

Long-term behavior of reinforced concrete beams strengthened by iron-based shape memory alloy strips

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ABSTRACT: During the last two decades, low cost Fe-Mn-Si based shape memory alloys have attracted much attention in the research community and practice, as a cost-effective alternative to the expensive Ni-Ti based shape memory alloys. A shape memory alloy (SMA) has the unique property to remember its initially given shape after being deformed. The reason is that its crystal transformation is reversible. Empa and Company re-fer developed an iron based shape memory alloy (Fe-SMA), also denominated as ‘memory-steel’. The Fe-SMA can be used as near surface mounted NSM strengthening reinforcement. The NSM Fe-SMAs can more easily be prestressed than NSM FRP, because prestressing of SMAs does not require any mechanical jacks and anchor heads. This practice requires cutting grooves in the cover of the concrete and no surface preparation work is needed afterwards.

When NSM Fe-SMAs are used for the strengthening of concrete structure, one critical aspect that needs to be investigated is the long-term behavior of such applications. The current paper presents an experimental investigation to determine the long-term behavior of strengthened RC beams under sustained loading in an outdoor exposure environment using an older prototype of Fe-SMA elements. Two beams strengthened with NSM ripped Fe-SMA strips, one with activated Fe-SMA strips and one with not-activated Fe-SMA strips, have been loaded until more than their cracking loads and their behavior has been monitored for about four years. Results show that both beams have similar trends in their mid-span deflection measurements, what indicates a stable prestressing force in the Fe-SMA strips.

1 INTRODUCTION

Reinforced concrete (RC) is used worldwide for the construction of buildings, bridges, retaining walls, tunnels, etc. RC consists of ribbed steel bars embedded in concrete. At some point of their lifecycle, RC and PC structures may be in need of rehabilitation due to aging or because of a change in usage, e.g., greater live loads (Czaderski et al. 2014). Available strengthening methods include, for example, adding an additional concrete layer in the compression zone or externally bonding (EB) steel or fiber-reinforced polymer (FRP) strips with an epoxy adhesive onto the concrete surface in the tensile zone. Alternatively, small FRP strips or FRP bars can be glued into 2–3 cm deep grooves in the cover of the concrete in the tensile zone. The latter strengthening method is known as “near-surface mounted” (NSM) reinforcement. Because of the reduced reinforcement cover and, therefore, reduced durability due to corrosion, ordinary steel reinforcements are not used in this technique. In contrast, FRP’s do not corrode so that they can be used in this technique in combination with epoxy adhesives as the grouting filler.

Many research works have studied the behavior of NSM reinforcement (and are still ongoing) by using FRP strips or bars to strengthen concrete structures. El-Hacha and Rizkalla (El-Hacha and Rizkalla 2004) presented the effectiveness of using NSM FRP reinforcing bars or strips for

strengthening concrete beams. In some of the strengthening cases, FRPs are prestressed. The advantages of prestressing FRPs is that existing deformations and crack widths in concrete structures can be reduced, the cracking and yielding loads are increased, and the FRP material is better utilized. The problem with prestressing NSM FRP strips/bars is that gripping the FRPs in the groove and prestressing them is very difficult. At the University of Calgary, a system to prestress FRP NSM reinforcement was developed (El-Hacha and Gaafar 2011). As mentioned in (Rezazadeh, Ramezansafat, and Barros 2016) due to the easy accessibility of the structure ends, a mechanical anchorage system can only be used to prestress the NSM reinforcement in laboratory experiments. However, in real structures, most of the times there is no access to the ends of the structural element to install the system. Therefore, application of Fe-SMAs could be a clever solution for this problem, as mentioned in the following section.

SMAs have a special property known as the “shape memory effect” (SME), in that if they are deformed they can return to the initial shape upon heating. The physical background for that behavior is the reversible transformations that occur between the atomic crystal structures, austenite (face center cubic, fcc) and martensite (hexagonal-close-packed, hcp). Depending on the alloy, the SME either happens instantaneously after the force is released, an effect that is called “superelasticity”, or it can be activated by heating the alloy. The most commonly known SMAs are NiTi alloys. These materials are used in the automotive, aerospace, robotic, and biomedical domain (Mohd Jani et al. 2014). In addition to the SME, SMAs have other interesting properties and can therefore be used as self-centering elements, dampers, sensors, or actuators. There is a considerable amount of literature on the topic of SMAs and their application in the construction industry (Cladera, Oller, and Ribas 2014).

The vast majority of the previous studies in civil engineering applications have used the superelasticity properties of SMA. For example, Saiidi and Wang (Saiidi and Wang 2006) studied the application of superelastic SMA bars in combination with a special engineered cementitious composite in the plastic hinge area of concrete columns. Several investigations on the prestressing of small concrete or mortar prisms by using SMAs can be found in the literature. Additionally, SMAs are used to actively confine concrete cylinders, large-scale concrete columns (Shin and Andrawes 2011), and non-circular concrete elements (Chen, Shin, and Andrawes 2014). Tran et al. (Tran, Balandraud, and Destrebecq 2015) performed crush tests on concrete cylinders confined by nickel–titanium SMA wires. They studied active confinement by SMA wires previously prestrained in the martensitic state and then subjected to the memory effect by heating. For comparison, they also studied passive confinement by using the same SMA, but in the austenite state.

The Fe-SMA material was discovered by Sato et al. (Sato et al. 1982) in 1982. Already in 2001, it was demonstrated that it was possible to strengthen a bridge with Fe-SMAs (Soroushian et al. 2001). Fe-SMA bars were used to apply corrective prestressing forces to a shear crack in a beam of the bridge. Furthermore, iron-based SMA fishplates are successfully used in Japan to connect crane rails (Maruyama et al. 2008). Sawaguchi et al. (Sawaguchi et al. 2015) developed an Fe-SMA with an improved low-cycle fatigue life and installed it in the JP Tower Nagoya in 2015.

At Empa, extensive studies on SMAs for civil engineering applications have been done over, approximately, the last 17 years (Czaderski et al. 2015). From 2005 to 2008, a new Fe-based shape memory alloy for civil engineering applications was developed (Dong et al. 2009) at Empa. The developed Fe-SMA can be activated at temperatures just above 100°C by resistive heating over a short period of about one minute. Furthermore, the alloy exhibits corrosion resistance clearly superior to that of conventional reinforcement steels, like S500 (Lee et al. 2016), so that it might be feasible for the NSM technique. In 2012, studies at Empa were

performed on the usage of Fe-SMA for the strengthening of reinforced concrete structures (Czaderski et al. 2014; Shahverdi, Czaderski, and Motavalli 2015; Shahverdi, Czaderski, and Motavalli 2016). The idea was to use Fe-SMA strips as NSM reinforcement. In this project, several RC beams were strengthened with the NSM technique using Fe-SMA strips (Shahverdi, Czaderski, and Motavalli 2015; Shahverdi, Czaderski, and Motavalli 2016). In addition to Fe-SMA strips, ribbed Fe-SMA bars were produced for strengthening of RC structures in combination with shotcrete (Shahverdi et al. 2016). The company re-fer was established in 2012 in order to promote and introduce Fe-SMA reinforcements to the construction market. In 2017, a first real application of externally fixed Fe-SMA strips on a concrete slab in a storage hall has been conducted by Empa and the company re-fer (Michels, Shahverdi, and Czaderski 2018) and up to now more than 20 real applications have been carried out by the Company re-fer.

Although many studies has been performed on the characterization of Fe-SMAs, e.g. (Shahverdi et al. 2018), (Michels et al. 2018) and the Fe-SMA behavior has been numerically modeled (Abouali et al. 2019), but still the long-term behavior of the studied Fe-SMAs are not fully known. Current study aims at providing some first investigation on the long-term behavior of reinforced concrete beams strengthened by iron-based shape memory alloy strips.

2 MATERIAL PROPERTIES

In the framework of this study, two large scale beam experiments under four-point bending tests in an outdoor environmental condition under sustained load were considered, see Figure 1. These two beams are similar to the beams presented in (Shahverdi, Czaderski, and Motavalli 2016) under quasi-static and monotonic cyclic loading.

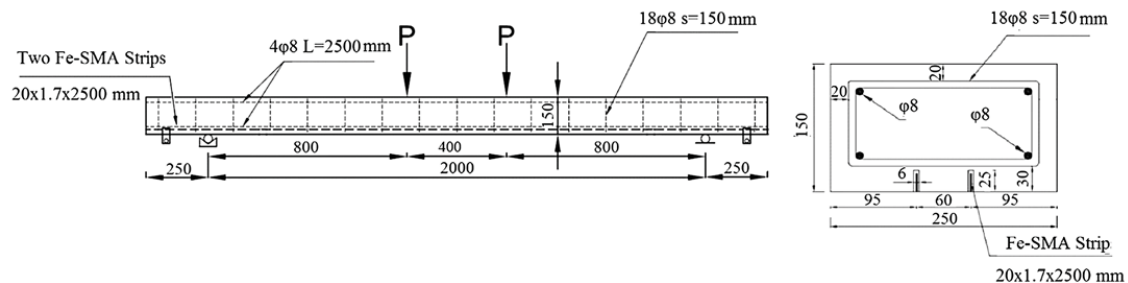


Figure 1: Beam reinforcements and dimensions. One beam Fe-SMA strips were activated while in other one Fe-SMA strips were not activated

2.1 Iron-based shape memory alloys (Fe-SMA) strips

The iron-based shape memory alloy Fe-17Mn-5Si-10Cr-4Ni-1(V,C) (ma.-%) developed at Empa in Switzerland was used in this study. A large quantity of the new alloy was produced and strips were manufactured. The detailed production procedure of the Fe-SMA strips is described in (Czaderski et al. 2014). The Fe-SMAs used in this study, from an old production in 2014, were initially in the form of long ribbed strips from a prototype production in 2013. They were delivered to Empa in two batches. To ensure a good bond between the Fe-SMA strips and the concrete, ribs were applied on the strips by cold forming. The presented lap-shear tests on the Fe-SMA strips proved the feasible bond behavior of the ribbed Fe-SMA strips (Czaderski et al. 2014). The nominal thickness, initial width and initial length of the Fe-SMA strips were 1.7 mm, approximately 25 mm and more than 3 m, respectively. However, these Fe-SMA strips were cut into strips with a length of 2.6 m and a width of 20 mm. The strips were ground on the

edges to remove the edge cracks. The remaining short pieces of the strips were used for material characterization.

2.2 *Concrete and grout*

A concrete mix of Type I Portland cement (350 kg/m^3) and a coarse aggregate with a maximum size of 16 mm and a water cement ratio of 0.50 by weight was used to cast the beams. Additional concrete samples of $150 \times 150 \times 150 \text{ mm}$ were casted for each beam and were tested at the age of 28 days and on the day of performing the experiments. The average compressive strength, splitting tensile strength, and elastic modulus of the concrete after 28 days were, respectively, 53.4 MPa, 3.4 MPa, and 35.4 GPa.

The cement-based mortar for the grouting of the Fe-SMA strips into the grooves was a flowable and expanding grout (SikaGrout-311) from Sika in Switzerland, and it was purchased from the market. According to the technical datasheet from the company, the maximum grain diameter size, compression strength after 28 days and elastic modulus of this mortar are 1.2 mm, 80–90 MPa and approximately 37.2 GPa, respectively.

2.3 *Internal steel reinforcement*

The diameter of the four flexural reinforcement bars was 8 mm ($\text{Ø}8$), see Figure 1. The internal stirrups also had a diameter of 8 mm and a spacing of 150 mm. The elastic modulus and yielding strength of the internal flexural reinforcement were 200 GPa and 508 MPa, respectively.

3 EXPERIMENTAL SETUP AND PROCEDURES

The beam experimental procedure was based on the following main steps:

- Prestraining of the strips
- Grouting of the Fe-SMA into the grooves
- Activation, i.e., the prestressing of Fe-SMA strips embedded in the concrete beams
- Sustained loading of beams up to a defined level (more than concrete cracking load)
- Long-term monitoring of the beam behaviors under sustained loading

3.1 *Prestraining of the long strips*

The long Fe-SMA strips test specimens, which were embedded in the grooves of the RC beams in a later stage (length of 2.6m), were prestrained to a 2% elongation at room temperature by a manually operated oil hydraulic jack and then relaxed to a stress-free state with the recovery of the elastic strain. The Fe-SMA strips were clamped at the ends with steel clamps and then fixed in a vertical test set-up on the strong floor, Figure 3.

3.2 *Grouting of the Fe-SMA into the grooves*

The grooves with dimensions $25 \times 6 \text{ mm}$ at the bottom of the beams were made on a saw cut table machine. The SMAs were inserted into the grooves and the grooves were filled by a cement-based grout that was prepared according to the supplier's recommendations. Finally, the excess grout was removed, and the surface was leveled. Before embedding the Fe-SMA strips in the concrete, each Fe-SMA strip was equipped with three Type K thermocouples. The thermocouples mounted on each strip measured the temperature at the surface of the strips inside the concrete beams, for more details see (Shahverdi, Czaderski, and Motavalli 2016).



Figure 2: Photograph of ribbed Fe-SMA strips

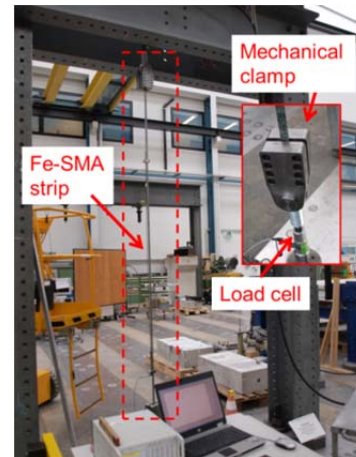


Figure 3: Prestraining of long Fe-SMA strips

3.3 Activation of the long strips embedded in one beam

The activation of embedded Fe-SMA strips in one beam was performed after the grout for the Fe-SMA strips was fully cured. One beam was not activated in order to compare the effect of activation (prestress force) on the long-term behavior of the studied beams. The activations were performed by resistive heating. A programmable electrical power supply was used to provide the resistive heating. This power supply was controlled by a LabView program. The program acquired the signals from the thermocouples and controlled the current supply for resistive heating. A relatively high current density of approximately 9 A/mm^2 was applied to minimize the heating times and reduce the heat flow into the concrete. When the temperature that was measured by selected thermocouples, which measured the strip temperatures in the concrete, reached the target temperature of $160 \text{ }^\circ\text{C}$, the power supply was switched off. Copper clamps Figure 4 were used to secure the contacts between the cables from the power supply and the Fe-SMA strips. The two Fe-SMA strips in the beam were connected by a copper cable and could therefore be heated together (i.e. in series). During the activation and the subsequent cooling phase, the mid-span displacements were measured by using two LVDT's. The strain on the top side and bottom side of the beam were also measured.

3.4 Sustained loading of the beams in an outside environment

Both beams (with Fe-SMA strips activated and not-activated) were simply supported at the ends and were loaded using a concrete block with a weight of 1535 kg hanged at two loading point with 400-mm spacing in the middle of the Figure 5. The weight of each concrete block was hold first by steel profile, sees Figure 6, and then slowly applied to the strengthened beams by turning the bolts hanging the concrete block. Both beams were placed outside the laboratory under unprotected environment. The loading happened on 7th May 2015.

3.5 Long-term monitoring of the beam behaviors

Mid-span deflection and crack propagation in both beams (activated and not activated) have been monitored and recorded since beginning of May 2015. Mid-span deflections were measured by a dial-gage LVDT, Figure 6. The temperature beside the beams were always recorded when the mid-span deflections were measured. Strains in the concrete were measured on the top side and bottom side by deformatometer measurements.

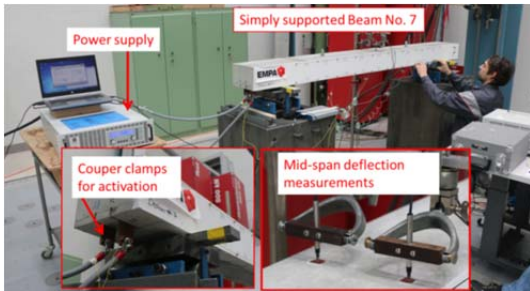


Figure 4: Setup for the activation of Fe-SMA strips

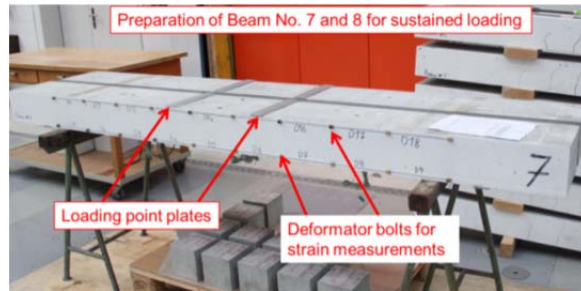


Figure 5: Left: preparation of beams with the loading point in the middle of the beams, 400-mm spacing



Figure 6: Top: Application of sustained load. Bottom: a photo of the mid-span deflection measurement of activated beam and a photo of the crack propagation marking



Figure 7: A photo of both beams in winter. Depth of the snow is approximately 80 mm

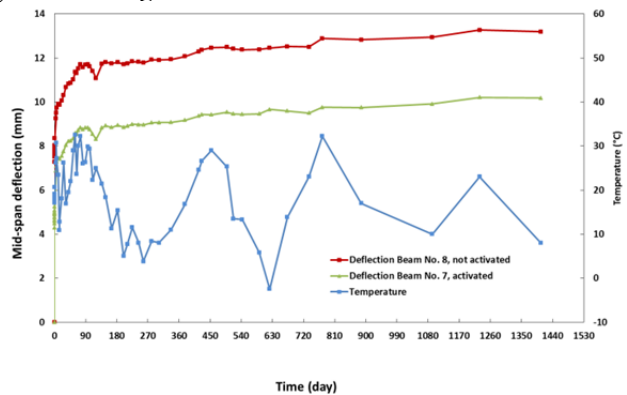


Figure 8: Load-mid-span deflection curves of both beams over about four years. Similar trend is monitored

4 RESULTS AND DISCUSSIONS

In Figure 8 load-mid-span deflection curves of both beams over about four years are depicted. The similar trend is monitored for both beams. The increase in mid-span deflection by time is mainly associated by the concrete creeping, initiation of new cracks in the concrete and propagation of the main cracks. In activated beam, the mid-span deflection has increased from about 4.3 mm to 10.2 mm. In non-activated beam, the mid-span deflection has increased from about 7.3 mm to 13.2 mm. As expected, deflections in the activated beam are smaller due to the existing prestress force and the main increase in mid-span deflections in both beams has happened in first three months.

5 CONCLUSIONS

Long-term behavior of the application of Fe-SMA reinforcements in the form of ribbed strips as a prestressing technique for flexural strengthening of RC beams was studied and presented in this work. The behavior of two similar beams strengthened by Fe-SMA strips over about four years under sustained loading has been monitored continually. Comparison of the mid-span deflection from both beams shows similar trends. It can therefore be concluded that the increase in the mid-span deflections is mainly associated with the creep in the concrete and the effect of concrete flexural cracks. Since the prestressed and un-prestressed beam showed fairly similar behavior, it can be concluded that the reduction in prestressing force is not significant and Fe-SMA strips have therefore a good long-term behavior.

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