The development of memory steel at Empa

Christoph CZADERSKI [1], Moslem SHAHVERDI [1], Elyas GHAFOORI [1], Masoud MOTAVALLI [1], Christian LEINENBACH [2], Ariyan ARABI-HASHEMI [2], Julien MICHELS [3], Josef SCHERER [3]

[1] Empa, Structural Engineering, Dübendorf, Switzerland

[2] Empa, Advanced Materials Processing, Dübendorf, Switzerland

[3] re-fer AG, Brunnen, Switzerland

Contact e-mail: christoph.czaderski@empa.ch

ABSTRACT: Shape memory alloys have the unique property that they remember their shape after they have been 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 of ducts, anchor heads, and oil hydraulic cylinders. However, most of the commercially available shape memory alloys are made of Nickel Titanium (NiTi), and are too expensive for a broad application in the construction industry. Therefore, an iron-based shape memory alloy (memory steel) with lower production costs, which is more suitable for concrete reinforcement was developed at Empa. The company re-fer AG was founded in 2012 with the goal to establish memory steel reinforcements on the market. In this paper, investigations and developments by a multidisciplinary team at Empa during more than 15 years in the field of concrete prestressing with memory steel are outlined. The impressive and long way from first trials with NiTi wires up to the industrial production of memory steel strips and bars and site applications to renovate buildings with memory-steel is described.

1 INTRODUCTION

Figure 1 illustrates the shape memory effect with a SMA spring, which is initially strongly deformed and then exposed to elevated temperature in warm water. As soon as the spring contacts the warm water, it starts returning to its original shape, i.e. it ‘remembers’ its original shape. During deforming (prestraining) SMA undergoes an austenite to martensite transformation. Then, during heating above the austenite start transformation temperature, a reverse transformation from martensite to austenite occurs and the memory-steel tries to shrink to achieve its initial shape. Using this principle, concrete elements can be prestressed using SMA reinforcements. SMA elements are prestrained and then embedded in concrete (see insert diagram in Figure 1). After sufficient concrete cure, the SMA elements are heated (e.g. by electric resistive heating), and since their deformation is constrained in the concrete, a prestress develops in the memory-steel. 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. This principle has the advantage that no ducts, anchor heads, oil hydraulic jacks or duct injections are needed as for conventional prestressing techniques. Furthermore, no prestress force loss due to friction occurs during prestressing. Hence, the application of memory-steel is promising also for reinforcing strongly curved structures or wrapping of columns as a prestressed confinement. 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, high damping capacity or the use as actuators. Many research papers can be found in the literature regarding 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), Chang et al. (2016), 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. Empa developed an iron-based shape memory alloy (subsequently named as memory-steel) suitable for civil engineering applications. They can be produced at a much lower cost compared to Nitinol. Cladera et al. (2014b) described the different atomic characteristics of iron-based shape memory alloys and NiTi-alloys and Czaderski et al. (2015) gave a short explanation of the shape memory effect on atomic scale.

In this paper, investigations and developments on memory-steel by a multidisciplinary team at Empa over the last more than 15 years are outlined.

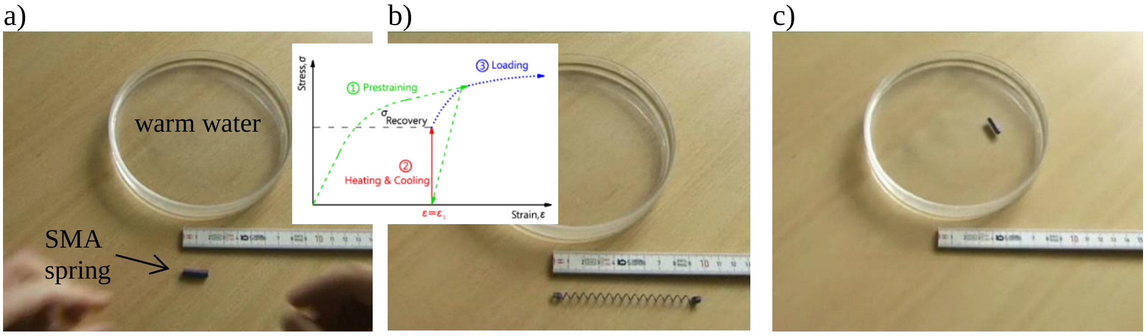

Figure 1: a) SMA spring and a dish of warm water, b) the spring strongly deformed, c) the spring ‘remembering’ its former shape when exposed to elevated temperature. Insert diagram: typical actions of memory-steel: No. 1 (in the factory): deforming (prestraining). No. 2 (on site): heating and cooling of the in-stalled Fe-SMA reinforcement. No. 3: loading (service or ultimate).

2 PROGRESSION FROM THE FIRST IDEA TO APPLICATIONS ON SITE

In the early 2000s, researchers at Empa started investigating if and how SMAs could be used in construction. Possible application ideas were mainly for NiTi-SMAs such as controlled or fixed prestressing or superelasticity with high energy dissipation. In 2003, in the framework of a master thesis collaboration with the Bauhaus University of Weimar (Germany), a concrete beam with a span of 1.14 m was reinforced with SMA wires, Czaderski et al. (2006). The NiTi wires had an approximate 4.3 mm diameter. To improve the bond behavior, the surfaces of the NiTi wires were sandblasted and coated with quartz sand using an epoxy adhesive (Figure 2). Electrical resistive heating was used to increase the temperature in the NiTi wires. Figure 2 shows the copper clamps for the electrical contact. One purpose of this study was to determine whether it was possible to combine NiTi wires with concrete to achieve an adaptive structure. A further aim was to obtain valuable experience regarding the behavior and practical application of NiTi-SMAs as concrete reinforcement. Test results proved that it was possible to produce an RC beam with variable stiffness and load bearing capacity. The tests also showed that a prestress in the NiTi wires could be achieved by using the shape memory effect.

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). Shaping into loop- and star-shaped fibers, as shown in Figure 3, prestrained the wires. The fiber shapes were chosen to obtain a 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, and compacted on a vibration table. The total fiber content was 1.2% in volume. 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).

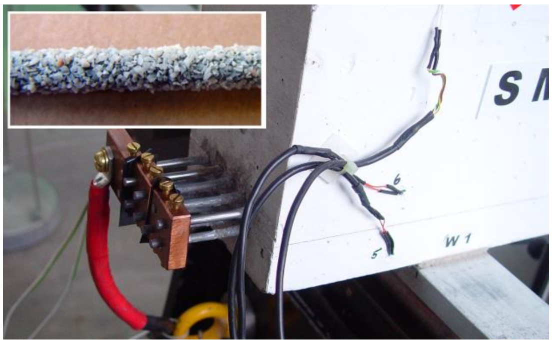

Figure 2: Concrete beam reinforced with NiTi wires, copper clamps for electrical resistive heating, quartz sand treatment (zoom) of the NiTi wires for better bond to the concrete.

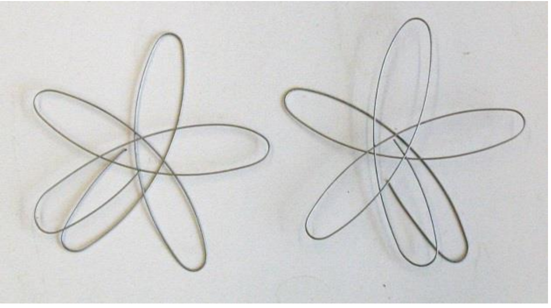

Figure 3: Prestrained and star shaped NiTi wires (short fibers) afterwards mixed with mortar. The diameter of the stars was approximately 35-40 mm, see Moser et al. (2005).

The aim of a PhD work in collaboration with the Bauhaus University of Weimar starting in 2004 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), see Janke et al. (2009) and Figure 4. A model for determining the residual load-bearing capacity of prestressed confined concrete was developed by 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%). Empa patented the alloy in 2009. For civil engineering applications, Fe-based shape memory alloys represent a promising technology for a wide 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 above 100°C, which is feasible in combination with concrete without crucial damage in the concrete matrix due to the elevated temperatures. It can be produced on 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.

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 memory-steel alloy. The project 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). The behavior after prestress (activation) under loading cycles and thermal cycles was also studied, Lee et al. (2013b).

A feasibility study was performed from 2012 to 2014 on the usage of Fe-SMA for the strengthening of reinforced concrete structures; the Swiss Commission for Technology and Innovation 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, memory-steels were first produced at laboratory scale, as given in Figure 5. The cast was produced at the Montan University of Leoben in Austria, hot deforming and rolling 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 GmbH in Germany, Czaderski et al. (2014).

Figure 4: Test specimens to investigate the effect of prestressed confinement, Janke et al. (2009).

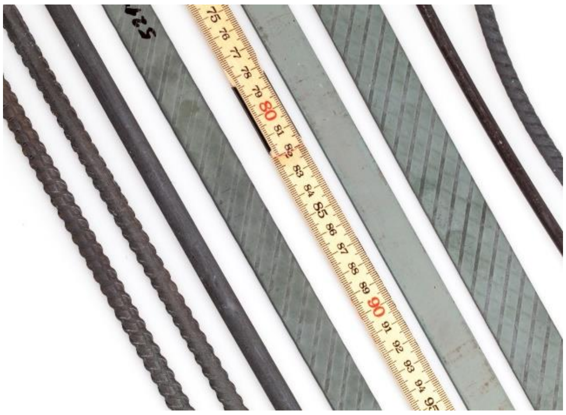

Figure 5: Different prototypes of memory-steel strips and bars.

The stress-strain behavior and the recovery stresses of the Fe-SMA strips were measured. The recovery stresses after prestraining to 2 or 4% and heating to 160°C were in the range of 250 - 300 MPa. 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. Furthermore, concrete bars with centrally embedded Fe-SMA strips were produced. The Fe-SMA strips were prestressed or activated by resistive heating. 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). Furthermore, several RC beams were strengthened with the NSMR technique using Fe-SMA strips. Each of the beams was strengthened with two strips. After activation, an uplift displacement at the mid-span of 0.15 - 0.17 mm over a span of 2000 mm was measured. Recovery stresses in the Fe-SMA strips of 190 - 210 MPa were calculated from these uplift displacements. For more details, refer to Shahverdi et al. (2016a). Abouali et al. (2019) studied the mechanical behaviors of the examined beam by non-linear finite element models. More tests were performed to 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 were installed outside under constant load. One beam was strengthened with non-activated Fe-SMA strips, and the other was strengthened with activated Fe-SMA strips, Shahverdi et al. (2019a). In addition to the ribbed Fe-SMA strips, also ribbed Fe-SMA bars were produced (Figure 5). 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. The bars were used in combination with shotcrete to strengthen similar beams as described above. Again, an uplift could be measured after the activation of the memory-steel reinforcements. For more details refer to Shahverdi et al. (2016b).

Lee et al. (2016) performed a preliminary study on the corrosion behavior of the memory-steel. It was found, that the memory-steel has a superior corrosion resistance compared to conventional structural steel. However, it is very sensitive to chloride ions. Therefore, it is recommended to apply to memory-steel the same corrosion measures (e.g. cover, etc.) as for the lowest stainless steel classes.

In the end of 2012, based on the developments by Empa, the company re-fer AG was founded with the aim to establish memory-steel in the building industry. re-fer produced large-scale batches of 50 mm, 100 mm, and 120 mm wide memory-steel strips without ribs and ribbed memory-steel bars with diameters of 12 mm and 16 mm. An anchorage technique for the memory-steel plates by using a Hilti direct fastening system (X-CR nails) was developed and large-scale beam experiments were performed in the laboratory, Michels et al. (2018a). The bars and strips were characterized by Michels et al. (2018b) and Shahverdi et al. (2018), respectively. Furthermore, re-fer introduced the product names 're-bar' and 're-plate' and several application patents were registered. In autumn 2018, seminars for civil engineers were hold at four locations in the German part of Switzerland with the aim to to present the new material to a broader public of builders, engineers and other players in the construction industry.

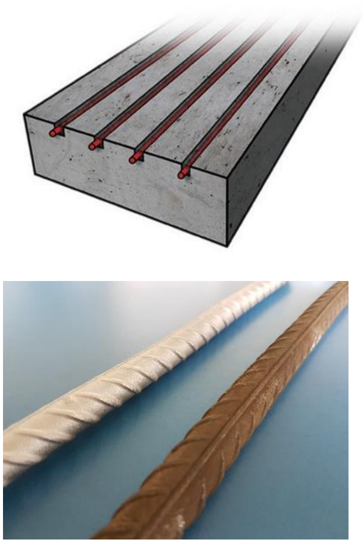

Figure 6. Flexural strengthening of RC beams with memory-steel bars grouted in grooves in the concrete surface (NSMR).

Figure 7. Flexural strengthening of a RC slab in a building by using externally fixed memory-steel strips.

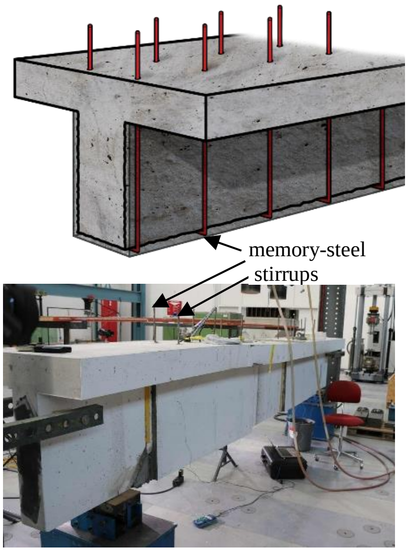

Figure 8. Shear strengthening of a RC beam in the Empa laboratory with shotcrete and memory-steel stirrups.

Furthermore, the fatigue and cycle behavior of memory-steel after multiple thermal activation and the behavior of memory-steel at elevated temperature (i.e. fire) was investigated. Furthermore, it was examined if and how steel structures can be strengthened for fatigue by using memory-steel. For more details refer to Fritsch et al. (2019), Ghafoori et al. (2019), Hosseini et al. (2018), Izadi et al. (2018 a and b) and Ghafoori et al. (2017).

Material scientist from the Empa explored the memory-steel by using in-situ neutron diffraction measurements to study the microstructural changes during mechanical loading. Furthermore, the low-temperature creep and stress relaxation behavior of the memory-steel was characterized and rolling technology of the memory-steel was developed. What's more, the impact of precipitates, textures and grain size on the recovery stress was studied and HR-EBSD (High Resolution Electron Backscatter Diffraction) measurements were performed to correlate stress induced phase transformation and stress fields. For more details refer to Leinenbach et al. (2017), (2016a and b), (2012) and Arabi-Hashemi et al. (2018a and b).

3 ONGOING RESEARCH PROJECTS

At Empa, the flexural and shear strengthening of reinforced concrete by using standard geometry ribbed memory-steel bars is currently investigated. In a PhD project, the bond behavior of ribbed memory-steel bars grouted into grooves in the concrete cover for flexural strengthening, is studied (Figure 6). The method is known from FRP strengthening as near-surface mounted (NSM) strengthening technique, and is sponsored by the Swiss National Science Foundation, Schranz et al. (2019). In another research project, ribbed memory steel bars are used in combination with shotcrete for prestressed shear strengthening of RC concrete structures (Figure 8). The prestressing of the shear reinforcement has the advantages that shear cracks width can be reduced and new shear cracks occur under higher loads. Large-scale experiments on T-beams with a length of 5.2 m are performed to study the practical application and effectiveness of memory steel for such retrofitting scenarios, Shahverdi et al. (2019b). The project is financially supported by the Commission for Technology and Innovation and the industry partner is the Company re-fer, Brunnen, Switzerland.

Furthermore, in the framework of a PhD project, Empa is currently investigating, if and how the recovery stress of the memory-steel can be increased. The project is running in collaboration with the companies re-fer from Switzerland and Böhler Edelstahl from Austria.

Additionally, Empa is currently working on the development of a strengthening system for metallic members as in steel bridges or aircraft structures using Smart “Shape Memory” Patches to predominantly improve the structure’s behavior against fatigue.

4 COMPANY RE-FER

The Company re-fer, which brings the developed memory-steel on the market, focuses on strengthening applications in building renovations. Up to now, more than 20 site applications were performed in Switzerland and France. One example is given in Figure 7. Photos and descriptions of the projects can be found on www.re-fer.eu and are presented in Michels et al. (2019). For the future, also new structures on construction sites or in the prefabricating industry (in precast concrete) might be possible. In addition to replacing existing applications in the construction industry, new applications are foreseen with the memory-steel reinforcements, which are not possible with existing construction methods (or too complicate) for example confinements of silos. This implies that new markets could be developed.

5 ACKNOWLEDGMENTS

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