SHAKE TABLE TESTING OF AN ENERGY DISSIPATING SYSTEM APPLIED TO BRACED STEEL FRAMES

Mehrtash MOTAMEDI¹, Carlos E. VENTURA²

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. The proposed technique consisted of the X-bracing system with a steel ring element at the mid-point connection. 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. In order to investigate the effectiveness of the proposed system on the seismic response of the frame and study of performance of the SRC as energy-dissipating device, a series of shake table tests were conducted on a full-scale single storey steel frame. The uniaxial shake table at the Earthquake Engineering Research Facility of the University of British Columbia was used for performing these tests. The frame was upgraded with proposed system consisting of X-braces and the SRC. Hysteretic load-deformation response, lateral strength, stiffness, equivalent effective damping, drift ratio and shear force were studied for the upgraded braced frame. The upgraded braced frame with SRC exhibited enhanced energy-dissipation and damping potential. This experimental study confirmed that the SRC is an excellent energy-dissipating device and the proposed technique is a suitable concept for using 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; shake table tests

1. INTRODUCTION

In designing the 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 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 (Balendra 1997). 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 (Ming-Hsiang et al. 2004). The application of passive control systems is rapidly increasing throughout the world both in new construction and seismic retrofitting of existing buildings (Tsai et al. 1993).

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 metal 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

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fuses are the other types of these elements which take advantage of uniform yielding of steel (Timoshenko 1982). Kafi and Abbasnia performed a testing program on ductile steel ring elements attached to braces (Kafi 2008). The ring elements are the new flexural fuses which can be installed in CCBF’s. Abbasnia et al. (2005) conducted some studies on the performance improvement of CCBF specimen which approved the efficiency of this system. Maleki et al. (2013) studied dual-pipe system in the frame connection and showed the potential of the system in energy dissipation during an earthquake. 

In this paper, a series of shake table tests were performed on the upgraded frame with SRC system and tension only braces to provide full scale verification of the proposed technique. The objective of these tests was to determine the dynamic response and evaluate seismic performance of the upgraded frame during a severe ground motion and confirm the cyclic behavior observed in quasi-static tests in past studies (Motamedi et al 2013). 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 Figure 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 (Hafezi 2012).

The objectives of this test program were the following: 1) to evaluate the effectiveness of using SRC for upgrading the steel frames; 2) to determine the seismic performance and mechanical characteristics of the steel frame upgraded with SRC.

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 (Motamedi 2013). 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.
A section of 19mm dia. tension rod made of grade B7, conforming to ASTM A193/A193M were used for bracing system. 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. A close up view of the SRC specimen and the detailed connections is illustrated in Figure 2. 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. Table 1 gives the characteristics of the test specimen used in this testing program.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Specimen ID</th>
<th>Diameter (mm)</th>
<th>Thickness (mm)</th>
<th>Wide (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ring168x7</td>
<td>168</td>
<td>7</td>
<td>90</td>
</tr>
<tr>
<td>2</td>
<td>Ring220x8.25</td>
<td>220</td>
<td>8.25</td>
<td>90</td>
</tr>
<tr>
<td>3</td>
<td>Ring274x8.75</td>
<td>274</td>
<td>8.75</td>
<td>90</td>
</tr>
</tbody>
</table>

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

3. TEST SETUP, GROUND MOTIONS AND TESTING PROGRAM

3.1 Test Frame

A prefabricated test frame was used for shake table test program (Figure 3). Three steel plates, each 1500x600x64mm with mass of 1350 kg were employed at the top of the frame’s beam to generate the inertia force during the table motions. Total mass participated in inertia force, including steel plates, top beam and half length of the columns was about 1700 kg. For this test program, the out-of-plane restraint of the test frame was provided by a couple of pre-tensioned diagonal cables at each side of the frame. The 25 mm dia. steel cables were connected to the frame’s beam at top and bolted to the shake table at bottom. At each end, a high strength shackle was used for the connection. This restraint system prevented any out-of-plane movement of the test frame and allowed the frame moves only in direction of the uni-axial shake table motion. Figure 3 shows the test frame, top mass and out-of-plane restraint cables.

3.2 Shake Table

The dimensions of the shake table at the UBC Earthquake Engineering Research Facility used for these tests are 3000mm by 4000mm. It has a pump with a maximum capacity of 0.53 m3/min (140gal/min) at 20MPa pressure. This pump is driven by a 200 HP electric motor that can produce a
rotational velocity of 1800 rpm. The table itself can displace +/- 450mm, with a maximum velocity of 75 cm/s. The actuator has a maximum pushing force of 260 kN.

The shake table is displacement controlled. The hydraulic pressure, which controls the displacement position of the table, is electronically controlled. The earthquake ground motion is put in as a displacement command signal. The displacement signal is normalized into a voltage value by the control computer. The output voltage sent to the actuator is provided by an MTS servo-controller. A command signal is sent to the servo-controller, and this controller determines the level of voltage that is output to the actuator.

3.3 Instrumentation

For this testing program, the shake table and the test frame were instrumented to capture their accelerations and displacements. The instrumentation for these experiments consisted of piezo-resistive accelerometers, position transducers and LVDTs (Linear Variable Differential Transformers). Two position transducers were placed on the east column to measure the test frame displacements. Two LVDTs were connected to south side of the shake table to observe the probable uplift of the table. A position transducer and an accelerometer were installed on the shake table, internally to check the input movement of the table. Two accelerometers were fixed on the top of the test frame and shake table. Two accelerometers were also connected to the frame beam laterally to observe the out-of-plane movement of the test frame.

Figure 3. General view of the shake table test set-up.

3.4 Ground Motion Records

For the testing program, six ground motion records were selected and used. Table 2 presents the ground motion records with their designated name, station, scaling factor and the peak motion values. The selected ground motions were given as acceleration time histories. Prior to testing, these acceleration time histories were double integrated to generate the needed displacement time histories for the input signal for the shake table. The acceleration time histories of the used ground motions at the 100% amplitude are illustrated in Figure 4.
Table 2. Ground motion records used in testing program.

<table>
<thead>
<tr>
<th>Ground Motion</th>
<th>Station</th>
<th>Scale Factor</th>
<th>PGA (cm/s²)</th>
<th>PGV (cm/s)</th>
<th>PGD (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-164</td>
<td>Synthetic</td>
<td>1</td>
<td>264.6</td>
<td>23.8</td>
<td>7.28</td>
</tr>
<tr>
<td>Chi Chi</td>
<td>TCU079</td>
<td>1</td>
<td>799.27</td>
<td>65.71</td>
<td>6.68</td>
</tr>
<tr>
<td>Lloleo</td>
<td>Universidad de Chile-Renadic</td>
<td>1</td>
<td>1584.81</td>
<td>35.87</td>
<td>4.04</td>
</tr>
<tr>
<td>Curico</td>
<td>Universidad de Chile-Renadic</td>
<td>1</td>
<td>1829.98</td>
<td>41.678</td>
<td>6.78</td>
</tr>
<tr>
<td>Angol</td>
<td>Universidad de Chile-Renadic</td>
<td>1</td>
<td>1863.33</td>
<td>39.821</td>
<td>6.84</td>
</tr>
<tr>
<td>Verteq 4</td>
<td>Synthetic</td>
<td>1</td>
<td>2285.03</td>
<td>103.699</td>
<td>11.65</td>
</tr>
</tbody>
</table>

PGA=Peak ground acceleration, PGV= Peak ground velocity, PGD= Peak ground displacement

3.5 Test Procedure

To provide full scale verification of the proposed seismic upgrade technique, nine steel ring specimens in three different types: Ring274x8.75, Ring168x7 and Ring220x8.25 were installed in the tension only braced frame and tested. An extra Ring274x8.75 specimen was used to refine the proposed system by adjusting the pre-tension load at the braces. Each steel ring specimen was first subjected to a ground motion sequence scaled to an initial amplitude. The severity of shaking was increased until the specimen damaged. For the list of the tests on nine steel ring specimens, including ground motion sequences and amplitude values refer to Motamedi et al. (2013).

4. OBSERVATIONS AND TEST RESULTS

This section describes overall behavior observed during the shake table testing program and also discusses test results obtained from the tests. Test results include calculated frequency, damping and stiffness, measured seismic time history responses and hysteretic responses of the upgraded frame with various types of steel ring specimens.
Figure 4. Acceleration time history of ground motions for testing program (100% amplitude).
4.1 Overall Behavior

The shake table simulated the ground motions in east-west direction and generated in-plane inertial forces in the frame. The table moved horizontally during the entire tests and no uplift was observed in the wheels based on the processed signals captured by the LVDTs. Also, no sliding was noticed between the column base plates and the shake table surface. This means that the total movements of the table transferred to the base frame without any energy dissipation.

Generally, the same behavior as reported before for quasi-static tests was observed in these series of tests (Motamedi et al. 2013). No structural damage or deformation was detected in test frame members during the tests and the deformation was concentrated on the braces and the SRC. Further, all the brace connections did not show any sign of yielding of stiffeners and pins or failure of welding during the test. The pre-tension of the braces played an important role in the performance of the SRC. When the braces were not pre-stressed the out-of-plane movement of the specimens was very significant. Pre-stressing the braces is very important to achieve the desire in-plane response of the frame and performance of the SRC.

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 the ring nearby the washers adjacent the tension braces. Thus, input energy was dissipated by forming of plastic hinges in these eight points of the ring. However, bending of washers and flange plates and bearing failure of washer plates were not observed during the tests. The shape of the deformed ring was similar for all the different ring sizes tested. Concentrated inelastic deformation of the steel ring indicated a significant contribution of the ring to the total dissipated energy in the system. Even after the application of a severe loading protocol which consisted of long and short duration ground motions the rings kept their integrity. This is an indication of high ductility provided to the frame by the rings. The damage mechanism expected was observed. Initially, yielding occurred in the ring and then buckling on the braces happened. Therefore, this mechanism protected the frame.

Tests with and without tension in the cables used to provide out-plane restraint system were conducted. The tests showed that the cables do not have an influence in the final in-plane capacity of the frame. However, tension in the cables is required in order to keep in-plane motion of the frame during the test.

4.2 Frequency, Damping and Stiffness

Hammer tests were performed on the test frame to evaluate the effect of SRC system on dynamic characteristics of the tension only braced frame under seismic condition. Hammer tests included recording the acceleration response of the test frame due to free vibration. Free vibration was generated by an in-plane impact load at the top of the frame by hammer. These tests were performed in the elastic range of the upgraded frame and on undamaged specimens prior to shake table test. The same setup as shake table tests was used for these tests. The impact load was applied at the top of the frame and the acceleration was recorded by an accelerometer. The SeismoSignal software package was used for signal processing. Each recorded data was first filtered and corrected and then transformed to the spectral response functions. The acceleration time histories and Fourier Amplitude of the responses obtained from the frame upgraded with Ring 168X7 are shown in Figure 5. The first mode of vibration shows significant change which is related to the characteristics of the steel ring specimen used in the test frame.

Natural frequency of the frame upgraded with specimens Ring168x7, Ring220x8.25 and Ring274x8.75, obtained from a frequency domain analysis of the recorded acceleration time histories and viscous damping, determined from the decay of free motions, are presented in Table 3. The frame with smaller ring showed higher frequency than the frame with larger ring. This means the frame upgraded with smaller ring shows higher stiffness that that of the frame with larger ring. As presented in Table 3, damping ratio is increased by increasing the size of the ring.

Table 3 also shows the stiffness of the upgraded frame with various types of SRC systems. The stiffness values were calculated based on obtained frequencies. The frame upgraded with Ring168x7 shows higher frequencies than that of the Ring220x8.25 and Ring274x8.75. Moreover, the stiffness is decreased for the larger size of the ring.
Figure 5. Acceleration time history and Fourier Amplitude of the response of the test frame upgraded with steel ring connections in hammer test.

Table 3. Frequency, damping ratio and stiffness of the specimens obtained from hammer test.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Test No.</th>
<th>Frequency (Hz)</th>
<th>Period (Sec.)</th>
<th>Damping Ratio (%)</th>
<th>Lateral Stiffness (kN/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring 168x7</td>
<td>1</td>
<td>7.690</td>
<td>0.130</td>
<td>0.79-1.2</td>
<td>3.97</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7.630</td>
<td>0.131</td>
<td>0.61-1.12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>7.996</td>
<td>0.125</td>
<td>0.63-0.94</td>
<td></td>
</tr>
<tr>
<td>Ring 220x8.25</td>
<td>1</td>
<td>5.798</td>
<td>0.172</td>
<td>0.65-1.4</td>
<td>2.46</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6.055</td>
<td>0.165</td>
<td>0.9-1.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6.065</td>
<td>0.165</td>
<td>1.1-2.1</td>
<td></td>
</tr>
<tr>
<td>Ring 274x8.75</td>
<td>1</td>
<td>5.469</td>
<td>0.183</td>
<td>2.0-2.4</td>
<td>1.92</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>5.249</td>
<td>0.191</td>
<td>1.2-2.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>5.310</td>
<td>0.188</td>
<td>1.17-1.59</td>
<td></td>
</tr>
</tbody>
</table>

4.3 Time History Response

Time history responses of the test frame upgraded with different types of the SRC under Chi-Chi earthquake record at 200% amplitude are shown in Figure 6. In these figures, relative displacement of the frame is presented. Relative displacement time histories illustrate permanent displacements of the test frame upgraded with all SRC systems at the end of the record. Permanent displacements of the frame which are 7, 9 and 2 mm for Ring 168x7, Ring 220x8.25 and 274x8.75, respectively were caused by forming the plastic hinges in the rings.

Maximum drift ratio versus record amplitude for test frame upgraded with various types of the SRCs is presented in Figure 7. As this figure shows maximum drift ratio occurred for Ring 168x7 and Ring 220x8.25 as 2% and 2.3%, respectively under Verteq 4 record at 100% and happened for Ring 274x8.75 as 1.6% under Chi-Chi report at 200% amplitude.

The test frame upgraded with Ring 168x7 and Ring 220x8.25 carried 47 kN and 43 kN, respectively as shear force under Verteq 4 at 100% and 29 kN under Angol at 200% amplitude, as shown in Figure 7. Maximum acceleration versus record amplitude at top of the frame upgraded with different type of the SRCs was also studied. Maximum acceleration was achieved as 2750 cm/sec² for Ring 168x7 and 2500 cm/sec² for Ring 220x8.25 under Verteq 4 record at 100% and as 1750 cm/sec² for Ring 274x8.75 under Angol record at 200% amplitude.

4.4 Hysteretic Response

Hysteresis responses of the upgraded frame with Ring 220x8.25 under Chi-Chi earthquake records are shown in Figure 8. Upgraded frame with this specimen performed in elastic range due to Chi-Chi record at 50% and 100% amplitudes and showed very fat shape with stable hysteresis loops under Chi-Chi record at 200% amplitude, that demonstrates suitable performance of SRC system as energy...
dissipation device.

Hysteresis responses of the upgraded frame with Ring 168x7 under Chi-Chi, Verteq 4 and Angol records was studied. This specimen behaved in elastic range under Chi-Chi record at 50% and 100% amplitudes whereas exhibited full and stable but not symmetric hysteresis loops when subjected to Chi-Chi record at 200%, Verteq 4 record at 100% and Angol record at 200% amplitude.

Hysteresis responses of the upgraded frame with Ring 274x8.75 under Chi-Chi, Verteq 4 and Angol earthquake records were also studied. As these studies demonstrate, SRC system performed in elastic range when subjected to Chi-Chi record with severity of 50% and acted as a ductile device with fat and stable hysteresis loops. Further, the specimens did not show any degradation in strength and stiffness during the entire loading procedure of all the tests.

Figure 6. Relative displacement time history response of the upgraded frames under Chi-Chi record, 200% amplitude.
Figure 7. Maximum drift ratio and shear force of the upgraded frame with: a) Ring 168x7; b) Ring 220x8.25; c) Ring 274x8.75.
Figure 8. Hysteresis loops for the upgraded frame with Ring 220x8.25 under Chi-Chi earthquake record.

5. CONCLUSIONS

Important observations from these tests include:

1. The results of the 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 eight points. 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.

3. Shake table testing results confirmed the results obtained from quasi-static tests. No damage was observed in the test frame members and the deformation was concentrated in the tension rods and the SRCS. The deformed shape of the rings was similar to the rings tested under quasi-static condition. The plastic hinges were formed in the ring nearby the steel washers.

4. The pre-tension of the braces played an important role in the performance of the SRC in shake table tests. When the braces were not pre-stressed the out-of-plane movement of the specimens was very significant. Pre-stressing the braces is very important to achieve the desire in-plane response of the frame and performance of the SRC.

5. Frequency, damping and elastic stiffness of the upgraded frames with SRCS were calculated by conducting the hammer tests on the test frame. The larger rings exhibited higher frequencies than the smaller rings. In contrast, elastic stiffness of the system decreased by increasing the size of the rings.

6. Maximum drift ratio of the upgraded frame with Ring 168x7 and Ring 220x8.25 was 2% and 2.3%,
respectively while maximum shear force carried by the frame with these systems was 47 kN and 42 kN under Verteq 4 record at 100% amplitude. Frame with Ring 274x8.75 exhibited 1.6% drift ratio and 29 kN shear force under Chi-Chi record at 200% and Angol record at 200%, respectively.

7. The hysteresis loops of the SRCs show very fat shape and stable cycles under earthquake records with high amplitude in shake table tests. No strength reduction and stiffness degradation is observed during the whole dynamic tests. Thus, hysteretic behavior of the frame demonstrates suitable performance of SRC system as energy dissipation device. 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.

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7. REFERENCES


