Ductility behavior of RC beams strengthened in flexure with NSM Iron-based Shape Memory Alloy bars

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ABSTRACT: The superior mechanical behavior of Shape Memory Alloys (SMAs) has attracted the researchers from different fields. Less interest was noticed in the structural engineering field due to the high cost of these materials especially for large-scale applications. The SMAs are mainly characterized by the super-elasticity and shape memory effect phenomenon that reflects the ability of the SMAs to recover their original shape after being deformed beyond the elastic limits upon stress removal by heating through thermal heat transformation from martensite to austenite and can provide an active external strengthening mechanism to Reinforced Concrete (RC) members. Recently, an Iron-based SMA (Fe-SMA) reinforcement has been developed. The Fe-SMA is relatively inexpensive compared to the conventional Nickel Titanium (NiTi) alloys due to the lower cost of the constitutive materials and availability of mass production facilities of structural steel.

As part of an ongoing research project studying the potential capability of Fe-SMA in strengthening RC beams for flexure, this paper reports on the static flexural behavior and ductility of RC beams strengthened with prestressed near-Surface Mounted (NSM) Fe-SMA bars in the form of bars embedded inside a groove pre-cut into the concrete cover on the tension side of beam and filled with epoxy adhesive. The pre-strained Fe-SMA bar was mounted in a groove cut near the concrete surface on the tension side of the beam. The Fe-SMA bar was then heated up to 350^{o}C which resulted in a stress recovery in the bar that counteracts the applied loads to the beam, and eventually increases its flexural capacity. The results showed that the yielding and ultimate loads of the strengthened beam were considerably improved. More importantly, the ductility was also significantly improved. The test results were compared to another experimental results found in literature for RC beam with the same properties but strengthened with Carbon Fibre Reinforced Polymer (CFRP) NSM strip having the same prestressing force. Although the NSM CFRP strip resulted in higher ultimate flexural capacity, but the ductility was compromised unlike the beam strengthened with NSM Fe-SMA bar.

1 INTRODUCTION

Retrofitting of deficient RC structures has been widely adopted as an alternative to the demolition and rebuild option. The most common materials used for the retrofitting and strengthening techniques were the Fiber Reinforced Polymers (FRPs). For flexural strengthening of RC beams, the FRPs are typically applied in the form of sheets, strips, and bars. Several techniques are used to attach the FRPs to the soffit of RC beams and girders; namely, the externally bonded system (EB), the near surface mounted system (NSM), and the mechanically fastened/anchored system (MF/MA) (Baky et al., 2007; El-Hacha and Rizkalla, 2004; Lamanna et al., 2001). To improve the serviceability behavior of the RC beams, researchers have developed a prestressed FRP technique, where the FRPs are prestressed against the RC beam (El-Hacha and Gaafar, 2011). This technique has shown a remarkable enhancement of the flexural performance of the strengthened beams at service and ultimate limit states. However, because of the brittle nature of the FRPs, the ductility is compromised, and the beams typically failed suddenly by rupture of the FRPs.

This ongoing research project proposes a strengthening technique that makes use of the Shape Memory Effect (SME) of the iron-based Shape Memory Alloys (Fe-SMA). The SME represents the ability of the SMAs to recover their original shape after being deformed beyond the elastic limits through heating. The recovered strain in this transformation can be utilized for several engineering applications such as applying prestressing force to the RC beams, and active confinement to RC columns (Cismasiu, 2010; Lagoudas, 2008). Test results showed that because of the ductile nature of the Fe-SMA material, the RC beam strengthened with NSM Fe-SMA bar failed in a ductile failure mode by yielding of the NSM Fe-SMA bar and the internal steel reinforcement prior the crushing of concrete. This paper presents part of the ongoing research project that involves the investigation of RC beams strengthened with Fe-SMA bars under different loading and environmental conditions. In this paper the ductility of the RC beam strengthened with NSM Fe-SMA bar is compared to a RC beam with same properties but strengthened with prestressed NSM CFRP strip tested by Hadisiraji and El-Hacha (2014). Both strengthening materials (i.e. Fe-SMA bar and CFRP strip) were used to apply same prestressing force at the tension face of the RC beam.

2 BACKGROUND

The two main characteristics of the SMAs are the pseudoelasticity and the Shape Memory Effect (SME). These properties are attributed to the temperature and stress dependent phase transformation. The SMAs exist in low-symmetry martensite phase at low temperature, and a high symmetry austenite phase at high temperature (Cismasiu, 2010; Lagoudas, 2008). The crystallography of the two phases is different, and therefore different mechanical properties. The most common SMA (i.e. Nickel Titanium, NiTi) exhibits the temperature-induced martensite transformation as presented in the phase diagram in Figure 1. In the absence of load at high temperature austenite finish temperature (A_f) the SMA is in austenite phase. Upon cooling, the crystal structure starts to change from austenite to martensite at martensite start temperature (M_s) and fully transferred to martensite phase at martensite finish temperature (M_f). The heating of the SMA again above the austenite start temperature (A_s) will result in reverse transformation from martensite to austenite phase. The σ_s is the stress at which the twinned martensite (several martensite variants) will start to change in detwinned martensite (where one variant become dominant), and σ_f is the stress at which the material is fully transformed to detwinned martensite. The SME occurs when the SMA is deformed while on the twinned martensite phase at temperature below A_s. When it is subsequently heated above A_f, the SMA starts to recover part of the induced strain called the recovered strain. The proccess of SME is presented in Figure 2. If the SMA is restrained from both ends, a tensile stress will be developed in the SMA called the recovery stress. Although the Fe-SMA exhibits the SME, but the martensite transformation occurs in a different mechanism. The Fe-SMA material at austenite phase transofrms to martensite phase upon mechanical loading (rather than temperature change as for NiTi) at an intermediate temperature (higher than M_s and less than A_s) (Cladera et al., 2014). Upon heating, the stress-induced martensite toransforms to austenite causing the SME. According to the manufacturer, high level of initial strain causes slip deformation associated with martensite transformation. Therfore, the recovered strain is about 50% of the initial strain (Awaji, 2014).

The use of Shape Memory Alloys (SMA) in strengthening of reinforced concrete (RC) structures is very limited due to its high cost relative to other smart materials (i.e. Fiber Reinforced Polymers). Very few attempts were conducted to use SMA in large-scale application. One of the applications of SMA in structural engineering field is the seismic isolation and energy dissipation devices (Cardone et al., 2004; Ocel et al., 2004). Moreover, the SMAs were used as actuators to control internal prestressing forces in respond to external loads using the SME ability of the material (Li et al., 2006). Hadiseraji and El-Hacha (2014) used NiTi SMA bars as actuators to apply a prestressing force to the NSM-FRP strips to strengthen RC beams. The recent development of an Iron-based SMA (Fe-SMA) with considerably lower cost, high recovery stress, and a very large thermal hysteresis, which prevents reverse transformation, is considered to be a suitable choice for structural engineering applications (Awaji, 2014; Dong et al., 2009; Li et al., 2013). The first reported attempt to use Fe-SMA in external prestressing real life application was in 2001 by Soroushian et al., (2001), where a corrosion resistant Fe-SMA bars were used to strengthen RC bridge girder for shear. The 10.4 mm diameter bars were anchored to the sides of concrete beams inclined by 35 degrees and then heated using resistive heating technique with a current of 1000 Ampere. The recovery stress was about 120 MPa, which is less than the expected due to the slippage of the anchorage set.

Rojob and El-Hacha (2015a and 2015b) studied the effect of thermo-mechanical training of the Fe-SMA bar on the static flexural behavior of strengthened RC beam and compared with beam strengthened with un-trained Fe-SMA bar. The results showed that one cycle of thermo-mechanical training of the Fe-SMA NSM bar resulted in a higher yield load of the strengthened beam. However, because the post-yield behavior of the trained and un-trained Fe-SMA bars are the same, the ultimate capacity of the beam was not significantly improved. The ductility of the strengthened beams was also improved. Rojob and El-Hacha (2015c) developed a nonlinear FE model to simulate the behavior of beam strengthened with NSM Fe-SMA bar.

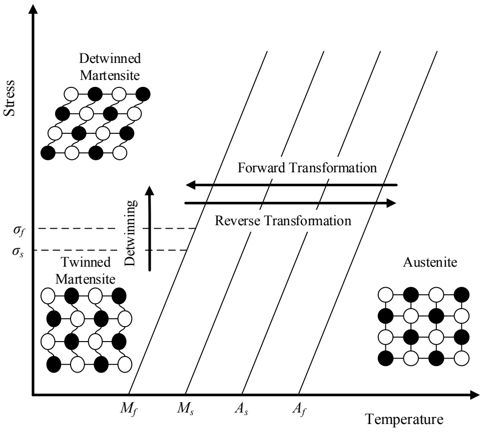

Figure 1. Phase Diagram of NiTi SMA, after Lagoudas (2008).

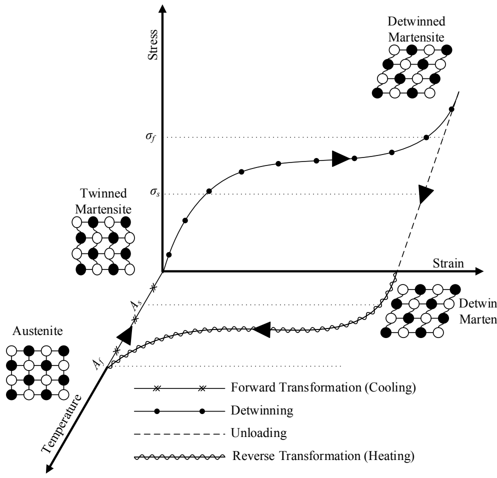

Figure 2. Shape memory effect of NiTi SMA, after Lagoudas (2008).

3 EXPERIMENTAL PROGRAM

3.1 Beam details

The experimental program of the ongoing research project includes several RC beams tested under different loading and environmental conditions and strengthened using different NSM reinforcement. In an accompanying paper, El-Hacha and Rojob (2015) reported on the results of the fatigue performance of RC beam strengthened with NSM Fe-SMA bar. This paper reports on the results of static flexural behavior and ductility of a beam strengthened with NSM Fe-SMA bar (Beam-SMA) and compared with the results reported by other researchers (Hadiseraji and El-Hacha, 2014) of a beam strengthened with NSM CFRP bar (Beam-CFRP) and a control un-strengthened beam (Beam-C). The geometrical details of the tested beam are shown in Figure 3. The beams are 2000 mm long with span length of 1800 mm, and cross-section of 150×305 mm. The average 28 days compressive strength of concrete is 38 MPa. The beams were reinforced with two 15M steel bars in tension and two 10M steel bars in compression with total cross-sectional area of 400 mm^2 and 200 mm^2, respectively. To avoid shear failure, the beams were reinforced with two-legged 10M steel stirrups at 150 mm center-to-center. The average yield strength of the tension and compression steel reinforcements was 458 MPa.

3.2 Strengthening procedure

The beam was strengthened with 1000 mm long and 14.3 mm diameter Fe-SMA bar produced by Awaji Materia Co. (2014). The bar was hot rolled without surface finish. To make use of the SME of the bar, it was strained to 6% strain before being anchored in a groove cut on the tension face of the RC beam. The 6% strain is the optimum strain value, which results in the highest shape recovery (Awaji, 2014). The bar was then attached to the beam using 10 mm thick steel plates anchored by Carbon Steel Kwik Bolt 3 Expansion anchor produced by Hilti Inc. (2011). Then the bar was heated using flexible heating tapes up to 315^{o}C to initiate the transformation from the detwinned martensite to austenite phase. Because the bar is anchored at both ends, a stress was developed in the bar. After the bar cooled down to room temperature, the groove was filled with epoxy adhesive produced by Sika Canada (2012).

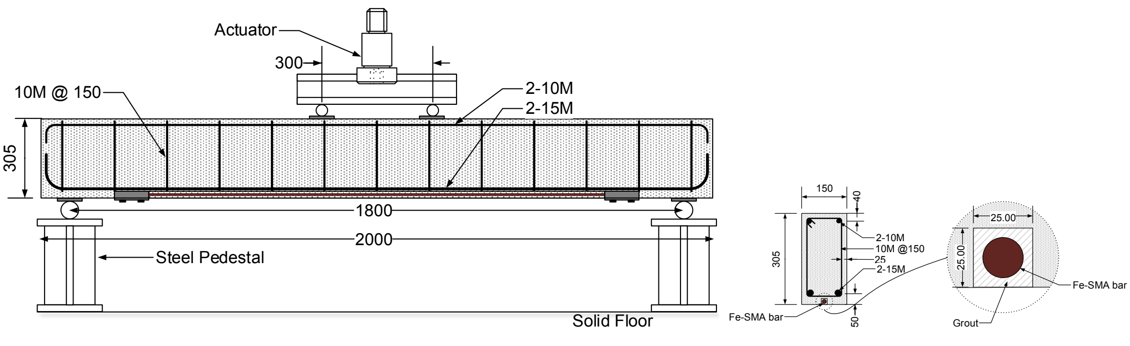

Figure 3. Geometrical details of the strengthened beam (all dimensions are in mm).

3.3 Testing procedure

As shown in Figure 3 the beam was tested on four point bending setup. The load was applied monotonically under a load control scheme. The beam was instrumented with four Linear Strain Conversion (LSC) at the mid-span of the beams to monitor the stain at the concrete surface (two LCSs were placed on the side of the beam in which one of each is mounted at the level of the internal longitudinal bottom and top steel; and two LCSs were mounted at the top of the beam to measure the strain in the concrete) in compression. Two strain gauges (SG) were installed on the tension steel and one was installed on the compression steel, at mid-span of the steel bars. Two laser transducers were used to measure the vertical deflection at the mid-span of the beam.

3.4 Strengthening materials properties

To compare the flexural behavior between the beam strengthened with NSM CFRP strip and the beam strengthened with NSM Fe-SMA bar, it is essential to check the stress strain curves of both materials. Figure 4 presents the stress strain curves of the CFRP strip and the Fe-SMA bar. It is obvious that the Fe-SMA bar is much more ductile which reflects on the overall flexural behavior of the strengthened beam. The ultimate capacity of the CFRP strip is 2068 MPa and the ultimate strain is 1.7%, while the Fe-SMA bar ultimate strength is 826 MPa and the ultimate strain is 41%. As mentioned earlier, the prestressing force produced by the heating of Fe-SMA bar and prestressing the CFRP strip were close (21kN, 23.5kN, respectively).

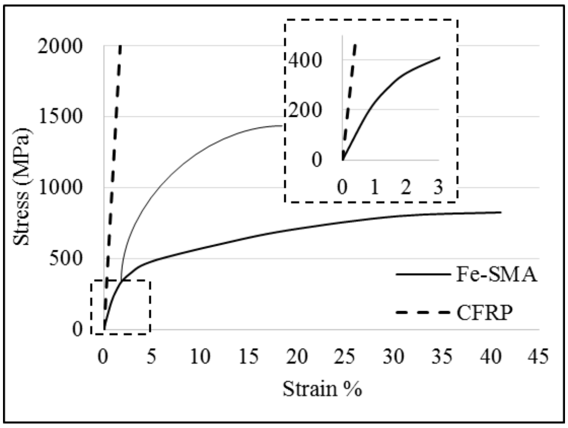

Figure 4. Stress strain curves of the Fe-SMA bar (after Awaji, 2014), and the CFRP strip (after Hadiseraji and El-Hacha, 2014).

4 RESULTS AND DISCUSSION

The beam strengthened with NSM Fe-SMA bar tested in the current research project and the beam strengthened with NSM CFRP strip tested by Hadisiraji and El-Hacha (2014) have the same dimensions, steel and concrete material properties, and tested under the same loading conditions. However, the strengthening materials were different. The prestressing force resulted from the heating of the Fe-SMA bar and the prestressing force of the CFRP strip was almost the same. Hadisiraji and El-Hacha (2014) have reported that the CFRP strip produced 23.5 kN when prestressed to 5712 micro-strain, which is equivalent to 33.6% of the ultimate strain of the CFRP strip. In the case of Fe-SMA bar it wasn't possible to measure the prestressing force directly during the heating process. Therefore, the stress was calculated based on the manufacturer material properties. If the Fe-SMA bar is strained to 6% strain and then exposed to heat, the recovery stress will start to develop at 150^{o}C (A_s) and increases gradually up to 130 MPa at temperature of 315^{o}C (just above A_f) (Awaji, 2014). This value of stress is equivalent to 21 kN, which is very close to the prestressing force produced by the prestressed CFRP strip. Figure 5 shows the load versus mid-span deflection curves of the control unstrengthened beam (Beam-C) and the beam strengthened with NSM-CFRP strip (Beam-CFRP) which were tested by Hadisiraji and El-Hacha (2014), and the beam strengthened with NSM Fe-SMA bar (Beam-SMA). The Beam-SMA failed in a ductile failure mode by yielding of tension steel and yielding of Fe-SMA bar prior to the crushing of concrete. Figure 6 shows the strain distribution across the depth of Beam-SMA at mid-span for different loading levels. The strain on the Fe-SMA bar was not measured since the bar was exposed to heating process and no strain gauges were attached. The Beam-CFRP failed in a sudden brittle failure mode by rupture of the CFRP strip.

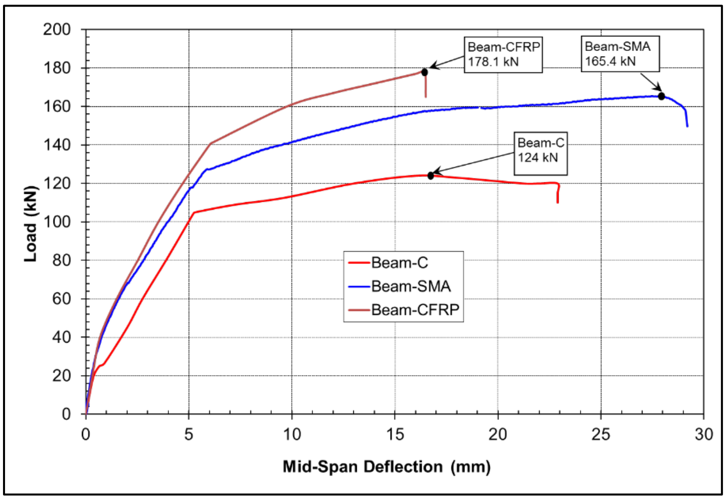

Figure 5. Load deflection curves of the control beam (Beam-C) (Hadiseraji and El-Hacha, 2014), beam strengthened with CFRP strip (Beam-CFRP) and beam strengthened with Fe-SMA bar (Beam-SMA).

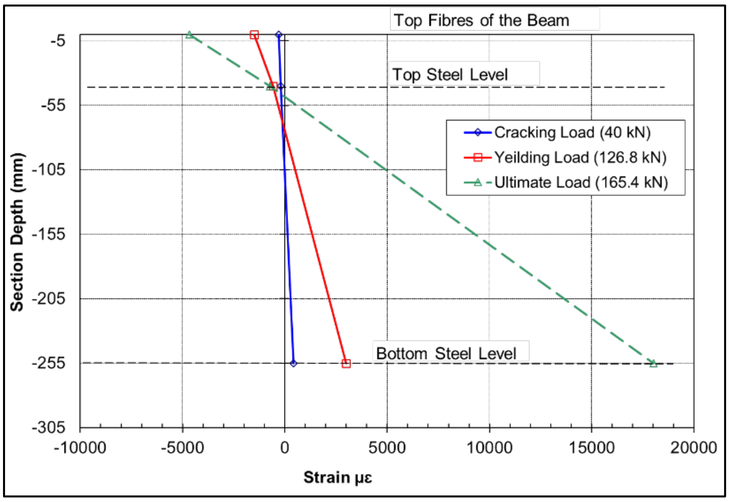

Figure 6. Strain distribution across the depth of Beam-SMA at mid-span at different loading levels.

The beams were both strengthened with close values of prestressing forces. In terms of flexural behavior at service and ultimate loads, Beam-CFRP shows slightly better performance. The cracking loads, yielding loads, and ultimate loads were within 11-15% higher than Beam-SMA as presented in Table 1. However, the energy dissipation for the Beam-SMA was significantly improved with 70% increase compared to a reduction of 6% in the case of Beam-CFRP relative to the control beam. This is due to the ductile behavior of the Fe-SMA bar compared to the CFRP strip as shown in Figure 4. The ductile behavior of the Beam-SMA is also reflected by the 41% increase in the ductility index, while the Beam-CFRP had 8% reduction in the ductility index. The ductility index was calculated as the ratio of deflection at ultimate load to the deflection at yield load. The total dissipated energy was computed as the total area under the load deflection curve up to the failure load (the point at which the load dropped) as shown in Figure 5. This means, with little compromise of service and ultimate loads, Beam-SMA shows a significant gain of ductility.

Table 1: Summary of test results.

	Beam-C[a]	Strengthened Beams			
		CFRP[a]	%Δ	Fe-SMA	%Δ
Cracking Load: P_{cr} (kN)	19	43	126	40	111
Yielding Load: P_y (kN)	104	141	36	126.85	22
Ultimate Load: P_u (kN)	124	178.1	44	165.4	33
Deflection at Yield: Δ_y (mm)	5.3	5.31	0	5.8	8
Deflection at Ultimate: Δ_u (mm)	18	16.5	-8	27.5	53
Ductlity Index Δ_u/Δ_y	3.4	3.1	-9	4.8	41
Energy Dissipated (kN·mm)	2376	2223	-6	4051	70

[a] Results were obtained from Hadiseraji and El-Hacha (2014)

5 FUTURE WORK

The Fe-SMA material performance can be improved by thermo-mechanical training that can be done before using the bar to strengthen the RC beam in flexure. The training can be achieved by one cycle of 6% strain followed by heating to 600^{o}C. This process will results in a better shape memory effect, or in other word, higher recovery stress and higher prestressing force. This means that the ultimate strength of a RC beam strengthened with thermo-mechanically trained Fe-SMA bar would be higher than a beam strengthened with non-trained bar. However, this training process will also affect the ductile behavior of the bar and eventually the overall flexural behavior of the strengthened beam. The effect of the thermo-mechanical training on the behavior of the Fe-SMA bar and the strengthened beam is part of the ongoing research project studying the performance of the RC beams strengthened with Fe-SMA bars under different loading and environmental conditions. To study the long-term performance of the proposed strengthening technique it is essential to study the effect of cyclic loading and the effect of freeze-thaw cycles. The ongoing research project will investigate these effects.

6 CONCLUSIONS

The new Fe-SMA material shows a potential capability to strengthen RC beams in flexure without compromising the ductility. Furthermore, the shape memory effect phenomena of the SMA makes the application of prestressing force much easier than the FRP materials. It is worth mentioning that the lower cost of the Fe-SMA is due to their inexpensive constituent materials. Furthermore, the production of such materials would be even cheaper providing the availability of normal steel bars mass production facilities, which can be used to produce the Fe-SMA bars. A comparison with another beam strengthened with CFRP strip with close amount of prestressing force revealed a better ductile performance of the beam strengthened with Fe-SMA bar.

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