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Seismic performance of steel frames with controlled buckling mechanisms in knee braces

H.-L. Hsu *, Z.-C. Li

Department of Civil Engineering, National Central University, Chung-Li 32054, Taiwan

A R T I C L E   I N F O

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A B S T R A C T

This study experimentally evaluates the seismic performance of knee braced moment resisting frame (KBRF) systems. A series of cyclic load tests were performed on the special moment resisting frame (SMRF) and KBRF systems with in-plane and out-of-plane controlled buckling mechanisms in the knee braces. It was found from the test results that the strength and energy dissipation capacity of the KBRFs was significantly enhanced regardless of whether the knee braces buckled in the in-place or out-of-plane direction. Further test result comparisons demonstrated that the allowable drift at which the knee braces reached the buckling stage was higher for KBRF frames equipped with in-plane buckling braces. It is therefore suggested that braces with in-plane buckling modes be adopted for greater earthquake resistance in KBRF frame structure designs.

1. Introduction

Steel frames, such as special moment resisting frames (SMRF) and concentrically braced frames (CBF), are commonly used in building constructions designed for earthquake-resistant purposes. For SMRF structures subjected to lateral load, as shown in Fig. 1, structural ductility can be achieved when adequate beam-to-column connections are detailed [1–5]. In such designs the excessive drift due to higher structural flexibility and inevitable stress concentration at the welds of connecting columns and beams are essential parameters that limit the applicability of these structures.

Improved stiffness to reduce excessive structural deformation could be achieved in CBF frames, as shown in Fig. 2, when brace members are added to the above-mentioned SMRF [6–8]. Although effective stiffness is accomplished, the lower ductility of CBF hampers the applicability of such designs if seismic performance is a concern. A further concern in CBF designs includes the performance deterioration when the brace members reach the buckling state. It has been indicated in several previous studies [9,10] that brace member buckling in CBF incurs significant losses in structural strength and energy dissipation capability. Gusset plate damage and the subsequent torsional failure of structural beams also hamper structural usefulness and architectural function due to buckled brace out-of-plane deformation. A remedy to improve braced frame designs to achieve higher structural performance and architectural functionality enhancement is essential.

A modified structural form that improves design efficiency by adopting knee brace elements in the corner regions of beams and columns, namely knee-braced moment resisting frame (KBRF), as shown in Fig. 3, is proposed in this study. The benefits of using the proposed KBRFs include improved structural stiffness and higher energy dissipation than SMRFs with equivalent structural members [11–16]. Furthermore, due to the effective restraint of relative joint deformation at those regions by the applied knee braces, the stress at the beam-to-column regions is significantly reduced; therefore, effectively alleviating the demand for connections.

As mentioned previously, brace member buckling usually leads to gusset plate damage and structural beam twisting [17]. Further improvement in knee brace member design is proposed in this study by replacing traditional gusset plates with bolted end plates in the brace-to-beam and brace-to-column connections. In addition, the two ends of the knee braces are trimmed to desired dimensions, forming controlled buckling mechanisms, as shown in Fig. 4. The proposed brace design could be arranged for various buckling modes, i.e., in-plane buckling or out-of-plane buckling, according to the strength requirements and could be easily replaced should the knee brace members reach the buckling stages under extreme loads.

This study focuses on the experimental evaluation of controlled-buckling knee brace design and KBRF performance with various buckling modes in the knee braces. A series of cyclic load tests were conducted on SMRF and KBRF frames with knee braces applied in the in-plane and out-of-plane buckling directions. Test results, such as the structural strength and energy dissipation capability, were compared to evaluate the seismic performance of these structures. A design recommendation is proposed for KBRF structure engineering practice.

* Corresponding author at: 300, Jhongda Road, Chung-Li 32054, Taiwan

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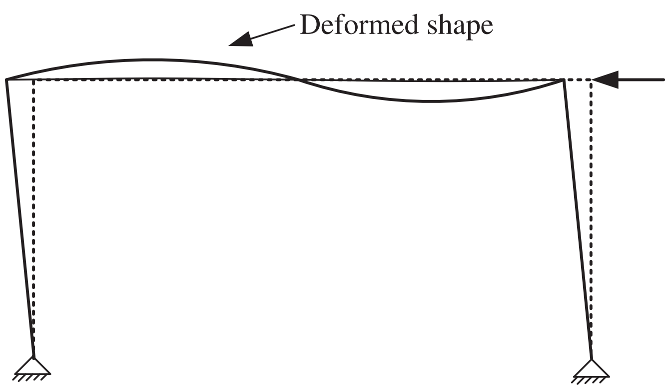

Fig. 1. SMRF structure subjected to lateral load.

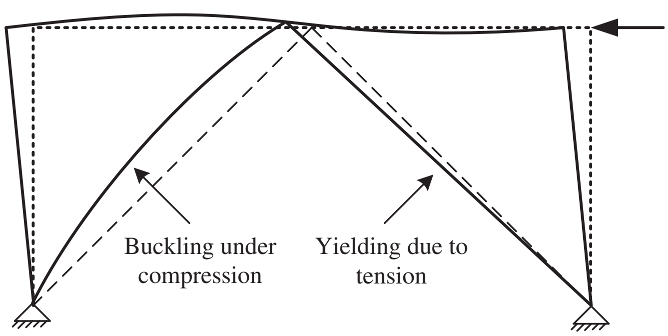

Fig. 2. CBF structure subjected to lateral load.

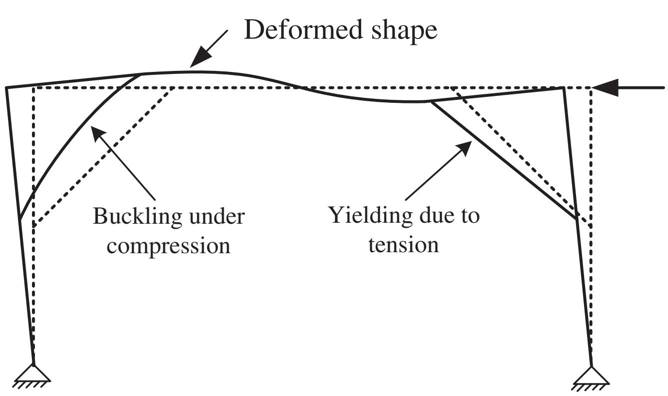

Fig. 3. KBRF structure subjected to lateral load.

Table 1
Specimen details.

Specimen		W (mm)	W_e (mm)	A_e (mm^2)	L_e (mm)	KL_e/r_y
SMRF		100	N.A.	N.A.	N.A.	N.A.
KBRF	30-2D	100	30	1070	200	38
	30-3D	100	30	1070	300	57
	30-4D	100	30	1070	400	76
	35-4D	100	35	1150	400	64.4
	40-4D	100	40	1230	400	55.5

2. Experimental program

2.1. Specimens

Eleven sets of steel frames were fabricated for testing, including one SMRF and ten KBRFs with various knee-brace arrangements. ASTM A36 H175 × 175 × 7.5 × 11 and H250 × 250 × 9 × 14, respectively, were used to fabricate the beams and columns. Knee braces were fabricated using ASTM A36 H100 × 100 × 6 × 8 sections. The yield stresses for the beams, columns and knee braces were 310 MPa, 324.6 MPa and 350.8 MPa, respectively. The beam for each test frame was welded to a pair of 30-mm-thick end plates and connected to the columns using A490 high strength bolts. Identical beam-to-column connections were used in all SMRF and KBRFs so that the knee brace effect could be evaluated.

The flanges at the two ends of the knee braces were trimmed, as shown in Fig. 4, according to the desired strength so that prescribed plastic zones could be formed and controlled buckling mechanisms could be anticipated. Each knee brace was also welded to a set of 30-mm-thick end plates that were attached to the beam and column at the corner of the structure's in-plane and out-of-plane directions, respectively. These arrangements yielded different structural stiffness, various allowable drift ratios and various in-plane or out-of-plane brace buckling deformations in the framed structures. This test approach allowed the possibility to compare different buckling mode effects in the structural performance.

Since the design concept of this study was to enhance the structural performance while maintaining structural member integrity, i.e. the beams and columns. The knee braces should therefore be designed to reach the buckling or yielding state before the beams or columns reached the inelastic stage. In this regard, a set of preliminary analyses was conducted first using ABAQUS [18] to define the adequate dimensions of the controlled buckling knee braces. A series of knee braces with various dimensions in the controlled buckling regions were fabricated based on the numerical approximation. The total length of the

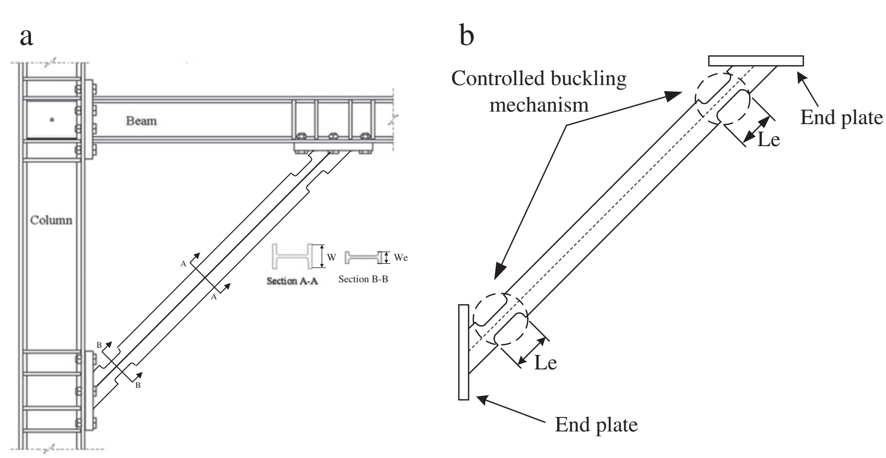

Fig. 4. Controlled buckling knee brace description. (a) Geometry. (b) Sectional composition.