Feasibility of iron-based shape memory alloy strips for prestressed strengthening of steel plates

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ABSTRACT: Iron-based shape memory alloys (Fe-SMAs) are advanced materials that can be used as prestressing elements for strengthening and rehabilitation of civil structures. In this paper, the results of a feasibility study on the application of shape memory effect (SME) of Fe-SMA strips for prestressed strengthening of steel plates are provided and discussed. The Fe-SMA strips were anchored to the steel plates using a pair of mechanical anchorage system. Electrical resistance heating (ERH) technique was then used to heat up the Fe-SMA strips to 260 °C, resulting in activation of the Fe-SMA material. The activated Fe-SMA strips apply a prestressing force to the steel plate. The Fe-SMA-strengthened steel plates were then subjected to static tensile load to simulate the external loading on the retrofitted member. Based on the preliminary experimental results, it can be concluded that strengthening of steel plates with activated Fe-SMA strips can considerably decrease the tensile stress level in such members.

1 INTRODUCTION

There are various types of damages reported for steel structures including in building and bridge sectors. These damages can be caused by aging, accident, vandalism, increasing service load, or harsh environmental condition. Therefore, different types of repair and strengthening works are vital to keep the existing steel structures in service. Advanced materials such as carbon fiber-reinforced polymer (CFRP) composites have shown their great potential to strengthen metallic structures (Ghafoori et al. 2015; Aljabar et al. 2016; Aljabar et al. 2017). Strengthening by pre-stressed CFRP strips is particularly appealing since CFRP reinforcements could considerably increase the static and fatigue strength of steel members (Ghafoori et al. 2012; Ghafoori et al. 2015). However, for prestressing the external CFRP strips, there is often a need for a hydraulic actuator, which sometimes makes the pre-stressing process difficult or impossible (e.g. due to lack of space). It is believed that application of shape memory alloys (SMAs) can make the pre-stressing procedure easier and faster, as there is no need for hydraulic actuators.

In principle, SMAs have two main characteristics of so-called shape memory effect (SME) and superelasticity. Both features refer to the ability of SMAs to recover their primary shape after permanent deformation. The SME is the phenomenon that SMA returns to its original shape upon heating and a subsequent cooling process. Superelasticity, however, refers to the ability of SMA material to recover its shape after unloading without heating (Janke et al. 2005). Recently, a novel iron-based shape memory alloy (iron-based or Fe-SMA), Fe–17Mn–5Si–10Cr–4Ni–1(V,C), has been developed at Empa in Switzerland (Dong et al. 2009). The Fe-SMA has shown promising mechanical properties (e.g., high recovery stresses and elastic stiffness) with a relatively low cost of raw materials and manufacturing process. More details about behavior of the Fe-SMA can be found in (Lee et al. 2013; Lee et al. 2015; Koster et al. 2015; Leinenbach et al. 2016).

In general, SME in Fe-SMAs is a result of a stress-induced phase transformation from a parent γ-austenite phase to a ε-martensite phase at room temperature and its reverse phase transformation (ε→γ) upon heating at high temperature. As the Fe-SMA tries to return to its original shape during the reverse phase transformation, upon constraining the Fe-SMA (e.g., by clamping), recovery stresses can be produced in the member.

Although there are some feasibility studies on the use of Fe-SMA for strengthening of concrete structures (e.g., Czaderski et al. 2014; Shahverdi et al. 2016), to the authors' best knowledge, no study can be found in the literature dealing on application of Fe-SMA for strengthening of metallic members. Thus, the current paper focuses on the use of SME of Fe-SMA strips for strengthening of tensile steel members. In this study, some preliminary static tests have been performed on steel plates retrofitted with non-prestressed (i.e., non-activated) and prestressed (i.e., activated) Fe-SMA strips. A total number of four steel plates (including three Fe-SMA-retrofitted and one reference sample) with 1100-mm length and 150-mm width were tested.

2 EXPERIMENTS

2.1 Specimens and material properties

Static tests were performed on four steel plate specimens with dimensions of $1100\times150\times10$ mm (length$\times$width$\times$thickness). The experimental program was designed to demonstrate the applicability of non-activated and activated Fe-SMA strips for strengthening of steel plates. Thus, different configurations of steel plate specimens, strengthened with Fe-SMA strips, were used. Different cross-sections of Fe-SMA strips have been applied on steel plates to gain different levels of prestressing forces. In addition, strengthening with non-activated strips was also incorporated in the test plan in order to evaluate the effect of prestressing.

Fe-SMA strips, from the company re-fer AG in Switzerland, with dimensions of $590\times46.7\times1.5$ mm (length$\times$width$\times$thickness) were used to strengthen steel plates with nominal yield strength and Young's modulus of 355 MPa, and 200.9 GPa, respectively. A mechanical anchorage system was developed to anchor the Fe-SMA strips to the steel plates. More details about the design and testing of the utilized mechanical anchorage system can be found in Izadi et al. (2017). In this study, three steel plates were strengthened with Fe-SMA strips, while a bare steel plate without strengthening served as reference specimen. Table 1 shows an overview of the test program.

2.2 Test procedure

In Specimen S2, the Fe-SMA strips were anchored to steel plate using the friction-based anchorage system, each clamp included two M16 high strength bolts (with a grade class of 12.9). In Specimens S3 and S4, the strengthening procedure is summarized as follows and

Table 1. Text matrix.

Specimens.	SMA strip width (mm)[1]	Strengthening type	Schematic cross-sections
S1	N/A	Reference, no strengthening	
S2	46.7	Non-activated, double-side	
S3	46.7	Activated, single-side	
S4	46.7	Activated, double-side	

[1]*All Fe-SMA strips had a thickness of 1.5 mm.*

schematically shown in Figure 1:

i. Prestraining of Fe-SMA strip up to strain of 2% at room temperature (see Figure1a)

ii. Anchoring of the prestrained Fe-SMA strip on the steel plate using mechanical anchorages (see Figure 1b)

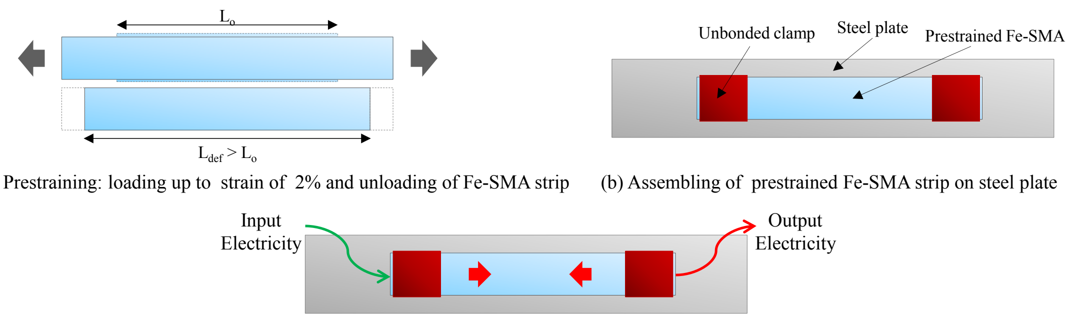
iii. Activating (prestressing) of Fe-SMA strips using electricity through a heating process and subsequent cooling (see Figure 1c).

2.2.1 Prestraining

Before anchoring Fe-SMA strips to the steel plates, they were prestrained at ambient temperature using a manually operated oil hydraulic jack up to a strain of 2% and then unloaded to a stress-free state. The strain was measured with an external linear variable differential transformer (LVDT). The prestraining setup is shown in Figure 2.

2.2.2 Assembling

Prior to tightening mechanical clamps, glass fiber-reinforced polymer (GFRP) laminates were used to electrically and thermally isolate the Fe-SMA strips from the steel plates during the activation procedure. GFRP laminates were of type high temperature epoxy glass fabric laminate, G-11 type, class H with a thermal class of 180 °C. Furthermore, the Fe-SMA strips and the steel plates were equipped with Type K thermocouples. The mounted thermocouples measured the temperature along the strips and the steel plates.



(a) Prestraining: loading up to strain of 2% and unloading of Fe-SMA strip

(b) Assembling of prestrained Fe-SMA strip on steel plate

(c) Activating (prestressing) of Fe-SMA strip

Figure 1. Schematic procedure of steel plate strengthening with Fe-SMA strips.

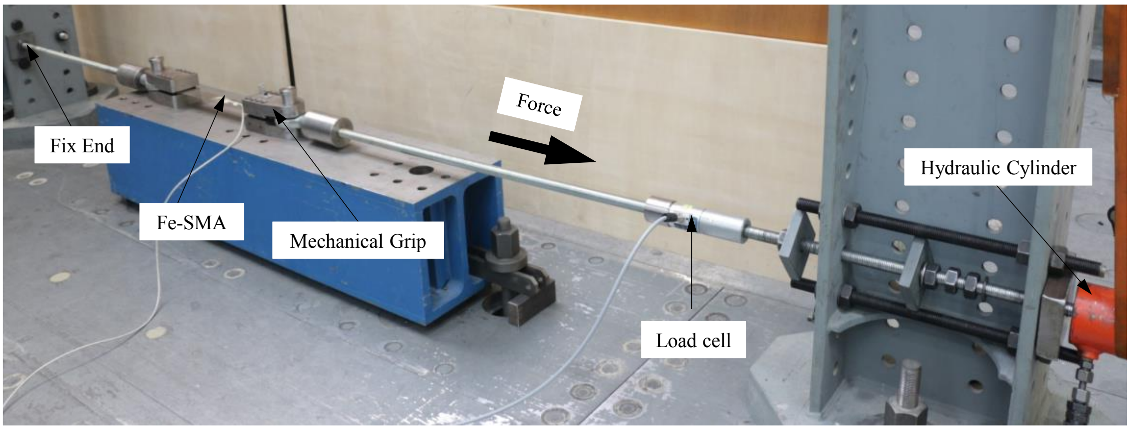


Figure 2. Different elements of the prestraining setup.

2.2.3 Activation process

Fe-SMA strips were heated up to temperature 260 ^{o}C, and subsequently cooled down to room temperature of about 20 ^{o}C. Thermal energy was provided using electrical resistive heating (ERH) method. An electrical power supply was used to provide the resistive heating. Two copper clamps were used to secure the connection of electrical grips of the power supply. Figure 3 shows the activation setup of Specimen S3.

Input current provided by power supply was controlled with the thermocouples mounted on the strips and the steel plates. When the average maximum temperature in Fe-SMA strips reached the target temperature of 260 ^{o}C, the power supply was switched off. Additionally, temperatures in steel plates were monitored to observe any possible increase of temperature in the steel plates.

2.2.4 Static tensile loading

The specimens were equipped with strain gages on the steel plates and the Fe-SMA strips. A 1000 kN static-fatigue servo-hydraulic machine was then used for loading the specimens. Quasi-static loading under displacement-controlled condition with a deformation rate of 1 mm/min was employed for static loading of all the specimens. Figure 4 provides a photo of the loading test setup.

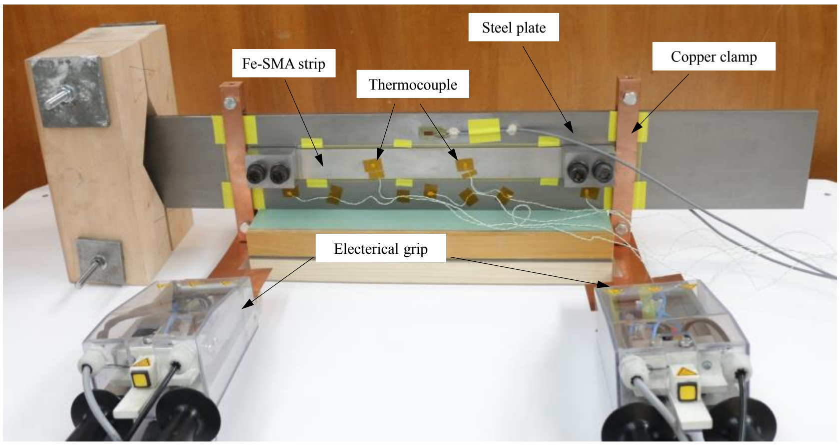


Figure 3. Different elements in the activation setup.

3 RESULTS AND DISCUSSIONS

3.1 Prestraining

As it is explained in Introduction section, the Fe-SMA strips are in the austenite phase before the prestraining. As a result of prestraining, stress-induced martensite phase will be produced. Stress–strain diagram of prestraining is given in Figure 5. In this figure, the nonlinear behavior during loading is attributed to the austenite to martensite phase transformation (i.e., forward transformation) and plastic deformations, while the non-linear behavior during un-loading process shows the pseudoelasticity of the Fe-SMA strips. The residual strain after unloading the strips for all of the Fe-SMA strips was about 1.3%.

3.2 Activation

Activation process was performed for Specimens, S3 and S4. An electricity current of about 600 A was applied. The current density of approximately $8.6\,A/mm^2$ flowed to Specimen S3 as it had only one Fe-SMA strip with a cross-section of 46.7×1.5 mm. Specimen S4 received half of this current flow as it had two parallel Fe-SMA strips. Recorded average temperatures (from the thermocouples) in the Fe-SMA strip and the steel plate at the mid-length for Specimen S3 during activation process is shown in Figure 6. The temperatures along the steel plates were monitored to verify the insulation between the SMA strip and the steel plate. The results showed that the insulation technique (i.e., using GFRP laminates) performed well as the temperature of the steel plates was not increased. An increase in temperature is attributed to heat conductivity between the Fe-SMA strip and the steel plate. The measured strain in the steel plates was used to calculate the generated prestressing force in the Fe-SMA strips. The average compressive strains in the middle of the steel plates were about 90, and 172 µm/m for Specimens S3 and S4, respectively. The recovery stresses in the Fe-SMA strips were then estimated to be 387 and 369 MPa for Specimens S3 and S4, respectively.

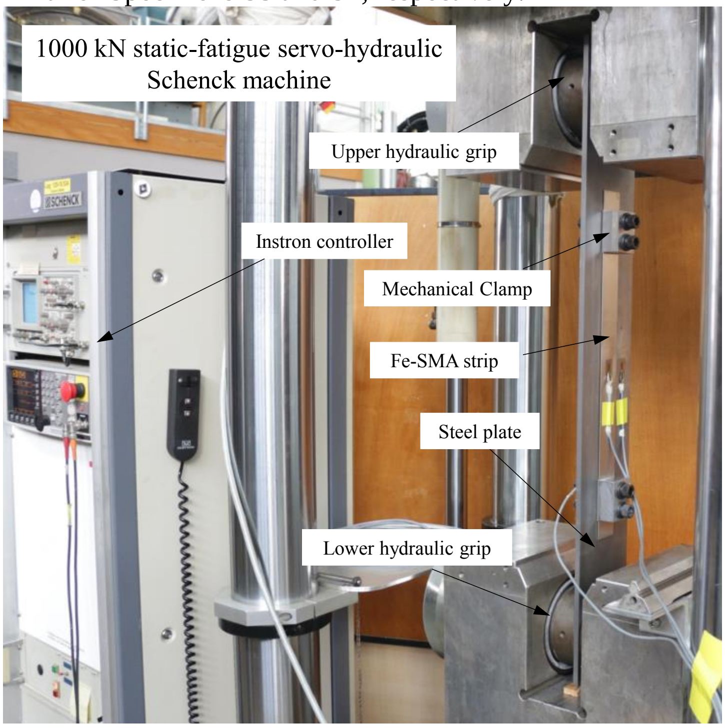


Figure 4. Loading test setup.

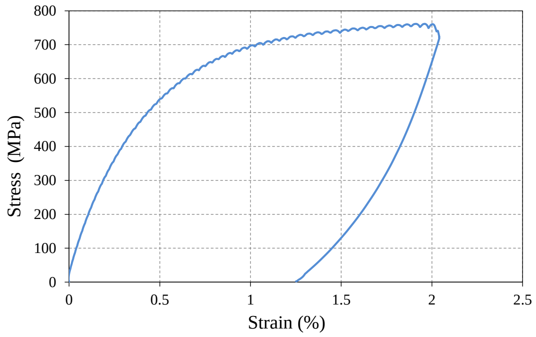


Figure 5. Stress-strain behavior during prestraining of a Fe-SMA strip.

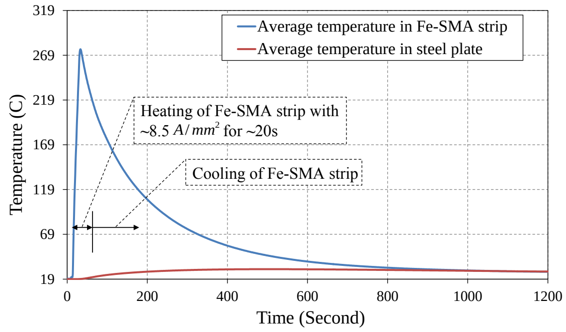


Figure 6. Evolution of temperature in the Fe-SMA strip and the steel plate during activation process for Specimen S3.

3.3 *Static tensile loading*

In all the specimens, steel yielding was the failure mode. No failure was observed in the anchorage systems. The load-strain behavior in the mid-section of the steel specimens is shown in Figure 7. The curves have been depicted up to a load of 500 kN, which corresponds approximately to yield strength of the bare steel. As it can be seen, elastic stiffness of strengthened steel plates are increased compared with the non-strengthened reference specimen. It can be also observed that the strain in the steel section has been reduced for activated specimens. Furthermore, Specimen S4, which was retrofitted with larger cross-section of the Fe-SMA strips (i.e., two 46.7-mm width SMA strips), gained the most reduction in the strain in the steel cross-section.

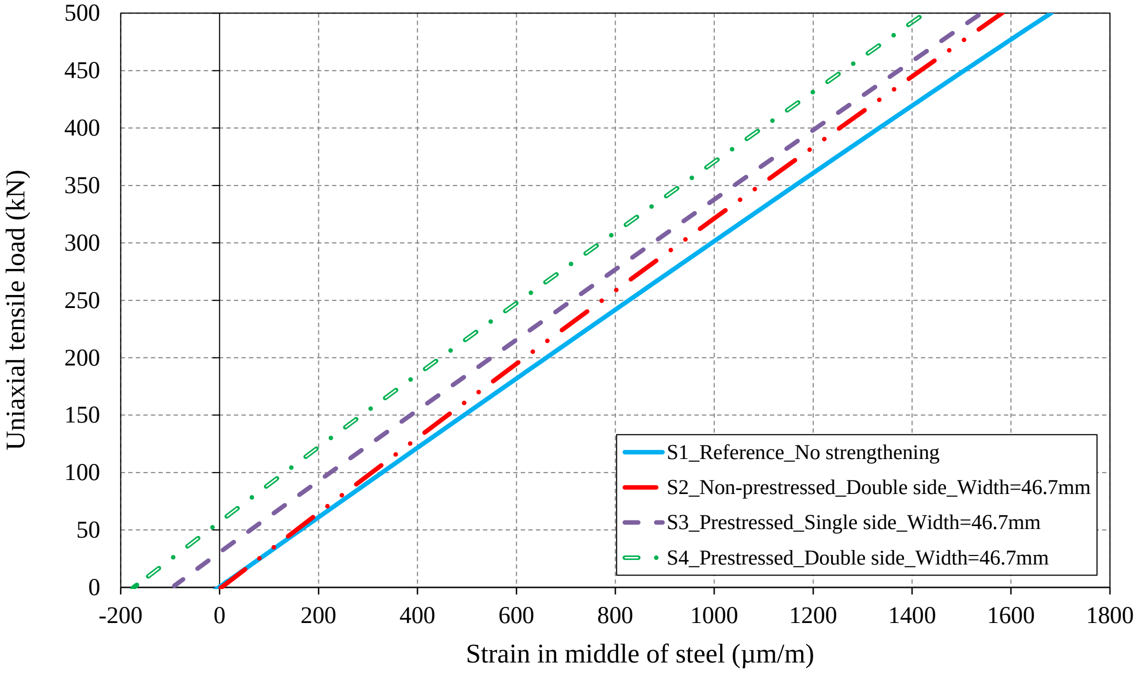


Figure 7. Load-strain behavior of tested specimens subjected to quasi-static tensile loading.

4 SUMMARY AND CONCLUSIONS

A new retrofit system for strengthening of steel plates using an iron-based shape memory alloy has been successfully tested. Activated and non-activated Fe-SMA strips were used for strengthening of steel plates. An electrical resistive heating technique was used to heat up the Fe-SMA strips while cooling down process was conducted in ambient temperature. Preliminary results of an ongoing test plan are presented in this paper. The results showed that the activated Fe-SMA strips could apply a considerable prestressing force to the steel plate. This compressive force decreased the stresses in the steel plate, and, therefore, could enhance the performance of the retrofitted steel plates, particularly within the linear-elastic domain. It is believed that application of activated Fe-SMA strips could increase the fatigue life of steel members. There are ongoing experimental tests at the Structural Engineering Research Laboratory of Empa to evaluate the fatigue performance of the proposed retrofitting system.

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REFERENCES

Aljabar N.J., Zhao X.L., Al-Mahaidi R., Ghafoori E., Motavalli M., Powers N. Effect of Crack Orientation on Fatigue Behaviour of CFRP- Strengthened Steel Plates, 2016, *Composite Structures*, 152: p. 295-305.

Aljabar N.J., Zhao X.L., Al-Mahaidi R., Ghafoori E., Motavalli M., Koay Y.C, 2017, Fatigue tests on UHM-CFRP strengthened steel plates with central inclined cracks under different damage levels. *Composite Structures*, 160, 995-1006.

Cladera, A., Weber, B., Leinenbach, C., Czaderski, C., Shahverdi, M., Motavalli, M, 2014, Iron-based shape memory alloys for civil engineering structures: an overview, *Construction and building materials*, 63: 281-93.

Czaderski, C., Shahverdi, M., Brönnimann, R., Leinenbach, C., Motavalli, M, 2014, Feasibility of iron-based shape memory alloy strips for prestressed strengthening of concrete structures, *Construction and Building Materials*, 56, 94-105.

Dong, Z., Klotz, UE., Leinenbach, C., Bergamini, A., Czaderski, C., Motavalli, M, 2009, A Novel Fe-Mn-Si Shape Memory Alloy With Improved Shape Recovery Properties by VC Precipitation, *advanced engineering materials*, 11: 40-44.

Ghafoori E., Motavalli M., Botsis J., Herwig A., Galli M, 2012, Fatigue strengthening of damaged metallic beams using prestressed unbonded and bonded CFRP plates, *International Journal of Fatigue*, 2012. 44: p. 303-315.

Ghafoori E., Schumacher A., Motavalli M, 2012, Fatigue behavior of notched steel beams reinforced with bonded CFRP plates: Determination of prestressing level for crack arrest, *Engineering Structures*, 45: p. 270-283.

Ghafoori E., Motavalli M, 2015, Lateral-torsional buckling of steel I-beams retrofitted by bonded and un-bonded CFRP laminates with different pre-stress levels: experimental and numerical study. *Construction and Building Materials*, 76: p. 194–206.

Ghafoori E., Motavalli M, 2015, Innovative CFRP-Prestressing System for Strengthening Metallic Structures, *Journal of Composites for Construction*, 19(6): p. 04015006.

Ghafoori E., Motavalli M, 2015, Normal, high and ultra-high modulus CFRP laminates for bonded and un-bonded strengthening of steel beams, *Materials and Design*, 67: p. 232–243.

Ghafoori E., Motavalli M., Nussbaumer A., Herwig A., Prinz G., Fontana M, 2015, Determination of minimum CFRP pre-stress levels for fatigue crack prevention in retrofitted metallic beams. *Engineering Structures*, 84: p. 29–41.

Ghafoori E., Motavalli M., Nussbaumer A., Herwig A., Prinz G.S., Fontana M, 2015, Design criterion for fatigue strengthening of riveted beams in a 120-year-old railway metallic bridge using pre-stressed CFRP plates, *Composites Part B: Engineering*, 68: p. 1-13.

Izadi, M., Ghafoori, E., Hosseini, A., Motavalli, M., Maalek, S, 2017, Development of mechanical anchorage systems for SMA-to-steel joints', , *Fourth International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures (SMAR)*, Zurich, Switzerland.

Janke, L., Czaderski, C., Motavalli, M., Ruth J, 2005, Applications of shape memory alloys in civil engineering structures—overview, limits and new ideas, *Materials and Structures*, 38: 578-92.

Koster M., Lee W.J., Schwarzenberger M., Leinenbach C, 2015, Cyclic deformation and structural fatigue behavior of an FE–Mn–Si shape memory alloy, *Materials Science and Engineering*: *A*, 637(0): p. 29-39.

Laminates, VETRONIT G11, Von Roll Deutschland GmbH, D-86199 Augsburg, www.vonroll.com.

Lee W.J., Weber B., Feltrin G., Czaderski C., Motavalli M., Leinenbach C, 2013, Stress recovery behaviour of an Fe–Mn–Si–Cr–Ni–VC shape memory alloy used for prestressing, *Smart Materials and Structures*, IOP Science, 22: p. 1-9.

Lee W.J., Weber B., Feltrin G., Czaderski C., Motavalli M., Leinenbach C, 2013, Phase transformation behavior under uniaxial deformation of an Fe–Mn–Si–Cr–Ni–VC shape memory alloy, *Materials Science and Engineering*: *A*, 581: p. 1-7.

Lee W.J., Weber B., Leinenbach C, 2015, Recovery stress formation in a restrained Fe–Mn–Si-based shape memory alloy used for prestressing or mechanical joining, *Construction and Building Materials*, 95: p. 600-610.

Leinenbach C., Lee W.J., Lis A., Arabi-Hashemi A., Cayron C., Weber B, 2016, Creep and stress relaxation of a FeMnSi-based shape memory alloy at low temperatures, *Materials Science and Engineering A*, 677: p. 106-115.

Shahverdi, M., Czaderski, C., Motavalli, M, 2016, Iron-based shape memory alloys for prestressed near-surface mounted strengthening of reinforced concrete beams, *Construction and Building Materials*, 112, 28-38.