Nonlinear Behavior and Dissipated Energy of Knee Braced Frames Based on Cyclic Analysis

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Abstract

Knee braced steel frame (KBF) 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 connected to a knee element instead of beam-column joint. Knee bracing can provide a stiffer bracing system but reduces the ductility of the steel frame. In this paper frames with similar dimensions in three systems (concentric (CBF), eccentric (EBF), and knee braced (KBF)) 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, dissipated energy and secant stiffness are compared. One-bay single-story frames were modelled, and nonlinear analyses were performed using finite element analysis software. Finally the inelastic performances of knee braced frames are investigated, in terms of available ductility, energy dissipation capacity and equivalent viscous damping ratio.

Keywords: Knee bracing, Seismic performance, Finite element analysis, Cyclic analysis.

INTRODUCTION

Braced frames are among the most common steel structures for resisting lateral loads. In general, they are divided into three groups: concentric (CBF), eccentric (EBF) and knee braced (KBF) (Figure 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. 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. . This is because they mainly yield in bending and, therefore their hysteresis behaviour is close to ideal elastic-plastic systems without significant degradation of strength and stiffness

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[1]. 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.

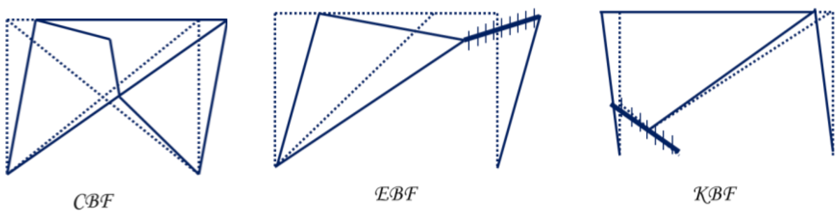


Fig.1 Commonly used steel braced frame systems

Although the moment-resisting frames (MRF) are an 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, Reoder and Popov proposed a new structural system, named EBF [1]. 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 [2]. 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. A new braced frame, called knee bracing frame (KBF), having all the favorable features of the above frames but without having the deficiencies, was presented by Aristizabal-Ochoa and further investigated by Sam et al. [4,5] Mofid and Khosravi, Balendra et al. and William et al.[3]. 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 stiff ness through the setting of the diagonal brace [3]. By 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, systematic cyclic analysis of the KBF structure with finite element method was conducted in this work. Finally, general design recommendations were suggested by the analysis results. [4,5]

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. 1991). 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. Nondimensional analysis shows (Balendra et al.) that shorter knees are preferred for higher stiffness. 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 [6]. 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:

$$l_k < 2\frac{M_p^*}{V_p} \quad (1)$$

Where M^*_p is the reduced plastic moment contributed by flanges only; and V_p the plastic shear force [4]. They are defined as follows:

$$M_p^* = t_f b_f (d - t_f) F_y \quad (2)$$

$$V_p = t_w (d - t_f) \frac{F_y}{\sqrt{3}} \quad (3)$$

in which 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 (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 Figure 1. For compare between frames, CBF and EBF modeled. 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 research on hysteresis behaviour of CBF's, many problems of this system has been specified and many suggestions are presented to achieve sustainable behaviour of CBF's during severe earthquakes. Recent research 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’. The frames have a total span of 4.5 m and height of 3 m. The frames base was hinged at both ends by restraining the displacement in X, Y, and Z translational directions and the rotation in the three directions (Rx, Ry and Rz). 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.

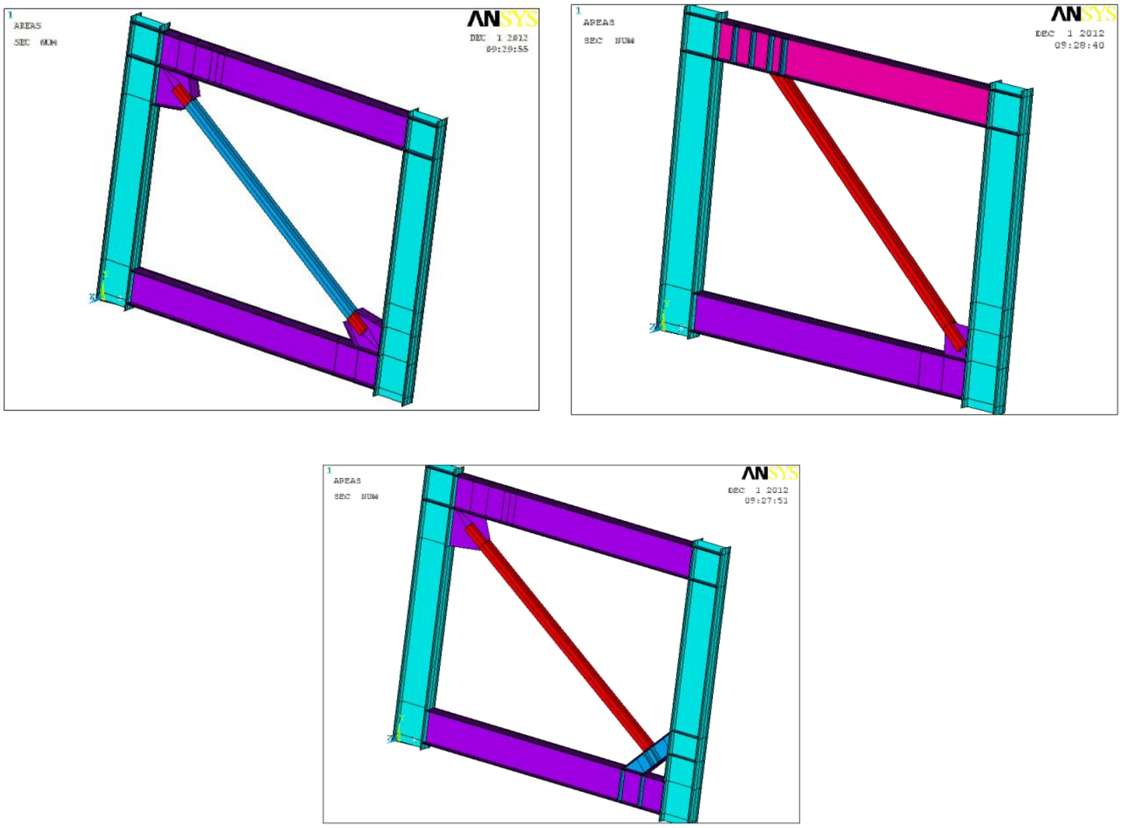


Fig.2 Finite element model of the frames.

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 ANSYS software is used and a typical model is shown in Figure 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 are introduced. Afterwards, noticing the finite elements that are used in this field element, the SHELL181 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. Mesh refinement studies were conducted to determine the level of refinement necessary to accomplish the objectives.

Standard shell elements were used in the models, with four nodes per element and six degrees of freedom per node. 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. SHELL181 is suitable for analyzing thin to moderately-thick shell structures [7,8]. It is a 4-node element with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z-axes. All materials used in the analysis are supposed to have: the elastic module, $E = 2\times10^{11}$ N/m^2, the yielding strength, $F_y = 2.35\times10^{8}$ N/m^2 and the specified minimum ultimate tensile strength $F_u = 3.62\times10^{8}$ N/m^2. The profiles of the structural elements are wide flange *H* and brace element is a tube box. The stress-strain curve used in this study show in Figure 3.

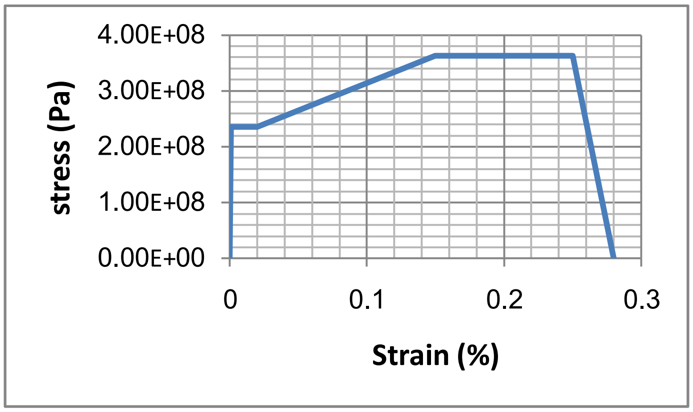


Fig.3 stress-strain curve

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 (ANSYS^{V12}). 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 Figure 4.

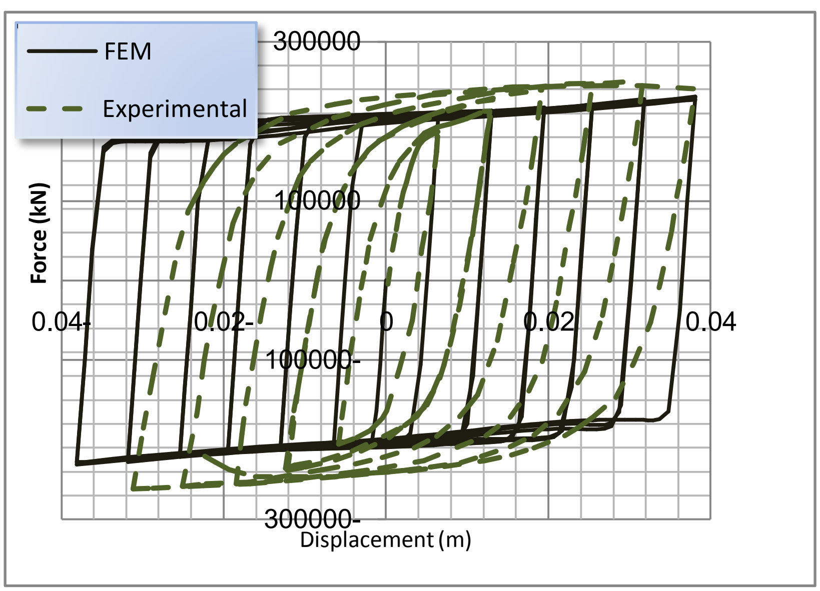


Fig.4 Good agreement between numerical and experimental models [9]

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 [9].

ANALYSIS RESULTS AND DISCUSSION

The nonlinear static pushover Analyses, with a comparison of KBF, CBF and EBF are demonstrated in Figure 5. In this figure 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 EBF will has limited drift, and hence a more desirable performance under the effect of small to moderate intensity earthquakes.

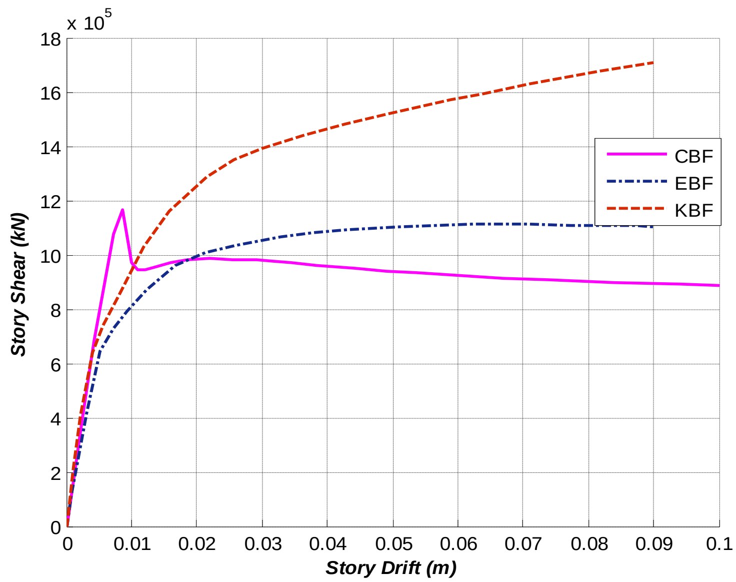


Fig.5 Lateral performance of CBF, EBF and KBF frames

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 Figure(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 (HSS).

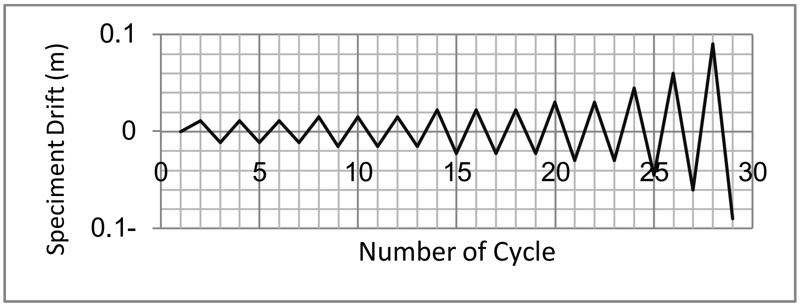


Fig.6 Loading Protocol based on SAC

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

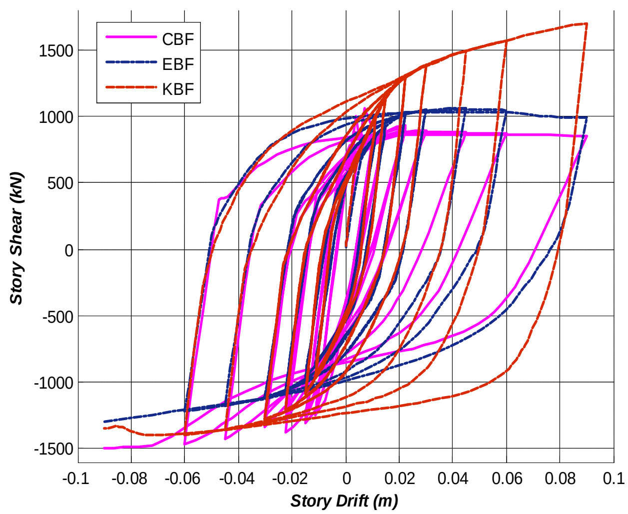
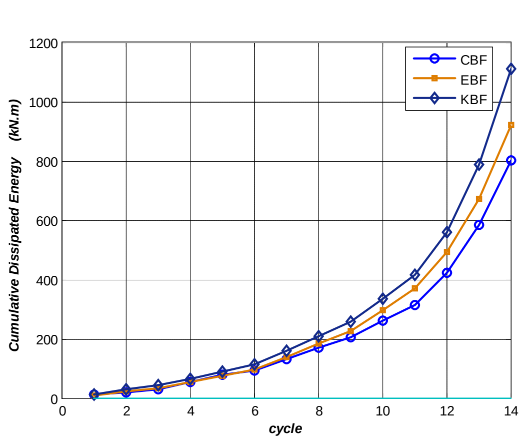


Fig.7 Hysteretic curves of specimens and comparison between finite element results



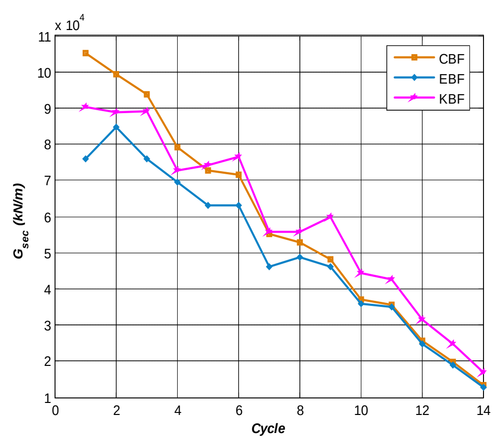


Fig.8 Cumulative dissipated energy and secant stiffness of the specimens

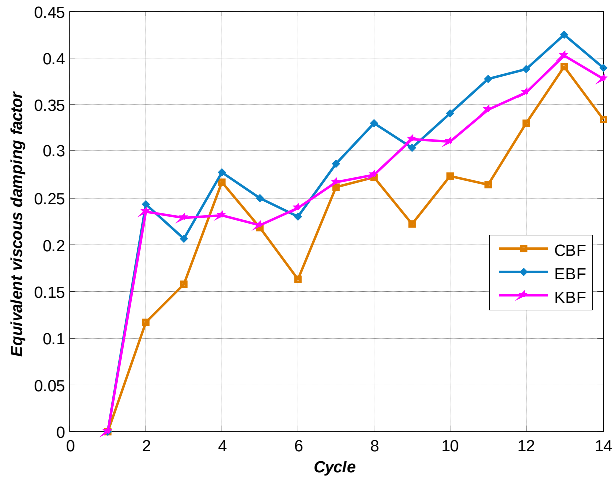


Fig.9 Equivalent viscous damping ratio

In Figure(8), the comparison in terms of cumulative dissipated energy of all specimens is provided. Also the comparisons in terms of secant shear stiffness of all specimens are represented. Numerical results show that KBF is able to increase cumulative dissipated energy .In Figure(9), the comparison in terms of equivalent viscous damping ratio of the all specimens is provided. Numerical results show that EBF have more than equivalent viscous damping ratio.

CONCLUSIONS

In this paper, 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 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.
- As an energy dissipating system, the knee bracing frame combines excellent ductility and lateral stiffness and is easy for application to rehabilitation if earthquake damaged buildings. With the protection of the knee elements, no damage occurs to the major structural members during a severe earthquake.
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