Stress recovery behavior of an Fe-Mn-Si-Cr-Ni-VC shape memory alloy subjected to high-cycle fatigue loading

Elyas Ghafoori[1,2], Ehsan Hosseini[1,3], Julien Michels[4]

[1] Empa, Swiss Federal Laboratories for Material Science and Technology, Dübendorf, Switzerland
[2] Swinburne University of Technology, Melbourne, Australia
[3] Inspire Centre for Mechanical Integrity, c/o Empa, Switzerland
[4] re-fer AG, Brunnen, Switzerland

ABSTRACT

Cyclic deformation and high-cycle fatigue (HCF) behavior of an iron-based shape memory alloy (Fe-SMA) Fe-17Mn-5Si-10Cr-4Ni-1(V,C) was studied. In the first step, tests were performed to characterize the mechanical properties (e.g., yield and tensile strengths, elongation) as well as the shape memory response of the alloy (i.e., stress recovery behavior). In the next step, the behavior of the SMA after pre-staring and thermal activation under strain-controlled HCF was evaluated. The results showed that the SMA recovered stress decreases under fatigue loading conditions (indicating a phase transformation-induced relaxation during cycling). This implies that the pre-stress of SMA-retrofitted structures decreases when the structure is under a cyclic loading condition. The results of this study can be used to quantify this reduction and to better estimate the mechanical integrity of SMA retrofitted civil engineering structures under fatigue loading conditions.

1 INTRODUCTION

A novel Fe-17Mn-5Si-10Cr-4Ni-1(V,C) SMA has been recently developed at Empa (Dong et al. 2009, Lee et al. 2013b, Lee et al. 2013a, Leinenbach et al. 2012). The alloy shows very promising mechanical and shape memory effect (SME) properties (e.g., a high recovered stress). The alloy can be manufactured by standard melting and casting process under atmospheric conditions, which makes the large-scale production of the alloy for civil engineering applications feasible and cost-competitive. Studies on stress recovery (Lee et al. 2013b), phase transformation (Czaderski et al. 2014), creep and stress relaxation (Leinenbach et al. 2016), electrochemical characterization and corrosion behavior (Lee et al. 2016) of the Fe-17Mn-5Si-10Cr-4Ni-1(V,C) SMA have shown a good potential of the alloy as pre-stressing members for civil engineering applications.

Pre-stressed elements made of fibre-reinforced polymer (FRP) have been already proven to be very effective in increasing the performance of concrete (Michels et al. 2014, Michels et al. 2013) and metallic (Ghafoori and Motavalli 2015b, Ghafoori et al. 2012a, Ghafoori et al. 2015a, Ghafoori et al. 2015b) structures. However, easy pre-stressing method of the SMA elements offers clear advantages over complex pre-stressing techniques required for FRP composites (e.g., Ghafoori and Motavalli 2015a, Kianmofrad et al. 2017). It has been shown in previous studies that application of a compression stress to structural members using pre-stressed elements can enhance the flexural capacity (Ghafoori and Motavalli 2013), buckling strength (Ghafoori and Motavalli 2015b) and fatigue behaviour (Ghafoori et al. 2012b) of civil structures. This study aims to further characterize the alloy with a focus on the behavior of the activated SMA under cyclic loading conditions.

1.1 Fatigue behavior of Fe-Mn-Si SMAs

Although there are several studies on stress recovery behavior and phase transformation of Fe-Mn-Si SMAs, the cyclic and fatigue behavior of the alloy have not yet been well investigated. Sawaguchi et al. 2015 have studied the low cycle fatigue (LCF) behavior of the alloy but with a focus on its seismic damping and vibration mitigation capabilities. Koster et al. 2015 have recently conducted a series of fatigue tests on Fe-17Mn-5Si-10Cr-4Ni-1(V,C) SMA strips. The tests were performed on non-activated SMA strips under stress controlled loading conditions (not-prestressed low- and high-cycle fatigue). It was found that the cyclic hardening mostly dominates the LCF regime.

1.2 Fe-Mn-Si SMAs as pre-stressing elements in civil engineering structures

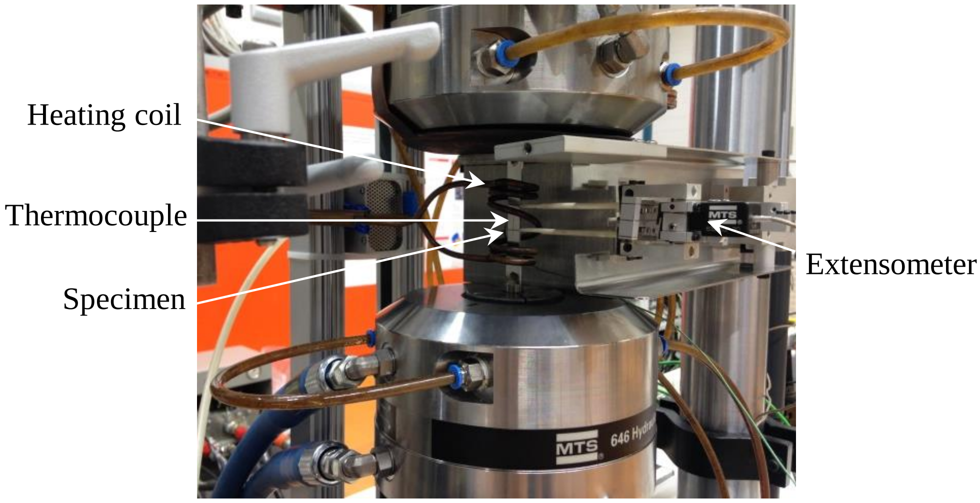
There exist many studies on application of pre-stressed carbon fibre-reinforced polymer (CFRP) for strengthening of concrete (e.g., Czaderski and Motavalli 2007, Gallego et al. 2016, Michels et al. 2014) and steel (e.g., Ghafoori et al. 2015a, Ghafoori et al. 2015b, Ghafoori et al. 2015c) girders. Strengthening of concrete and metallic girders using pre-stressed CFRP has been shown to be very effective method for increasing the load-carrying capacity and enhancing the serviceability of existing bridge girders. In particular, pre-stressed CFRP laminates can apply a compressive stress to existing cracks in critical metallic details and therefore can enhance their cyclic life by reducing crack propagation rate (e.g., Ghafoori et al. 2012a). Despite all advantages of using composite members for strengthening, pre-stressing procedure of them is often complicated and requires hydraulic jacks, which makes it difficult or sometimes impossible. The advantage of using the SMA material as a pre-stressing member is that it can be easily pre-stressed by heating up to a certain temperature (so-called activation temperature).

A retrofit system that includes SMA strips as pre-stressed elements for strengthening of concrete and metallic structures has been recently developed at Empa (e.g., Cladera et al. 2014, Czaderski et al. 2006, Janke et al. 2005). In this new retrofit concept, the SMA strip is attached to the existing concrete or steel girders. The alloy will be then heated up by electrical resistivity heating to 160 °C, and subsequently cooled down to room temperature. This heating and cooling (i.e., activation process) is accompanied with a phase transformation process (martensite to austenite) which results in development of a tensile stress in the SMA strip (and a compressive stress in the girder). Application of SMA strip as a pre-stressing element enhances the load carrying capacity as well as the serviceability of the retrofitted girder. The SMA-retrofitted concrete or steel girders will be often subjected to cyclic loadings (e.g., due to traffics when used for strengthening of bridge girders). Design and mechanical integrity assessment of such retrofitted girders must account for evolution of the SMA recovered stress (i.e. pre-stress) during such a cyclic loading condition. The effect of cyclic loading on the recovered stress in the Fe-17Mn-5Si-10Cr-4Ni-1(V,C) SMA member after activation has not yet been investigated. Since the SMA strips have negligible effect on the stiffness of the large civil structures, the in-service imposed cyclic loading condition to the SMA is close to a strain-controlled condition.

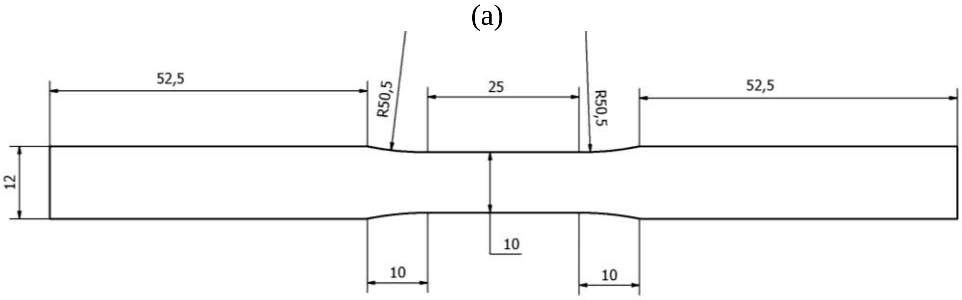
Therefore, the main aim of the present study is to examine the behavior of the activated SMA alloy under a strain-controlled cyclic loading condition.

2 TEST SPECIMENS AND EQUIPMENT

A MTS servo-hydraulic uniaxial testing machine, as shown in Fig. 1.a, was used. A clip-on high temperature axial extensometer with gauge length of 15mm was used to measure and control the strain during the tests. A PC-controlled inductive heating system was used for heating the specimen at the desired rate (i.e. 2 °/min). Dog bone specimens with a thickness of 1.5 mm were used for the experiments (Fig. 1.b). The ultimate tensile strength, elongation at break, and yielding stress (based on 0.01% of non-linear strain) of the alloy were obtained as 1015 MPa, 54.9% and 230 MPa, respectively.



(a)



(b)

Fig. 1. (a) Testing equipment, (b) dog bone specimens with 1.5mm thickness (dimensions in mm).

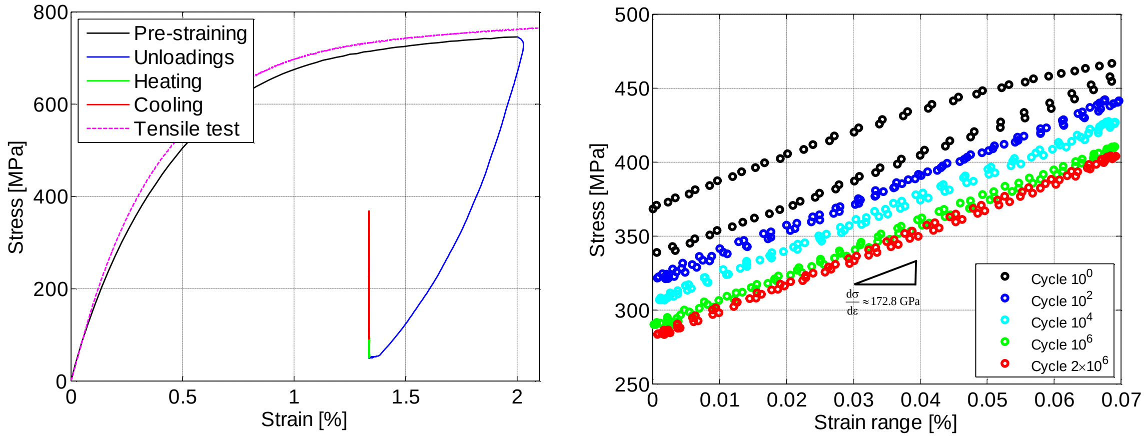
3 TEST PROCEDURE

In this study, a total of three samples were activated and then subjected to cyclic loading. Before activation, all samples were pre-strained to 2%. The unloading after pre-straining was to a small tensile stress of 50 MPa to avoid buckling of the sample during the initial phase of activation due to thermal expansion. The permanent strain for all samples after unloading was about ε_r =1.3%. The specimens were then heated up to 160 °C and cooled down to room temperature (2 °C/min) under a constant strain condition.

After activation, Specimens F1, F2 and F3 were subjected to 2×10^6 cycles with tensile strain ranges of 0.070%, 0.035% and 0.105%, respectively. The strain ranges of 0.035% and 0.070% are supposed to be the common (service) strain ranges that are subjected to pre-stressing elements in steel (Hosseini et al. 2017, Izadi et al. 2017) and concrete (Lee et al. 2013b) structures, respectively. The testing matrix was further complemented with an additional test with a strain range of 0.105 %. The frequency and temperature during fatigue loading was kept constant for all the tests to be 10 Hz and 25.5 °C, respectively. The stress ranges on Specimens F1, F2 and F3 in the first cycle were 127 MPa, 67 MPa and 188 MPa, respectively, indicting larger stress ranges for larger applied strain ranges.

Table 1. Summary of test results.

	Stress recovery			Cyclic loading				
Sample	σ_r (MPa)	$\Delta\varepsilon_0$ (%)	N_l	Freq. (Hz)	1^{th} cycle		N_l th cycle	
					σ^1_{min}	σ^1_{max}	$\sigma^{N_l}_{min}$	$\sigma^{N_l}_{max}$
F1	368	0.07	2×10^6	10	339	466	284	405
F2	369	0.035	2×10^6	10	358	425	324	384
F3	359	0.105	2×10^6	10	293	481	170	350



(a) (b)

Fig. 2. Specimen F1. (a) stress-strain curve during activation process, (b) SMA (activated) stress-strain behavior under fatigue loading with $\Delta\varepsilon_0$ =0.070%.

4 TEST RESULTS

Figure 2.a shows the observed stress-strain response during pre-straining, unloading and activation processes for Specimen F1. In this figure, the black, blue, green and red curves represent pre-straining, unloading, heating-up and cooling-down processes, respectively. Furthermore, this figure shows the results of the original material test, which is shown by a dashed line. The strain rate during pre-straining to 2% was 0.15 $\%s^{-1}$. A recovered stress of σ_r =368 MPa was achieved after cooling down to room temperature. Table 1 summarizes details of the samples and test results. The sample was then subjected to strain-controlled cyclic loading with $\Delta\varepsilon_0$ =0.07% and a frequency of 10 Hz.

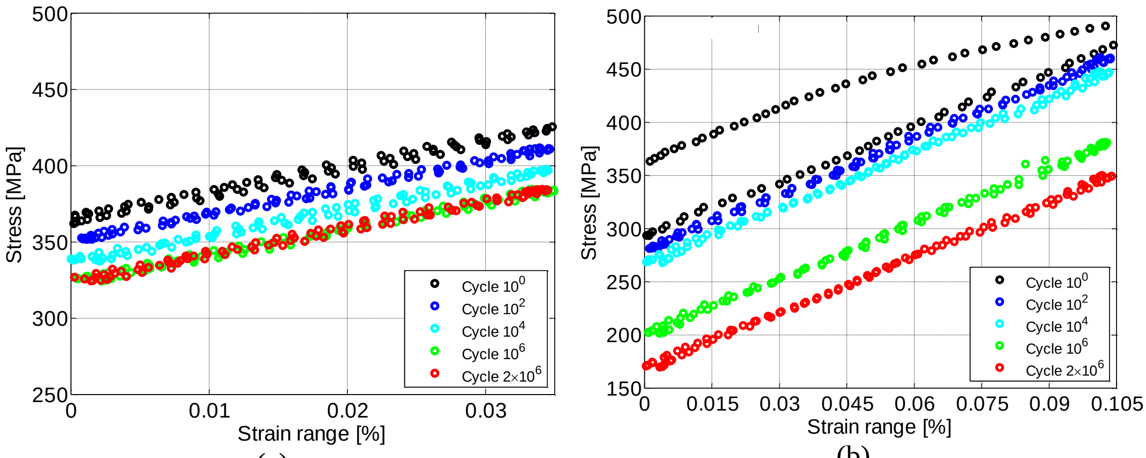


Fig. 3. SMA (activated) stress-strain behavior under fatigue loading for (a) Specimen F2 with $\Delta\varepsilon_0$ =0.035%, (b) Specimen F3 with $\Delta\varepsilon_0$ =0.105%.

The stress-strain behavior of the activated SMA under cyclic loading for different cycles of N=1, 10^2, 10^4, 10^6, 2×10^6 are shown in Fig. 2.b. The SMA shows an inelastic behavior in the first load cycle, and the recovered stress is decreased from 359 MPa to 339 MPa. For the cycles N=2 to 2×10^6, the SMA shows an almost linear elastic behavior. The SMA recovered stress decreased gradually during cycling and was 284 MPa after 2×10^6 cycles. Figure 2.b shows that the majority of stress loss (due to phase transformation-induced relaxation) occurs during the first 10^4 cycles. This observation is in line with the findings reported by . Fig. 2.b indicates that more than 50% of the stress loss occurs between 10^2 to 10^4 cycles.

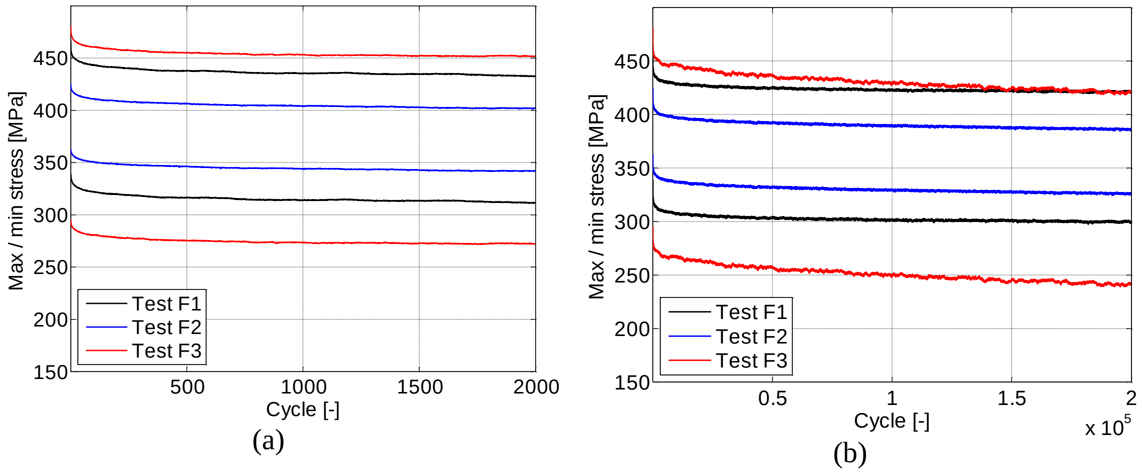


Fig. 4. Evolution of σ_{max} and σ_{min} versus cycles for (a) 2000 and (b) 200000 cycles.

The stress-strain behavior of the activated SMA under fatigue loading for Specimen F2 (i.e., with $\Delta\varepsilon_0$ =0.035%) and Specimen F3 (i.e., with $\Delta\varepsilon_0$ =0.105%) are presented in Figure 3. Figure 4 depicts the evolution of σ_{max} and σ_{min} during cyclic loading for the three specimens. Note that σ_{min} is basically the SMA recovered stress σ_r , for each cycle number. It can be seen that the majority of the loss in recovered stress occurred in the very early stage of the fatigue loading (see Figures 4.a and 4.b). More details about the results of this study can be found in Ghafoori et al. 2017.

5 SUMMARY

The performed SMA activation tests confirmed the earlier reports regarding the high magnitude of recovered stress for the Fe-Mn-Si-Cr-Ni-VC SMA. The alloy is therefore very suitable for civil engineering applications, in particular for retrofitting of existing constructions.

The SMA recovered stress after activation reduced during fatigue loading. The strain amplitudes applied in the fatigue tests are representative of the expected in-service conditions for the SMA when used as retrofitting elements. The findings can be interpreted as decrease of SMA-resulted prestress and therefore be employed for design and mechanical integrity assessment of SMA retrofitted civil engineering structures under cyclic loading condition

In a next step, conduction of stress-controlled fatigue tests for the activated SMA and generation of the S-N curves, to better characterize the Fe-Mn-Si-Cr-Ni-VC SMA, are of major interest.

6 REFERENCES

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**,** 281-293.

Czaderski, C., Hahnebach, B. & Motavalli, M. 2006. RC beam with variable stiffness and strength. *Construction and Building Materials,* 20**,** 824-833.

Czaderski, C. & Motavalli, M. 2007. 40-Year-old full-scale concrete bridge girder strengthened with prestressed CFRP plates anchored using gradient method. *Composites Part B: Engineering,* 38**,** 878-886.

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, U. E., 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.

Gallego, J. M., Czaderski, C. & Michels, J. 2016. Prestress force-release tests at elevated temperatures - Gradient anchorage stability for prestressed EB CFRP strips. *Composite Structures,* 137**,** 159-169.

Ghafoori, E., Hosseini, E., Leinenbach, C., Michels, J. & Motavalli, M. 2017. Fatigue behavior of a Fe-Mn-Si Shape Memory Alloy used for Prestressed Strengthening. *Materials & Design,* Submitted.

Ghafoori, E. & Motavalli, M. 2013. Flexural and interfacial behavior of metallic beams strengthened by prestressed bonded plates. *Composite Structures,* 101**,** 22-34.

Ghafoori, E. & Motavalli, M. 2015a. Innovative CFRP-Prestressing System for Strengthening Metallic Structures. *Journal of Composites for Construction,* 19**,** 04015006.

Ghafoori, E. & Motavalli, M. 2015b. 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**,** 194–206.

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

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

Ghafoori, E., Motavalli, M., Nussbaumer, A., Herwig, A., Prinz, G. S. & Fontana, M. 2015b. 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**,** 1-13.

Ghafoori, E., Motavalli, M., Zhao, X. L., Nussbaumer, A. & Fontana, M. 2015c. Fatigue design criteria for strengthening metallic beams with bonded CFRP plates. *Engineering Structures,* 101**,** 542-557.

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

Hosseini, A., Ghafoori, E., Motavalli, M., Nussbaumer, A. & Zhao, X.-L. 2017. Mode I Fatigue Crack Arrest in Tensile Steel Members Using Prestressed CFRP Plates. *Composite Structures,* DOI: doi.org/10.1016/j.compstruct.2017.06.056.

Izadi, M. R., Ghafoori, E., Hosseini, A., Motavalli, M., Maalek, S. & Shahverdi, M. 2017. Feasibility of iron-based shape memory alloy strips for prestressed strengthening of steel plates. *the fourth International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures (SMAR 2017).* 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/Materiaux et Constructions,* 38**,** 578-592.

Kianmofrad, F., Ghafoori, E., Elyasi, M. M., Motavalli, M. & Rahimian, M. 2017. Strengthening of metallic beams with different types of pre-stressed un-bonded retrofit systems. *Composite Structures,* 159**,** 81-95.

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**,** 29-39.

Lee, W. J., Partovi-Nia, R., Suter, T. & Leinenbach, C. 2016. Electrochemical characterization and corrosion behavior of an Fe-Mn-Si shape memory alloy in simulated concrete pore solutions. *Materials and Corrosion,* 67**,** 839-846.

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

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

Leinenbach, C., Kramer, H., Bernhard, C. & Eifler, D. 2012. Thermo-mechanical properties of an Fe-Mn-Si-Cr-Ni-VC shape memory alloy with low transformation temperature. *Advanced Engineering Materials,* 14**,** 62-67.

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**,** 106-115.

Michels, J., Martinelli, E., Czaderski, C. & Motavalli, M. 2014. Prestressed CFRP strips with gradient anchorage for structural concrete retrofitting: Experiments and numerical modeling. *Polymers,* 6**,** 114-131.

Michels, J., Sena-Cruz, J., Czaderski, C. & Motavalli, M. 2013. Structural strengthening with prestressed CFRP strips with gradient anchorage. *Journal of Composites for Construction,* 17**,** 651-661.

Sawaguchi, T., Nikulin, I., Ogawa, K., Sekido, K., Takamori, S., Maruyama, T., Chiba, Y., Kushibe, A., Inoue, Y. & Tsuzaki, K. 2015. Designing Fe–Mn–Si alloys with improved low-cycle fatigue lives. *Scripta Materialia,* 99**,** 49-52.