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Experimental evaluation on the seismic performance of steel knee braced frame structures with energy dissipation mechanism

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Abstract. This study experimentally evaluated the seismic performance of steel knee braced frame structures with energy dissipation mechanism. A series of cyclic load tests were conducted on the steel moment resisting frames and the proposed knee braced frames. Test results validated that the demand in the beam-to-column connection designs was alleviated by the proposed design method. Test results also showed that the strength and stiffness of the proposed design were effectively enhanced. Comparisons in energy dissipation between the steel moment resisting frames and the steel knee braced frames further justified the applicability of the proposed method.

Keywords: Seismic performance; steel knee braced frame; energy dissipation; analytical model.

1. Introduction

Steel moment resisting frame structures (SMRF) possess high strength and significant ductility, thus are effective structural forms for earthquake-resistant designs (Kim *et al*. 2002, Lee *et al*. 2005, Tsai and Popov 1990). However, the load carrying efficiency of such designs is limited when an earthquake induces large story drift because of the lower structural stiffness of the steel frames. This is a concern, as shown in Fig. 1(a). Further concern on the structural performance of SMRF is attributed to the beam-to-column connection design. Higher demand is required in the connections if sufficient ductility is desired (Abdalla *et al*. 2007, Ciutina and Dubina 2006, Lehman *et al*. 2008, Pucinotti 2006, Yoo *et al*. 2008). In such cases, brace elements are usually adopted, forming braced frames, as shown in Fig. 1(b), to enhance the structural stiffness and meet the deformation requirements specified in the design codes (AISC 2005).

Although significant improvement in structural stiffness is achieved in the braced frames, major reduction in the structural ductility is an inevitable trade-off (Martinelli *et al*. 1996, Remennikov and Walpole 1997, Tremblay *et al*. 2003). In addition to the ductility concern, the design requirements, as well as the fabrication costs, for the brace members are usually high, because those members are required to exhibit effective buckling strength and adequate post-buckling performance during earthquake excitation (Lee and Bruneau 2005, Uriz *et al*. 2008). To improve the seismic performance of the steel framed structures, further modification to enhance the structural performance is essential.

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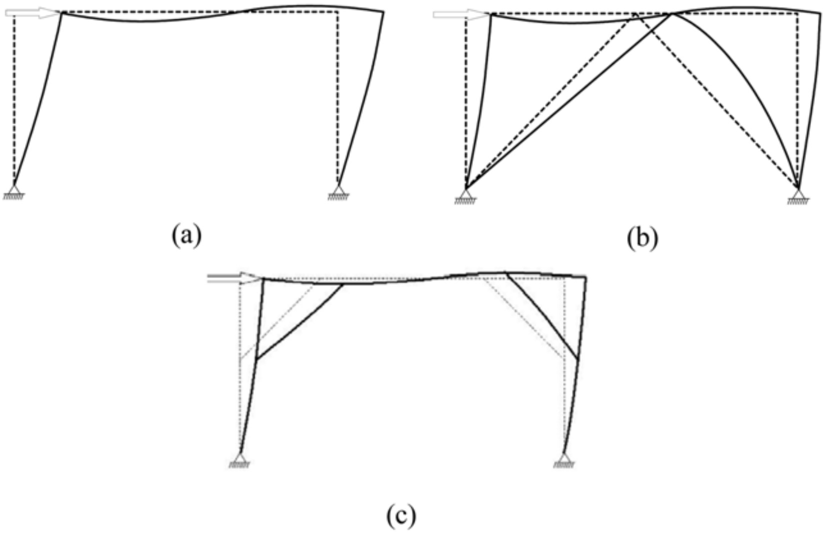

Fig. 1 Description of framed structures subjected to lateral load: (a) steel moment resisting frame; (b) braced frame; (c) knee braced frame

For this purpose, a modified structural form that adopts knee brace elements in the corner regions of the beams and columns, namely knee braced moment resisting frame (KBRF), as shown in Fig. 1(c), is considered in this study. In general, the application of knee braces to the steel frames reduces the lateral displacement of the structure due to enhanced structural stiffness. The design requirements for the brace member strength in KBRF, as stipulated in the designs of braced frames, can be eased as the knee brace member length is smaller than those used in braced frames. Fig. 2 shows the stress distribution along the KBRF structural members. It can be found from the figure that the plastic hinges in the SMRF frames shifted from the critical beam-to-column connection regions to locations where knee braces and beams joined. This characteristic prevents the brittle fracture of beam-to-column connections, reduces

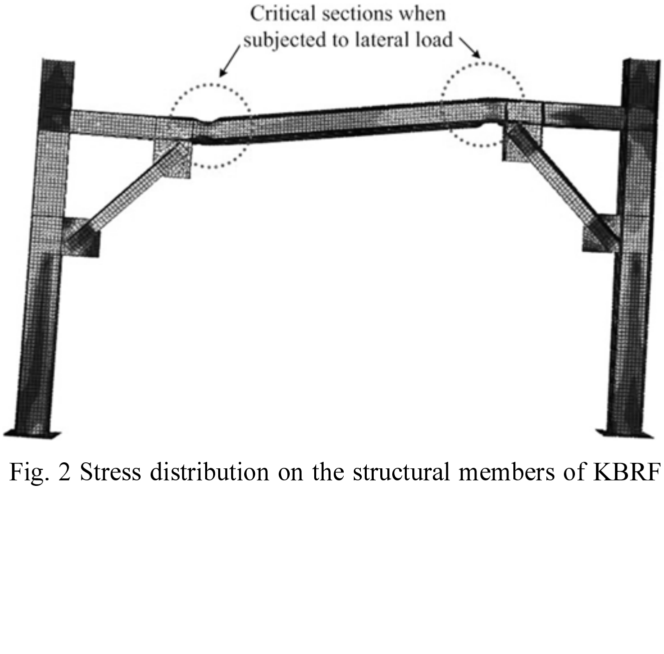

Fig. 2 Stress distribution on the structural members of KBRF

the demand in the connection designs, and provides possible energy dissipation mechanisms in the shifted plastic hinge zones.

In this regard, an energy dissipation mechanism that consists of reduced section plates in conjunction with knee braces, is proposed in this study so that the seismic performance of steel framed structures could be further enhanced. This study focused on experimental evaluation of the seismic performance of steel knee braced moment resisting frame with an energy dissipation mechanism. A series of cyclic load tests were conducted on the SMRF and KBRF structures with various energy dissipation plates. The relationships between the energy dissipation devices and the structural performance were quantitatively investigated so that design references could be established.

2. Experimental program

2.1 Specimens

Seven steel frames, including two SMRFs and five KBRFs, were fabricated for testing. One of the two SMRFs was designed to be semi-rigidly connected. The other was rigidly connected. Rigid beam-to-column connections for the SMRF were fabricated using full penetration welds. The semi-rigid connections were composed of steel angles and high strength bolts. The beam and column sections used in all test frames were ASTM A-36 H175 × 175 × 7.5 × 11, and H244 × 175 × 7 × 11, respectively. Knee brace members used in the KBRF tests were composed of a pair of ASTM A-36 L100 × 100 × 13 angles. The brace members were designed to maintain elasticity during the loading process, so that inelastic behavior can be limited to the replaceable energy dissipation plates. The five KBRFs were composed of identical beam-to-column connections, as those used in the semi-rigid SMRF, except that the beams for the former were cut at locations where the knee braces and beams joined.

Five types of ASTM A-36 energy dissipation plates with various thicknesses and different reduced sectional geometries were fabricated and used to connect the segmented KBRF beams. The energy dissipation plates were installed with high strength bolts. This selection was made to establish comparison datum between the SMRFs and the KBRFs, to investigate the feasibility of reducing design requirements of connections in KBRFs, and to investigate the effectiveness of the proposed method. For clarity, the steel moment resisting frames (SMRFs) were abbreviated to SF series, and the steel knee braced moment resisting frames (KBRFs) were denoted KF series, respectively. The specimen details are described in Table 1 and shown in Fig. 3.

Table 1 Specimen labels and details

Specimen	Beam-to-column connections	Knee brace	Energy dissipation plates			
			b_e (mm)	t_e (mm)	L_e (mm)	Cross-sectional area (mm^2)
MF-S	Semi-rigid	N.A.	N.A.	N.A.	N.A.	N.A.
MF-R	Rigid	N.A.	N.A.	N.A.	N.A.	N.A.
KF120 × 12	Semi-rigid	2L100 × 100 × 13	120	12	150	1440
KF140 × 12	Semi-rigid	2L100 × 100 × 13	140	12	150	1680
KF160 × 12	Semi-rigid	2L100 × 100 × 13	160	12	150	1920
KF140 × 14	Semi-rigid	2L100 × 100 × 13	140	14	150	1960
KF120 × 16	Semi-rigid	2L100 × 100 × 13	120	16	150	1920

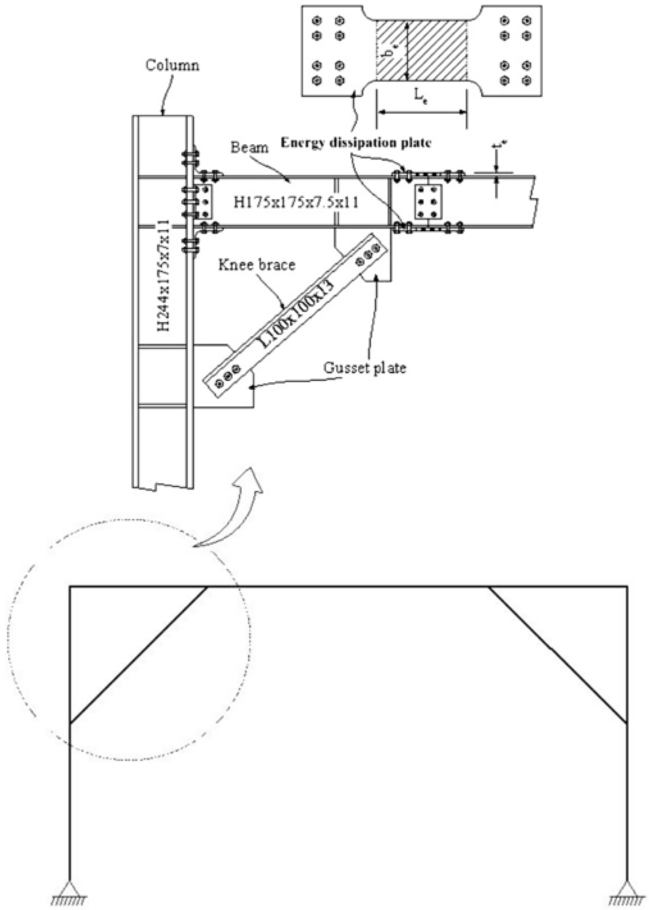

Fig. 3 Specimen details

2.2 Test set-up

Performance of each frame structure was evaluated using the cyclic loading test. A servo-controlled hydraulic actuator, driven under a series of increasing displacement commands, was attached to the test frame at the beam level. The column bottoms of the test frames were hinged to a stiffened floor beam that was fastened to the strong floor. The structural responses of each test frame were measured using installed stain gages, displacement transducers and tiltmeters, respectively. The test results were recorded using data acquisition system and personal computer, and were used for later comparisons. Lateral support systems were provided in the center portion of the test frame so that out-of-plane instability could be prevented. The test set-up and the loading history are shown in Figs. 4 and 5, respectively.

3. Failure patterns

For rigid SMRF structure subjected to cyclic load, yielding was first observed at the beam flanges near the beam-to-column connection regions. Although significant structural ductility was achieved

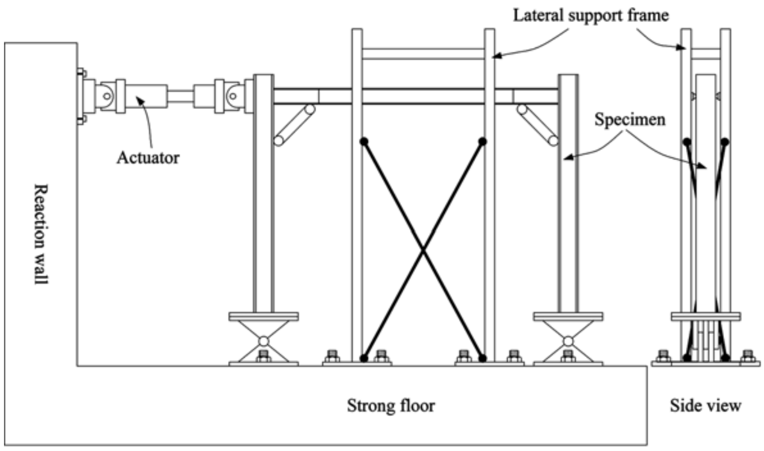

Fig. 4 Test set-up

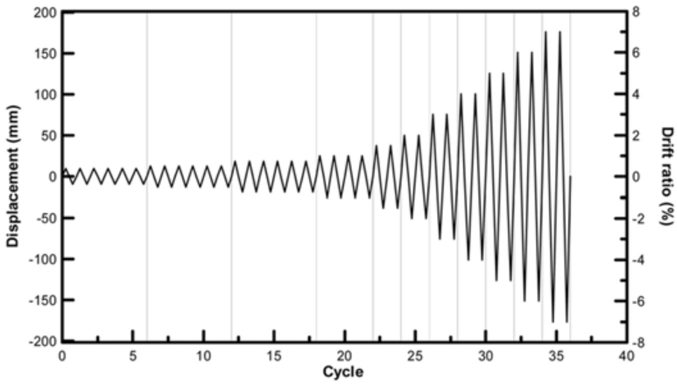

Fig. 5 Loading history

during the test, brittle fracture of the welds due to heavy stress concentration was also observed at large deformation. Similarly, for semi-rigid SMRF subjected to lateral load, the top and bottom angles that connected the beam and the columns deformed due to excessive stress. These phenomena led to significant reduction in strength, energy dissipation and validated the importance of alleviating the beam-to-column connection design demands.

For KBRF subjected to cyclic loads, a load-deformation relationship similar to that in SMRF at the elastic stage was observed, except that the former exhibited higher strength and stiffness. Yielding of the bottom energy dissipation plate located at the beam-brace connection regions was observed when the drifts were increased, approximately at 0.5%. Since the energy dissipation plates were designed with prescribed reduced sections, inelastic behavior in the structure was limited to those plates and the rest of the structural members remained intact. Fig. 6 shows the typical deformation mode of the proposed KBRF frame. At these stages, plate elongation and shortening occurred when subjected to alternating tensile and compressive stresses when the cyclic load was applied. This phenomenon led to stable energy dissipation through plastic plate deformation. This energy dissipation mechanism was

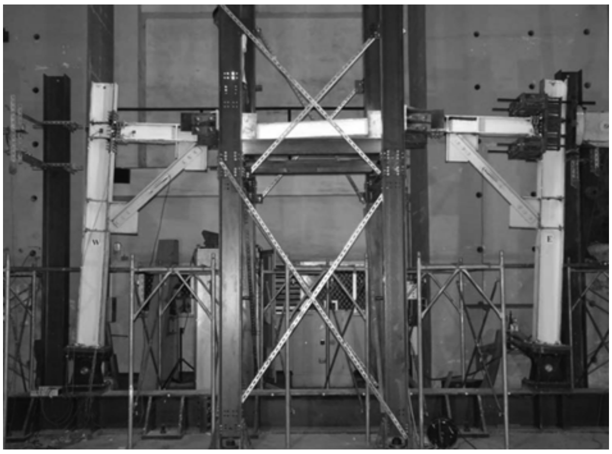

Fig. 6 Typical deformation mode of the proposed KBRF

sustained when the plates remained functional. Failure modes in the energy dissipation plates are shown in Fig. 7.

4. Comparisons and interpretations

4.1 Strength and stiffness

Fig. 8 shows the load-deformation relationships of the tested frame structures. It can be found from Fig. 8(a) and 8(b) that both semi-rigid and rigid SMRFs exhibited significant deformation capabilities. However, the strength of the former was less than that of the latter. This characteristic justified the importance of beam-to-column connection rigidity to the structural performance of steel moment resisting frames. For framed structures that require connections with sufficient rigidity, e.g. rigid joints, design costs and fabrication feasibility would be important concerns, as high construction costs hamper

(a) (b)

Fig. 7 Failure modes of the energy dissipation plates: (a) buckling under compression; (b) yielding under tension

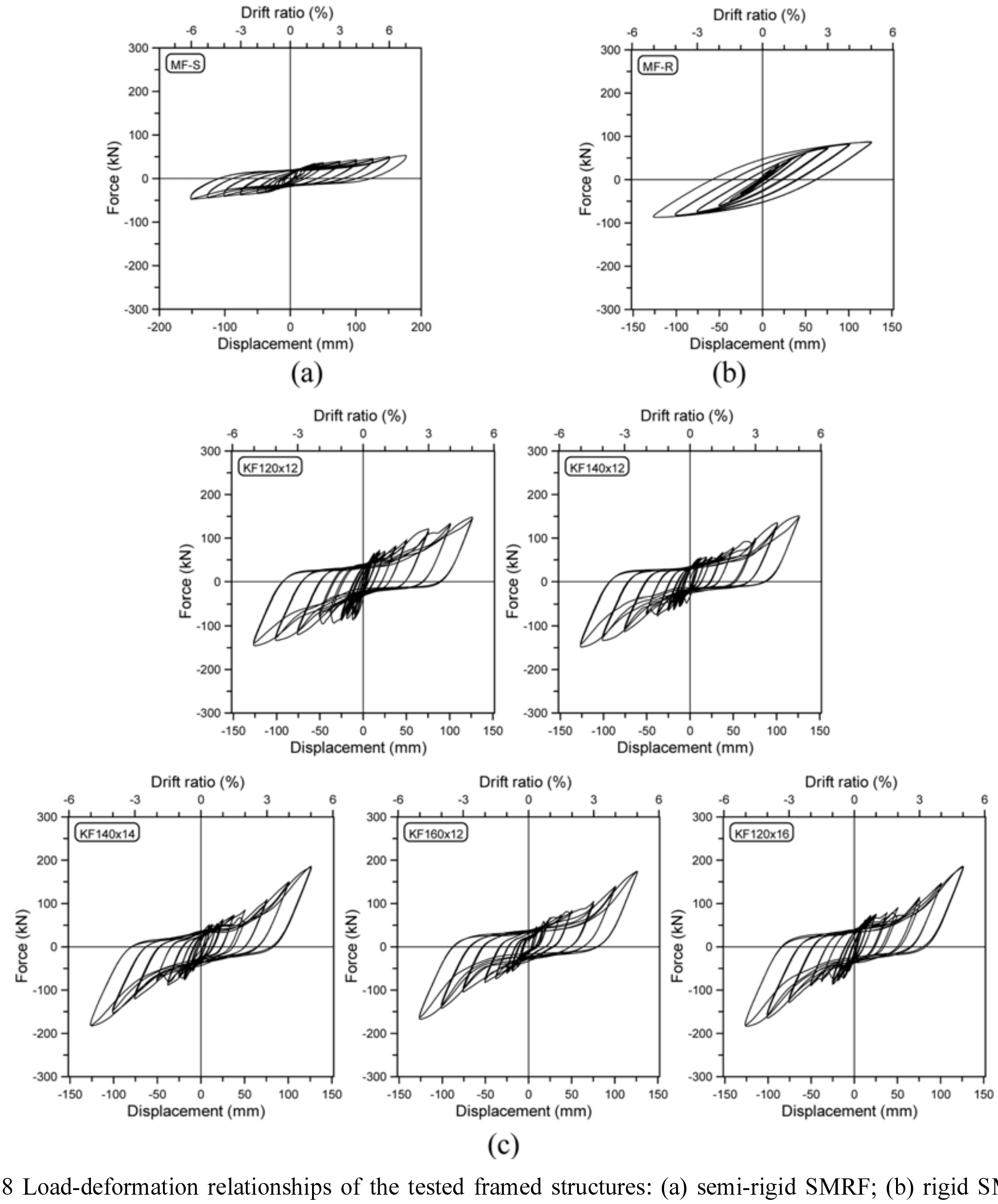

Fig. 8 Load-deformation relationships of the tested framed structures: (a) semi-rigid SMRF; (b) rigid SMRF; (c) KBRFs with different energy dissipation plates

design competitiveness and inevitable heavy stress concentration leading to fracture at the connection welds limits the deformation capability of the system. Although the performance of the rigid SMRF structure was validated by the results shown in Fig. 8, the fracture at the welds also verified the necessity for a remedy to reduce the fracture potential in the beam-to-column connection so that performance enhancement in the steel framed structure could be achieved.

This concern was resolved using the proposed KBRF with energy dissipation devices. As shown in Fig. 8(c), the KBRF structures exhibited significant strength and stable hysteretic behavior during load application. It was further observed from the strength comparisons between SMRFs and KBRFs, as shown in Fig. 9, that significant improvement in strength was achieved when knee braces and energy dissipation plates were used. For example, the lowest yield strength and elastic stiffness of the KBRF structures, i.e., KF120 × 12, were approximately 1.60 and 1.57 times those of the rigid SMRF with the same column and beam sections, even though the former was only designed with semi-rigid connections. The comparisons validated the feasibility of the proposed design, as reduction in connection design requirements and enhancement in structural performance were simultaneously accomplished.

4.2 Deformation of the beam-to-column connections

Fig. 10 compares the relative deformation between the beam-to-column connections for typical KBRF and SMRFs with semi-rigid and rigid connections, respectively. It can be found from the comparisons that the rigid connections were effective in restraining the deformation between the beams and columns. It is also observed that excessive deformation at beam-to-column connection resulting in lower structural strength, as shown in Fig. 8(a), was exhibited in the semi-rigid SMRF structure. This phenomenon validated the necessity of maintaining connection integrity in the designs of SMRF. This demand could be alleviated in the design of the proposed KBRF. As shown in Fig. 10, the deformation of the semi-rigid connections in the tested KBRF was approximately 1/7 of that of a SMRF with identical semi-rigid connections; and was slightly less than that of a SMRF designed with rigid connections. The comparisons validated the efficiency of the proposed KBRF designs.

4.3 Energy dissipation capacity

The energy dissipations of the test frames were compared to further define the structural performance.

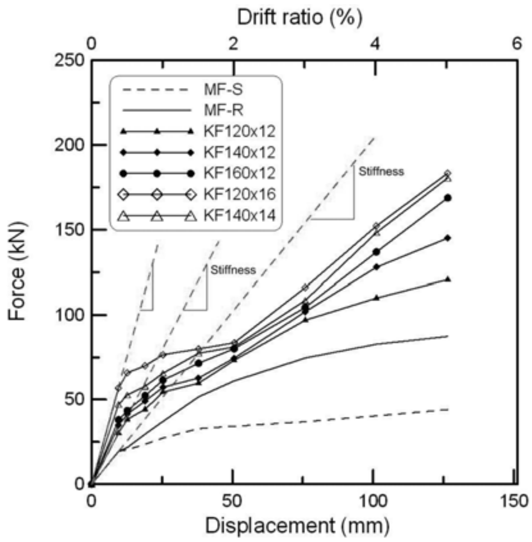

Fig. 9 Comparisons of strength and stiffness of the tested framed structures

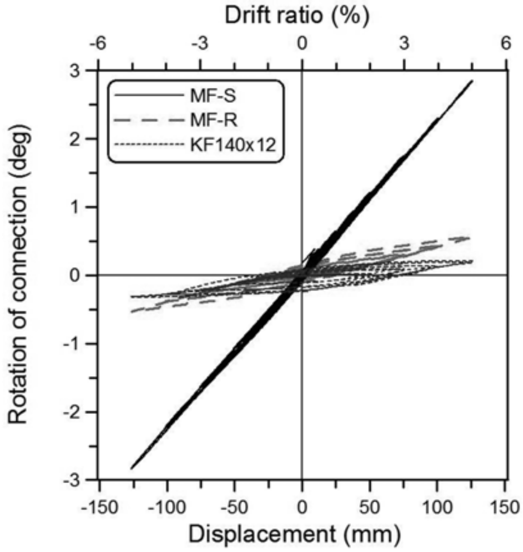

Fig. 10 Comparisons of deformation of beam-to-column connections

Energy dissipations were evaluated using the cumulative hysteretic loop areas of the test structures. Fig. 11 compares the energy dissipations of the SMRFs, the KBRFs with energy dissipation plates of similar cross-sectional areas and different plate thicknesses; and KBRFs with energy dissipation plates of the same thickness, however various cross-sectional areas, respectively. It can be found from the figure that the energy dissipation capabilities of the KBRFs, regardless of the geometries of the energy dissipation plates, were higher than those of the semi-rigid and the rigid SMRFs. For example, the cumulative

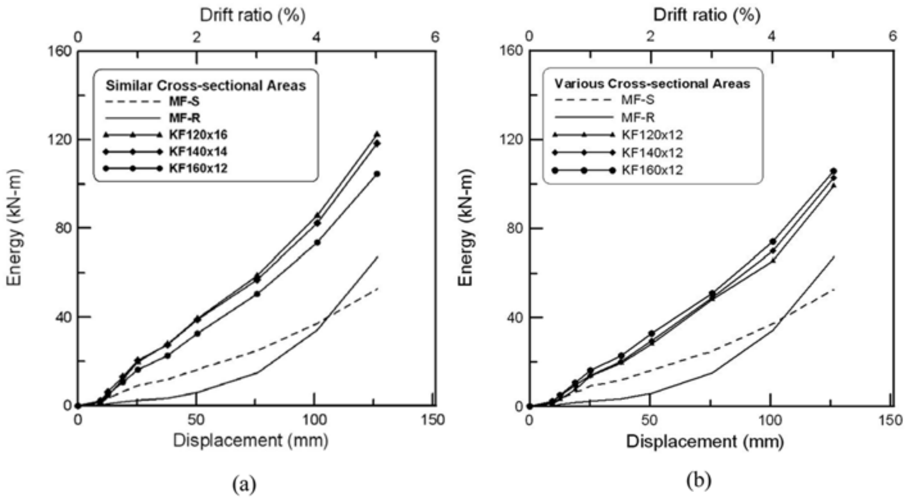

Fig. 11 Comparisons of energy dissipation for the tested framed structures: (a) KBRFs with energy dissipation plates of similar cross-sectional areas; (b) KBRFs with energy dissipation plates of various cross-sectional areas

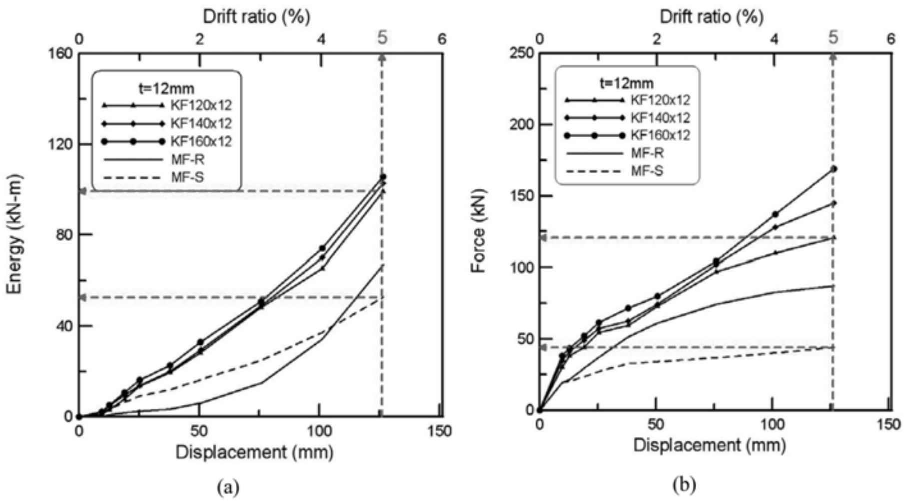

Fig. 12 Correlation for performance evaluation: (a) energy dissipation; (b) strength

energy dissipation of the test frame KF120 × 12 was approximately 88% higher than that of the semi-rigid SMRF, when the structures reached 5% drift. It was also found from further examination that the energy dissipation enhancements were higher for KBRF frames equipped with thicker energy dissipation plates, even though the plates possessed similar cross-sectional areas. This is attributed to the higher flexural rigidity in the energy dissipation plates when thicker plates were used.

Fig. 12 further correlated the energy dissipation and the strength for the tested SMRFs and KBRFs. It can be observed from the comparisons that larger energy dissipation and also higher strength was sustained in the proposed KBRF designs. The above phenomena justified the effectiveness of the proposed method in the seismic design of steel framed structures.

5. Analytical model for performance evaluation

A finite element tool, ABAQUS (2006), was adopted to effectively evaluate the bearing behavior of KBRF structures with energy dissipation mechanism. In general, the simulation processes for framed structures requires large numbers of computations because the structural responses calculations involve complicated nonlinear behavior among the thin-walled members (Cavdar *et al.* 2009, Kim and Park 2008, Longo *et al.* 2008, Saravanan *et al.* 2009, Vu and Leon 2008, Yoo *et al.* 2009). However, for the proposed knee braced frame system, nonlinear behavior was concentrated at the designated energy dissipation mechanism and the major structural components, such as beams and columns, remained intact. Therefore, a simplified analytical model that assumes elastic beams and columns, approximating the energy dissipation mechanism using a rotational spring, as shown in Fig. 13, is proposed in this study.

Fig. 14 shows the measured moment-rotation relationships of the proposed rotational springs for the test specimens. It can be found from the figure that similar moment-rotation relationships were exhibited in the tested KBRFs. This relationship can be approximated, as shown in Fig. 15, using tri-linear segments, K_1, K_2 and K_3, which represent the stiffness of the rotational spring at elastic, and various inelastic stages, respectively. The above-mentioned stiffnesses for the test specimens are listed in Table 2, and can be approximated using the following expressions

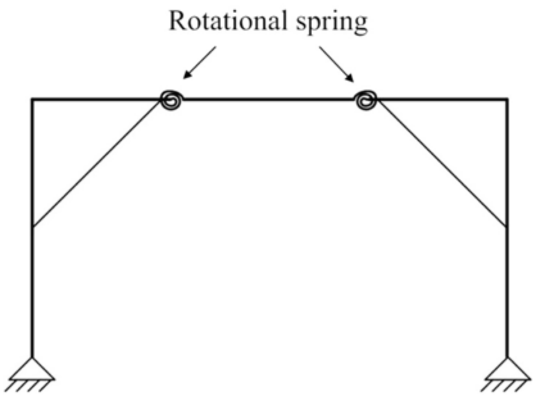

Fig. 13 Modeling of the energy dissipation mechanism

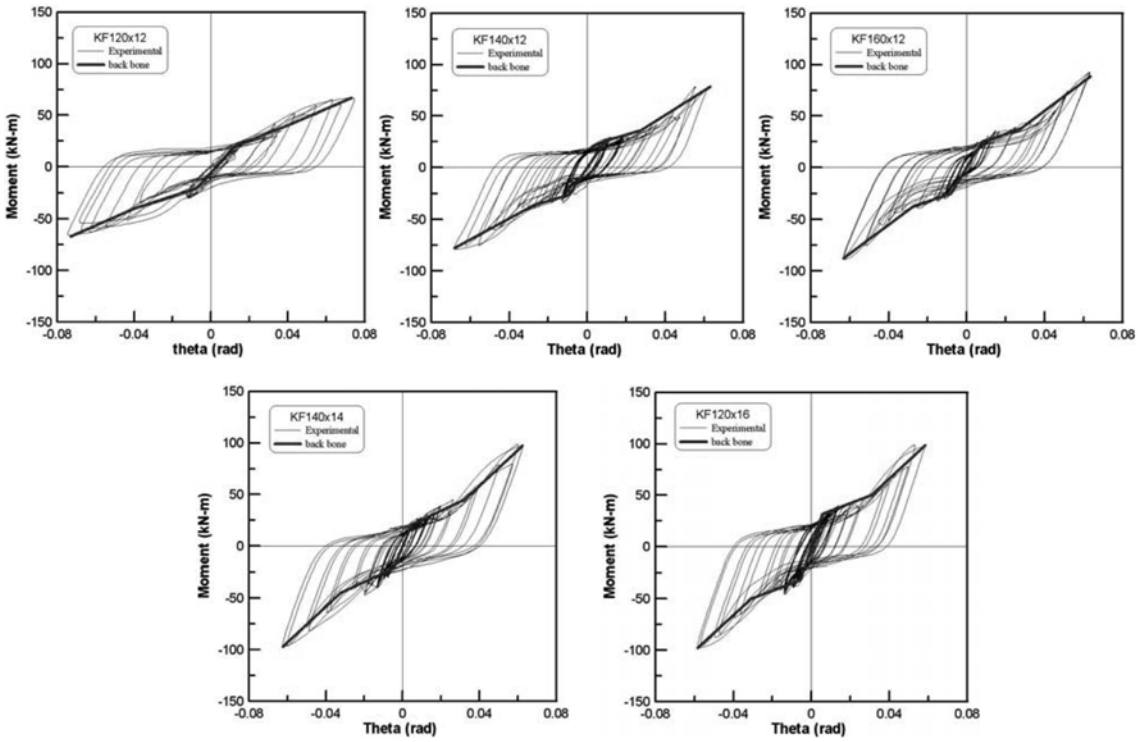

Fig. 14 Moment-rotation relationship of the tested KBRFs

$$K_2 = 0.2\ K_1 \tag{1}$$

$$K_3 = 0.4\ K_1 \tag{2}$$

These relationships were adopted in the analysis tool, ABAQUS, to evaluate the effectiveness of the simplified model in predicting the structural responses of knee braced frames with energy dissipation

Table 2 Effectiveness of the proposed analytical model for KBRFs

Specimen	K_2/K_1	K_3/K_1	W5e (kN-m)	W5a (kN-m)	Discrepancy in energy dissipation (%)
KF120 × 12	0.212	0.390	15.43	16.80	8.13
KF140 × 12	0.203	0.396	16.56	17.72	8.11
KF160 × 12	0.199	0.403	17.07	18.54	7.95
KF140 × 14	0.201	0.399	19.46	21.05	7.57
KF120 × 16	0.190	0.408	19.94	21.66	7.98

Notes:
1. K_1 represents the elastic stiffness of the structure.
2. W5e represents the energy dissipation of one cycle at 5% drift evaluated by the test results.
3. W5a represents the energy dissipation of one cycle at 5% drift evaluated by the analytical results.

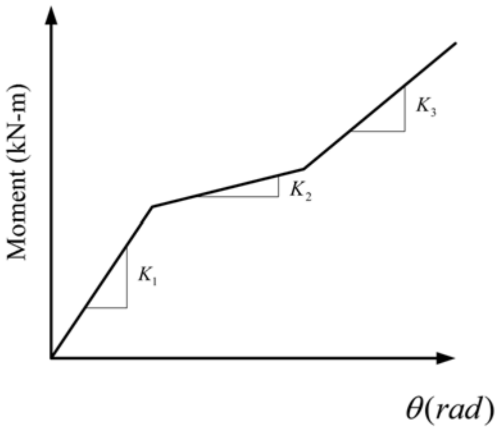

Fig. 15 Tri-linear approximation for the stiffness of the rotational spring

mechanisms. The flow chart of the analytical model is shown in Fig. 16.

Fig. 17 compares the strength envelops between the test results and the results obtained from the proposed method. Comparisons of the hysteretic behavior between the experimental and analytical results are also shown in Fig. 18. It can be found from the above-mentioned figures and from the comparisons listed in Table 2, that results with adequate accuracy were achieved. For example, the discrepancies in strength and energy dissipation were approximately 3% and 8%, respectively, when the structures were subjected to 5% drift. The above-mentioned parameters can be used for engineering practice and can be further refined to improve the accuracy of the model when more test information becomes available.

6. Conclusions

This paper presented test information on steel moment resisting frames and steel knee braced moment resisting frames with energy dissipation mechanisms. The relationships between structural performance and the proposed design details were evaluated. Test results validated that the demand in the beam-to-column connection designs was alleviated by the proposed method. Test results also showed that the

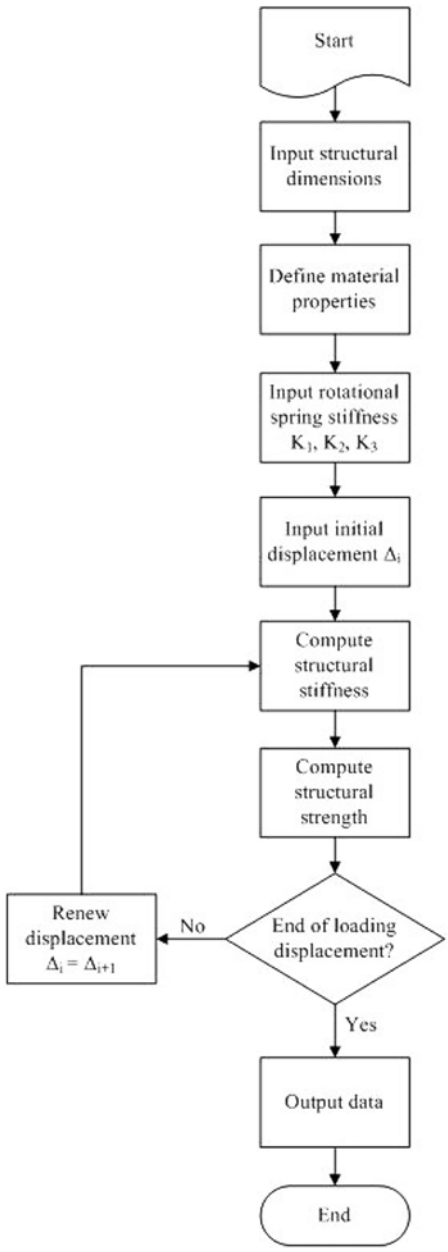

Fig. 16 Flow chart of the analytical model

strength and stiffness of the proposed design were effectively enhanced. Comparisons in energy dissipation between the steel moment resisting frames and the steel knee braced moment resisting frames with energy dissipation plates justified the applicability of the proposed method. Finally, a simplified yet effective analytical model for the performance evaluation of the steel knee braced frames was proposed for engineering practices.

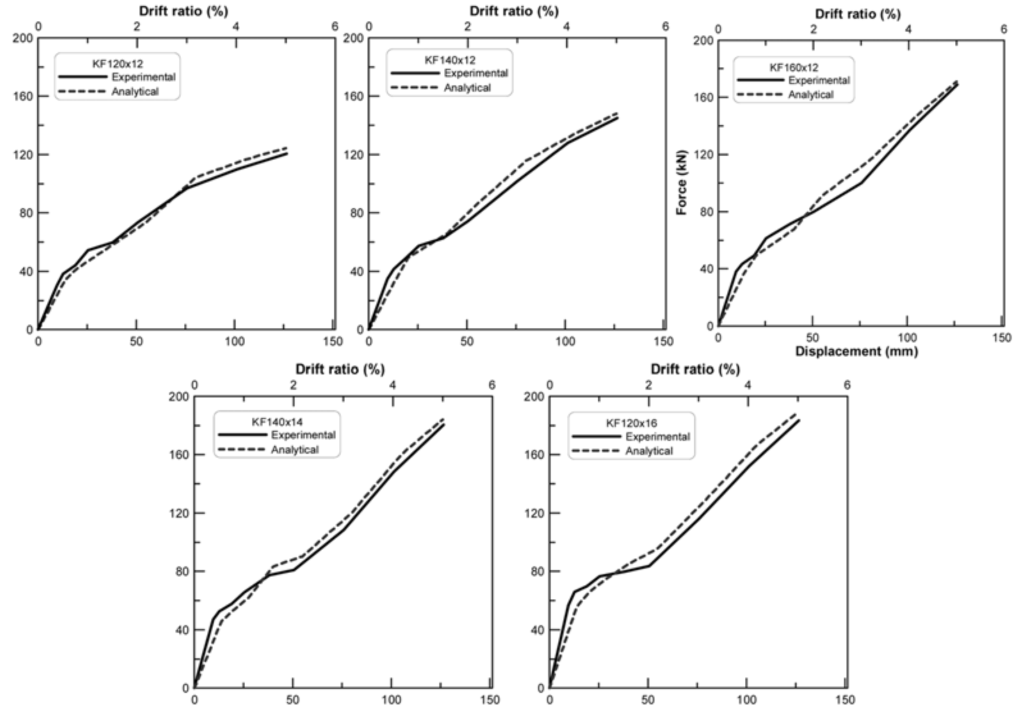

Fig. 17 Comparisons of strength envelops between the experimental and analytical results for the tested KBRFs

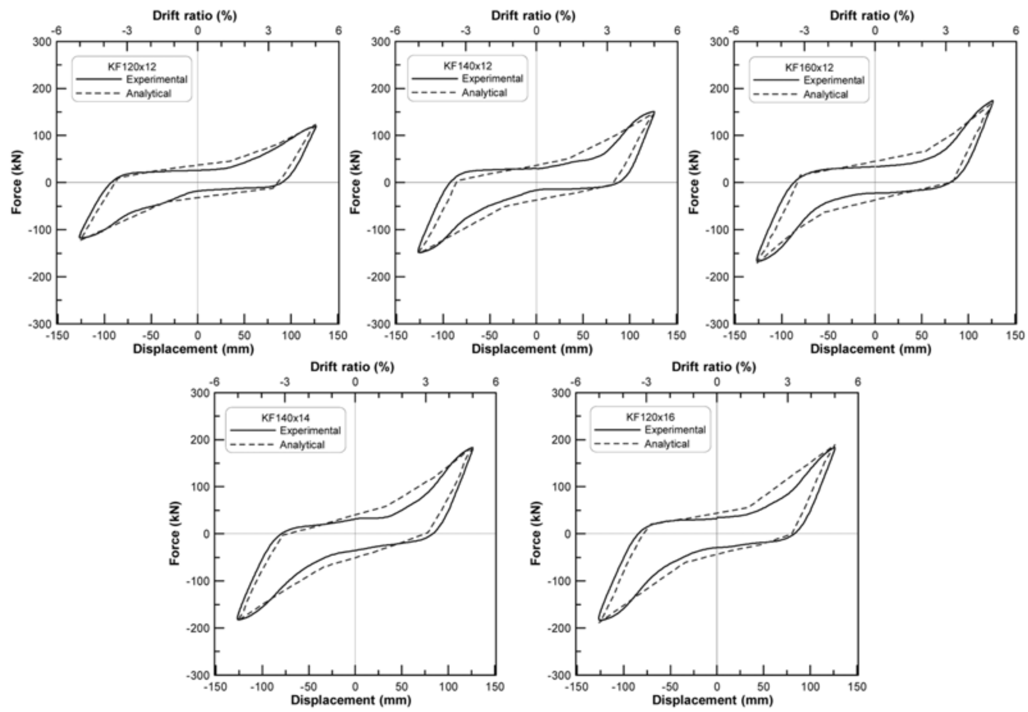

Fig. 18 Comparisons of hysteretic behavior between the experimental and analytical results for the tested KBRFs

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