Iron-based shape memory alloy strips for strengthening RC members: Material behavior and characterization

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Abstract: Shape memory alloys (SMAs), in the form of bars and strips, can be used as prestressing elements in new reinforced concrete (RC) members or for strengthening existing RC structures, owing to their special characteristic known as the shape memory effect (SME). When the SME comes into play, the material returns to its initial shape upon heating after having been deformed at ambient temperatures. If a return to the initial shape is prevented by mechanical fixation, stress develops in the SMA. A cost-effective iron-based SMA (Fe-SMA) has been developed for application in civil engineering structures. The composition of the developed alloy is Fe–17Mn–5Si–10Cr–4Ni–1(V,C) (mass%). This Fe-SMA exhibits high tensile strength, excellent shape recovery stress (prestress force), and high elastic stiffness. Moreover, its material cost is low and it is easier to manufacture than nickel-titanium (NiTi) alloys. Recently, Fe-SMA strip production has been started at an industrial scale. In this study, the experimentally determined properties of such industrially produced Fe-SMA strips are presented, and their recovery stress and recovery strain have been measured. The effects of prestraining and maximum heating temperature on the obtained recovery stress have been studied. These Fe-SMA strips can be used as external end-fixed reinforcements to strengthen RC structures.

Keywords: Shape memory alloy (SMA), iron-based SMA (Fe-SMA), recovery stress, shape memory effect (SME), prestress, material characterization

This document is the accepted manuscript version of the following article: Shahverdi, M., Michels, J., Czaderski, C., & Motavalli, M. (2018). Iron-based shape memory alloy strips for strengthening RC members: Material behavior and characterization. *Construction and Building Materials*, 173, 586-599. <http://doi.org/10.1016/j.conbuildmat.2018.04.057>

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27 Terminology, abbreviations, and nomenclature

A_s	austenite start temperature
b	width of the specimen
$\Delta\sigma_{\text{relx}}$	reduction in stress during the relaxation experiment
E_1	elastic modulus determined in the stress range of 20–200 MPa in tensile mode
E_2	elastic modulus determined in the stress range of 20–80 MPa after activation
$E_{\text{act-eq}}$	equivalent elastic modulus of activation
ε_{rec}	recovery strain; strain in the SMA which recovers during activation
ε_{pl}	plastic strain
ε_{pel}	pseudoelastic strain; strain in the SMA which recovers nonlinearly by unloading
ε_u	ultimate tensile strain; maximum strain reached in axial tensile tests
ε_{el}	elastic strain
ε_{p}	prestraining strain
f_u	ultimate tensile strength; maximum stress reached in axial tensile tests
$\sigma_{\text{max-relx}}$	maximum stress applied to the specimen during the relaxation experiments
σ_{rec}	recovery stress; stress developed in the SMA during activation, i.e., the prestress
P_{ini}	preload applied to the specimens before activation
P_{ser}	service load
$R_{\text{p0.2}}$	offset yield point (proof stress) at 0.2% plastic strain
t	thickness of the specimens, 0.5 mm or 1.5 mm
T_{max}	maximum temperature applied during activation
t_{relx}	relaxation experiment time
Activation	triggering of phase transformation in the SMA so that a prestress is developed
Fe-SMA	iron-based shape memory alloy
NiTi	nickel-titanium
NiTi-SMA	nickel titanium SMA
NSM	near surface mounted
RC	reinforced concrete
RT	room temperature
SMA	shape memory alloy
SME	shape memory effect

1. Introduction

New and innovative methods to strengthen existing civil structures such as bridges and buildings and to build new structures are necessary in the construction industry. A new type of advanced materials entering the construction market are shape memory alloys (SMAs). SMAs have two main characteristic properties: “superelasticity” and “shape memory effect” (SME). SMAs with superelasticity can return to their initial shape after loading and unloading; however, SMAs with SME return to their initial shape upon heating. Such materials, for e.g. NiTi alloys, have been around for a long time, but were not considered suitable for the construction industry due to their expensive nature [1, 2].

The most commonly known SMAs are NiTi alloys. These materials are used in the automotive, aerospace, robotic, and biomedical domains [3]. SMAs can be used as self-centering elements, dampers, sensors, or actuators. Furthermore, there are a multitude of reports on SMAs and their applications in civil engineering [4-9].

In civil engineering applications, SMAs can be exploited for their superelasticity or SME properties for example NiTiNb alloys [10-12]. Some demonstration projects do exist in this context [1, 13-18]. However, the application of SMAs in this domain is still in the research stage [19]. The vast majority of previous studies concentrated on the superelasticity properties of SMA. Although the expensive NiTi-based alloys are the most widely used SMAs [1], low-cost copper-based shape memory alloys (Cu-SMAs) and Fe-SMAs are gaining ground [2, 20-22]. Cu-SMAs have superelastic properties with a low elastic modulus and low cycle fatigue resistance [22]. However, in the case of Fe-SMAs, in addition to their lower cost than the NiTi-based alloys, they have a higher elastic modulus and can be activated at relatively lower temperatures [23]. This makes them very promising for strengthening existing civil structures and for prestressing new civil structures as well.

The Fe-SMA material was discovered by Sato et al. [24] in 1982. Fundamental research on the transformation behavior, microstructural and crystallographic characteristics, and mechanical properties of Fe-Mn-Si-based alloys were performed at the National Institute for Materials Science (NIMS), Japan [25-27]. Watanabe et al. [28] worked on the reinforcement of an 80 mm long plaster prism specimen with a 1 mm diameter prestressed wire made of Fe-27Mn-6Si-5Cr-0.05C. The wires were subjected to a pretensile strain (1%, 2%, and 3%) at room temperature (RT) and were embedded into a plaster matrix. In 2001, Soroushian et al. reported the strengthening of a bridge in Michigan, USA through external post-tensioning with Fe-Mn-Si-Cr SMA rebars [29].

At Empa, the Swiss Federal Laboratories for Materials Science and Technology, extensive studies on SMAs for civil engineering applications have been carried out over the past few years [23, 30-33]. In 2003, a concrete beam was longitudinally reinforced with SMA wires [34]. In 2003/2004, NiTi-SMA wires were embedded in mortar to demonstrate the feasibility of prestressed short fiber reinforced concrete [35]. The total fiber content was 1.2% by volume. A compression stress of approximately 7 MPa was determined in the concrete prisms. A new Fe-SMA for civil engineering applications was developed by Dong et al. [30]. The composition of the developed alloy was Fe-17Mn-5Si-10Cr-4Ni-1(V,C) (mass%). For civil engineering applications, Fe-SMAs represent a promising technology in a number of areas because of their properties and lower cost than NiTi. Fe-SMAs are less expensive compared to (NiTi) alloys because their raw material cost is low and they are easier to be manufactured than nickel-titanium (NiTi) alloys. The newly developed Fe-SMA can be activated at temperatures between 100 °C and 250 °C by resistive heating over a short period time (about one minute). Furthermore, it can be produced on an industrial scale at atmospheric conditions without expensive, high-vacuum processing facilities. For different applications, it can be manufactured in appropriate shapes such as ribbed bars or strips by hot and/or cold forming.

In 2012, a feasibility study began on the use of Fe-SMAs for strengthening reinforced concrete structures [36, 37]. The idea was to use Fe-SMA strips as near surface mounted (NSM) reinforcements. In this project, several RC beams were strengthened with the NSM technique using prototype Fe-SMA strips [37]. The recovery stress (prestressing force) after prestraining to 2.0% or 4.0% and heating to 160 °C was in the range of 250–300 MPa [36]. In another project, prototype ribbed Fe-SMA bars were produced at the laboratory level to strengthen RC structures in combination with shotcrete [38]. Both products were produced at lab scale in collaboration with the Montanuniversität, Leoben (Austria) and the Bergakademie TU, Freiberg (Germany).

The application of Fe-SMA strips for prestressing concrete members consists of three main actions, as schematically shown in Figure 1. (1) Prestraining: The Fe-SMA strips are pre-strained to a specific strain level and later fully released. (2) Activation: The Fe-SMA strips are activated (heating and cooling back to RT while they are fixed externally to the concrete structure. (3) Service loading: When the concrete structure is loaded, the Fe-SMA strips will carry load as shown in the left panel in Figure 1.

The heating and cooling of an Fe-SMA strip while it is constrained will produce a recovery stress, as shown in Figure 1 (red line noted as 2). The shape memory effect (i.e., generating the recovery stress) of the iron-based SMAs is due to the stress-induced martensite transformation from a parent γ -austenite phase (face-centered cubic, fcc) to an ϵ -martensite phase (hexagonal

close packed, hcp) at RT and the reverse transformation (ϵ - to γ -phase) when heated beyond the transformation temperature. At the beginning of the heating cycle, the SMA will thermally expand. At austenite start temperature, A_s , the transformation from hcp to fcc starts and compressive stresses are created in the concrete element due to the development of tensile stresses in the SMA. During cooling, further compressive stresses build up in the concrete element due to thermal contraction of the SMA (Figure 1, right panel). Phase change temperatures for the studied Fe-SMA have been reported in [32] as follow: $M_f=-64$ °C, $M_s=-60$ °C, $A_s=103$ °C, and $A_f=163$ °C.

From an application point of view, it is important to have a clear understanding of the thermomechanical behavior of SMAs in order to fully exploit their potential. Transformation phase diagrams are particularly important when using SMA strips since their thermomechanical behavior is determined by the phase transformations between ϵ and γ phases. However, due to differences in the crystal structure, Fe-SMAs exhibit different thermomechanical properties as compared to the classic NiTi alloys [31]. The amount of recovery strain in Fe-SMAs strongly depends on the temperature at which the martensitic transformation takes place [23, 30]. The physical background for such a behavior is the reversible transformation occurring between the atomic crystal structures, i.e., austenite (fcc) and martensite (hcp) [2, 25, 31].

There are few studies available on the basic phase transformation behavior of Fe-SMAs. Maruyama and Kubo [39] and Baraj et al. [40] investigated the critical stress for martensitic transformation in Fe-SMAs. Lee et al. [31] studied the phase transformation behavior and transformation conditions of the Fe–17Mn–5Si–10Cr–4Ni–1(V,C) (mass%) alloy. It was shown that the critical stress for the formation of ϵ -martensite in the alloy initially increases and then decreases with increasing temperature. It, therefore, indicated two distinct deformation states caused by martensitic transformation and irrecoverable slip.

In this study, the material properties of the Fe-SMA strips produced at an industrial scale are determined experimentally. The aim of the investigation is to provide a detailed material characterization of the iron-based SMAs. Such investigations are useful to propose (or modify and extend [31]) a phase diagram, which is helpful in understanding the thermo-mechanical characteristics and in developing constitutive models. In addition, these results can be used directly for the real-time application of the strips, e.g., as proposed by Michels et al. as an external end-anchored and unbonded prestressing system for structural retrofitting [41, 42].

2. Production of the Fe-SMA strips

As mentioned earlier, an iron-based shape memory alloy with a composition of Fe–17Mn–5Si–10Cr–4Ni–1(V,C) (mass%) was developed at Empa [30]. In the past, production was limited to lab scale alone in which around 100 kg could be produced. However, re-fer AG in collaboration with a stainless steel producer recently manufactured Fe-SMA strips at the industrial level. Roughly, the following steps were performed. Initially, a batch of 8 tons of the alloy with the same composition as described in [30] was cast. Subsequently, billets with dimensions of approximately $130 \times 130 \times 4000 \text{ mm}^3$ were produced. In the next step, the billets were heated in an oven to a temperature higher than 1100 °C and the cross-sections of the blocks were reduced to approximately 3 mm $\times$ 150 mm by hot-rolling. After this process, strips with final thicknesses of 1.5 mm and 0.5 mm with corresponding widths of 100 mm and 50 mm were produced by a few cycles of cold rolling. The final coils of the strip material are presented in Figure 2.

3. Experiments

3.1. Specimen geometry and cutting

To characterize the thermo-mechanical properties of the studied Fe-SMA strips, tensile specimens with a length of 250 mm and width of 15 mm were cut out from the as received Fe-SMA strips, see Figure 3. In the case of the 1.5-mm-thick strips, two different cut-outs were procured, one from the middle (denoted as M) and the other from the border (denoted as R). In addition, these samples were used for activation in a climate-controlled chamber.

In another series of experiments, long specimens with a length of 2200 mm and width of 10 mm were cut out from the middle of the 100-mm-wide and 1.5-mm-thick strips. These specimens were used for activation “in air” and relaxation experiments.

3.2. Failure tensile experiments (testing set-up No. 1)

Tensile experiments were performed at RT at a displacement rate of 3 mm/min up to failure on a 200 kN Zwick tensile testing machine [43]. An extensometer of the Zwick Makro type was used for strain measurement, as shown in Figure 4.

3.3. Prestraining, activation, and recovery strain of short Fe-SMA strips

3.3.1. Prestraining of short Fe-SMA strips (testing set-up No. 2)

Before the activation of Fe-SMA strips, the 250 mm long strips were prestrained at RT by a 20 kN Zwick machine. The experiments were performed at a displacement (strain) rate of 1

mm/min. The developed strain was measured using an extensometer with a gauge length of 100 mm. After the desired prestrain was reached, the load was completely released (machine displacement controlled at a rate of 0.5 mm/min).

3.3.2. Activation of short Fe-SMA strips (testing set-up No. 2)

For the heating experiments on short specimens, a climate-controlled chamber was added to the 20 kN Zwick machine. Figure 5 shows the climate-controlled chamber, the clamps, the Fe-SMA strip, and the extensometer. A special clip-on extensometer with a gauge length of 100 mm was used for the heating experiments. The temperature-induced expansion of the extensometer was continuously compensated during the experiments by a control in the testing machine.

At the start of the heating experiments, the Fe-SMA test specimens were preloaded to avoid compression due to thermal expansion during heating. Then, while holding the strain constant (i.e., a strain change of zero), the temperature was increased from 23 °C up to a target temperature, T_{max} , at a rate of 2 °C/min. After holding the test specimen for 1 h at T_{max} , the temperature was decreased again at approximately 2 °C/min down to 23 °C. The maximum axial stresses in the Fe-SMA strips after a further waiting time of 1 h at 23 °C were considered to be the recovery stresses, σ_{rec} .

The effects of the following parameters on the recovery stress were studied.

- Strip thickness, t
- Cutting position
- Machine preload, P_{ini}
- Prestraining, ε_p , and
- Maximum heating temperature, T_{max}

The behavior of the activated Fe-SMA strips subjected to axial tensile loading after activation or “service loading” was studied in another series of experiments. In such experiments, after the activation process, the strips were held in the machine and an additional tensile load, 3–4 times greater than the service load, was applied. The strains and stresses were then recorded continuously.

3.3.3. Recovery strain, ε_{rec} , in short Fe-SMA strips (testing set-up No. 2)

After prestraining the Fe-SMA strips, the residual prestrain is partially recovered when the sample is heated. This strain is called the “recovery strain” due to heating. It is important to know

the amount of recovery strain that can be obtained when the Fe-SMA strip is free to move back to its initial shape. To measure the recovery strain, experiments on Fe-SMA strips with different prestrains were conducted on the Zwick testing machine equipped with a climate-controlled chamber. For these tests, the Fe-SMA strips were fixed at both ends and subjected to a very small preload of about 1 MPa. Keeping this preload constant, heating and cooling cycles were performed, similar to a normal activation experiment inside the climate-controlled chamber, as described in Section 3.3.2 for stress recovery. During the heating and cooling processes, the axial strains in the strip were measured with a clip-on extensometer and recorded continuously. The final strain measured at the end of the experiment was reported as the “recovery strain.”

3.4. Prestraining, activation, and stress-relaxation of long Fe-SMA strips

3.4.1. Prestraining of long Fe-SMA strips (testing set-up No. 3)

Prestraining of the long Fe-SMA strips was done on a testing set-up shown in Figure 6. The strips were prestrained to a 2.0% elongation at RT by a manually operated oil hydraulic jack and then released to a stress-free state when the elastic strain was recovered. The Fe-SMA strips were clamped at the ends with mechanical steel clamps, which were then supported vertically. The resultant elongation was measured by a draw-wire displacement sensor, as shown in Figure 6.

3.4.2. Activation of long Fe-SMA strips (testing set-up No. 4)

Long Fe-SMA strips were activated in a testing set-up shown in Figure 7. The Fe-SMA strips were mechanically clamped at both ends between two steel columns; the length between the clamps was approximately 2 m. A load cell with a capacity of 100 kN was placed on one side in between the mechanical clamp and the steel column. Wooden plates were used to electrically isolate the mechanical clamp from the load cell and steel column and a Teflon tube was used to isolate the load cell electrically from the Fe-SMA strip. Teflon tubes were used to secure the isolation between the strip and steel columns.

The Fe-SMA strips were activated by resistive heating with a custom-made electric power supply. Special clamps (Figure 7, right panel) with air pressure were used to secure the contacts between the cables from the power supply and the Fe-SMA strips. A relatively high current density of approximately 8.3 A/mm^2 was applied. The temperature on the strip was measured by means of Type K thermocouples. In some experimental runs, an infrared camera was employed in addition to the thermocouples to record the temperature on the strip and its distribution over the length. When the temperature measured by the thermocouples reached the target tempera-

ture, the power supply was manually switched off. Because the specimens were subjected to air flow, such activation is named “activation in air.”

3.4.3. Stress relaxation of long Fe-SMA strips (testing set-up No. 4)

Using testing set-up No. 4, stress relaxation behavior of the Fe-SMA strips was studied. The set-up was equipped with a wireless long-term data acquisition system to record the load and temperature continuously. The measurements are accessible online at all times [44]. Three different stress relaxation experiments were performed.

- i) Relaxation behavior of the mechanically prestressed as received Fe-SMA strip: In these experiments, the Fe-SMA strip was mechanically loaded to a pre-determined stress level and fixed by mechanical clamps. Keeping both ends fully fixed, the reduction in the stress in the Fe-SMA strip over time was recorded continuously.
- ii) Relaxation behavior of the activated Fe-SMA strip: In these experiments, the Fe-SMA strip was fixed at both ends with mechanical clamps. The strip was then activated by resistive heating and the subsequent reduction in the stress level over time was continuously recorded.
- iii) Relaxation behavior of the activated and subsequently service loaded Fe-SMA strip: In these experiments, the Fe-SMA strip was activated as described earlier; later, an additional tensile stress of about 80 MPa, which simulates the service load, was manually applied by a hydraulic jack. The strip was then once again kept fixed at both ends by mechanical clamping and the subsequent reduction in stress over time was continuously recorded.

4. Results and discussion

4.1. Stress-strain behavior

The stress-strain behaviors of the examined strips under axial tensile loading are depicted in Figure 8 and Figure 9 for strip thicknesses of 0.5 mm and 1.5 mm, respectively. The Fe-SMA strips had an ultimate tensile strength, $f_{SMA,u}$, of about 1000 MPa with a corresponding minimum strain of 47% and 37% at thicknesses of 0.5 mm and 1.5 mm, respectively (Table 1). The strains at failure, $\varepsilon_{SMA,u}$, were more than 48% and 42%, higher than the strains at maximum tensile strength. Both types of strips showed a very ductile behavior. The elastic modulus determined from the stress-strain results was approximately 160 GPa. The elastic modulus was determined by best fit trend line fitted within stress range of 20 to 200 MPa.

Because the yield point could not be easily defined from the shape of the stress-strain curve, an offset yield point is arbitrarily defined. The value for the offset yield point (proof stress), $R_{p0.2}$, is set at 0.2% plastic strain, as shown in Table 1.

Prestraining of the 1.5-mm-thick short Fe-SMA strips to different prestraining levels is depicted in Figure 10. Figure 11 shows the prestraining of the 1.5-mm-thick long Fe-SMA strips to a prestraining level of 2.0%. The fluctuations in the curves are due to the manually operated hydraulic jack. The overall stress-strain behaviors, however, are similar to the reference tensile experiment performed in the machine testing set-up No. 1, as shown in Figure 10 and Figure 11.

The nonlinear deformation behavior during loading is due to either a phase transformation from austenite to martensite or a plastic deformation or a combination of both. When unloading, the load also deviates from the linear elastic behavior. The deviation from linear elastic discharge is called a pseudoelastic strain (Figure 12). In Figure 12, the elastic strain ($\varepsilon_{el} = 0.42\%$), pseudoelastic strain ($\varepsilon_{pel} = 0.33\%$), and “recovery strain and plastic strain” (1.25%) are shown for a strip with $\varepsilon_p = 2.0\%$ prestraining. The remaining permanent deformation of 1.25% can be partially recovered by activation, see Section 4.2.

4.2. Recovery strain

The amount of recovery strain depends on the heating temperature and on the amount of martensite present in the alloy. The amount of martensite generated during prestraining depends on the deformation level and deformation temperature. Figure 13 shows recovery strain measurement of representative 1.5-mm-thick specimens prestrained to 0.5%, 1.0%, 2.0%, 4.0%, and 6.0%. The final recovery strains after heating to 160 °C and cooling to 23 °C were in the range of 0.15–0.4%, as detailed in Table 2. In general if there is a gap during the application, part of the recovery strain is used to compensate the gap, it is, therefore, expected to receive less efficient recovery stress.

Figure 14 shows the effect of prestraining on the obtained recovery strain. It increases up to 2.0% initial prestraining; however, more prestraining does not lead to a clear higher recovery strain. It can therefore be concluded that an initial prestraining of 2.0% is enough to achieve the maximum recovery strain.

4.3. Recovery stress

When the recovery strain is hindered due to a controlled constant strip strain, “recovery stress” is generated inside the sample. In this section, recovery stresses obtained from the constrained

heating and cooling experiments on different specimens are described (Table 3). The effects of different parameters on the final recovery stress are discussed hereafter.

4.3.1. Effect of strip thickness on the recovery stress

Figure 15 compares the recovery stress versus temperature curves of representative specimens for 0.5-mm-thick and 1.5-mm-thick strips prestrained to 4.0% and heated to a maximum temperature of 160 °C. Although the two curves showed some differences and were not identical, they were similar in overall. The obtained recovery stresses are approximately the same and the difference lies in the range of scattering. Therefore, it could be concluded that there is no difference between the 0.5-mm-thick and 1.5-mm-thick Fe-SMA strips in terms of the obtained recovery stress.

4.3.2. Effect of cutting position on the recovery stress

Figure 16 and Figure 17 compare the recovery stress versus temperature curves of the specimens cut out from middle and the border of a 1.5-mm-thick Fe-SMA strip (Figure 3). The specimens were subjected to 2.0% and 4.0% prestraining before activation and heated to a maximum temperature of 160 °C. The recovery stresses obtained by cooling down the specimens to RT were approximately the same for both cutouts. Therefore, it could be concluded that there is no effect of the cutting position on the obtained recovery stress.

4.3.3. Effect of machine preload on the recovery stress

As mentioned in Section 3.3.2, at the start of the heating experiments, the Fe-SMA test specimens were preloaded to avoid compression in the test specimens due to thermal expansion during heating. Figure 18 compares the recovery stresses versus temperature curves of the representative specimens subjected to different machine preloads. A higher preload leads to a higher temperature point for the start of the phase transformation. In Figure 18, the temperature point for a preload of 100 MPa is higher than 50 °C; however, for the other preloads, it is below 50 °C. The obtained stress at the end of the heating phase and the “recovery stress,” after heating and cooling, are not significantly affected by the machine preload.

4.3.4. Effect of prestraining on the recovery stress

Figure 19 shows the effect of strip prestraining on the recovery stress versus temperature curves of the 1.5-mm-thick Fe-SMA strips subjected to a maximum temperature of 160 °C. It can be observed that the obtained recovery stress depends on the amount of prestraining before the ac-

tivation as shown in Figure 20, in which the obtained recovery stresses at different prestrain levels are depicted. The increasing trend of the recovery stress by increasing the prestraining reaches a plateau at 2% prestraining. According to the obtained results, a prestraining of 2.0% or 4.0% is the optimum level to achieve the highest recovery stress when heating to 160 °C. Determination of the optimal prestraining for higher temperature can be obtained by the same procedure. A different optimal value for higher temperature is expected, see Section 4.3.5.

The results described in this section are in agreement with the results obtained in Section 4.2. The generated recovery stress is directly linked to the recovery strain. An equivalent elastic modulus of 95 GPa, averaged from the different prestraining levels, could be used to determine the recovery stress according to the obtained recovery strain.

4.3.5. Effect of the maximum heating temperature on the recovery stress

Figure 21 compares the recovery stress versus temperature curves of the representative specimens subjected to three different maximum heating temperatures, 120 °C, 160 °C, and 195 °C. The 1.5-mm-thick strips used in this study were prestrained to 2.0% before activation. The recovery stresses were higher in the strips subjected to a higher maximum temperature, as shown in Figure 21 and Table 3. As the austenite finish temperature, A_f , of the studied alloy is about 163°C [32], recovery stresses obtained by maximum temperature of below A_f are due to partial activation. As Due to the limitations of the experimental set-up No. 2, temperatures above 200 °C were not possible.

Activation at higher temperatures was conducted “in the air” by resistive heating, according to testing set-up No. 4. Figure 22 exhibits an image captured by the infrared video camera from the left side of the Fe-SMA strip during activation in the air (see Figure 7). As can be seen in Figure 22 the temperature in the Fe-SMA strip is about 180 °C. Figure 23 shows the stress that was developed in the strip at the corresponding maximum temperature recorded by the infrared camera on the strip. A recovery stress of about 445 MPa was determined at the maximum activation temperature of 380 °C. Table 4 summarizes the results of all the activation experiments performed in air. Basically, higher temperature induces more phase transformation in the alloy; it therefore results in higher recovery stress. However, such increase is not always the case, and there is a maximum portion of phase transformation that can be expected by increasing the maximum heating temperature.

The results obtained from 2% prestrained strips are depicted in Figure 24. The combination of the results obtained after activation in the climate-controlled chamber and activation in the air

shows the effect of maximum temperature on the obtained recovery stress. The trend in the obtained results is also depicted in Figure 24. It is expected that the increasing trend reaches a maximum with no further increase in the stress even though the temperature is increased; probably, a decrease will occur at higher temperatures.

It is worth mentioning that the heating phase during resistive heating was less than one minute whereas the cooling phase took about ten minutes. In comparison with the activation experiments carried out in the climate-controlled chamber over several hours, such an activation procedure is very fast. The activation experiments in air resulted in recovery stresses similar to those obtained from experiments performed in the climate-controlled chamber. It was therefore concluded that the heating and cooling rates do not have a significant influence on the obtained recovery stress.

4.4. Relaxation of the Fe-SMA strips

Figure 25 shows an example of the stress relaxation behavior of the studied Fe-SMA strips on a logarithmic scale. In this example, the changes in the tensile stress over time after the activation of the strip are shown. The experiment was performed in laboratory conditions at ambient room temperature, the variation in which was about ± 2 °C; this causes a slight fluctuation in the stress level recorded over time. The stress relaxation (ratio of actual stress to maximum stress) in percentage terms is depicted in Figure 25. The maximum stress relaxation values after more than 1000 h for differently examined strips are presented in Table 5. The results indicate that the relaxation behavior of the studied Fe-SMA strips was similar under the three different prestressing scenarios.

4.5. Loading after activation

An important aspect of the application of prestressed Fe-SMA strips is their behavior under additional load after activation. Such a load can be considered as the service load in buildings and construction structures. A thorough knowledge of this behavior is needed for designing SMAs for real-time applications. Figure 26 shows the stress-strain behavior of a representative 1.5-mm-thick strip prestrained to 2.0% and activated at a maximum temperature of 160 °C. The stress-strain curve due to additional loading reaches the initial curve; however, the tensile stiffness is different at the beginning. For design purposes, an elastic modulus (as shown in Figure 26) should be used. For such a high additional loading the effect of pre-straining disappears, however, this will not be the case in reality. In the current investigation, such extremely high additional loading has been applied to determine the stress-strain behavior of the studied SMA

after activation. The reason for such loss could be correlated by the unrecoverable plastic deformation in the alloy. In fact, the reserved-recovery-strain is employed to compensate the high plastic strain introduced into alloy by high level of additional loading.

The additional stress-strain behavior after activation depends on the recovery stress obtained from the activation experiments. In Figure 27, the stress-strain curves of representative specimens subjected to maximum temperatures of 120 °C, 160 °C, and 195 °C are depicted. The initial slopes in those cases with lower recovery stresses are higher than those with higher recovery stresses. This difference is important and should be considered during design when Fe-SMA strips are used for real-time structural applications [41].

5. Conclusions

In this study, material characterization of Fe-SMA strips produced at an industrial level for the strengthening of RC members was performed. The characterizations were carried out at engineering standards to match the intended purpose of application in civil engineering structures. The following conclusions were drawn from our investigation.

- The Fe-SMA strips showed excellent mechanical properties. Their behavior in unidirectional tension is very ductile till their failure. An ultimate tensile strength of about 1000 MPa with a corresponding strain at failure of more than 40% was obtained. Recovery stresses of 300 to 350 MPa were measured after heating the Fe-SMA strips to 160 °C.
- The cutting position did not have any significant effect on the obtained recovery stress. In terms of prestress, the material behaves uniformly along the whole width of 100 mm.
- The obtained recovery stresses for both thin (0.5 mm) and thick (1.5 mm) strips were identical.
- Prestraining influenced the obtained recovery stress. For the studied Fe-SMA strips, a prestraining of 2.0% was found to be sufficient in order to obtain the maximum possible recovery stress after heating the Fe-SMA strips to 160 °C.
- Activation at higher temperatures leads to a higher recovery stress. It is expected that the increasing trend reaches a maximum at a heating temperature of about 400 °C. At this temperature, the obtained recovery stress is about 450 MPa.
- Recovery strains of about 0.15% to 0.40% were measured during the heating/cooling cycle of the 1.5-mm-thick strip to/from a temperature of 160 °C.
- Loading the Fe-SMA strips after activation showed that their stress-strain curve overlaps the stress-strain curve obtained during tensile studies. However, the tensile stiffness is dif-

ferent just after activation, and it also depends on the prestress level. These stiffness values should be used for design purposes.

The results from this study can be directly used for structural design purposes. Furthermore, these results can also be used to develop a phase diagram for the studied alloy.

ACKNOWLEDGEMENTS

The authors acknowledge financial support and Fe-SMA material supply from re-fer AG. Furthermore, the laboratory staff of the Structural Engineering Research Laboratory and the Mechanical Engineering Systems Laboratory at Empa are acknowledged for their support in conducting the experimental investigation.

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Tables

Table 1. List of Fe-SMA strips under tensile loading, studied using testing set-up No. 1

Strip No.	Cut out - M (middle) or R (border)	Thickness, t [mm]	Width, b [mm]	Offset yield point, $R_{p0.2}$ [MPa]	Maximum Stress, f_u [MPa]	Strain at f_u [%]	Maximum strain, ε_{max} [%]
S-1	M	0.5	15	496.93	1000.75	51.50	53.47
S-2	M	0.5	15	500.83	967.02	47.22	48.22
S-3	M	0.5	15	502.13	963.38	45.27	47.90
S-4	R	1.5	15	537.70	976.39	38.12	42.42
S-5	R	1.5	15	538.12	976.25	38.46	41.62
S-6	R	1.5	15	532.63	975.98	36.81	41.74
S-7	R	1.5	15	537.77	984.74	40.61	44.66
S-8	R	1.5	15	527.64	982.97	39.55	43.55
S-9	M	1.5	15	533.63	991.63	39.63	43.53

Table 2. List of Fe-SMA strips subjected to recovery strain measurement in testing set-up No. 2

Strip No.	Cut out - M (middle) or R (border)	Thickness, t [mm]	Width, b [mm]	Prestrain, ε_p [%]	Pre-load, P_{ini} [MPa]	Maximum temperature, T_{max} [°C]	Recovery strain, ε_{rec} [%]
S-10	R	1.5	10	0.5	1	160	0.16
S-11	R	1.5	10	1	1	160	0.25
S-12	M	1.5	10	2	1	160	0.37
S-13	R	1.5	10	2	1	160	0.37
S-14	R	1.5	10	2	1	160	0.36
S-15	M	1.5	10	4	1	160	0.32
S-16	R	1.5	10	4	1	160	0.33
S-17	R	1.5	10	4	1	160	0.38
S-18	R	1.5	10	4	1	160	0.38
S-19	R	1.5	10	4	1	160	0.39
S-20	R	1.5	10	6	1	160	0.36

550 **Table 3.** List of Fe-SMA strips activated in the climate-controlled chamber in testing set-up No. 2

StripNo.	Cut out -M (middle) or R (border)	Thickness, t [mm]	Width, b [mm]	Prestrain, ε_p [%]	Machine preload, P_{ini} [MPa]	Maximum temperature, T_{max} [°C]	Recovery stress, σ_{rec} [MPa]
S-21	R	1.5	15	0.5	50	160	259.59
S-22	M	1.5	15	0.5	50	160	291.79
S-23	M	1.5	15	0.5	50	160	293.07
S-24	R	1.5	15	1	50	160	291.57
S-25	R	1.5	15	1	50	160	326.57
S-26	R	1.5	15	1	50	160	327.72
S-27	M	1.5	15	2	50	120	270.77
S-28	M	1.5	15	2	50	120	273.30
S-29	R	1.5	15	2	50	140	274.32
S-30	R	1.5	15	2	50	140	276.20
S-31	R	1.5	15	2	50	120	277.69
S-32	R	1.5	15	2	50	160	303.32
S-33	R	1.5	15	2	50	160	310.52
S-34	M	0.5	15	2	50	160	317.55
S-35	R	1.5	15	2	50	160	328.00
S-36	M	1.5	15	2	50	160	342.46
S-37	R	1.5	15	2	50	160	344.66
S-38	M	1.5	15	2	50	160	346.10
S-39	M	1.5	15	2	50	160	348.84
S-40	M	1.5	15	2	50	195	379.69
S-41	M	1.5	15	2	50	195	387.69
S-42	M	1.5	15	2	50	195	392.77
S-43	M	0.5	15	4	50	160	315.63
S-44	R	1.5	15	4	50	160	322.00
S-45	R	1.5	15	4	70	160	324.00
S-46	R	1.5	15	4	50	160	324.00
S-47	M	1.5	15	4	50	160	329.17
S-48	R	1.5	15	4	70	160	330.00
S-49	M	0.5	15	4	50	160	331.02
S-50	M	1.5	15	4	50	160	334.00
S-51	M	1.5	15	4	50	160	338.79

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552 **Table 4.** List of Fe-SMA strips activated in the air in testing set-up No. 4

Strip No.	Thickness, t [mm]	Width, b [mm]	Prestrain, ε_p [%]	Pre-load, P_{ini} [MPa]	Maximum temperature, T_{max} [°C]	Recovery stress, σ_{rec} [MPa]
L-1	1.5	10	2	10	190	389
L-2	1.5	10	2	10	268	443
L-3	1.5	10	2	10	280	395
L-4	1.5	10	2	10	177	356
L-5	1.5	10	2	10	171	334
L-6	1.5	10	2	10	380	445

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554 **Table 5.** List of Fe-SMA strips subjected to long-term loading (relaxation) in testing set-up No. 4

Strip No.	Thickness, t [mm]	Width, b [mm]	Pre-strain, ε_p [%]	Experiment type, see Section 3.4.3	Pre-load, P_{ini} [MPa]	Maximum temperature, T_{max} [°C]	Recovery stress, σ_{rec} [MPa]	Load after activation, P_{ser} [MPa]	Time under loading, t_{relx} [h]	Relaxation, $\Delta\sigma_{relx}/\sigma_{max}$ [%]
L-7	1.5	10	2	<i>i</i>	330	-	-	-	1423	9.0
L-8	1.5	10	2	<i>ii</i>	10	160	378	-	712	9.3
L-9	1.5	10	2	<i>ii</i>	10	160	380	-	1674	9.9
L-10	1.5	10	2	<i>iii</i>	10	160	375	85	960	8.9
L-11	1.5	10	2	<i>iii</i>	10	160	390	95	1960	9.7

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Figures

Figure 1. Left: schematic of three main actions in SMA application for prestressing a RC member. Right: schematic illustration of the activation (2nd action) and the recovery stress development

Figure 2. Fe-SMA strips. Left: 1.5 mm thickness and 100 mm width, Right: 0.5 mm thickness and 50 mm width

Figure 3. Left – cut out from the Fe-SMA strips; on top: Fe-SMA strips with 0.5 mm thickness and on bottom: Fe-SMA strips with 1.5 mm thickness cut out from the middle and the border. Right: Fe-SMA strips before the tensile test; marks on the painted background are for strain measurements. The scale dimensions are in cm

Figure 4. Fe-SMA strips installed in a Zwick testing machine equipped with an extensometer over a length of 100 mm [43] (testing set-up No. 1)

Figure 5. A 20 kN Zwick machine equipped with a climate-controlled chamber. The machine was used for prestraining and activation of the Fe-SMA test specimens (testing set-up No. 2)

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Figure 6. Set-up and instrumentation for the prestraining of long Fe-SMA strips (testing set-up No. 3)

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Figure 7. Set-up and instrumentation for the activation of long Fe-SMA strips in air (testing set-up No. 4)

Figure 8. Stress-strain diagrams of 0.5-mm-thick Fe-SMA strips from tensile experiments performed in testing set-up No. 1

Figure 9. Stress-strain diagrams of 1.5-mm-thick Fe-SMA strips from tensile experiments performed in testing set-up No. 1

Figure 10. Stress-strain diagrams from prestraining experiments on 1.5-mm-thick short Fe-SMA strips (testing set-up No. 2)

Figure 11. Stress-strain diagrams from prestraining experiments on 1.5-mm-thick long Fe-SMA strips (testing set-up No. 3)

Figure 12. Prestraining (2.0%) diagram of a 1.5-mm-thick Fe-SMA strip (testing set-up No. 2)

Figure 13. Recovery strain measurement performed in testing set-up No. 2

Figure 14. Effect of strip prestraining on the recovery strain for the 1.5-mm-thick Fe-SMA strips subjected to a maximum temperature of 160 °C (testing set-up No. 2)

Figure 15. Effect of strip thickness on the recovery stress versus temperature curves of the Fe-SMA strips subjected to 4.0% prestrain (testing set-up No. 2)

Figure 16. Effect of strip position cut on the recovery stress versus temperature curves of the 1.5-mm-thick Fe-SMA strips subjected to a 2.0% prestrain (testing set-up No. 2)

Figure 17. Effect of strip position cut on the recovery stress versus temperature curves of the 1.5-mm-thick Fe-SMA strips subjected to 4.0% prestrain (testing set-up No. 2)

Figure 18. Effect of machine preload on the recovery stress versus temperature curves of the 1.5-mm-thick Fe-SMA strips subjected to 4.0% prestrain (testing set-up No. 2)

Figure 19. Recovery stress versus temperature curves of the 1.5-mm-thick Fe-SMA strips at different pre-strain levels subjected to a maximum temperature of 160 °C (testing set-up No. 2)

Figure 20. Effect of strip prestraining on the recovery stress for the 1.5-mm-thick Fe-SMA strips subjected to a maximum temperature of 160 °C (testing set-up No. 2)

Figure 21. Recovery stress versus temperature curves of the 1.5-mm-thick Fe-SMA strips subjected to 2.0% prestrain in the climate chamber (testing set-up No. 2)

Figure 22. Left: A photo captured by the infrared camera during the activation of a Fe-SMA strip in air. Right: Actual photo of the Fe-SMA strip visible in the infrared photo (testing set-up No. 4)

Figure 23. Stress and temperature measurement in a long Fe-SMA strip activated in air (testing set-up No. 4)

Figure 24. Effect of maximum temperature on the recovery stress versus temperature curves of the 1.5-mm-thick Fe-SMA strips subjected to 2.0% prestrain (testing set-up No. 2 and 4)

Figure 25. Stress relaxation of a Fe-SMA strip activated in air to a recovery stress of about 380 MPa (testing set-up No. 4)

Figure 26. Stress-strain behavior of a 1.5-mm-thick Fe-SMA strip prestrained to 2.0%, activated at a maximum temperature of 160 °C, and subjected to an additional tensile load which is 3–4 times greater than the service load (testing set-up No. 2)

Figure 27. Stress-strain behavior of a 1.5-mm-thick Fe-SMA strip prestrained to 2.0%, activated at different maximum temperatures, and subjected to an additional tensile load 3–4 times greater than the service load (testing set-up No. 2)