ECCENTRICALLY KNEE BRACING: IMPROVEMENT IN SEISMIC DESIGN AND BEHAVIOR OF STEEL FRAMES

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ABSTRACT

The use of passive control systems is widely considered as a reliable approach for controlling earthquake vibrations in steel structures. First, under frequently occurring low to moderate earthquakes, the structure should have sufficient strength and stiffness to control deflection and prevent any structural damage. Second, under rare and severe earthquakes, the structure must have sufficient ductility to prevent collapse. For this case, significant damage of the structure and nonstructural elements is acceptable. In this paper, the performance of a new innovative eccentrically and knee bracing system called Eccentrically Knee Bracing (EKB) is discussed and the behavior is investigated. A combination of eccentrically braced steel frames and knee braced steel frame has been assessed and concepts of the design of defined schemes are reviewed. As the structural fuse of the frame, the knee element will yield first during a moderate earthquake. In large earthquakes, both of them contribute in dissipating energy. Two half-scale EKB were tested using the SAC loading protocol and an innovate loading protocol.

INTRODUCTION

For some decades now eccentrically braced frames (EBFs) have been indicated as the distinctive elements of a structural typology suitable for satisfying the different design objectives of modern performance-based seismic engineering in medium or high-rise steel buildings. They have often been proposed as a cheaper and more valid alternative to the most common moment resisting frames (MRFs) and concentrically braced frames (CBFs), as they incorporate the good qualities of the abovementioned structures. Indeed, owing to the presence of bracings and links, EBFs are expected to incorporate characteristics of both high lateral stiffness and high energy dissipation capacity. Experimental investigation has gradually persuaded the scientific community of the structural effectiveness of EBFs and, hence, induced building codes to propose rather high values of the behaviour factor for the design of such structures. An alternative system which combines the advantages of the moment resisting frame and those of the concentric braced frames is the knee braced frames (KBFs), where one end of the brace is connected to a knee member (anchor) instead of the beam-column joint. In this system, the knee element acts as a “ductile fuse” to prevent collapse of the structure under extreme seismic excitations by dissipating energy through flexural and shear yielding. A diagonal brace with at least one end connected to the knee element provides most of the elastic lateral stiffness. As the nature and occurrence of earthquakes are random, it is necessary to consider different levels of earthquake intensity in designing earthquake resistant structures. To improve the seismic performance of the steel framed structures, further modification to enhance the structural performance is essential. In this paper, one of the most effective braced frame systems through which a high level of energy dissipation capacity may be attained is investigated. For this purpose, a modified structural form that adopts knee brace elements in the corner regions of the beams and columns, namely Eccentrically Knee Braced frame (EKB) and this paper describes the seismic behavior of EKB, as shown in Fig.1, is considered in this study. The design of an EKB is based on creating a frame which will remain essentially elastic outside a well-defined link and knee. During moderate lateral loads, the knee element deform inelastically and during extreme loading it is anticipated that the link and the knee will deform inelastically with significant ductility and energy dissipation.

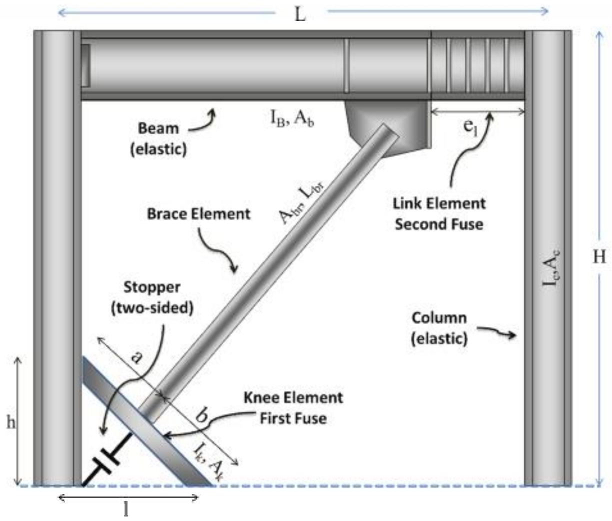

Figure 1. The proposed frame configuration.

As the nature and occurrence of earthquakes are random, it is necessary to consider different levels of earthquake intensity in the design of earthquake resistance structures. To improve the seismic performance of the steel framed structures, further modification to enhance the structural performance is essential. The design of an EKB is based on a preselected yield mechanism that limits inelastic activities to ductile segments of the frame. For this structural system, seismic energy is dissipated by means of the first yielding of the knee braces (first fuse) and second yielding of the link beam (second fuse) with a selected yield mechanism. The knee and link beam acts as a fuse to prevent other element in the frame being overstressed. The strength of the knee and link elements is selected to achieve the desired mechanism. The other members (columns, beam outside the link and brace) in the frame are designed to remain elastic under the largest forces generated by fully yielded and strain-hardened plastic hinges, except at the column bases where plastic hinges are required to complete the mechanism. For this purpose columns base are designed to resist horizontal and vertical movement, but with rotation (Columns were hinged at their base). Where the knee with length e_k and link with length e_l deforms inelastically and resists the applied base shear, V_b, while the framing outside the link is designed to remain elastic. In FEMA 356 a wide range of structural performance requirements could be desired by individual building owners. Table C1-3 FEMA356, relates structural performance levels to the limiting damage states for common vertical elements of lateral-force-resisting systems. For this configuration, the knee element designed for 1% drift (a performance Level between immediate occupancy and life safety) and link element designed for 2% drift (collapse prevention performance) [7]. The KBF must have sufficient stiffness to prevent structural as well as nonstructural damage during frequently occurring minor earthquakes. For a properly designed EKB to perform satisfactorily under moderate and severe seismic loading, one must ensure that its ductility capacity is greater than the ductility demand. The elastic lateral stiffness of an EKB depends on its geometry and section properties of its member. Most specific contributions of this paper are summarized here: (1) experimental work on Eccentrically Knee Bracing (EKB) by cyclic testing of two half-scale frame specimens; (2) studying the capability of using a new and practical technique of lateral bracing system in simple frames; (3) application of IPE sections for the knee and link members (previous researchers have mostly studied Wide flange sections (IPB)); (4) investigation of the hysteretic loops and nonlinear behavior (such as the strength and stiffness, energy dissipations, equivalent viscous damping ratio and secant stiffness) of the EKB.

EXPERIMENTAL PROGRAM

To study the application of an EKB in buildings, a one-story test frame shown in Fig. 2 had been designed, constructed, and tested using an actuator quasi-static testing system. An inelastic quasi-static test was performed to study the energy dissipating capacity of the knee and link members and the overall ductility of the frame. This frame represents a half-scale model of a normal building with a panel height-to-width ratio of 3/4. The experimental program was undertaken to establish the actual performance of the EKBs in structural laboratory of International Institute of Earthquake Engineering and Seismology (IIEES). The proof-of-concept EKB was designed to be as large as possible considering the constraints of the available equipment in the Structural Engineering Research Center Laboratory at IIEES. In this program, two half scale single span single-story models were fabricated and tested. The following sections describe the EKB design approach, the main features of test set-up, and the applied load protocol. Quasi-static cyclic loading was chosen and the maximum force output of the actuator available (980 kN) was divided by 1.5 to account for the possibility of obtaining material with a higher than specified yield stress as well as strain hardening, making the design base shear 653 kN. The philosophy of design for the EKB is that in the event of a moderate earthquake, the knee element should yield (first fuse) and dissipate energy through shear or flexural yielding and in the strong motion, the link element should yield (second fuse) and dissipate energy through shear or flexural yielding before any damage can occur to other members, thereby preserving the main structural elements. The knee and link members must be designed to satisfy several conditions. The specimens were designed according to AISC (2010) Seismic Provisions, similar with an EBF. The knee and link elements must also resist against premature failure due to local and lateral torsional buckling. Four full depth stiffeners were welded on the knee element web to provide its complete shear yielding behavior. Also three full depth stiffeners were welded on the web of link element to prevent local buckling. In actual buildings, the lateral displacement of the frames is prevented by the cross frames. Thus, in the laboratory testing, the test frame has to be supported laterally to ensure in-plane deflection. Two lateral bracing was provided to the link element and other one was provided to mid-point of the beam.

Figure 2. General configuration of the test frame

The actual material characteristics of the steel specimens were determined from testing of tensile coupons taken from web of the knee and link members, and were tested in accordance with the ASTM (2003) Standard. Specifications of the specimens are given in Table 1. The test specimens were only different in loading protocol. Two inelastic quasi-static tests, designated as SP-1 and SP-2, were conducted on this test frame when it was subjected to base excitation. All of the sections (beams, brace, knee and the columns) used were grade ST37 hot rolled carbon steel. The beams and columns were I-sections of IPE200 and IPB160 respectively. The beam-to-column joint was designed as hinge joint and the link-to-column joint was designed as moment-resisting joints. To develop full moment-resistant capacity, the joint was flange welded full penetration weld. All welding was performed according to the shielded metal arc welding (SMAW) process by using E7018 electrodes for link connection and E6013 electrodes for other connection. Welding and weld-access hole details for the link-to-column connection followed recommendations for SMF beam-to column connections outlined in AISC 341-10. For the test, the frame was constructed with a knee-brace with moment connection. The frame was designed so that the brace, beam and columns remain elastic until the end of the test.

Table 1. Summary of EKB specimens [16]

Spec.	Link		Knee		Brace		Column		Loading
	Length (mm)	Section	Length (mm)	Section	Length (mm)	Section	Length (mm)	Section	
SP-1	500	IPE200	664	IPE120	1850	Box100x100x10	1600	IPB160	Protocol-1
SP-2	500	IPE200	664	IPE120	1850	Box100x100x10	1600	IPB160	Protocol-2

Table 2 lists the key characteristics of the test specimens. The test specimens were only different in loading protocol.

Table 2. Summary of EKB specimens

Specimen No	Link Section	Knee Section	Brace Section	loading protocols
SP-1	IPE200	IPE120	Box100x100x10	Protocol-1
SP-2	IPE200	IPE120	Box100x100x10	Protocol-2

Two different subassemblies in two different loading protocols were tested, each with the same beam-column components and sections. The frame was mounted on clevises at the base of each column fastened to a foundation beam attached to the strong floor of the IIEES structural laboratory. A hydraulic actuator applied horizontal force to top of right column (a small variation in the displacement to each column is expected due to the axial flexibility of the beam). In actual structures, the lateral displacement of the frames is prevented by the cross frames and secondary beams.

The EKB system has a fundamental part called “Stopper Device” (SD) which can create two separate levels of energy dissipation by restricting displacement of knee element. The gap between knee element and SD is limited to 0.9 cm. This limitation has coincided with 1% drift of frame. The configuration of SD has been shown in Fig 3. A typical knee is shown in Fig 3. To prevent tearing of the web, stiffeners are provided.

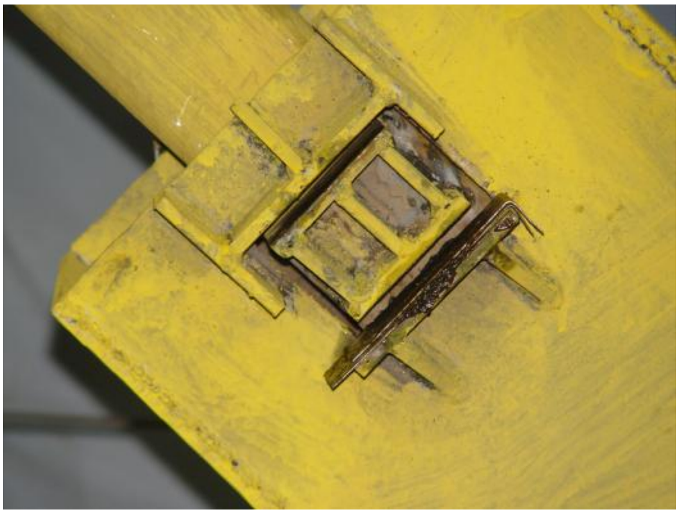

Fig 3. Stopper Device (SD)

The baseplates were connected to reaction floor with high strength friction grip bolts to prevent slippage. External displacement transducers are used to monitor the lateral displacements of the frame at floor level during quasi-static testing. Instrumentation, including displacement transducers for global frame in-of-plane displacements, and strain gauges (type FRA-5-11 and FLA-6-11), allows subsequent determination of knee, link, brace and columns stresses and forces. One linear variable type displacement transducers (LVDT) is used for this purpose. A microcomputer is used to control the data logger that scans data from strain gauges and displacement transducers monitoring the lateral displacement of frame. The displacements and forces obtained in the test provide the displacement-time history and the force-displacement hysteretic curves. However, in order to obtain the stress-strain hysteretic curves for individual members, the strain level of each individual member needs to be measured with strain gauges. The types of strain gauges used for this purpose were TML's FLA-6-11 with a gauge length of 6 *mm* (with gage resistance

120±0.3 Ω and transverse sensitivity -0.2%) for axial strains, and FRA-5-11 with a gauge length of 5 *mm* (with gage resistance 120±0.5 Ω and transverse sensitivity -0.1%, However, these values can be achieved only if the contact surface is smooth and very clean) for shear strains.

EXPERIMENTAL RESULTS

The initial stiffness of the specimen was determined to be 32 kN/mm from the elastic cycles. After yield of knee element, stiffness of frame is only provided by link element. The yield drift was identified as 0.28% and corresponded to a base shear of 220 kN, while the maximum base shear and drift reached were 600 kN and 4%, respectively. The experimentally their hysteretic responses is shown in Fig 4 and Fig 5. The applied load on the beam, (bese shear), is plotted against the imposed displacement on the center of beam. As shown in this figures, very good hysteretic performance of EKB in two level can be noticed.

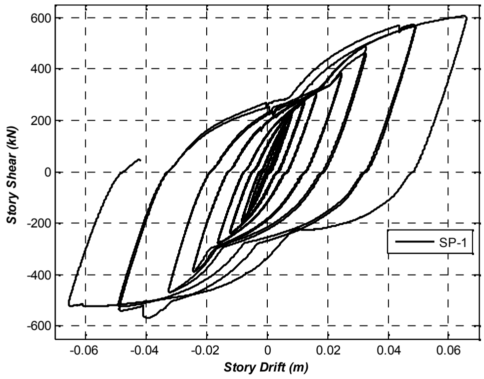

Fig. 4. Hysteretic response of specimen SP-1

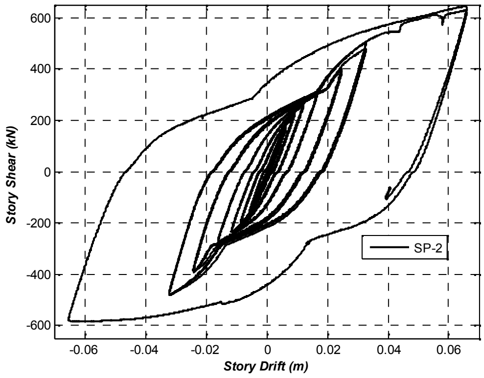

Fig. 5. Hysteretic response of specimen SP-2

The failure mode of the link and knee was the yielding of web. Also the failure mode of the brace to link connection was at the peak of the negative excursion of Cycle 19 for SP-2 is shown in Fig. 6. Factors that likely contributed to this are the large plastic strain demands at that location, the high degree of constraint due to the presence of the stiffeners, and welds used for the link-to-brace connection, and heat-affected-zone (HAZ) brittleness near the connection weld. There was no evidence of crack initiation in the full penetration groove weld used to assemble the flanges of the link and knee.

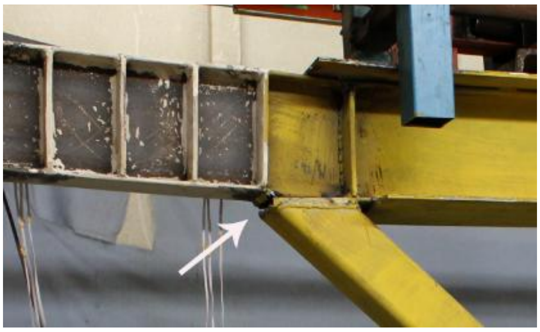

Fig. 6. Brace to link connection fracture during Cycle 19

The energy dissipations of the test frames were compared to further define the structural performance. Energy dissipations were evaluated using the cumulative hysteretic loop areas of the test structures [13]. In Fig 7 and Fig 8 the comparison in terms of cumulative dissipated energy and dissipated energy in each cycle of all specimens is provided. This parameter is one of the most important characteristics affecting the seismic performance of the EKB system. In the specimens, with increasing drift, cumulative dissipated energy of the specimens increased.

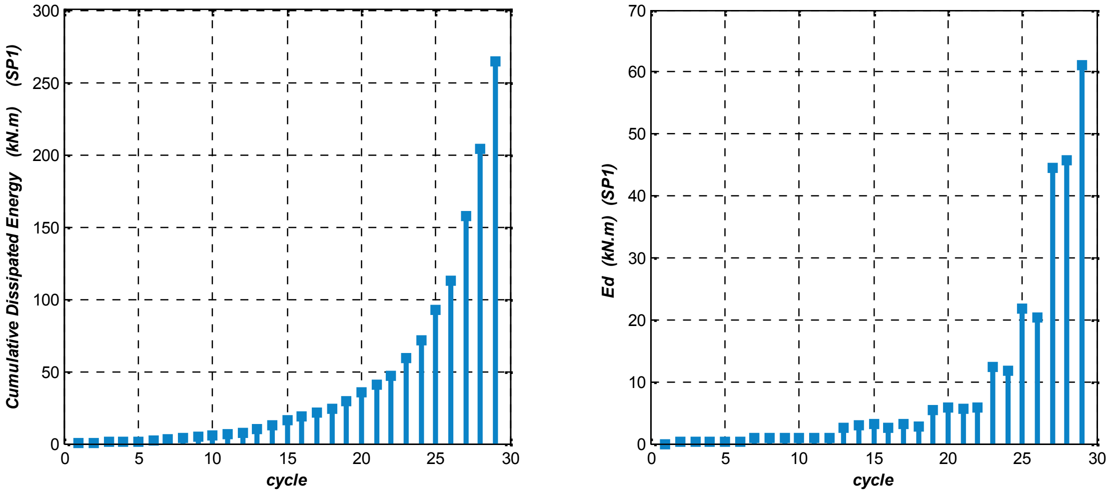

Fig 7. Dissipated energy in each cycle and cumulative dissipated energy of the SP1

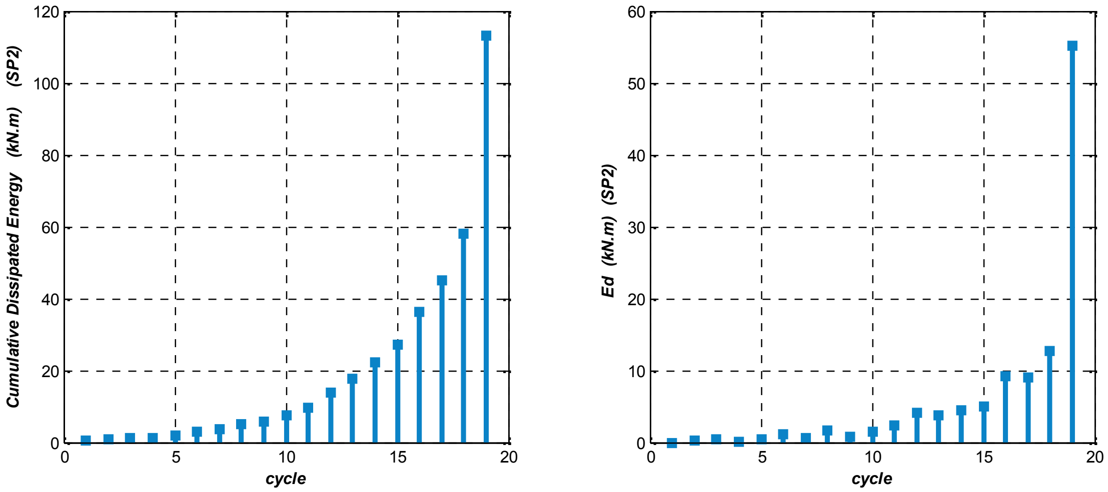

Fig 8. Dissipated energy in each cycle and cumulative dissipated energy of the SP2

CONCLUSIONS

Two half-scale, one story that are combination of eccentrically braced steel frames and knee braced steel frames with shear yielding knees and link has been tested for ductility using the cyclic quasi-static tests. The objective of these tests was to examine performance of such systems under idealized seismic loading conditions and the proposed system details were evaluated. The specimen responses were assessed in terms of failure mode, strain behavior of the members, energy dissipation and general hysteretic behavior. The tests reveal that the EKB can dissipate a large amount of energy without an appreciable loss of strength in two level of performance. The knee and link beam act as a fuse to prevent other element in the frame being overstressed. A proof-of-concept experiment showed that can achieve and exceed the maximum drift for frame specified in the ASCE. In the large displacement of frame, strain rate in the columns reduced (seismic demand reduction). Comparisons in energy dissipation and ductility between the steel moment resisting frames (or steel knee braced frames [9] of eccentrically braced frames) and the EKB justified the applicability of the proposed system.

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