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Retrofitting of Concrete Exterior Beam-Column Joints using NiTi-SMA Sheets

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ABSTRACT: Deficient reinforced concrete structures exist in significant numbers worldwide in the seismic prone regions. The mode of failure in these buildings being predominantly a brittle shear failure at the beam-column joints. Several techniques, including steel sheets and elements and fiber-reinforced polymers including carbon fiber (CFRP) and glass fiber (GFRP) sheets, have been extensively used to strengthen the existing deficient beam-column joints in shear. If BCJs can retrieve their predetermined strength and shape after a seismic event, then problems related to collapse and permanent damage might be solved. Shape Memory Alloy (SMA) are unique Nickel-Titanium based alloys and novel functional materials that exhibit small residual strain under loading and unloading cycles even after yielding of the material, in sharp contrast to the ordinary steel. This material has the capability for remembering its original shape even after severe deformation. It can undergo large deformations and return to its undeformed shape by heating or on the removal of the stress. SMA in the form of sheets provides one of the possibilities as reinforcement/strengthening of concrete joints. The use of SMA sheets in lieu of CFRP/GFRP and steel sheets in the deficient BCJs has not been explored to the best of our knowledge. BCJs strengthened with SMA sheets can enhance the ductility and load carrying capacity of the joints. It can also preclude the development of large cracks, which can render the existing deficient joints irreparable. This paper presents the results of an experimental investigation conducted on BCJs strengthened using NiTi-SMA sheets. The experimental results showed that SMAs sheets enhanced the ultimate load carrying capacity of retrofitted specimens as well as increased the residual load carrying capacity.

1 INTRODUCTION

Reinforced concrete structures consisting of moment resisting frames have suffered from significant damage during extreme seismic events in the recent years. The damage is mainly attributed to insufficient seismic detailing at the Beam-Column Joints (BCJs), which is the weakest zone in the lateral load resisting system. Reinforced concrete (RC) buildings constructed in the early part of the last quarter of the previous century were designed mostly for gravity loads without seismic joint detailing. Such structures exist in significant numbers worldwide in the seismic prone regions. The mode of failure in these buildings is generally a brittle shear failure at the joints (Saatcioglu et al. 2001). Several techniques including steel sheets and members and fiber-reinforced polymers including carbon fiber (CFRP) and glass fiber (GFRP) sheets have been extensively used for strengthening of the existing deficient beam-column joints in shear (Le-Trung 2010).

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Shape Memory Alloy (SMA) made from Nickel-Titanium alloy is a novel functional material which exhibits low residual strains under cycles of loading and unloading even after passing the yielding zone. They can remember a predetermined shape even after severe deformations, which enables them to be widely used in numerous applications including civil engineering applications (Janke et al. 2005, Alam et al. 2007). Application of SMA bars has been investigated for seismic response of concrete columns (Saiidi et al., 2006, Chen and Andrewas 2017), concrete beams (Li et al. 2006, Zafar and Andrewas 2013). The potential of using SMA bars as a reinforcement at the beam-column joint for enhancing the seismic performance has also been investigated (Nehdi et al. 2011).

SMAs can undergo large deformations but can return to its undeformed shape by heating or through the removal of the stress. The superelasticity (SE) effect, where a considerable strain can be achieved by the phase transformation from austenite to martensite upon loading which is then fully recovered in a hysteresis loop upon unloading and without changing the temperature (Abdulridha et al. 2013, Alam et al., 2007, Qian et al., 2010). SMAs can undergo large deformations, up to 10–20%, and has the capacity to, revert to their original undeformed shape through shape memory effect (SME), or superelastic effect as shown in Figure 1.

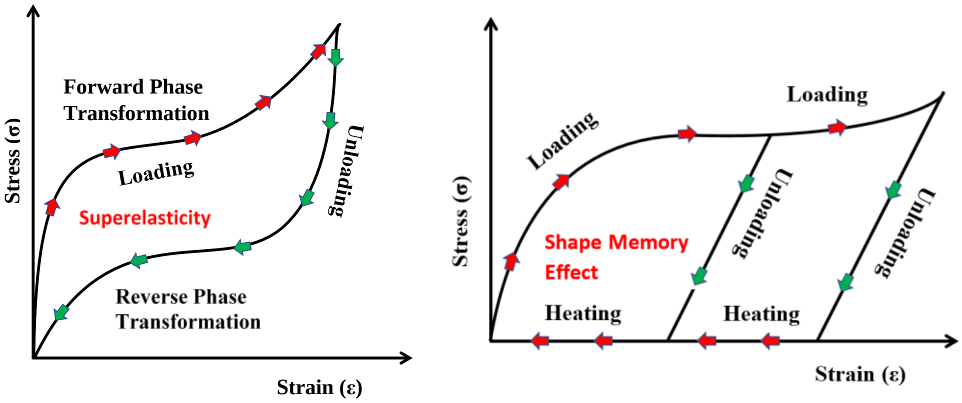

Figure 1. Stress-strain diagrams of Ni-Ti SMA Superelasticity (left); SME Effect (Right).

The unique properties of SMAs under cyclic load makes it amenable for usage in beam-column joints for enhancing the seismic response. Several researchers have tested the cyclic properties of SMA under tension, compression and shear (DesRoches et al. 2004a, Liu et al. 1999). DesRoches et al. (2004b) evaluated the superelastic properties of NiTi SMA bars under cyclic loading. The cyclic load tests by the authors on a NiTi-SMA bar 12 mm in dia is shown in Figure 2.

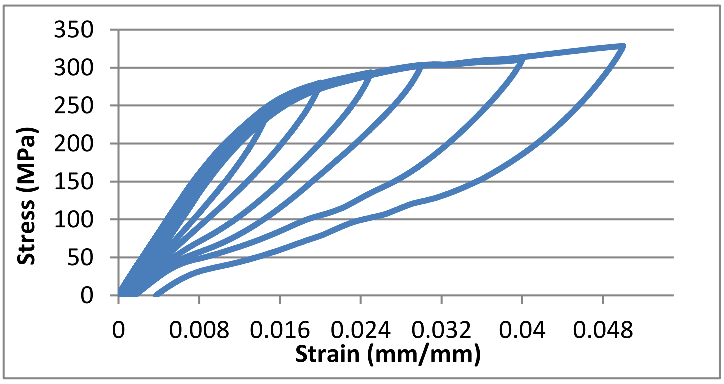

Figure 2. Stress-strain curve of NiTi-SMA bar (12 mm dia) under cyclic load

An experimental investigation conducted to explore the use of SMA sheets instead of CFRP sheets in the deficient BCJs. BCJs strengthened with SMA sheets can enhance the ductility and load carrying capacity of the joints and preclude the development of large cracks, which can render the existing deficient joints irreparable. The results of selected experimental investigation conducted on shear deficient BCJs strengthened using SMA sheets are presented.

2 EXPERIMENTAL SETUP AND PROCEDURES

2.1 SMA sheets for Retrofitting BCJ Specimens

The SMA sheets used in the experimental program were obtained from China. X-Ray Fluorescence (XRF) test was conducted to get the material composition for SMAs sheets. The XRF test showed that the SMA sheet has 57.28 % nickel and 41.18 % titanium. The SMA sheets obtained for retrofitting were not heat treated. Activation of the superelastic response of the SMA sheets was achieved by heat treatment. The sheets were heated in a furnace for 30 minutes under a constant temperature of 350 ^{o}C, and after removal from the furnace, it was immediately dipped into cold water.

2.2 Testing of SMA Sheets under Cyclic Loading in Uniaxial Tension

Two sheets were tested in a universal testing machine under cyclic load with a constant loading rate of 0.1 mm/ minute. To preclude any slippage the sheets were held in 2mm thick aluminum plates with high strength epoxy. The sheets failed at approximately 29 % strain. It has been reported that maximum recovery of residual strain is achieved when sheets are loaded up to 8 % strain. Figure 3 shows the stress-strain curve of SMA sheets up to 8 % strain.

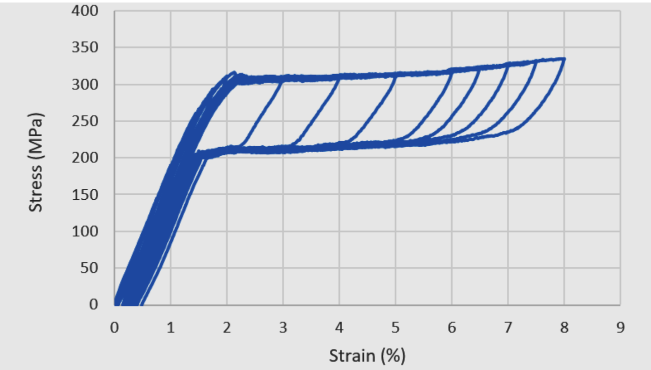

Figure 3. Stress-strain curve SMA sheet.

2.3 Beam-Column Joint Specimen Size

The geometric size and dimensions of BCJ specimens used for the experimental testing program are shown in Figure 4. The beams are 250 mm wide by 300 mm deep with a cantilever length of 900 mm. The columns are 250 mm x 300 mm with a total height of 1400 mm. Six longitudinal reinforcements 20 mm in dia were provided in beams and column, whereas 8 mm dia bars were used for stirrups and ties. Six strain gauges were attached to the steel reinforcement at selected locations, where maximum stresses can occur during loading. Three beam-column joints strengthened with superelastic SMA sheets were tested under cyclic loads. The specimens were deficient in joint shear strength with no transverse reinforcement. One specimen was for control and remaining two specimens were retrofitted by SMA sheets of different configurations. The first specimen the SMA sheets were applied diagonally. Diagonally applied SMA strips are held at the ends by CFRP sheets as shown in Figure 4. In the second specimen SMA sheets are applied in horizontal and vertical directions and are held at the edges by CFRP strips. The results of control specimen and only the specimen reinforced with diagonal SMA strips are presented in this paper.

The compressive strength of concrete used for casting the BCJs has an average value of 33 MPa at 28 days. Split cylinder test gave an indirect tensile strength of concrete with an average value of 2.6 MPa. The yield strength of 8 mm and 20 mm dia bars were measured as 480.5 MPa and 607.2 MPa respectively.

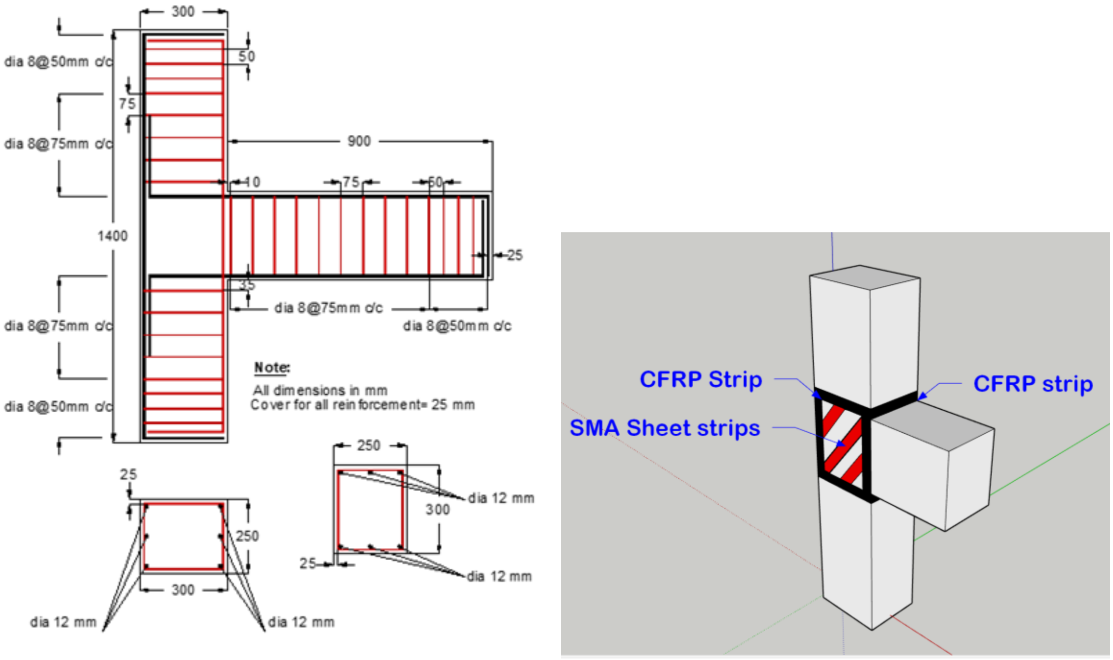

Figure 4. Geometry and reinforcement details (Left) and SMA retrofitting (Right) of BCJ specimen.

2.4 *Testing Arrangements for BCJ Specimens*

All BCJ samples used in this Research were tested in a self-reaction loading frame at KFUPM lab. Two jacks were used for applying the loads. One hydraulic jack was placed on the top face of the column to apply the axial load. The second jack was placed at the beam tip to apply push/pull displacement at the tip of the beam, as illustrated in Figure 5.

Loads and strains in concrete and SMA sheets and crack openings were monitored using load cells, strain gauges and LVDT's during the testing of specimens as shown in Figure 5. Displacement control method was used to test the specimens. The specimens were tested under cyclic loading using the loading scheme shown in Figure 5 (Right). A constant axial load (150 kN) was applied on the column top before applying the displacement on the beam tip. A quasi-static cyclic loading approach was used by applying incremental displacement at the tip of the beam. The tip of the beam was pushed and then unloaded gradually till the failure of the specimens. Each cycle was repeated twice for control specimens, whereas, for retrofitted specimen cycles were not repeated.

3 EXPERIMENTAL RESULTS

3.1 *Control Specimens without Retrofit under Cyclic Loading*

The load-deflection response of the control specimen, tested under cyclic loading, is shown in Figure 6. The first flexural crack was observed near the BCJ interface at a load of 42 kN (Δ=3.44 mm), and the first shear crack in the front face of the joint was observed at a load of 59 kN (Δ=6.4 mm). Figure 7 shows the flexural and shear cracks on the front and back face of the joint during loading and unloading cycles. Shear cracks widened with increasing load, and residual displacement increased with each loading/unloading cycle. The ultimate load was measured as 110.4 kN at a displacement Δ=22.4 mm. The specimen failed in shear.

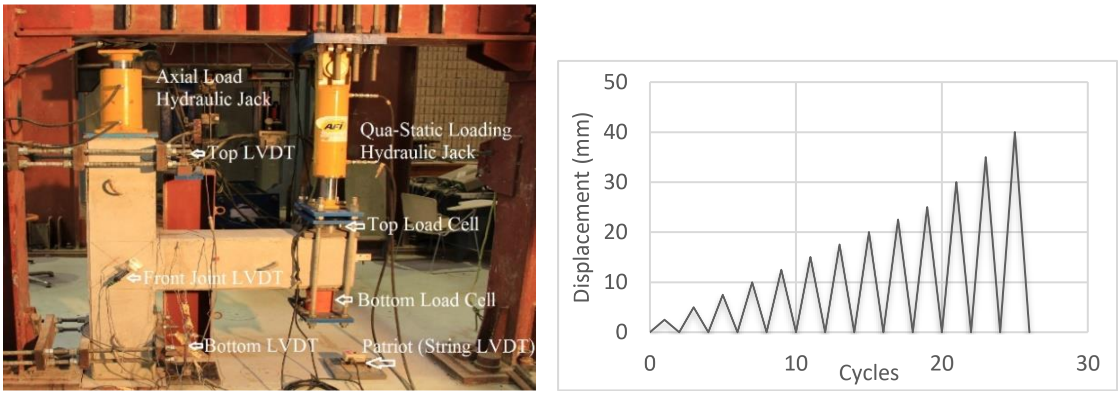

Figure 5. Testing arrangement and specimen (Left) and loading scheme (Right)

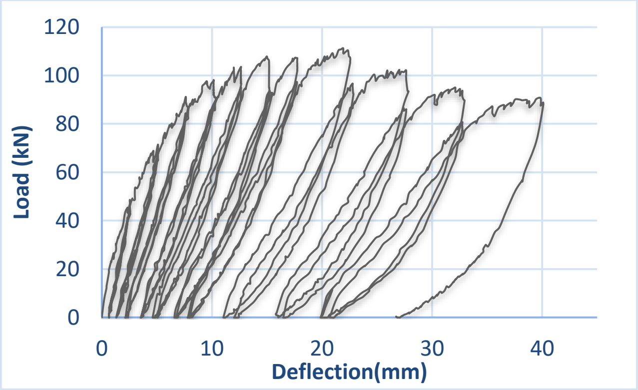

Figure 6. The load-displacement response of control specimen

LVDTs were used to measure the crack opening in the joint regions. Figure 8 shows the crack opening in the joint region measured using the LVDT and the width of the cracks on the two faces during loading and unloading cycles.

3.2 *SMA Sheet Retrofitted BCJ Specimen with Inclined SMA Strips*

The beam column joint retrofitted with inclined SMA sheets was tested under cyclic loading. The initial cracks (3 cracks) were flexural, and they were observed near the BCJ interface at different location of the beam at a load of 31 kN and a displacement of 2.2 mm. The first shear crack in the joint region (front face) was observed at a load of 53 kN when the beam was pushed up to a displacement of 4.4 mm. The second and third shear cracks at the front face were observed at a load of 117 kN at a displacement of 15 mm. The ultimate load in the retrofitted specimen was 139.2 kN at a displacement of 24.88 mm. The load-deflection response of the specimen is shown in Figure 9. Figure 10Figur shows shear crack formation on the front, and back face of the joint region during loading and unloading cycles and the width of these cracks were recorded.

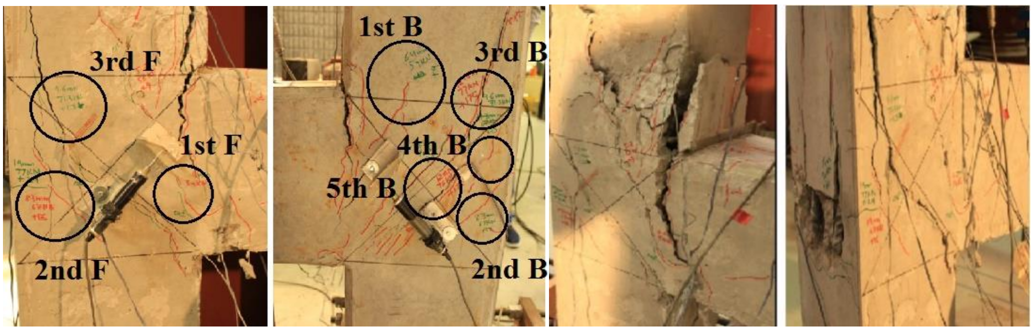

Figure 7. Shear cracks at the front and back face of joint and failure of the specimen

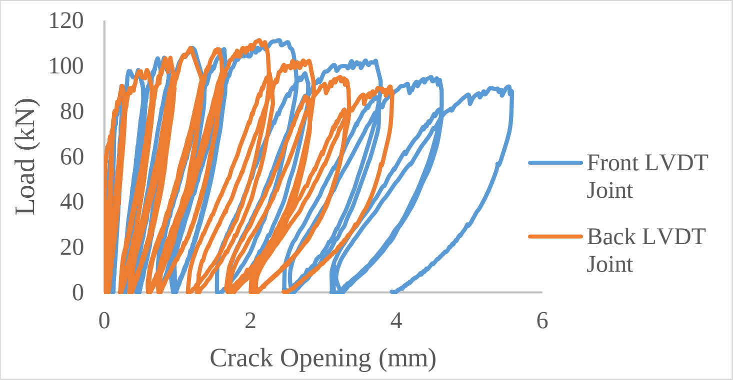

Figure 8. Crack opening in Joint region

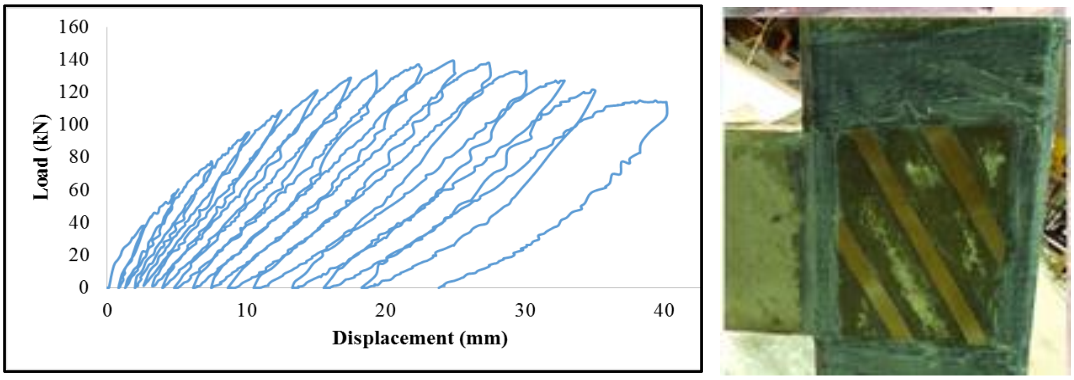

Figure 9. Load-deflection curve for BCJ retrofitted with SMA sheets.

There was no spalling of concrete in this specimen, which was observed in the control specimen. Figure 11 shows the crack opening in the joint region during the test. The comparison of load-deflection response of the control specimen and the SMA retrofitted specimen with inclined SMA sheet strips under cyclic loading is shown in Figure 12. The SMA retrofitted specimen showed controlled cracking in the joint and the number and widths of crack in the joint region were also reduced. The ultimate load for SMA specimen was 139.23 kN which is 26 % more than the ultimate load of 110.36 kN for the control specimen.

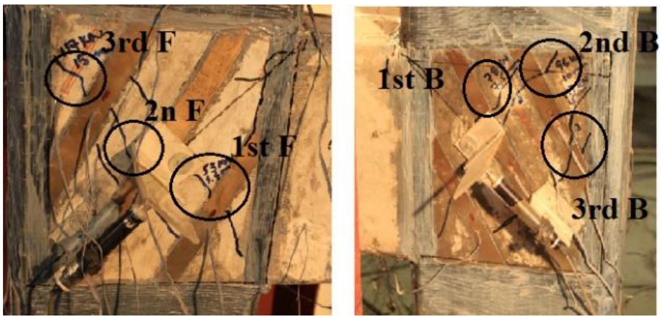

Figure 10. Shear crack at the front and back face of the joint region.

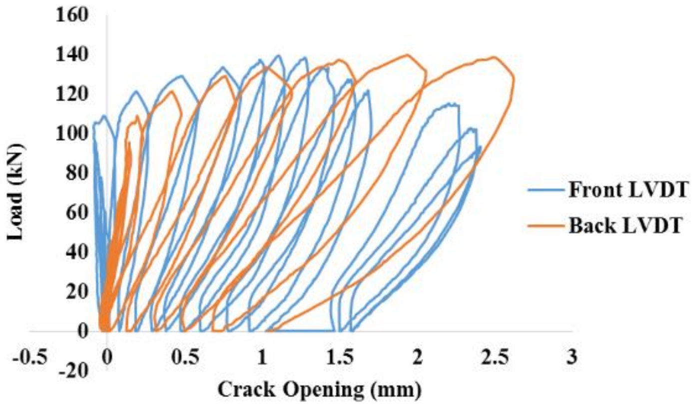

Figure 11. Crack opening at the joint region

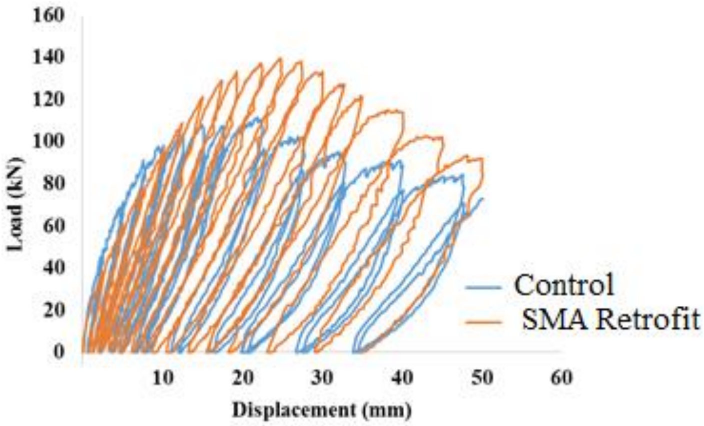

Figure 12. Comparison of response of BCJ-CL and BCJ-CLIS and their envelope

4 CONCLUSIONS

1. The SMA sheets recovers substantial part load induced deformation with a small permanent residual strain less than 0.5 %, failing by rupture at a very high strain of 29 %. The sheets showed pseudo elasticity behavior and flag type stress-strain curve was obtained.
2. The BCJ retrofitted with SMA sheets showed enhancement in shear strength of the joint, reduction in the number and widths of the cracks as compared to the control specimen, as well as a reduction in the crack width upon unloading.
3. The shear capacity of SMA retrofitted BCJ increased by about 26 % as compared to the control specimen. It also resulted in an improvement in the hysteresis behavior with more energy dissipation.

5 ACKNOWLEDGEMENT

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