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# Strengthening of RC beams by iron-based shape memory alloy bars embedded in a shotcrete layer

Moslem Shahverdi *, Christoph Czaderski, Philipp Annen, Masoud Motavalli

*Empa, Swiss Federal Laboratories for Materials Science and Technology, Überlandstrasse 129, 8600 Dübendorf, Switzerland*

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ABSTRACT

Shape memory alloys (SMAs) have the special property of returning to their initial shape upon heating which is called shape memory effect (SME). If the returning to the initial shape is prevented by a mechanical fixation, a prestress develops in the SMA due to the SME property. In the form of ribbed bars, the SMAs can therefore be used for the strengthening and stiffening of reinforced concrete (RC) structures. In particular, the recently developed iron-based shape memory alloy (Fe-SMA) with the composition of Fe–17Mn–5Si–10Cr–4Ni–1VC (mass-%) shows promising properties with regard to potential applications in civil engineering. In the framework of this paper, application of the recently developed ribbed Fe-SMA bars embedded in a shotcrete layer to strengthen RC structure is presented. Three beams were experimentally examined to demonstrate the application of this strengthening method. The flexural behaviors of the beams were investigated during activation and in a four-point bending loading test up to failure. Two of the beams were prestressed with ribbed Fe-SMA bars embedded in an additionally applied shotcrete layer. The third beam had normal steel reinforcement bars in the shotcrete layer and acted as the reference beam. The behavior at the serviceability stage was significantly improved by the prestressed Fe-SMA bars. The cracking load increased with this method compared with the reference beam. The results showed that the application of ribbed Fe-SMA bars embedded in a newly applied shotcrete layer on the bottom side of RC beams was successful and the strengthening technique worked well.


## 1. Introduction

As the importance of the renovation and conservation of existing civil structures and buildings increases, new and innovative methods to improve the load-carrying capacity and serviceability of existing civil structures are required. Wide-span and slender load-bearing structures are increasingly more demanded in the field of civil engineering. Therefore, new clever methods to strengthen and stiffen existing structures and to build new structures are necessary in the building industry. One set of advanced materials that is entering the industry are shape memory alloys (SMAs) [1–3]. SMAs have been known for a long time [1,4,5], but due to their expensive nickel and titanium alloys, they are not suitable for the building industry [1].

SMAs have the special property of returning to an initial shape upon heating, which is called shape memory effect (SME). Depending on the alloy, the SME either happens instantaneously after the force is released, what is called superelasticity, or it can be activated by heating the alloy what is called SME. The effect is based on the different lattice structures (austenite and martensite) that SMAs can have. The lattice structure can be changed by either mechanical stresses or the variation of temperature. The first reported steps toward the discovery of the SME were taken in an Au–Cd alloy in 1951; however, research investigations became more active after the effect was found in a Ti–Ni alloy in 1963 [6]. So far, most experiments and studies have been on NiTi-based alloys [2,3,5], which are currently commercialized in the automotive, aerospace, robotic and biomedical domains [7].

Application of SMAs in civil engineering can utilize the superelasticity or the SME properties of SMAs. There have been some demonstration projects [1,5,8–12], however, the application of SMAs in this domain is still in the research stage. The vast majority of the previous studies have used the superelasticity properties of SMA. For example: Saiidi and Wang [12] studied the application of superelastic SMA bars in combination with a special engineered cementitious composite (ECC) in the plastic hinge area of concrete columns. They showed that SMA-reinforced columns were able to recover nearly all of post-yield deformation. In another study, Moser and his coworkers [10] investigated the feasibility of reinforcing mortar with prestressed NiTi short fibers using the SME property. The wires, which were embedded in mortar, were

* Corresponding author. Tel.: +41 58 765 42 83.
*E-mail address:* moslem.shahverdi@empa.ch (M. Shahverdi).

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O- and star-shaped, and the activation was initiated by heating the whole specimen. The feasibility of prestressing the mortar with SMAs was shown. Furthermore, the relatively high temperature used for activation did not cause much interior damage to the mortar [10].

Although the expensive NiTi-based alloys are the most used SMAs so far, [1], low-cost copper-based shape memory alloys (Cu-SMAs) and iron-based shape memory alloys (Fe-SMAs) can be alternatives [2,13–15]. Cu-SMAs have superelastic properties with low elastic modulus and a low-cycle fatigue resistance [15]. However, in case of Fe-SMAs, in addition to the lower cost compared to NiTi-based alloys, another advantage is that they have a higher elastic modulus and can be activated at relatively low temperatures. This makes them very promising for the future of the strengthening of existing civil structures and also for prestressing new civil structures. In conventional prestressing, anchorages and jacks are needed to prestress the reinforcement. In contrast, SMA tendons can be used for prestressing extremely thin concrete members without the need for anchors, oil hydraulic cylinders, ducts and grout injection.

The Fe-SMA material was discovered by Sato et al. [4] in 1982. Furthermore, at Empa, Swiss Federal Laboratories for Materials Science and Technology, an iron-based SMA, Fe–17Mn–5Si–10Cr–4Ni–1(V,C) (mass-%), was developed [16–19]. There are two different phases in Fe-SMAs. The austenite phase, which occurs mainly at high temperature (and stays stable while cooling to room temperature), has a highly symmetric face-centered cubic (fcc) arrangement of the crystals. The martensite phase, the low-temperature phase, consists of hexagonal close-packed (hcp) crystals [2].

Already in 2001, it was demonstrated that it was possible to strengthen a bridge with Fe-SMAs [20]. Fe-SMA bars were used to apply corrective prestressing forces to a crack in a beam of the bridge. Furthermore, iron-based SMA fishplates are successfully used in Japan to connect crane rails [21]. Recently, Sawaguchi et al. [22] developed an Fe-SMA with an improved low-cycle fatigue life and installed it in the JP Tower Nagoya in 2015.

The newly developed Fe-SMA at Empa [16–19] was first used to prestress concrete bars with centrally embedded Fe-SMA strips [23] by using the SME property of the strips. The Fe-SMA strips were activated by resistive heating. Compressive stresses in the range of 3 MPa in the concrete section were obtained. The results indicate the general feasibility of the ribbed Fe-SMA strips for reinforcing and prestressing a concrete section. In another previous work at Empa [24,25], several reinforced concrete (RC) beams were strengthened using the near surface mounted (NSM) reinforcement technique with Fe-SMA strips. Grooves were cut in the cover of existing concrete beams, the ribbed Fe-SMA strips were put in the grooves, and then, the grooves were filled up with mortar. After activation, an uplift displacement at the mid-span was measured. Recovery stresses in the Fe-SMA strips of 190–210 MPa were back-calculated from these uplift displacements.

Embedding ribbed Fe-SMA bars in a new shotcrete layer can be another promising method to strengthen RC structures. This method has not been used before and was studied in the current work for the first time. Similar to NSM, shotcreting is a well-known technique to strengthen and repair existing RC structures. It is applied with wet or dry shotcrete technology to a roughened concrete surface. It can be applied to vertical or even overhead surfaces and is therefore an adequate material in combination with the ribbed Fe-SMA bars. In comparison to conventional shotcreting, application of Fe-SMA bars allowed the prestressing of the shotcrete layer without need for anchors.

The current study is a continuation of the study described in [23–25]. However, in this study, the Fe-SMA elements are ribbed bars, not strips, and the studied strengthening technique is shotcreting, not NSM. The main aim was to demonstrate the feasibility of the application of the newly produced ribbed Fe-SMA bars for the strengthening of RC beams in combination with shotcrete. In the framework of this study, two beams strengthened with ribbed Fe-SMA bars, and one beam strengthened with normal steel bars in the shotcrete layer, functioned as conventional strengthening by shotcreting, were examined.

## 2. Experiments

An overview of the test program appears in Table 1. The experimental program was designed to demonstrate the strengthening of RC beams with Fe-SMA ribbed bars embedded in an additionally applied shotcrete layer. The 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 one beam serving as a representative of conventional shotcrete strengthening by common steel ribbed bars (Beam No. 9), one beam strengthened with two prestressed ribbed Fe-SMA bars (Beam No. 10), and one beam strengthened with four prestressed ribbed Fe-SMA bars (Beam No. 11). These beams were compared with an un-strengthened reference RC beam (Beam No. 1), already presented in [24]. The material properties of the Fe-SMA bars, concrete, steel reinforcement, and shotcrete layer 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 Fe–17Mn–5Si–10Cr–4Ni–1(V,C) (mass-%) alloy was used in this study [16–19]. First, a large quantity of the new alloy was produced, and strips with ribs were manufactured to ensure a good bond to the concrete. These Fe-SMA strips were used to strengthen reinforced concrete beams using the near surface mounted reinforcement technique [24].

In this study, however, ribbed Fe-SMA bars were used instead of Fe-SMA strips. A cast with a weight of approximately 95 kg was forged after heating to 1200 °C to decrease its cross-section. Then, a part was cut from the sample and mechanically machined. The cross-section was at this stage approximately 95 × 95 mm. After reheating, the block was hot-rolled to a block with dimensions of approximately 38 × 38 × 1000 mm. Subsequently, several round bars with a diameter of 20 mm and a length of 650 mm were produced by hot rolling. Lastly, after reheating these bars to 1200 °C, ribbed bars with a diameter of approximately 8 mm and a length of more than 3 m were produced in a rolling line. These Fe-SMA bars were cut into bars with a length of 2.5 m that were used for the strengthening of the beams, and the remaining short pieces were used for material characterization.

*2.1.1.1. Material characterization of the Fe-SMA bars.* The short Fe-SMA bar 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 (prestressing force). A special clip-on

**Table 1**
Overview of the experimentally examined beams.

| Beam No. | Strengthening |
|---|---|
| 1 [24] | Without any strengthening, reference beam |
| 9 | Strengthened by two normal steel ribbed bars |
| 10 | Strengthened by two ribbed Fe-SMA bars |
| 11 | Strengthened by four ribbed Fe-SMA bars |