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Iron-based shape memory alloys (Fe-SMA) - a new material for prestressing concrete structures

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ABSTRACT: Shape memory alloys (SMAs) have the special property of remembering their shape after being deformed, either immediately upon unloading or by heating above a critical temperature. This shape memory effect can be used to prestress concrete without the need for ducts, anchor heads, oil hydraulic jacks or duct injections. Furthermore, it is possible for SMAs to be used for reinforcing strongly curved structures because no prestress force loss due to friction occurs during prestressing. However, the only available SMAs on the market are nickel titanium (NiTi)-based and are far too expensive for the construction industry. Therefore, Empa developed a low cost, iron-based shape memory alloy (Fe-SMA) suitable for concrete reinforcement.

In this paper, the shape memory effect of Fe-SMAs is briefly explained on the atomic scale. Next, investigations and developments by a multidisciplinary team at Empa during more than 10 years in the field of prestressing of concrete with SMAs are outlined. In the early 2000s, researchers at Empa investigated if SMAs could be used in civil constructions. A concrete beam was reinforced with NiTi wires and short NiTi fibers were embedded in mortar prisms. These investigations showed that it was possible to prestress concrete structures using NiTi wires. Subsequently, in collaboration with the Structural Engineering and Joining Technologies Research Laboratories at Empa, a new Fe-based SMA was developed for civil engineering applications. Next, strips made out of this alloy were produced and used for reinforcing concrete structures. In concrete bars, Fe-SMA strips were centrally embedded and the Fe-SMA strips were also used for strengthening reinforced concrete beams. Ongoing research uses ribbed Fe-SMA reinforcement bars for reinforcing large-scale beams.

Finally, this paper discusses the company (re-Fer AG) established in 2012 to promote and introduce Fe-SMA reinforcements to the construction market. Potential applications are presented for Fe-SMA reinforcement in new concrete structures and in various strengthening applications.

1   INTRODUCTION

Shape memory alloys (SMAs) have the special property that they remember their shape after they have been deformed, either immediately upon unloading or by heating above a critical temperature. Figure 1 illustrates the second effect with a SMA spring, which is initially strongly deformed and then exposed to elevated temperature in warm water. As soon as the spring contacted the warm water, it returned to its original shape, i.e. it 'remembered' its original shape.

a)   b)   c)

Figure 1: a) SMA spring and a dish of warm water, b) the spring strongly deformed, c) the spring 'remembering' its former shape when exposed to elevated temperature.

Using this principle, Figure 2 shows how concrete elements can be prestressed using SMA reinforcements. SMA elements are prestrained and then embedded in concrete. When the concrete has cured, the SMA elements are heated, e.g., by electric resistive heating, their deformation is constrained in the concrete and a prestress develops in the SMA. Hence, a compressive stress develops in the concrete. This effect can be applied to prestress various reinforced concrete (RC) elements, such as slabs, bridge girders or building constructions. The advantage, compared to conventional prestressing steel tendons, is that no ducts, anchor heads, oil hydraulic jacks or duct injections are needed. Furthermore, no prestress force loss due to friction occurs during prestressing, so the application of SMAs is promising also for reinforcing strongly curved structures.

1) Initial FeSMA element with length L_0 2) Prestrained FeSMA element with length L_{def} 3) Heating of the FeSMA with electrical current   4) Concrete is prestressed!
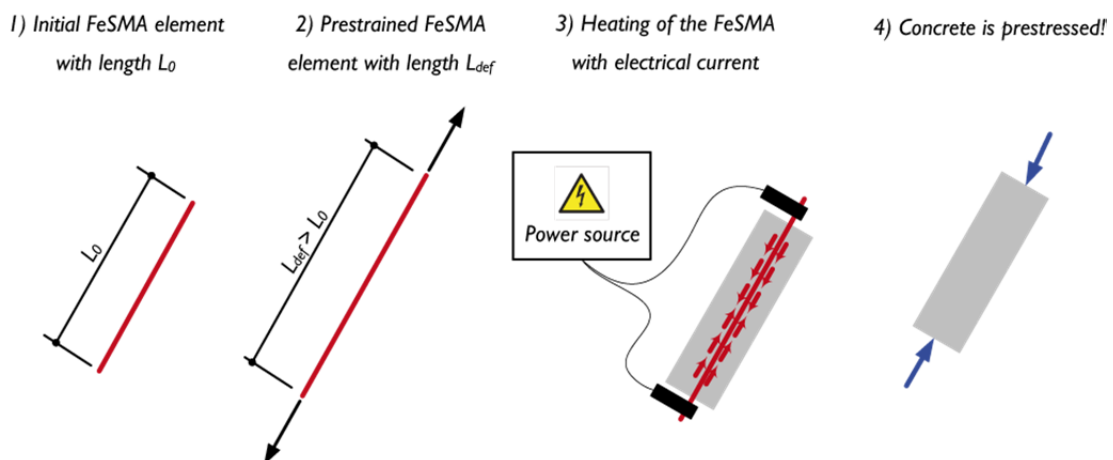
Figure 2: Schematic description of the prestressing procedure of concrete using FeSMA reinforcement.

In addition to the shape memory effect, which is used in the presented project, shape memory alloys have other interesting properties and capabilities that are not discussed in this paper including superelasticity, self-centering, damping or the use as sensors or actuators. Many research papers can be found in the literature in the field of SMAs and their application in the construction industry; interested readers can refer to Janke et al. (2005), Song et al. (2006), Alam et al. (2007), Dong et al. (2011), Ozbulut et al. (2011), Ling et al. (2012), Cladera et al. (2014a), and Cladera et al. (2014b).

The most commonly known SMAs are nickel-titanium (NiTi) alloys. These materials are used in the medical and electronics fields. However, a NiTi-alloy is too expensive for the construction industry; therefore, Empa developed an iron-based shape memory alloy (Fe-SMA) suitable for construction, which can be produced at a much lower cost.

In this paper, the shape memory effect of Fe-SMAs is briefly explained on the atomic scale. Then, investigations and developments by a multidisciplinary team at Empa during more than 10 years in the field of prestressing of concrete using SMAs are outlined. This paper presents the progression from the first NiTi wire trials through the production of ribbed Fe-SMA strips and bars; their application as reinforcements in concrete beams is also discussed.

2   IRON-BASED SHAPE MEMORY ALLOY (FE-SMA)

If a metal is being deformed and the elastic deformations are exceeded, dislocations in the atomic structure begin to move, resulting in plastic (irreversible) deformations. Dislocations are defects such as stacking faults in the atomic structure. When the dislocations move, bindings between the atoms are fractured, and new bindings are formed. In such cases, the atoms movements (dislocations) correspond to the complete spacing between the atoms, so the crystal lattice remains the same.

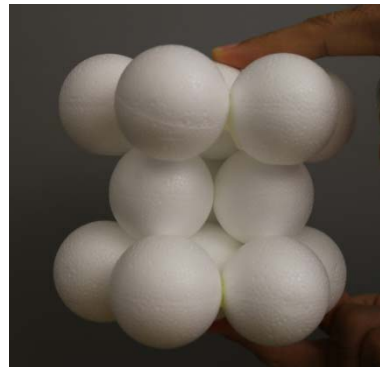Figure 3: Crystal lattice face-centered-cubic (fcc) model of the austenite γ-phase.

Figure 4: Cristal lattice hexagonal-close-packed (hcp) model of the martensite ε-phase.

When iron based shape memory alloys are cooled to room temperature after production, they have an atomic crystal structure that is termed the 'austenite γ-phase'. This phase has a face-centered-cubic (fcc) crystal structure. Figure 3 shows a photo of a model of a fcc crystal. It is a visible, cube-shaped structure, which has an atom in each corner and in the middle of each face. This crystal structure has close-packed atom planes with an order A/B/C in diagonal direction. If a Fe-SMA in the austenite γ-phase is deformed, 'martensite ε-phases' develop. The key point to understand is that the atom movements in this case do not correspond to the complete dislocation (spacing) between the atoms but only to a partial dislocation (a so-called partial

Shockley dislocation). Due to this partial dislocation, a new crystal lattice develops that is termed 'martensite ε-phase'. This phase has a hexagonal-close-packed (hcp) crystal structure. Figure 4 presents a photo of a model of a hcp crystal. It is visible as a pile of planes, which are close-packed with atoms with the order A/B/A. The switch (i.e., the partial dislocations or the martensite transformations) between the two phases is reversible. If the temperature in the metal increases over a specific temperature, austenite γ-phases develop again because austenite has a lower free enthalpy (driving power of a reaction) than martensite. This explains the shape memory effect. For more details on this effect, see the explanations by Cladera et al. (2014b).

The above atomic mechanism works in Fe-SMA and it is different in NiTi shape memory alloys.

3   PROGRESSION FROM THE FIRST IDEA TO INDUSTRIAL INTRODUCTION

In the early 2000s, researchers at Empa wondered if and how SMAs could be used in civil construction. Possible application ideas were mainly for NiTi-SMAs such as controlled or fixed prestressing, superelasticity with high energy dissipation or for sensors (Czaderski et al. (2003)).

In **2003**, in the framework of a master thesis collaboration with the Bauhaus University of Weimar in Germany, a concrete beam was reinforced with shape memory alloys (SMA) wires (Czaderski et al. (2006), Motavalli et al. (2008)). NiTi wires with an approximate 4.3 mm diameter were used to reinforce the tensile zone of a concrete beam with a span of 1.14 m (Figure 5). To improve the bond behavior, the surfaces of the NiTi wires were sandblasted and coated with quartz sand using an epoxy adhesive. Electrical resistive heating was used to increase the temperature in the NiTi wires. Figure 6 shows the copper clamps for the electrical contact. Figure 7 displays an infrared image of a trial heating, illustrating the temperature gradient in the cross-section. One purpose of this study was to determine whether it is possible to combine NiTi wires with concrete to achieve an adaptive structure with the potential to react to a changing environment. A further aim was to obtain valuable experience regarding the behavior and practical application of NiTi-SMAs as concrete reinforcement.

Figure 5: Concrete beam reinforced with NiTi wires and testing set-up for loading.
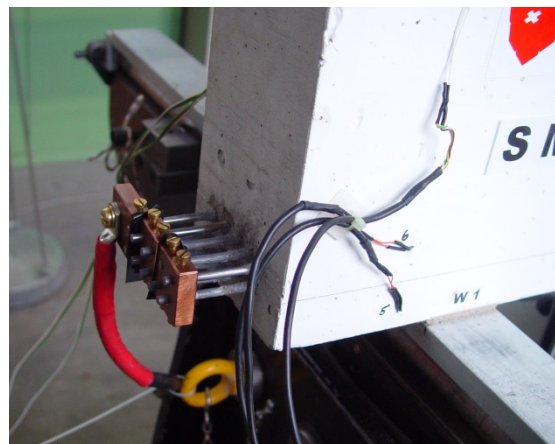
Figure 6: Clamps for resistive heating of NiTi reinforcement at the beam-ends.

The different loading cycles with NiTi wires in warm (T ~ 65 to 75°C) or room temperature states are shown in Figure 8. The test results proved that by using coated NiTi wires, it was possible to produce a RC beam with variable stiffness and strength (load bearing capacity). The

tests also showed that a prestress in the NiTi wires could be achieved by using the shape memory effect.
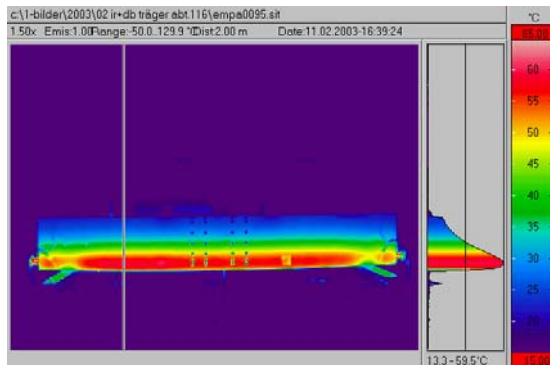

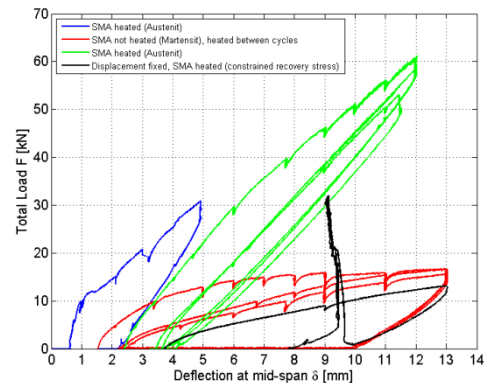Figure 7: Infrared image showing the beam during trial heating.

Figure 8: Load-displacement diagram showing load cycles with heated or unheated NiTi wires.

In **2003/2004**, shape memory alloy (SMA) NiTi wires were embedded in mortar to demonstrate the feasibility of prestressed short fiber reinforced concrete, Moser et al. (2005), Motavalli et al. (2008). Shaping into loop- and star-shaped fibers, as shown in Figure 9, prestrained the wires. The fiber shapes were chosen to best obtain solid anchorage with a feasible manual production process. The wires were mixed with mortar in a formwork; the mortar was placed in five layers in a prism formwork, alternating with four layers of fibers (Figure 10), and compacted on a vibration table. The total fiber content was 1.2% by volume.
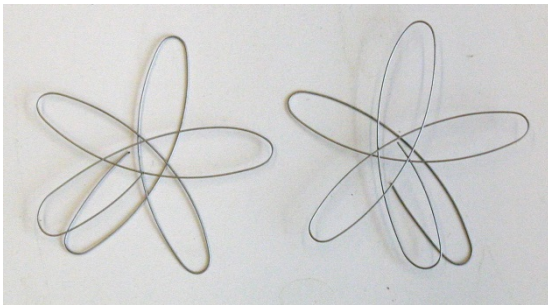

Figure 9: Prestrained and shaped NiTi wires (short fibers) that were mixed with mortar.

Figure 10: Mixing of the short NiTi fibers with mortar in a prism formwork.

By measuring the change of the prisms lengths during heating in an oven, a compression stress of ≈ 5.7 MPa in the concrete prisms was determined (considering temperature expansion, shrinkage and creep). This value can be roughly verified because the measured recovery stress of the NiTi wires at 180° was 845 MPa. Therefore, a fiber ratio of 1.2% results in a compression stress of ≈ 10.1 MPa. Because of the layer-wise production, this stress must be multiplied by a factor $2/\pi$ (randomly distribution in two directions), and the compression stress of ≈ 6.5 MPa is found to reasonably correspond with the measured compression stress of ≈ 5.7 MPa.

A PhD work started in **2004**. It was a continuation of the MS thesis described above and was again in collaboration with the Bauhaus University of Weimar. The aim was to find possible applications for SMAs in structural engineering. An overview of applications was published in Janke et al. (2005). Because of the lack of shape memory materials, the experiments on

prestressed confinement of concrete cylinders were performed with normal steel and carbon reinforced polymer (CFRP), Janke et al. (2009). A model for determining the residual load-bearing capacity of prestressed confined concrete was developed, Janke (2014).

From **2005** to **2008**, in the framework of a postdoctoral collaboration between the Empa Structural Engineering and Joining Technologies Research Laboratories, a new Fe-based SMA for civil engineering applications was developed, Dong et al. (2009). The new alloy had the following composition: Fe–17Mn–5Si–10Cr–4Ni–1(V, C) (mass%). For civil engineering applications, Fe-based shape memory alloys represent a promising technology for a number of applications because of their properties and lower cost when compared to NiTi: NiTi-alloys are too expensive for the construction industry. The developed Fe-SMA can be activated at temperatures between 100 and 160°C, which is feasible in combination with concrete without crucial damage in the concrete due to the elevated temperatures. The alloy exhibits corrosion resistance clearly superior to that of conventional reinforcement steels. It can be produced on the industrial scale under atmospheric conditions without the need for expensive, high vacuum processing facilities. For different applications, it can be formed into different shapes such as bars, strips, wires, foils, etc. by hot and/or cold forming. Empa patented the iron-based shape memory alloy in 2009.

The application oriented Structural Engineering Research Laboratory worked since then together with the material scientists from the Joining Technologies Research Laboratory to develop an iron based SMA for applications in civil structures. For example, in the framework of a master work at the University of Kaiserslautern in Germany, the thermo-mechanical properties of the new alloy were investigated, Leinenbach et al. (2012).
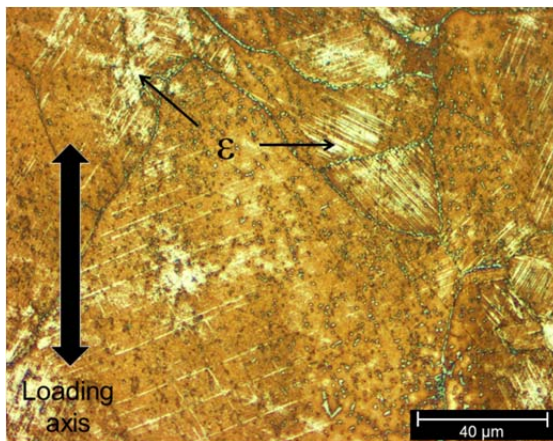

Figure 11: Optical microscopy image of a Fe-SMA sample strained to 4% at −45°C (500x). The inclined ε-phases are visible in white. Adapted from Lee et al. (2013a).
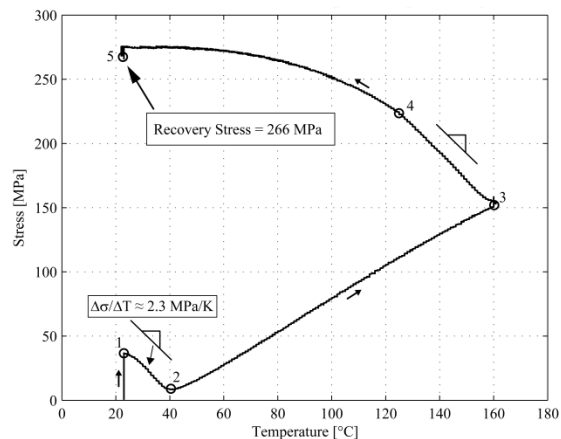
Figure 12: Stress–temperature diagram of a heating and cooling cycle on a 4% prestrained Fe-SMA strip sample.

In **2012**, financially supported by the Marie Curie Action COFUND of the European Commission, a postdoctoral project was initiated for more detailed evaluation of the microstructural and thermo-mechanical properties of the above-mentioned Fe-SMA alloy. The project first focused on the microstructural evaluation of the alloy upon loading and recovering, and a complete thermodynamic phase diagram for the alloy was developed, Lee et al. (2013a). Figure 11 shows an optical microscopy (OM) image of a Fe-SMA sample strained to 4% at −45°C. The austenite γ-phase appears in brown, and the martensite ε-phase appears in white.

The ε-phase is mostly oriented at approximately 45° with respect to the loading direction, where the habit planes coincide with the maximum shear stress induced by tensile loading, Lee et al. (2013a).

Then, the project focused on the thermo-mechanical behavior of the alloy in civil engineering applications particularly the alloy behavior in generating the prestress. The behavior after prestress (activation) under loading cycles and thermal cycles was studied, Lee et al. (2013b). Figure 13 shows the principle of prestraining and producing the recovery stress by heating and cooling. Figure 14 shows the behavior of the Fe-SMA after prestressing (activation) under increasing and decreasing loading. It is visible that the first loading cycle has a lower stiffness and after unloading, it has a lower recovery stress (prestress). However, all of the further loading cycles have a larger stiffness (elastic modulus of ~ 200 GPa), and no further prestress loss can be observed.
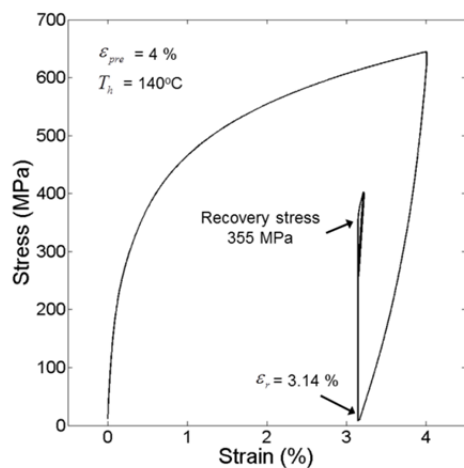

Figure 13: Representative mechanical cyclic stress–strain curve of a Fe-SMA sample with 4% pre-strain and heating to 140°C. From Lee et al. (2013b).
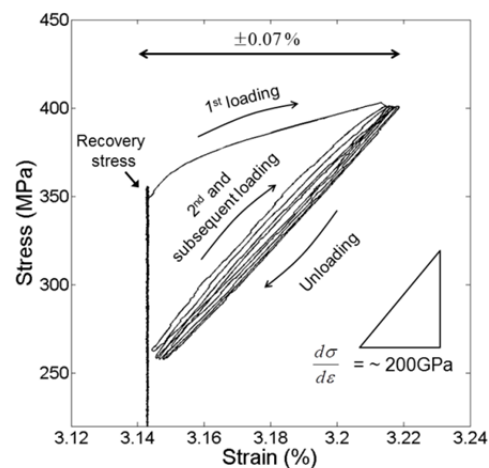
Figure 14: Enlarged detail of the cyclic behavior shown in Figure 13. From Lee et al. (2013b).

Continuing with the evolution of recovery stress used for prestressing, the effect of non-ideal boundary conditions was investigated. Under ideal conditions, the recovery stress develops under zero total strain. However, in practical situations, the evolving stress leads to an elastic compression of a concrete member, reducing the prestressing force. In other applications such as joining of pipes, a gap has to be closed first until a stress is developing. Is has been found experimentally, that under these conditions, still a large recovery stress can develop. Besides their practical relevance, these tests were also used as a database for investigating the evolution of recovery stress in a constitutive relationship. It has been shown that during heating (points 1 to 3 in Figure 12), the recovery stress can be calculated from the phase diagram using thermodynamics principles. During cooling (points 3 to 5), the recovery stress has a similar shape as the preloading curve (Figure 13) but is modified depending on the transformation strain developed during heating. These findings will eventually be used to develop a full constitutive relationship including martensitic transformation and plasticity.

Also in **2012**, a feasibility study began on the usage of Fe-SMA for the strengthening of reinforced concrete structures; the Swiss Commission for Technology and Innovation (CTI project 14496.1 PFIW-IW) financially supported the study. The idea was to use Fe-SMA strips as near surface mounted reinforcement (NSMR). In this technique, grooves in the concrete cover are cut, and the reinforcements are glued into these grooves. Usually, fiber reinforced polymer (FRP) strips or bars are used for this purpose, see De Lorenzis et al. (2007) for more details on this technique.

In this project, Fe-SMA strips were first produced, as seen in Figure 15. The cast was produced at the Montan University of Leoben in Austria, hot deforming was then performed at the Technical University of Freiberg in Germany, and the cutting, cold deformation (ribs) and heat treatment was performed by the Company Rau in Germany, Czaderski et al. (2014).

The stress-strain behavior and the recovery stresses of the Fe-SMA strips were measured at Empa. The recovery stresses after prestraining to 2 or 4% and heating to 160°C were in the range of 250 - 300 MPa. Figure 12 shows the typical behavior of a Fe-SMA sample during activation: between points 1 and 2, the stress in the sample decreases due to the thermal expansion effect. Then, at approximately 40°C, the stress starts to increase because of the phase transformations from the martensite ε-phase to the austenite γ-phase. In this test, the stress reached approximately 150 MPa at the maximum heating temperature of 160°C (point 3). Between points 3 and 4 in Figure 12, the stress further increases due to the thermal contraction effect during cooling. The inclination of the curve is approximately parallel to the starting section of the curve between points 1 and 2, which indicates similar coefficients of thermal expansion and elastic modulus for the two areas. Between points 4 and 5, the inclination of the curve decreases. This is attributed to a partial transformation from austenite to martensite. Eventually, at point 5, the recovery stress (prestress) at room temperature is reached, Czaderski et al. (2014).

Moreover, lap-shear tests on the Fe-SMA strip, which were glued in grooves using a cement based grout, were performed. Good bond behavior was found, i.e., a tensile failure occurred in the free length of the Fe-SMA strip.
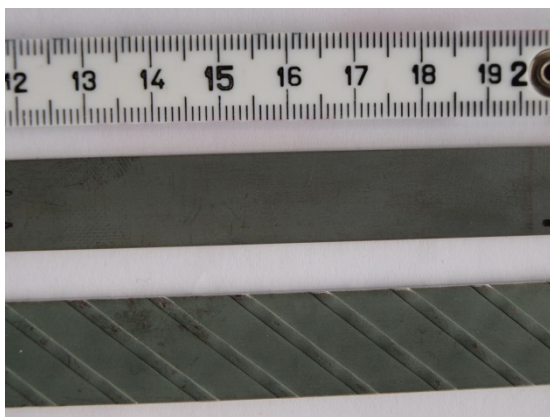

Figure 15: Detailed view of the ribbed Fe-SMA strips used for strengthening reinforced concrete beams.
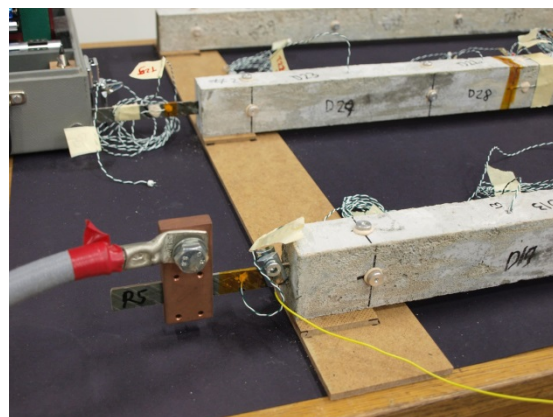

Figure 16: Detail view of the concrete bars with Fe-SMA strips centrally embedded. The copper clamps for connection of the strips with the power supply, i.e., the resistive heating, to heat the Fe-SMA strips in the concrete to 160°C.

Furthermore, concrete bars with centrally embedded Fe-SMA strips were produced. The Fe-SMA strips were prestressed or activated by resistive heating (Figure 16). The compression stresses in the concrete were indirectly determined by measuring the concrete bars shortening after activation of the Fe-SMA strips. Compressive stresses were observed in the 3 MPa range in the concrete section, which indicated the general feasibility of the ribbed Fe-SMA strips for reinforcing and prestressing a concrete section, Czaderski et al. (2014).

In the CTI project also several RC beams were strengthened with the NSMR technique using Fe-SMA strips. Figure 17 shows a photo of a test beam during activation. The cables from the power supply are fixed with copper clamps (copper plates fixed in the groove) on the Fe-SMA strips. Figure 18 displays the load mid-span displacement curves of two of the test beams. Each of the two beams was strengthened with two strips: however, the Fe-SMA strips were only activated in one of the beams (Beam 3). After activation, an uplift displacement at the mid-span of 0.15 - 0.17 mm was measured. Recovery stresses in the Fe-SMA strips of 190 - 210 MPa were calculated from these uplift displacements. The prestressing influence on the behavior at service loads is visible because a higher cracking load (4.5 kN compared to 2.5 kN) and smaller displacements (e.g. 1.3 mm compared to 2.8 mm at 6 kN) can be observed. However, similar failure loads were measured. For more details, refer to Shahverdi et al. (2015a, b).
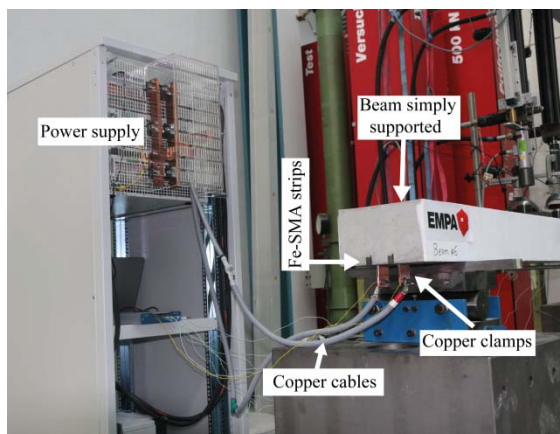

Figure 17: Activation of the Fe-SMA strips of one test beam.
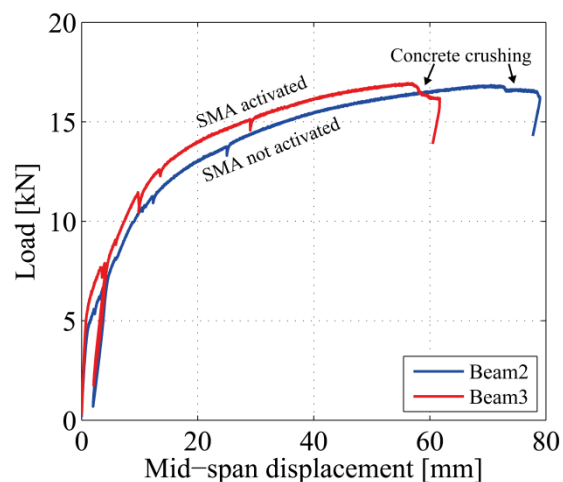
Figure 18: Selected test results of the beam tests. A clear influence of the prestressed (activated) Fe-SMA can be observed.

4   ONGOING RESEARCH

More tests will show the long-term behavior under load and environmental exposure of beams strengthened with activated Fe-SMA strips. Two similar beams as those described above will be installed outside under constant load. One beam is strengthened with non-activated Fe-SMA strips, and the other is strengthened with activated Fe-SMA strips.

In addition to Fe-SMA strips, ribbed Fe-SMA bars were produced for ongoing study, as seen in Figure 19. During the cold deformation of the Fe-SMA strips for rib production (Figure 15), cracks occurred at the edges of the strips, which occasionally led to premature tensile failure. Therefore, the edges required grinding, but grinding is no longer necessary if bars are produced. Ribbed reinforcement bars are very typical in the construction industry, and engineers are

comfortable with their use. Additionally, the circular cross-section is the optimal section for heating with the fewest heat losses.

Fe-SMA bars can be utilized in many different applications. For example, the bars can be used as reinforcement in new shotcrete layers for the strengthening of reinforced concrete structures such as slabs, beams or walls. Again, the Fe-SMA bars will be activated with resistive heating. Large-scale beam tests are planned to show the strengthening technique feasibility of prestressed shotcrete for the strengthening of RC structures.

Figure 19: Ribbed Fe-SMA bars with a diameter of 8 mm that can be utilized for concrete reinforcement.

5   TRANSFER TO INDUSTRY AND FE-SMA APPLICATIONS

The company re-Fer (www.re-fer.eu) was founded in 2012 based on the developments by Empa with the aim of producing and selling the patented, iron-based SMAs for civil engineering applications. In addition to the patented alloy, re-Fer and Empa hold patents for specific applications using Fe-SMA.

In comparison with NiTi alloys, the FeMnSi-based alloy will be significantly cheaper because of the lower raw materials costs and its processability under atmospheric conditions. A price comparable to highly alloyed stainless steel (~8-10 €/kg) is envisaged for the future.

Fe-SMA reinforcements can be used for strengthening existing structures and also for new structures on construction sites or in the prefabricating industry (in precast concrete). In addition to replacing existing applications in the construction industry, new applications are imaginable with the Fe-SMA reinforcements, which are not possible with existing construction methods (or too complicate). This implies that new markets can be developed. Possible applications for smooth or ribbed FeSMA rebars, strips or wires are as follows:

- prestressed shotcrete for strengthening existing RC structures
- prestressed near surface mounted reinforcement
- prestressed confinement of columns or silos
- prestressed short fiber concrete
- prestressing of new, very slender structures (no anchor heads necessary), e.g., facade elements
- prestressing of strongly curved structures, e.g., shells

6   ACKNOWLEDGMENTS

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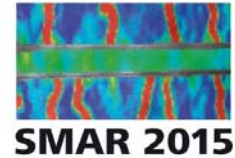
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