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Effectiveness of NiTi-SMA Bars at the Beam Column Joint Interface

Muhammad RAHMAN [1], Mohammed AL-HURI [1], Ali AL-GADHIB [1], Mohammed BALUCH [1], Mohammed ALOSTA [1]
[1] King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia

Contact e-mail: mkrahman@kfupm.edu.sa

ABSTRACT: Seismic detaining of BCJs in Codes require the incorporation of shear reinforcement in the joints to enhance their shear capacity. The mode of failure in seismically detailed joints precludes the brittle shear failure of joints and promotes a ductile failure in beams, with flexural cracking generally occurring at the BCJ interface. The functionality of such joints may also be compromised due to the yield zone at the interface penetrating in the joint. Shape memory alloy (SMA), is a functional material that exhibits small residual strain under loading and unloading cycles even after yielding of the material, in sharp contrast to the ordinary steel. It can undergo large deformations and return to its undeformed shape on the removal of the stress. SMA, in the form of bars, can be used at the beam-column joint interface. These bars can yield under the strains caused by seismic loads but potentially recover deformations at the end of the event. Some researchers have reported the ability of SMA to recover deformations and decrease residual deformations in concrete structural elements. Therefore, SMA used as embedded rebar, might have an excellent potential to be used in seismic zones in reinforced concrete structures, especially at the BCJs in new structures. BCJ specimens reinforced with 12 mm dia NiTi-SMA bars in the plastic hinge region were tested under monotonic and cyclic loading. Experimental investigation of BCJs reinforced with trained and ribbed plain SMA bars shows excellent results in terms of crack recovery, residual displacement, and load capacity.

1 INTRODUCTION

In the past two decades, several destructive earthquakes have occurred around the world during which deficiency in structural systems has resulted in the collapse of several buildings and other structures. In reinforced concrete (RC) structures, structural failure due to insufficient seismic detailing in beam-column joints (BCJ) was found to be most vulnerable (Saatcioglu et al. 2001). The vision has changed in recent years, and the seismic design of structures has evolved towards performance-based design where there is a need for new structural members and systems that possess enhanced deformation capacity and ductility, higher damage tolerance, concrete confinement, decreased or minimized residual crack sizes, recovered and reduced permanent deformations (Parra-Montesinos et al. 2005). BCJs with enhanced ductility, exhibiting little damage, thus, eliminating post-earthquake joint repairs are highly desirable under performance-based seismic design concept. Shape Memory Alloy (SMA) is a novel functional material which can undergo large deformations but can return to its undeformed shape by heating (shape memory effect) or through the removal of the stress (super-elasticity). This research focuses on the use of Nickel-Titanium SMA bars as reinforcement in the plastic hinge region at the BCJ interface. Only limited studies have been reported on using NiTi-SMA bars at the plastic hinge region of new RC buildings. During earthquakes, cracking and permanent deformation occurs at the BCJ interface due to yielding of reinforcing steel. These deformations cannot be repaired to rehabilitate the structures. Therefore, the potential of SMA bars (SMA bars in this paper refers to only NiTi-SMA Bars) to recover large deformation at the BCJ interface on unloading can be exploited to avoid such permanent deformation. This research aims to investigate the use of superelastic SMA bars in the BCJs to restore the serviceability of structures and enhance the ductility of BCJ during earthquakes.

2 BEHAVIOUR OF SUPERELASTIC SMA UNDER CYCLIC LOADING

When superelastic SMA specimen is subjected to a cycle of deformation within its superelastic strain range, it dissipates a certain amount of energy without permanent deformation. It results from the phase transformation from austenite to martensite during loading and the reverse transformation during unloading, ensuring a net release of energy. When SMAs is loaded in the martensite phase, it yields at nearly constant stress after an initial elastic deformation and displays strain hardening at higher strains. When unloaded, there remains some residual strain at zero stress. DesRoches et al. (2004) evaluated the superelastic properties of NiTi SMA Wires and bars under cyclic loading. They evaluated the strength, recentering ability and damping potential for wires and bars (Figure 1). It can be noticed that both wires and bars behaved superelastically and recovered maximum residual strain upon unloading. Figure 1 shows the curves under quasistatic cyclic loading.

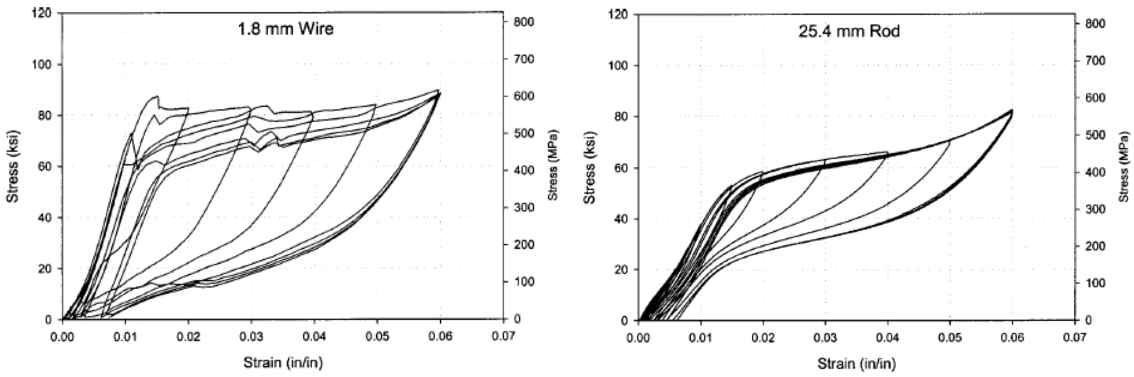


Figure 1. Stress-strain curve of SMA wire/bar under cyclic load (DesRoche et al. 2004).

3 SMA AS A REINFORCEMENT IN CONCRETE STRUCTURES

The unique characteristics of shape memory effect and super-elasticity SMAs have led to several applications in the form of reinforcement, prestressing strands and retrofitting technique. Applications, especially in the seismic field, have been investigated by Des Roches and Smith (2004); Wilson and Wesolowsky (2005), Song et al. (2006), and Janke et al. (2005).

3.1 SMA bars as a reinforcement in Columns

Wang (2004) investigated the seismic performance of RC columns with SMA as longitudinal reinforcement in the plastic hinge area. It was observed that the SMA-RC columns were superior to conventional steel-RC columns in limiting column top residual displacement. Moreover, SMA bar reinforced column withstood larger earthquake amplitudes compared to steel bar reinforced column. Alam et al. (2008) investigated numerically the response of RC bridge piers with SMA bars placed in the plastic hinge regions. The behaviour of the piers showed an excellent recentering ability when subjected to seismic loadings.

3.2 SMA Bars as a Reinforcement in Beam

Average residual displacement in beams reinforced with SMA (NiTi) bars was less than one-fifth comparing to beams reinforced with steel bars (Ayoub et al. 2003). Abdulridha et al. (2013) studied the behaviour of RC beams reinforced with superelastic SMAs subjected to monotonic, cyclic and reversed cyclic loading. Li et al. (2006) investigated the usage of NiTi bars and wires in concrete beams and showed that during a seismic event the damage induced in structure could be minimized in the form of crack closure or reduction in crack width by taking advantage of the superelastic property of SMA. Zafar and Andrawes (2013) used superelastic SMA composites (100 % SMA wires and hybrid SMA fibers and glass-FRP) and studied the cyclic behaviour of composites and showed high ductility, recentering capabilities and energy dissipation as compared to the conventional FRP reinforcing bars.

3.3 SMA bars as a reinforcement in Beam-Column Joints

The behaviour of BCJ specimens reinforced with Shape Memory Alloy material has been investigated by (Alam et al. 2007). BCJ specimens reinforced with ordinary steel reinforcement bars and SMA bars were tested under reverse cyclic loads. The results illustrated that the SMA-reinforced BCJ specimen could recover most of its deformation. SMA - FRP hybrid system was investigated by Nehdi et al. (2010) for an RC - BCJ tested under reverse cyclic loadings, where SMA bars have been used in the plastic hinge area and FRP bars in the other areas, which demonstrated the capability to recover large deformations upon unloading process. If SMAs can be used as a reinforcement in the plastic hinge region at the BCJs, they can yield under the strains caused by seismic loads but potentially recover deformations at the end of earthquakes (Saidi and Wang 2006).

4 EXPERIMENTAL PROGRAM

4.1 SMA bars Used in the Experimental Program

SMA bars used in this research were obtained from China. SMA bars are 12 mm in diameter. XRF test was performed to get the exact chemical composition of the SMA material. The chemical compositions of SMA bars show Nickel 51.92 % and Titanium 45.87 %. For use in the plastic hinge region of the BCJs, SMA bars were trained by heating. The specimens were heated to 350 °C in a furnace for one and a half hours. The specimens were taken out from the furnace and immediately quenched in water. SMA bars were also ribbed using a particular machine as per ASTM standards. This operation was challenging. Figure 2 illustrates the SMA bar before and after ribs formation.

4.2 *Couplers for connecting SMA Bars to Steel bars*

Single-barrel, regular type screw locks couplers were employed for connecting the steel reinforcement bars with SMA bars in all BCJ specimens. Figure 3 shows the coupler used in the BCJ specimens. The SMA bars placed in the couplers are also shown in the figure. These types of couplers comply with ASTM A615 and compatible with the reinforcing bars. In these couplers, each bar reinforcement end is inserted at the end of the coupler to the middle position that can be seen by a small hole in the middle. Then, bolts were tightened with proper torque until their heads go inside the bars.

Figure 2. SMA bars before and after ribs creation.

Figure 3. The mechanical coupler with SMA bars for tension testing.

4.3 Testing of SMA Bars under Cyclic Loading in Uniaxial Tension

The SMA bars were tested in tension to obtain the stress-strain relationship under monotonic and cyclic loading. For this purpose, the SMA bars were shaped according to ASTM standards, as shown in Figure 4. The specimens were tested under uniaxial cyclic loading at a speed of 2 mm/min. The bars were tested in 100 kN capacity Instron series 8000 testing machine, as shown in Figure 4. Figure 5 shows the response of the 12 mm diameter SMA bar under cyclic tension loading. The maximum stress at 5% strain is 330 MPa. It can be seen from the figure that upon unloading from strains up to 4%, the strain in SMA bar is less than 0.2%. As compared to steel SMAs have a low modulus of elasticity.

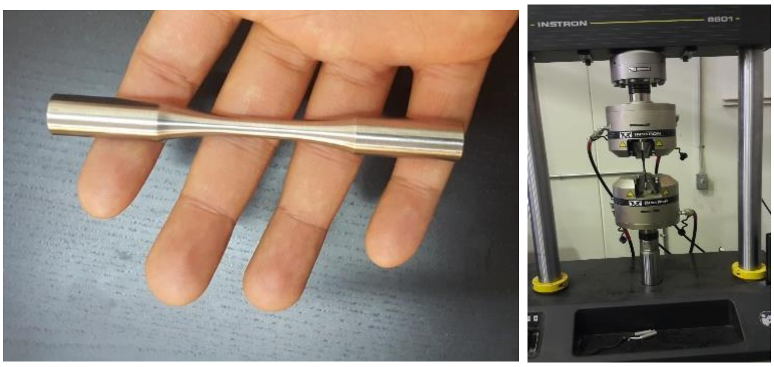


Figure 4. Specimen and arrangement for Testing of SMA bars under uniaxial tension.

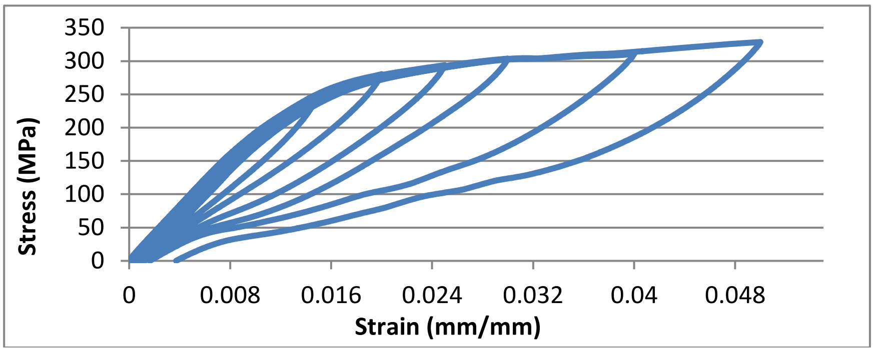


Figure 5. Stress-strain diagram curve of SMA bar used in the experiment.

4.4 Details of BCJ Specimens with SMA Bars

For SMA bar reinforced specimens, six 12 mm diameter steel bars were used in columns as primary reinforcement, whereas 8 mm diameter steel ties were used for transverse reinforcement. Similarly, three 12 mm diameter bars were used as bottom and top primary reinforcement in all beams. The main reinforcements were either standard steel bars or SMA bars. In addition, 8 mm diameter closed stirrups were used as transverse reinforcement for all beams.

Moreover, two 8 mm diameter ties were used in the joint for all the specimens. Geometry and reinforcement for two typical specimens are shown in Figure 6. The SMA bars are located only in the plastic hinge region, with the remaining being the ordinary steel. Fifteen (15) strain gauges were installed on the reinforcing steel, SMA bars and couplers in each specimen. These gauges were installed as illustrated in Figure 6.

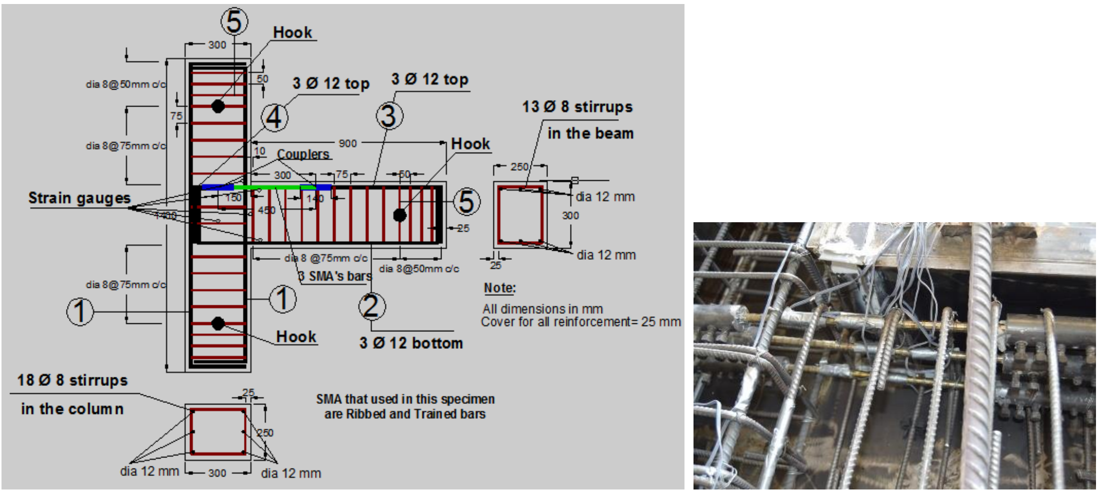


Figure 6. Details of steel reinforcement and SMA bars in BCJ specimen.

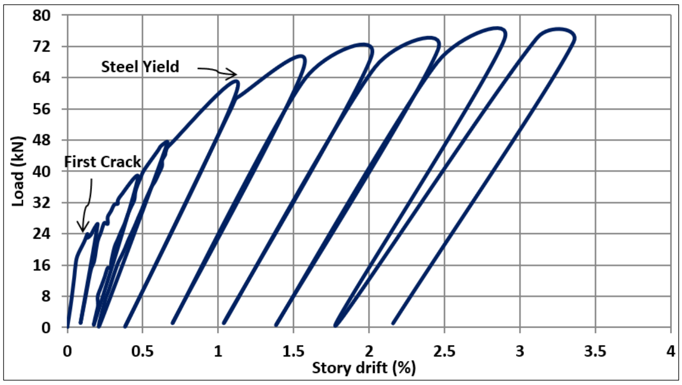
4.5 Testing of BCJ Specimens Reinforced with SMA Bars

Concrete stain gauges, LVDT's, and load cells were installed for all BCJ samples with SMA bars to record deflections, strains, and loads. A string type patriot LVDT was placed at the beam tip to record deflections during BCJ specimens testing. Two LVDT's were placed at the bottom and top of the column to measure any movements or rotations, and two were placed in the joint region for measuring any diagonal cracks. In addition, two LVDT's were installed at the critical section at the bottom and top of the beam for measuring the crack width during the test as shown in Figure 7. Concrete strain gauges were placed on the tension and compression side of the column and beam for measuring strains on the concrete surface.

Figure 7. Test specimen with Load cells and LVDT's.

5 TESTING OF CONTROL SPECIMEN UNDER CYCLIC LOAD

Two control specimens were tested, one under monotonic load and the other under cyclic load up to failure. The load vs deformation under various cycles for the cyclic load test is shown in Figure 8 (left). The yielding of steel occurred at a load of 63 kN, and the maximum load in the BCJ specimen under cyclic load was 76 kN. The maximum displacement reached during the test was 30 mm. The maximum load was of the same order in magnitude as compared to the specimen tested under monotonic loading. The first flexural crack occurred at the BCJ interface at a load of 26 kN with a corresponding displacement of 2.0 mm. The second major flexural crack close to the BCJ interface at a load of 38 kN with a displacement of 4.0 mm. At the same time, the third crack was formed at the beam top surface far away from the second crack. Figure 8 (right) shows the formation of cracks at the BCJ interface on the top of the beam.



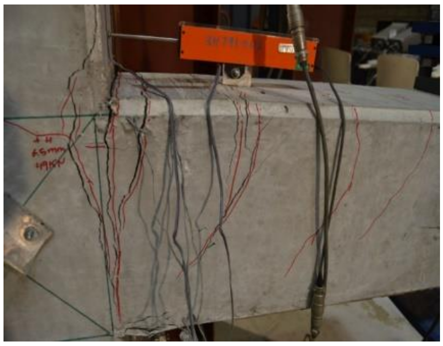


Figure 8. Load-displacement response (Left) and cracking at the interface in BCJ (Right).

6 BCJ SPECIMEN WITH SMA BAR UNDER CYCLIC LOADING

The specimen NiTi-BCJ-1 is reinforced with three ribbed SMA bars at the top in the plastic hinge region of the BCJ. These bars were trained and ribbed, connected to the regular reinforcing bars using couplers and epoxy before placing in the BCJ specimen. A cyclic load test was performed on this specimen. The load vs displacement curve is shown in Figure 9. The maximum load which the BCJ SMA reinforced specimen can carry was 32 kN. The maximum displacement during the test was 30 mm. During the test, only two major flexural cracks occurred in the beam of the BCJ specimen. One of them at the BCJ interface and the second at a small distance from the joint as illustrated in Figure 10. Both cracks started at loads of 18 kN, and following which, the load decreased suddenly from 18 kN to 13.7 kN at a displacement of 2.2 mm. The load then increased in each successive loading and unloading cycle up to a maximum value of 32 kN. The cracks became wider with an increase of the beam tip displacement on loading, and once the load was removed, the crack width decreased due to the superelastic effect of the SMA bars in the plastic hinge region. Figure 10 shows the wide cracks on loading during the last cycle, which closes after removing the load. The graph shows the expected behaviour of the BCJ in terms of closing the cracks after removing the applied loads. It shows a crack recovery of 80 % during the test, which means that SMA bars remained in the martensite stage.

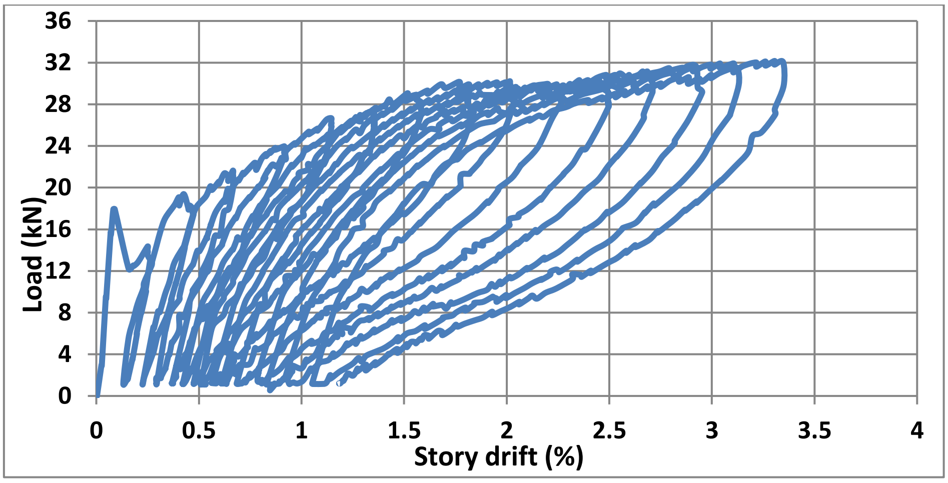


Figure 9. The load-displacement curve for a cyclic load on SMA NiTi-BCJ specimen.

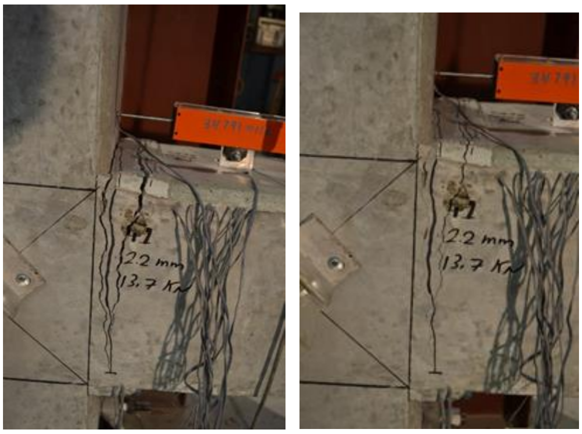


Figure 10. Opening (left) and closing (right) of the cracks for NiTi-BCJ-1.

7 CONCLUSIONS

Based on experimental investigation, which has been carried out for BCJ specimens reinforced with SMA bars in the plastic hinge region it can be concluded that the BCJ specimen with ribbed and trained SMA bars shows excellent results in terms of crack recovery, residual displacement, and load capacity. BCJ specimen with plain and trained SMA bars shows some crack recovery and residual displacement initially, but after the loss of bond between SMA bars and surrounding concrete, the plain SMA bars show no crack recovery

8 ACKNOWLEDGEMENT

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