Improving Seismic Performance of Steel Knee Braced Frame Structures

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SUMMARY:
This study focused on the experimental evaluation of the seismic performance of steel knee braced moment resisting frame with stiffened steel slit walls. A series of cyclic loading tests were conducted on the steel moment-resisting frame and knee braced moment resisting frame structures with various arrangements of the above-mentioned energy dissipation devices. It was found from the tests that the strength and stiffness of the proposed design were effectively enhanced. It was also validated from the comparisons that the energy dissipation of the knee braced frame structures with energy dissipation mechanisms was significantly higher than that of the moment-resisting frame, which justified the applicability of the proposed method.
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Keywords: steel frames, knee brace, performance, slit wall

1. INTRODUCTION

Steel moment-resisting frames (MRF) possess high strength and significant ductility, thus are effective structural forms for earthquake-resistant designs [Saravanan et. al. 2009; Tremblay et. al. 2003; Kim et. al. 2002]. However, excessive drift in the MRF structure due to higher structural flexibility might be a parameter that limits the applicability of the design. In order to improve the seismic performance of the steel frame structure, a modified form that adopts knee brace elements in the corner regions of the beams and columns, namely knee braced moment resisting frame (KBRF), is proposed in this study.

In general, the application of knee braces to the steel frame is capable of reducing the lateral displacement of the structure [Longo et. al. 2008; Yoo et. al. 2009] . Furthermore, the locations with maximum stress in the MRF frame could be shifted from the critical beam-column connections to the areas where knee braces and beam joins. This characteristic not only prevents the brittle fracture and reduces the demand in the beam-column connection design, but also provides a possible energy dissipation mechanism between the beam and the knee brace member. In this regard, an energy dissipating mechanism that consists of stiffened steel slit walls and knee brace members is proposed to further improve the seismic performance of the KBRF structures.

This study focused on the experimental evaluation of the seismic performance of steel knee braced moment resisting frame with stiffened steel slit walls. A series of cyclic loading tests were conducted on the steel moment-resisting frame and knee braced moment resisting frame structures with various arrangements of the above-mentioned energy dissipation devices. Performance of the frame structures was compared to evaluate the effectiveness of the proposed method.

2. EXPERIMENTAL PROGRAM

In order to evaluate the effectiveness of the proposed method in improving seismic performance of the frame structures, a series of cyclic loading tests on the stiffened steel slit walls, MRF and KBRFs were conducted. The slit walls were composed of 3mm-thick A-36 thin plates with laser-cut slits of various widths in-between. Two stiffened plates were added to the two ends of the slit walls to increase the out-of-plane stability of the devices. Specimen categorization and sectional details of the stiffened slit walls were shown in Figure 1 and listed in Table 1. The results from the cyclic loading tests of stiffened slit walls were used to define the characteristics of the proposed devices. Further tests on the frame structures, including one MRF and two KBRFs with various stiffened slit wall compositions, were conducted to validate the feasibility of the proposed method in practice.

Table 1. Specimen Details

Specimen	No. of slits	ls (mm)	bs (mm)
A-S5	5	180	33
A-S4	4		41.8
A-S3	3		56.4
A*-S5	5	120	33
A*-S4	4		41.8
A*-S3	3		56.4

The dimensions of the beam and columns for both MRF and KBRFs were identical. They were A-36 H175x175x7.5x11 and H250x250x9x14, respectively. Each beam was welded to a pair of end plates and was fastened to the columns by high strength bolts. For each KBRF, a group of four stiffened slit walls were attached to the frame by a pair of A-36 H100x100x6x8 knee braces and a transition beam. KBRFs equipped with A-S5 and A*-S5 slit walls were labeled FA-S5 and FA*-S5, respectively. All experiments were tested under cyclic load that was generated by a servo-controlled hydraulic actuator. The cyclic load was generated by a series of prescribed increasing displacement commands. The test set-up and loading history are shown in Figure 2 and Figure 3, respectively.

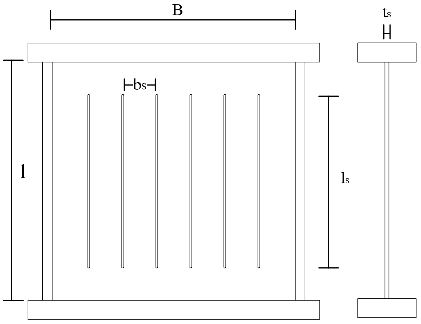


Figure 1. Description of stiffened slit wall

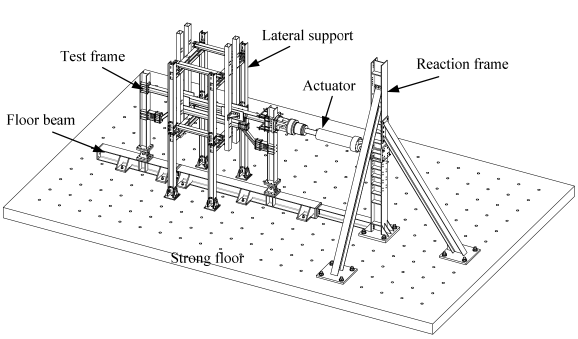


Figure 2. Test set-up

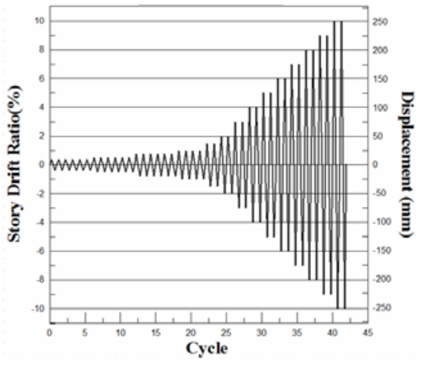


Figure 3. Loading history

3. OBSERVATIONS

3.1 Stiffened Slit Walls

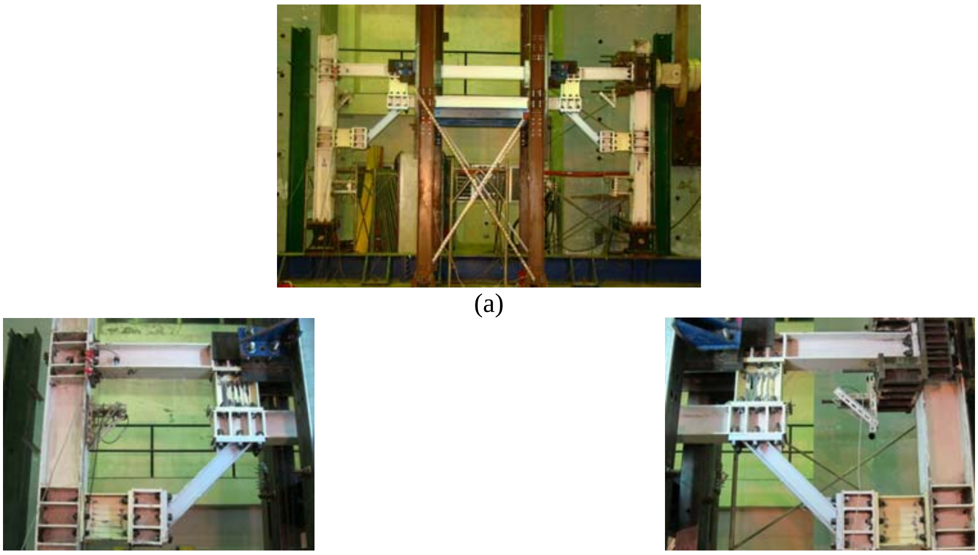
Figure 4 shows the failure patterns of the stiffened slit walls. It was observed from the tests that the stiffened slit walls exhibited stable hysteretic behavior and the failure of the devices started from the plate yielding at the corner of the slit cut due to stress concentration. Since the slits were subject to flexural stress when the device was laterally excited, flexural-torsional buckling of the slits was observed due to extensive stress at large deformation. The distorted slits deteriorated when the lateral deformation increased. Sequential fracture of slits due to fatigue was observed during the loading processes.

(a) (b)

Figure 4. Failure of stiffened slit wall: (a)yielding; (b)lateral-torsional buckling

3.2 Frame Structures

For the KBRF subject to cyclic load, yielding was first observed at the stiffened slit walls attached to the beam when the drift ratio was approximately 0.75%. Subsequent yielding of the slit walls at column locations followed when the frame drift ratio reached 1.5%. The major structural members, i.e. beam and columns, stayed elastic until the frame reached 3% drift. The characteristics validated the effectiveness of the design as the damage was effectively contained at the designated location, while the frame system remained intact within the desired service level. Figure 5 shows the responses of KBRF subject to lateral load.



(a)

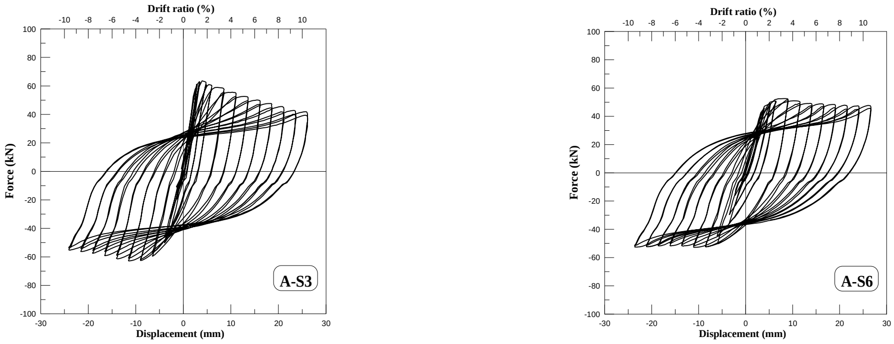
(b) (c)

Figure 5. Responses of KBRF: (a) front view; (b)yielding of slit wall at west side; (c)yielding of slit wall at east side.

4. COMPARISONS OF PERFORMANCE

4.1 Strength

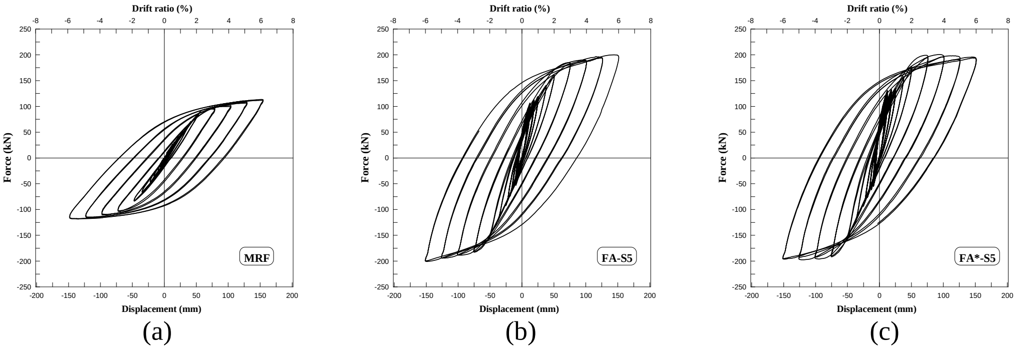
Figure 6 shows the typical hysteretic relationships for the stiffened slit walls. It can be found from the figure that significant energy dissipation mechanism was exhibited. It can also be observed that the strength and the post-buckling strength deterioration varied when the dimensions, particularly the length/width ratios (*ls/bs*), of the slits were different. For example, the strength of A-S3, which was 61kN, was higher than that of A-S6, i.e. 43.2 kN, however, the strength deterioration of the former was much larger than that of the latter. This phenomenon could be attributed to the length/width ratios of the slits as plates would exhibit higher deformation before buckling when the length/width ratios were larger. Therefore, the length/width ratios of the stiffened slit walls should be adequately adjusted so that the performance could be optimized.



(a) (b)

Figure 6. Typical hysteretic relationshops: (a)A-S3; (b)A-S6.

Figure 7 shows the hysteretic curves of the test frames. It can be found from the figure that both MRF and KBRFs exhibited significant hysteretic behavior. However, the strength of the latter was significantly larger than that of the former. The gains in strength were approximately 100% to 130%. This phenomenon, along with the adequate deformation capability, validated the effectiveness of the proposed KBRF structures with stiffened slit walls.

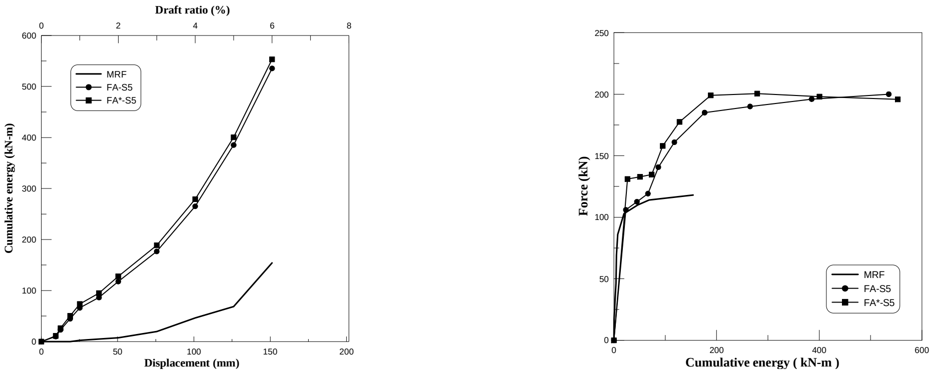


(a) (b) (c)

Figure 7. Hysteretic curves of the test frames: (a)MRF; (b)FA-S5; (c)FA*-S5

4.2 Energy Dissipation

Figure 8(a) compares the energy dissipation between MRF and KBRFs. The energy dissipation was evaluated by the cumulative areas of the hysteretic loops. It can be found from the figure that the energy dissipation capability of the KBRFs was significantly larger than the MRF. Further comparison of structural performance was made by correlating the structural strength and the energy dissipation of the test frames, as shown in Fig. 8(b). It can be observed from the figure that the KBRFs simultaneously sustained higher strength and larger energy dissipation than the MRF. These characteristics are particularly important to the seismic performance of frame structures, as adequate strength to sustain structural stability must be guaranteed while dissipating large seismic energy.



(a) (b)

Figure 8. Performance of the test frames: (a)cumulative energy;
(b)correlation between energy dissipation and strength

4.3 Beam-Column Joint Behavior

Figure 9 compares the bending moments at the beam ends of the test frames. The bending moment was measured by the strain gauges installed at the beam flanges. It was found from the figure that the moment at those regions increased when the frame drifts were increased. It could also be observed from the figure that the drift at which beam-column joint of MRF reached the yielding state, approximately 1.5%, was much smaller than those of the KBRFs. This phenomenon complied with the design concepts, i.e. restrained damage at the designated locations while maintained the integrity of the major structural members, thus further justified the effectiveness of the proposed method.

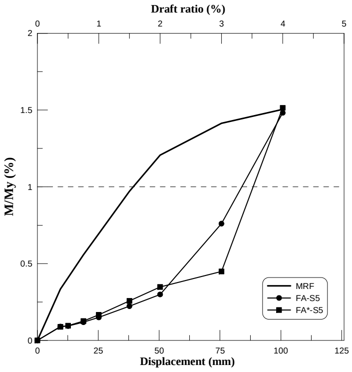


Figure 9. Bending moment at the ends of the beams

5. CONCLUSIONS

This paper investigated the seismic performance of steel knee braced frame structures with stiffened slit walls. A series of tests on the stiffened slit walls with various slit dimensions, MRF and KBRFs with stiffened slit walls were conducted under cyclic load. It was found from the tests that the stiffened slit walls were capable of developing ductile hysteretic behavior. It was also observed that the strength and stiffness of KBRFs with the proposed stiffened slit walls were effectively enhanced. Comparisons of energy dissipation between KBRFs and MRF indicated that the former structures possessed higher seismic resisting capability than the latter, which justified the applicability of the proposed method.

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