16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 2440

Registration Code: S-0000016200

TESTING A REPAIRABLE LATERAL RESISTING SYSTEM APPLIED TO BRACED STEEL FRAMES

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Abstract

A seismic upgrading technique using the steel ring connection (SRC) was presented to enhance the lateral ductility, energy-dissipation and damping potential of the existing frame systems. The SRC system performed as a repairable energy-dissipating device and was used with X-braces in the steel frames. Experimental studies were conducted on SRC system to evaluate the performance of the proposed system for upgrading the behavior of the steel frames. The proposed technique consisted of the X-bracing system with a steel ring element at the mid-point connection. The lateral load on the frame was allowed to transfer to the steel ring element through the braces. The lateral displacement of the braced frame caused yielding of the SRC in bending deformation mechanism and dissipated energy due to forming of plastic hinges in the ring in reversed cyclic deformations. No extensive retrofitting of the existing frame members was required for the proposed technique. In order to investigate the effectiveness of the proposed system on the cyclic response of the frame and study of performance of the SRC as energy-dissipating device, a series of quasi static cyclic tests were conducted on a full-scale single storey steel frame. The frame was upgraded with proposed system consisting of X-braces and the SRC. Two types of braces were used and studied for the proposed system: 1) Tension only rods which caused the SRC laterally deformed in tension in each half cycle, and 2) Hollow section tube (tubular brace) which made the SRC deformed in both tension and compression periodically in each cycle. A benchmark test was carried out on each brace type with no SRC (regular braced frame). Hysteretic load-deformation response, lateral strength, stiffness, equivalent effective damping and dissipated energy in reversed cyclic motions were compared for the upgraded braced frame and the regular system in both brace types. The upgraded braced frames with SRC exhibited enhanced energy-dissipation and damping potential as compared to the regular system. SRC system showed more stable hysteresis loops than the regular braced frames. This experimental study confirmed that the SRC is an excellent energy-dissipation device and the proposed technique is a suitable concept for use in the existing buildings to reduce the damage level in the frame members in high-risk seismic zones.

Keywords: steel ring connection; energy dissipation; damping; tension-only-brace system; experimental studies

1. Introduction

In designing structures for seismic loads, it is assumed that part of the seismic input energy is absorbed by specially designed structural elements through plastic deformation or hysteretic behavior. Examples of these plastic energy absorbing elements are plastic hinges forming in beams of rigid frames, in concentric braces and in shear walls. Passive control systems increase the energy dissipation capacity of a structure by using devices installed either at the base of the structure (as seismic isolation system) or at the floor levels. The objective is to absorb the seismic input energy as much as possible, thus reducing the force and displacement demand and damage to gravity-load carrying members. Passive control systems may also increase lateral stiffness and/or strength of structures Main advantages of passive systems over active and semi-active systems are their simplicity, low cost and ease of installation and replacement after an earthquake. The application of passive control systems is rapidly increasing throughout the world both in new construction and seismic retrofitting of existing buildings [1,2,3].

Different mechanisms such as yielding of metals, phase transformation of metals, friction, deformation of viscoelastic materials and fluid orificing have been used by researchers to develop several passive energy dissipation devices during the last four decades. Among these mechanisms, yielding of metals is one of the most effective, simple and economical mechanisms to dissipate earthquake input energy. Balendra conducted several works in this area from 1990 to 1997. X-shaped steel plates as flexural fuses are the other types of these elements which take advantage of uniform yielding of steel [4]. Kafi and Abbasnia performed a testing program on ductile steel ring elements attached to braces [5]. The ring elements are the new flexural fuses which can be installed in CCBF's. Abbasnia et al. and Wetr et al. conducted some studies on the performance improvement of CCBF specimen which approved the efficiency of this system [6]. Maleki and Mahjoubi studied dual-pipe system in the frame connection and showed the potential of the system in energy dissipation during an earthquake [7].

In this paper, a series of quasi-static cyclic tests on the full-scale steel frame upgraded with the proposed energy-dissipation system is described. The proposed energy-dissipation system is consisting of the X-bracing system with a Steel Ring Connection at the mid-point and has been suggested as a seismic upgrading technique for steel frames. For simplicity, the Steel Ring Connection is referred to as "SRC" in the text, tables and figures. This test program was designed for evaluation of the effect of SRC system on the seismic inelastic response and performance of the steel frames in lateral load condition. A typical building equipped with the SRC system is illustrated in Fig. 1. In the shown system the lateral load on the frame is allowed to transfer to the mid-joint ring element through the braces and the severe deformation zone is concentrated on this element. Therefore, the lateral displacement of the braced frame causes yielding of the SRC in lateral bending deformation mechanism and dissipates energy due to forming of plastic hinges in the ring in reversed cyclic deformations. No extensive retrofitting of the existing frame members is required for the proposed technique [8].

Fig. 1– Concept of adding steel ring connection (SRC) to a typical braced frame

The objectives of this test program were the following: 1) to evaluate the effectiveness of using SRC for upgrading the steel frames with two types of X-braces; tension only rods and hollow section tube (tubular brace); 2) to determine the cyclic performance and mechanical characteristics of the steel frame upgraded with SRC; 3) to compare the inelastic response of upgraded frame with conventional braced frames when subjected to lateral cyclic loads.

2. Description of Test Specimens

Ten SRC specimens with different dimension were prepared for testing program. Each specimen was composed of a steel ring and four couple of steel curved washers. The steel ring with 90mm wide and variable diameter and thickness in different specimens, was cut from steel pipe made of grade 350w structural steel material, conforming to CSA G40-21. Four 22mm dia. holes in 90 deg. center to center spacing were drilled into the side of the ring to let the specimen connect to the braces. The washers were used in couple and including of the inner convex washer with curve radius of 7.5mm; and the outer concave washer with curve radius of 8.4mm, both made up of steel plate (50x90x19mm) with 2mm corner cut and typical c/w 22m dia. hole [9].

The steel ring was assembled in the mid-joint of the X-bracing system by connecting to four individual brace segments. Each segment was connected to the ring directly in the location of the pre-drilled hole. Two types of section were used for bracing system: 19mm dia. tension rod made of grade B7, conforming to ASTM A193/A193M; and HSS 51x51x6.5mm as tubular section made of grade 350w structural steel material, conforming to CSA G40-21. In the tension rod brace system, the end of each rod segment passed through the holes of the outer washer, ring and inner washer, respectively and fixed by torquing two nuts on both sides. In the tubular brace system, a 75x75x20mm steel plate welded to the end of the HSS segment with a threaded hole in the center was used to connect to the ring. A 150mm long ready rod with 19mm diameter was employed to fix into the threaded hole in one end and connect to the ring by the washers and nuts in the other end. A close up view of the SRC specimen and the detailed connections is illustrated in Fig. 2.

To study the effect of the curved washers on cyclic behavior of the SRC, one of the test specimens were assembled without the washers (Test No. 5). To avoid the ring connections being loosed the nuts were tightened by wrench during the test. To investigate the effect of the geometry of the brace system and the accuracy of the ring installation on the behavior of the SRC, one specimen with each type of braces was installed with 100mm off center. (Test No. 1 & 2). This imperfection was created by lengthening of the upper brace segments and shortening of the lower segments that caused the steel ring located 100mm lower than the regular position.

The SRC system was installed in a pre-fabricated steel frame with frictionless pinned corner connections by 3120mm height and 3160mm length. The columns and beam were made up of HSS 127x127x9.5 and HSS 203x152x11, respectively and designed strong enough to avoid any plastic deformation during loading. A preliminary cyclic test prior to bracing and SRC installation showed the frictional force over any displacement cycle reached a maximum of 0.2 kN, and hence the test frame was assumed as a frictionless pinned frame.

Two X-braced systems without SRC were used as benchmark specimens and represented a typical conventional braced frame: Tension rod braces made of A307 structural steel material, conforming to ASTM, passing over each other in mid-point with no connection; and tubular braces made of grade 350w structural steel material, conforming to CSA G40.-21, with regular mid-joint connection consisting of two splice plates (400x100x20) that were welded to the HSS cut segments in longitudinal direction and to the continues HSS segment in transverse direction. Table 1 gives the characteristics and description of each test specimen.

Fig. 2 – Steel ring system fabricated for X brace mid- joint connection

3. Test Setup and Testing Program

A large-scale test setup was built to apply load on the steel test frame and the specimens. The supporting setup consisted of a rigid reaction frame, strong floor, lateral restraint system, loading system and instrumentations. A general view of the test frame and set up is illustrated in Fig. 3.

The rigid reaction frame fixed to strong floor was used to hold the actuator and force the test frame. It was supported with bracing at the location of the actuator in both in-plane and out-of-plane direction to prevent any movement. The test frame was firmly connected to the strong floor at the base plate location using four steel bolts, as well as to the actuator at the beam location by a hinged link.

The test frame was laterally restrained to avoid any eventual out-of-plane movement. The out-of-plane restraint system consisted of two pantographs attached to the test frame. Each was equipped with two steel rods and a hinge shaft. The rods were pin connected to the steel columns located on both sides of the test frame and the hinge shaft was connected to top of the steel beam. The steel beam could freely move between the rods in the north-south direction and the out-of-plane restraint system ensured the applied loading remained in-plane by pulling on four rods each connected to one column.

The load was applied by the hydraulic actuator with a two-way capacity of ±444 kN (200 kips) force and a maximum stroke limit of ±350 mm (14 inches). The actuator was connected to the reaction frame and the corner of the test frame at the location of the beam. It was pinned at both ends to rotate freely in the vertical direction. A 222kN (100 kips) capacity load cell was mounted on the actuator to measure the applied load signal. The displacement was measured by the internal displacement sensor of the actuator directly.

The instrumentations for these experiments consisted of two linear variable differential transformers (LVDT) and two position transducers. The LVDTs were used to control the small movement of the fixed base plates at the bottom of the columns and the position transducers measured the diametric deformations of the steel ring specimen in direction of the braces.

Fig. 3 – Test set-up and general view

To study of behavior of the steel ring connection and its effects on response of the frame cyclic loading were applied on the test frame with different added specimens and different types of braces. The testing program is presented in Table 1 including the specimens' characteristics and type of braces used.

Table 1– Testing Program and Description of specimens

Test No.	Specimen ID	Ring Characteristics			Bracing Type
		Diameter (mm)	Thickness (mm)	Wide (mm)	
1	Ring168x9.25	168	9.25	90	Tension rod
2	Ring168x9.25	168	9.25	90	Tubular
3	Ring168x9.25	168	9.25	90	Tension rod
4	Ring168x7	168	7	90	Tension rod
5	Ring168x7	168	7	90	Tension rod
6	Ring220x8.25	220	8.25	90	Tension rod
7	Ring274x8.75	274	8.75	90	Tension rod
8	Ring168x9.25	168	9.25	90	Tubular
9	Ring220x8.25	220	8.25	90	Tubular
10	Ring274x8.75	274	8.75	90	Tubular
11	Benchmark	No ring			Tension rod
12	Benchmark	No ring			Tubular

A cyclic loading protocol was developed for performing reversed cyclic tests on the steel frame to present the performance of the test specimens for a number of cycles with moderate amplitude demand drift. These tests were displacement-controlled using a gradually increasing displacement at a rate of 1 mm/sec and reached maximum amplitude of 1.5% drift level, which allows for a good comparison of the results among the specimens. To evaluate the potential of the SRC system in low cycle fatigue the repeated cycles with maximum amplitude of 1.5% drift (45 mm) were applied to the frame until the specimen failed. Fig. 4 shows the loading history used for cyclic testing.

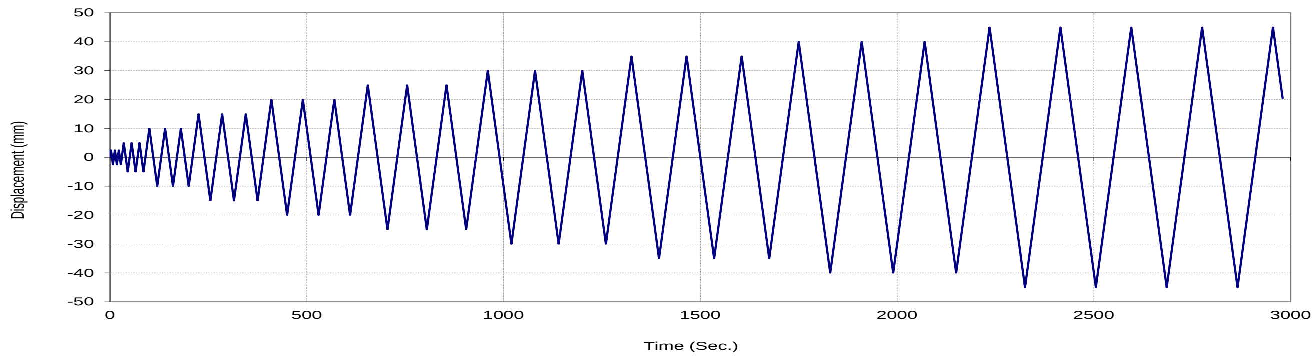

Fig. 4 – Loading protocol for cyclic tests

4. Observations and Test Results

The performance of various SRC elements and brace members of the upgraded frame was evaluated up to 1.5% story drift level. However, the benchmark frames (braced frames with no ring) were subjected to the same loading condition to compare the results. Since the same brace members were used in the testing of both upgraded and benchmark frames, the elastic properties, ultimate strength, ductility and dissipated energy of the specimens were monitored at various stages of testing. The results of experimental investigations on various specimens are discussed in the following sections.

As expected, frame members of the benchmark and the upgraded frames in 1.5% drift did not suffer any structural damage or deformation during the entire test. The beam and the columns were subjected to axial load only. The values of computed stress in the profiles were very small as compared to their yield stress value. Thus, these frame members were supposed to behave elastically.

In-plane buckling of the compression rod was observed in benchmark frame from the early stage of the test while the tensile rod carried the entire lateral load to base column plate. Out-of-plane buckling of the compression brace initiated at 0.25% story drift level and increased gradually in benchmark frame with tubular brace section. The braces in upgraded frames did not show any sign of buckling or yielding during the entire loading procedure. However, the braces were subjected to a bending moment in addition to an axial force in the upgraded frames, which may be attributed to the slight rigid-body rotation of the SRC due to lateral deformation of the frame. Further, all the brace connections did not show any sign of premature failures, such as yielding of stiffeners and pins, failure of welding, etc., during the test.

The SRC was subjected to tensile and compression axial forces of the braces and deformed in diameter direction. The severe bending deformation was concentrated in four points of the ring nearby the washers adjacent the tension braces. In the reversed cycle, inelastic deformation occurred in perpendicular direction. Thus, input energy was dissipated by forming of plastic hinges in these eight points of the ring in reversed cyclic deformations. However, the premature instabilities of the steel ring, such as sudden overall rotation, bending of washers and flange plates, bearing failure of washer plates and out-of-plane deformation of the ring were not observed at any story drift levels up to 1.5%. Further, no failure of the welds at the interface within the steel ring was noticed during entire test. The deformation and yielding of the SRC also suggested that the proposed upgrade system successfully transferred the frame lateral load to the braces cross point connection without any frame connection failure or brace buckling.

Cyclic load-displacement response of the upgraded frames is presented in Fig. 5. The upgraded frames with both systems; tension rods and tubular braces, exhibited full, stable, and symmetric hysteretic loops with significant post-yield strain-hardening behavior. Further, the specimens did not show any degradation in strength and stiffness during the entire loading procedure. Both systems carried the same level of lateral load when equipped with similar SRC. However, the system with tension rods exhibited very low stiffness between +0.75% and -0.75% drift ratio when subjected to larger cycles while this deficiency was not observed in the system with tubular braces. Significant pinching behavior was also observed in the system with tension rods where the SRC was assembled with 100 mm off-center. This may be because of the rapid rigid-body rotation of the ring due to unequal buckling load offered by the rods with different length in each side of the ring. Shortly after each load reversals, some loos of loading stiffness was observed due to bolt slippage at the connection between the specimen and the braces. This issue was significant in the system with tubular braces when subjected to imperfect installation of the SRC.

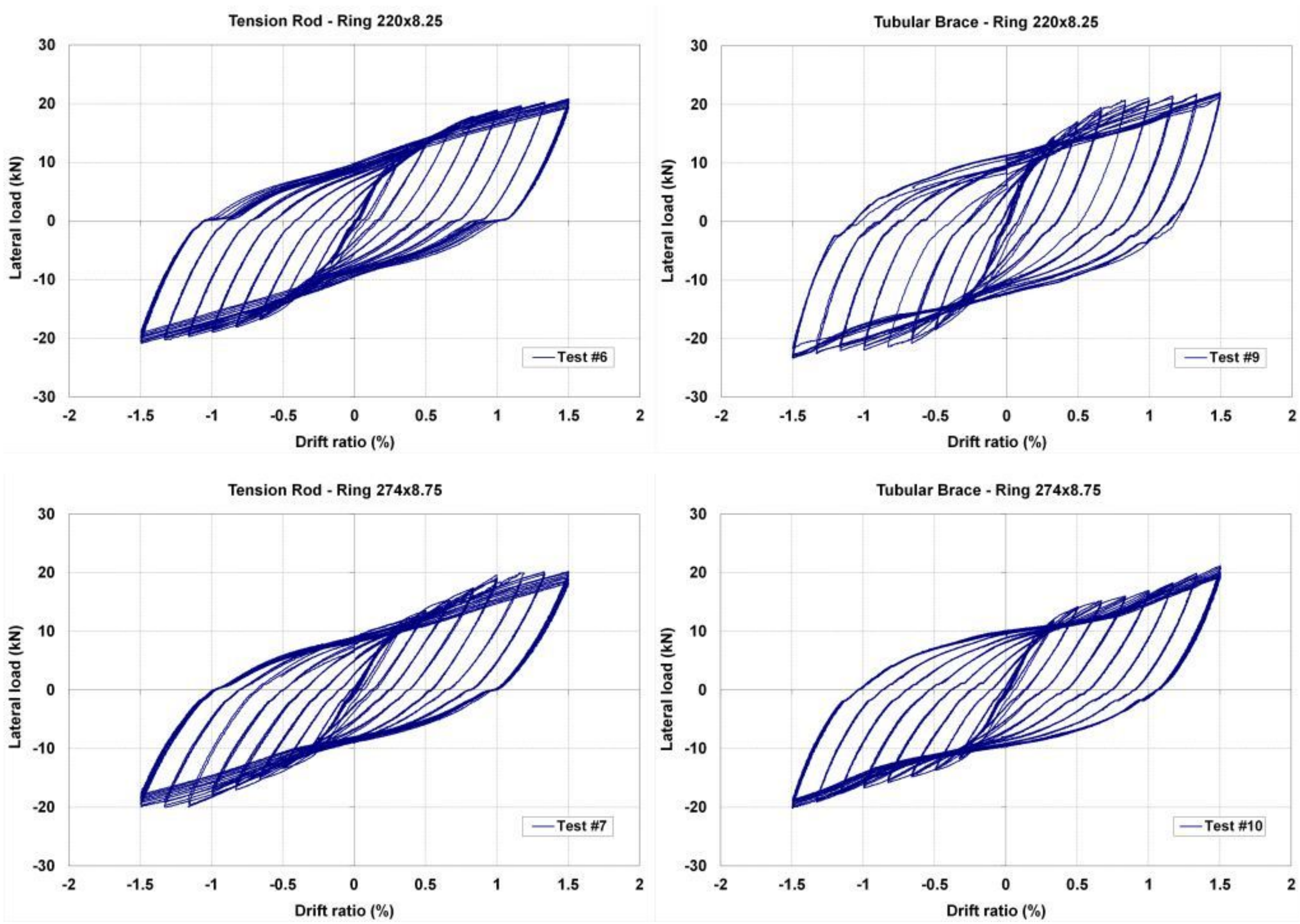

Fig. 5 – Cyclic load-displacement response of the upgraded frames

As stated earlier, three primary characteristics of the benchmark and upgraded frames evaluated in this study are lateral strength and energy-dissipation potential. Hence, a comparison of these parameters was carried out for the benchmark frames and the upgraded frames with SRC.

As discussed, the load–displacement behavior of the upgraded frames was characterized with full and stable hysteretic loops without any incidence of pinching up to 1.5% drift ratio. Further, significant post-yield hardening behavior was noted for the upgraded frames with no degradation of lateral strength even up to 1.5%

drift ratio. The upgraded frames exhibited nonlinear behavior from very low drift level, which the widening of the hysteretic loops showed initiation of inelastic behavior of the specimens. The maximum value of lateral load carried by the upgraded frames with Ring 168x9.25 was 81.4 kN at 1.5% story drift level. The lateral strength of the upgraded frames heavily depended on the size of the ring and this was reduced with the increase in the diameter and the decrease in the thickness. The lateral strength was measured as 20 kN at 1.5% drift level for Ring 220x8.25 and Ring 274x8.75. The lateral load carried by upgraded frames with these specimens was nearly constant after 0.5% story drift level. The lateral load on the upgraded frames at the smaller drift levels was increased with the increase in the drift level. It is worth mentioning that although the upgraded frames carried a smaller lateral load, more ductile behavior was achieved when SRC was used in the frames as compared to that of the benchmark frames. However, both the upgraded frames with tension rods and tubular braces did not exhibit any strength-degrading behavior during the entire test. Hence, except for the ring 168x9.25, the upgraded frames did not reach its failure state at 1.5% drift level, and it could have resisted few more lateral cyclic displacement excursions.

The amount of energy dissipated by the benchmark and the upgraded frames at any drift level was calculated as the total area enclosed in their respective hysteretic loops under cyclic excursions. The dissipated energy for the frame with tension rod braces in the first cycle was considerably higher than in the second and the third cycles at any drift level. The maximum value of dissipated energy was 0.63 kN-m noted in the first cycle at 30 mm displacement (1% drift). This value was then reduced in the next cycles to approximately constant value of 0.05 kN-m for all the drift levels. In the frame with tubular braces, the dissipated energy was gradually increased with the drift level and the maximum was noted as 7 kN-m in the first cycle at 45 mm displacement (1.5% drift). The energy was reduced in the next cycles but not significantly. Figure 6 shows the dissipated energy in the upgraded frames with tension rod and tubular braces. Dissipated energy has been also compared to the respective values in the benchmark frames. Using SRC system caused significant increase of dissipated energy compared to the benchmark frame with tension rod braces. However, this effect was not seen for the frames with tubular braces. In various SRCs with both types of bracing, the value of dissipated energy was increased gradually with the drift level. As shown in Fig. 6, the SRC system with tension rod braces dissipated energy nearly 7 times the respective benchmark frame while the SRC system did not increase the dissipated energy compared to the benchmark frame with tubular braces. The maximum values of energy dissipated per cycle by the upgraded frame was observed for Ring168x9.25 as 3.5 kN-m at 1.5% and 4.8 kN-m at 1.33% drift in systems with tension rod and tubular braces, respectively. This fact should be noticed that using SRC system offers concentrated structural damage in the frame that makes it as a repairable structure when subjected to permanent deformation, whereas damage in braced frames with no ring is not concentrated and repairing the frame is more costly.

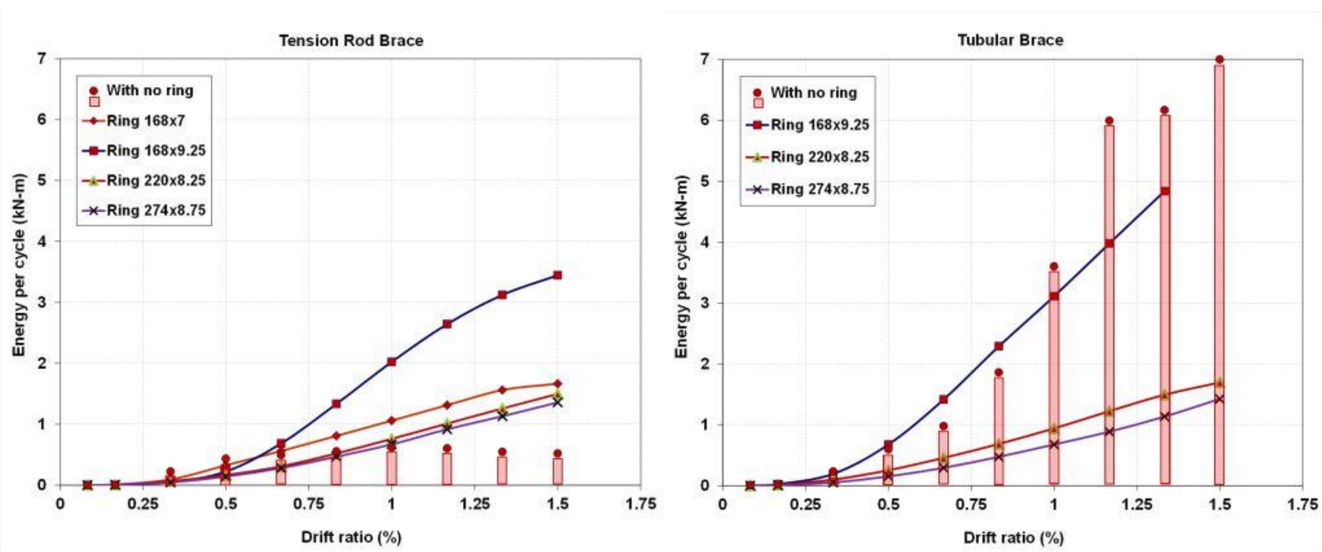

Fig. 6 – Dissipated energy in the braced frame equipped with the steel ring systems versus benchmark braced frame (with no ring)

The equivalent viscous damping potential of the benchmark and the upgraded frames at various drift levels was computed from the hysteretic behavior and is indicated in Fig. 7 for the frames with tension rod and the tubular braces. As illustrated, using SRC system amplified the damping ratio of the frame. This ratio was increased gradually with the drift level. As shown in Fig. 7, the value of equivalent damping for the benchmark frame with tension rods was reached to 8% at 5% drift level and then reduced to 5% in average at upper level of drift. However, the maximum damping ratio of the upgraded frame equipped with Ring 220x8.25 was 26% at 1.5% drift. The equivalent damping of the benchmark frame with tubular brace was fairly constant beyond 0.75% drift ratio and was reached to 10% at 1.5% drift, whereas the equivalent damping for the upgraded frames was gradually increased with the drift level. The maximum value was 28% at the 1.5% drift for the upgraded frame equipped with Ring 220x8.25. This enhanced damping potential reduced the damage levels of the brace members of the frame. Hence, the proposed upgrading technique significantly enhanced the energy-dissipation and damping potential of the braced frames.

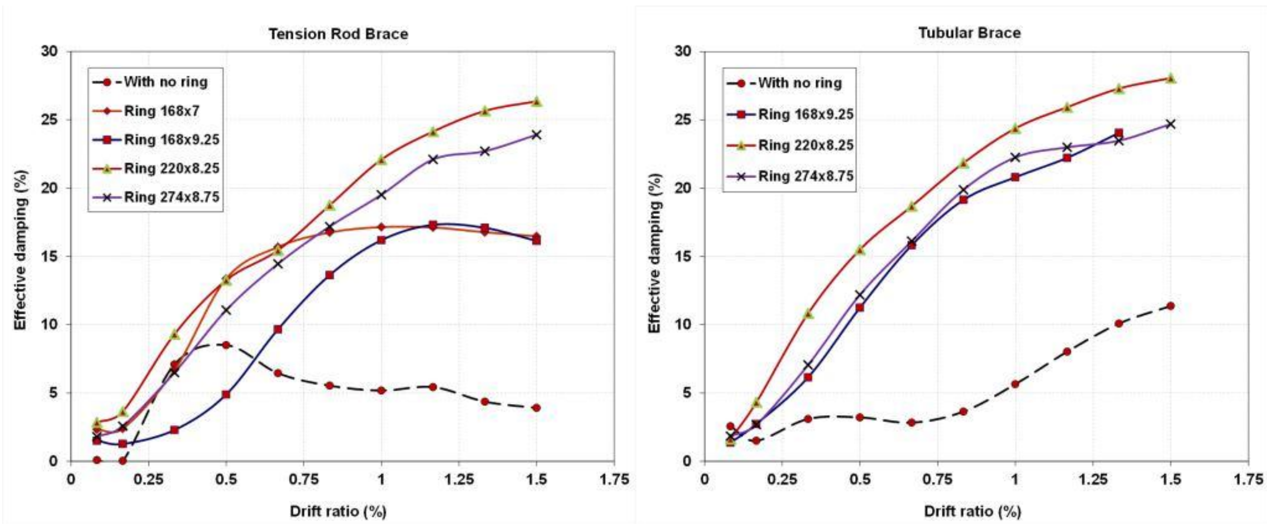

Fig. 7 – Effective damping of the braced frame equipped with steel ring systems versus benchmark braced frame (with no ring)

5. Conclusions

Important observations from these tests include:

1. The results of cyclic tests showed that using Steel Ring Connection system as a mid-joint connection of the X-braces has no problem in terms of stability, load transfer and compatibility of the frame and the ring deformation. Fabrication and installation of the SRC is very simple and it is a convenience technique for upgrading the frames although this system is very sensitive to braces geometry and accuracy of the installation.

2. The ring sustained large inelastic deformation with progressive strength degradation. The shape of the ring was changed to oval and plastic hinges were formed in the ring nearby the steel washers in four points in each half cycle of the frame displacement. Maximum bending deformation occurred when the frame was extremely pushed to north or south. Adding SRC system to the frame avoided visible large buckling of the braces while braces in benchmark frames experienced severe buckling in in-plane or out-of-plane direction.

3. The tension rod braced frame with no ring has no stiffness and capacity in descending curves when the frame was unloaded or reloaded before next peak displacement reached. In reverse, the tubular braced frame with no ring has load capacity in all displacement range but the strength is reduced rapidly in 1.2% drift ratio.

4. The hysteresis loops of the most of the SRC specimens show very fat shape with stable cycles that demonstrates suitable performance of SRC system as energy dissipation device. No strength reduction and stiffness degradation is seen before 1.5% drift ratio. The hysteresis loops of the ring 168x9.25 in tension rod

brace show zero stiffness in both ascending and descending curves in the range of ±0.5% drift ratio. This deficiency is not seen for the rings with larger size.

5. Backbone curves show that SRC systems have more ductility than braced frames with no ring. The type of the brace has no effect on capacity and ductility of the SRC system but has great effect on the shape of the hysteresis loops in the small rings. The tension rod braced frame equipped with the ring 168x9.25 was stronger than that without such a system but those braced frames equipped with the 20x8>25 or 274x7.75 were weaker than the tension rod braced frames with no ring. The capacity is increased for the thicker rings. In contrast, the capacity is decreased in the rings with larger diameter.
6. Adding the SRC system to the braced frames reduced lateral stiffness and the amount of stiffness was reduced gradually by increasing the drift ratio of the frame. That was resulted for both tension rod and tubular braced systems. The stiffness of the systems with the same SRC is higher in tubular than the tension rod braced frames. Initial elastic stiffness of each system can be recognized in the small range of the drift ratio. Braced frames with no SRC remained in elastic range up to 0.25% and 0.75% for tension rod and tubular braced frame, respectively.
7. Tubular braces systems dissipated energy 10 times more than what the tension rod braced systems did. Maximum energy dissipation of the tension rod braced frame occurred in 30 mm displacement of the frame (1% drift ratio) and this amount was decreased for higher displacement. Energy dissipation was increased in tubular braced frame by increasing the displacement amplitude. The second and the third cycles of the tension braced frame showed very low dissipated energy but the same issue was not seen in the tubular braced frame in compare with the dissipated energy during the first cycle of motion.
8. Using every SRC specimen with tension rod brace increased the dissipated energy compared to braced frame with no ring. In tubular braced systems, stiffer SRC (Ring 168x9.25) generated the same level of dissipated energy as braced frame with no ring did. The dissipated energy in other types of the SRC systems was lower than the benchmark frame. The amount of energy in both brace types was increased in the cycles with higher drift amplitude.
9. The SRC systems with both brace type exhibited higher equivalent effective damping than the braced frames without such a system. Effective damping was increased in all the test specimens by increasing the amplitude of the cycles.

Although it is recognized that additional testing is required to confirm this same kind of observed behavior for other types of Steel Ring Connection systems, it is clear from these tests that adding SRC system to the X-braced frame improves the performance of the frame.

6. Acknowledgements

Funding for this project was provided by Steel Structures Education Foundation, L.E. Steel Fabricators Ltd. and the University of British Columbia Earthquake Engineering Research Facility. The tests were conducted at the Earthquake Engineering Research Facility (EERF) of the University of British Columbia, and the support and collaboration of the EERF technicians and students are gratefully acknowledged.

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