent viscous damping ratio. Also the comparisons in terms of secant shear stiffness of all specimens show that initial stiffness of CBF is more than the EBF and KBF but in nonlinear range, the stiffness of KBF is more than two systems.

One of the important advantages of this study in comparison to previously published studies is that, each three type of KBF, CBF and EBF braces from the angles of hysteretic curves, cumulative dissipated energy, secant stiffness and equivalent viscos damping ratio are gathered simultaneously in order to compare them.

## CONCLUSION

In this study, nonlinear behavior of three system (EBF, CBF and KBF) has been investigated numerically. The main results can be summarized as follows:

- As an energy dissipating system, the KBF bracing frame combines excellent ductility and lateral stiffness and is easy for application to rehabilitation if earthquake damaged the buildings. With the protection of the knee elements, no damage occurs to the major structural members during a moderate earthquake
- Ductile hysteretic behavior without strength degradation and without pinching of the hysteretic loop was characteristics for KBF and EBF
- Initial stiffness (Elastic range) of CBF is more than the EBF and KBF. But in nonlinear range, the stiffness of KBF is more than two systems
- In the KBF system the diagonal brace provides most of the elastic lateral stiffness where the beams and columns are hinge-connected. The knee elements prevent collapse of the structure under extreme seismic excitations by dissipating energy through flexural yielding. Since the cost of repairing the structure is limited to replacing the knee members only
- Concentric bracing is more suitable for a strength-based design. However, the relatively small post-yield capacity and the brittle failure mode of the concentric braced frame make this system unfavorable for a ductile design. Knee bracing, on the other hand, is suitable for both the strength-based and ductility-based designs. A knee-bracing system can therefore be successfully utilized to design for both the damage-level and collapse-level earthquakes for which the damage level may be considered as the yield capacity of the knee elements. This study proves that the overall seismic performance of knee braced frames, regarding stiffness and ductility appears to be more favorable than either the frames without brace or the concentric braced frames

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