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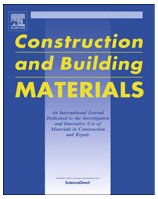

Iron-based shape memory alloys for prestressed near-surface mounted strengthening of reinforced concrete beams

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HIGHLIGHTS

- Manufacturing of long ribbed iron-based shape memory alloy (Fe-SMA) strips.
- Activation of long ribbed Fe-SMA strips by resistive heating.
- Demonstration of application of near surface mounted Fe-SMA strips for strengthening.
- Prestressing of RC beams with long ribbed Fe-SMA strips.
- Experimental examination of six large scale RC beams.

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ABSTRACT

Low-cost Fe-Mn-Si-based shape memory alloys (SMAs) have attracted much attention in the research community and in practice over the past two decades as a cost-effective alternative to the expensive Ni-Ti-based SMAs. The shape memory effect refers to the phenomenon in which SMAs, if they are deformed, return to their former shape upon heating. Near-surface mounted (NSM) strengthening techniques can be used to strengthen concrete beams. The advantages associated with NSM strengthening are its ability to significantly reduce the probability of harm that results from corrosion, fire, acts of vandalism, mechanical damage, and aging effects. Iron-based SMA (Fe-SMA) strips can be used as NSM reinforcements. The NSM Fe-SMAs can more easily be prestressed than NSM fiber reinforced polymers, because the prestressing of SMAs does not require any mechanical jacks and anchorheads.

In this study, an experimental program was established to investigate the flexural behavior of reinforced concrete (RC) beams that were strengthened and prestressed with Fe-SMA strips. The specific focus was on the demonstration of the feasibility of this strengthening technique. A total of six RC beams were experimentally examined under deflection control in a four-point bending loading rig. The experiments consisted of one beam strengthened by Fe-SMA strips but not prestressed, three beams strengthened by prestressed Fe-SMA strips, and one beam strengthened by one CFRP strip. Additionally, one beam with no strengthening, which served as the reference beam, was examined. The results showed that the cracking loads and mid-span deflections of prestressed beams compared to other beams were, respectively, higher and lower. Significant strengthening effects were achieved in NSM Fe-SMA-strengthened beams compared to the reference beam. These direct effects showed that the application of near-surface mounted Fe-SMA strips worked well as prestressing elements in concrete beams.

1. Introduction

Many existing concrete bridges must be strengthened due to aging or adapting to increase their load capacity. A popular strengthening technique currently is the application of fiber reinforced polymer (FRP) strips or fabrics by means of epoxy adhesives on a concrete surface [1]. In addition to the application on the surface, another technique exists, where the FRPs are inserted and glued into grooves in the concrete cover, which is called the near-surface mounted (NSM) strengthening technique [2]. This strengthening technique requires cutting grooves in the concrete cover, and no surface preparation work is needed afterwards. The advantages that are associated with NSM strengthening compared to the externally bonded technique are its ability to significantly reduce the probability of harm that results from corrosion, fire, acts

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of vandalism, mechanical damage, and aging effects. Furthermore, better bonding behavior due to a confining effect in the grooves can be expected.

In some of the cases, strengthening FRPs are prestressed. The advantage of prestressing is that existing deformations and crack widths can be reduced, and furthermore, the cracking and yielding loads are higher, and the FRP material is better utilized [3]. For the prestressing of externally bonded FRPs, different systems can be purchased from the market; however, prestressing systems for NSM FRPs are not available yet. The problem with prestressing NSM FRP strips/bars is that gripping the FRPs in the groove and prestressing them is very difficult. An overview of existing NSM prestressing systems used in laboratories is given in [4]. The application of iron-based shape memory alloy (Fe-SMA) strips instead of FRP strips will overcome this problem. Preliminary experiments to investigate the feasibility of the application of prestressed SMA strips for the strengthening of concrete structures have been presented by Czaderski et al. [5].

The available SMAs on the market are Nickel-Titanium (NiTi, Nitinol). However, this material is far too expensive for the construction industry [6]. Low-cost Fe-SMAs can be an interesting alternative. The Fe-SMA material was discovered by Sato et al. [7] in 1982. An extensive explanation of how this material works and some key properties of these materials, such as the recovery stresses and the corrosion resistance, have been presented by Cladera et al. [8]. A novel iron-based shape memory alloy Fe–17Mn–5Si–10Cr–4Ni–1(V,C) (ma.-%) has been developed at Empa in Switzerland [9–13].

Shape memory alloys (SMAs) have several unique properties. The two most important properties are the shape memory effect (SME) and superelasticity [6]. The SME refers to the phenomenon that if SMAs are deformed, they return back to their former shape upon heating. Superelasticity refers to the phenomenon that SMA can undergo a large amount of inelastic deformation and recover its shape after unloading automatically without heating. Due to the presence of the superelasticity property, SMAs are used in civil applications as a passive vibration damping and energy dissipation material [6]. Most of the research work in the field of SMAs for construction is focuses on these topics, for example [6,14–19]. Furthermore, recently 16 new seismic dampers were installed in JP Tower Nagoya in Japan using an Fe-SMA [20]. Moreover, in Japan, the material is used for the prestressing of crane rail joints using fishplates made of Fe-SMA [21,22] and for pipe joining [22].

The shape memory effect can be used to prestress an SMA strip/bar. For example, in principle, if a straight SMA bar is deformed by pulling and then heated above a certain temperature, it will return to its original length. However, if the deformation recovery is restrained (e.g., by embedding the SMA in concrete), a mechanical stress occurs in the material when it is heated and cooled afterwards. This stress is called "recovery stress", and it can be used for introducing prestressing forces in concrete structures to improve its serviceability. One of the advantages of such a prestressing technique compared to conventional prestressing is that there are no frictional losses due to the development of uniform tension force along the total length of the embedded SMA tendon. Therefore, such a prestressing technique would be even suitable for curved concrete members or if the tendon profile is strongly curved. Furthermore, in comparison to the conventional prestressing techniques, SMA tendons can be used for prestressing extremely thin concrete members without any need for anchorheads, oil hydraulic cylinders, ducts and grout injection.

Several investigations on the prestressing of small concrete or mortar prisms by using SMAs can be found in the literature, for example [6,23–30]. Additionally, SMAs are used to actively confine concrete cylinders [31,32], large-scale concrete columns [33] and non-circular concrete elements [34]. Tran et al. [32] performed some crush tests of concrete cylinders confined by nickel–titanium SMA wires. They studied active confinement by SMA wires previously prestrained in martensitic state and then subjected to the memory effect by heating. For the comparison, they also studied passive confinement by using the same SMA, but in austenite state. The results obtained in their study show that stiffness, strength, and ductility of the concrete were improved in both confinement systems. However, all of these investigations are still ongoing, and more research work is necessary.

The current study is a continuation of the study described in [5]. The same Fe-SMA strips described in [5] were used as prestressed NSM for the strengthening of RC beams. Six reinforced concrete beams with spans of 2 m were examined in the framework of the current study. The SME of the Fe-SMA strips was used to strengthen the RC beams. The obtained results showed the feasibility of the application of prestressed Fe-SMA strips for the flexural strengthening of concrete beams.

2. Experiments

Experimental work was conducted at Empa, the Swiss Federal Laboratories for Materials Science and Technology, on six two-meter span beams. The experimental program was designed to demonstrate the application of near-surface mounted prestressed Fe-SMA strips for the flexural strengthening of concrete beams. Beams were constructed with the dimensions shown in Fig. 1. All of the beams were loaded in a four-point bending test scheme with a span of 2.0 m. The experiments included a reference beam with no strengthening, three beams strengthened with two activated Fe-SMA strips, one beam strengthened with two non-activated Fe-SMA strips, and one beam strengthened with one CFRP strip for comparison. To have similar strengthening effects for all of the strengthened beams, only one CFRP strip was used as a strengthening element. An overview of the test program appears in Table 1. The material properties of the Fe-SMA strips, concrete, steel reinforcement, grout, CFRP strips, and adhesive used in the current study, the measurement set-up and the experimental procedure are presented in this section.

2.1. Materials

2.1.1. Iron-based shape memory alloys (Fe-SMA)

The novel iron-based shape memory alloy Fe–17Mn–5Si–10Cr–4Ni–1(V,C) (ma.-%) developed at Empa in Switzerland [9–12] 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 [5]. Tensile failure experiments, prestraining and heating/cooling experiments on the Fe-SMA strips are also presented in [5].

The Fe-SMAs used in this study were initially in the form of long ribbed strips. They were delivered to Empa in two batches. To ensure a good bond between the Fe-SMA strips and the concrete, ribs (Fig. 2) were applied on the strips by cold forming. The ribs were applied at an angle of approximately 40° on one side and 130° on the other side of the strip to ensure a regular strain pattern along the strip [5]. The presented lap-shear tests on the Fe-SMA strips proved the feasible bond behavior of the ribbed Fe-SMA strips [5].

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 (Fig. 2). The strips were ground on the edges to remove the edge cracks. The remaining short pieces of the strips were used for material characterization.

2.1.1.1. Characterization tests of the Fe-SMA strips. The short Fe-SMA specimens were prestrained in a 20 kN Zwick tensile testing machine. Then, they were heated by means of a climate chamber that was added to the Zwick testing machine to determine the recovery stress (prestress). A special clip-on extensometer with a gauge length of 100 mm was used for the heating experiments. The temperature expansion of the extensometer was continuously compensated during the experiments by respective control in the testing machine.

2.1.2. Concrete, steel reinforcement, grout, and CFRP strips

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 × 150 × 150 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 used internal reinforcement of the examined beams is presented in Fig. 1. The diameter of the four flexural reinforcement bars was 8 mm (Ø8). The internal stirrups also had a diameter of 8 mm and a spacing