Thermally Activated Iron-Based Shape Memory Alloy for Strengthening Metallic Girders

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Abstract

The study presents a new retrofit solution for strengthening metallic I-girders. The retrofit system involves two iron-based shape memory alloy (Fe-SMA, ‘memory-steel’) strips (each with a width and thickness of 50 and 1.5 mm, respectively) that are mechanically anchored (using friction clamps) to the girders. The shape memory effect (SME) of the Fe-SMA material has been used to activate/prestress the strips by heating to a predefined temperature. The main advantage of the proposed SMA-retrofit system is that, unlike conventional systems, it can prestress itself without a need for heavy hydraulic jacks, which then results in a significant reduction of the required time, labor works and cost of prestressing process. In order to evaluate the efficiency of the proposed retrofit system, in this study, a series of static and fatigue four-point bending tests were performed on a 6.4-m SMA-retrofitted beam. Five static

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tests were performed on a steel beam with different SMA prestressing levels and included a reference un-strengthened test. The test results indicated that the achieved prestressing levels (i.e., recovery stresses) in the Fe-SMAs for activation temperatures of 100, 160, and 260 °C were approximately 160, 330, and 430 MPa, respectively. The induced compressive stresses in the bottom flange were in the range of 10 to 30 MPa. It was demonstrated that the Fe-SMAs could be re-activated for multiple times even up to higher temperatures (than the initial activation temperature), which would then result in higher prestressing levels. These features make the proposed SMA-based system a versatile and adaptable retrofit solution. Furthermore, the SMA-strengthened beam with the maximum prestressing level (activation temperature of 260 °C) was subjected to 2 million load cycles with a load ratio of $R=0.2$ and a loading frequency of 4.35 Hz. The results of the high-cycle fatigue (HCF) tests showed no slippage in the anchorage system and a stable prestressing in the Fe-SMA members during the tests, which demonstrates the reliability of the proposed system under HCF loading regime.

Keywords: steel structures; prestressed strengthening; iron-based shape memory alloy (Fe-SMA); activation temperature; high-cycle fatigue (HCF)

Nomenclature

P	applied external load	σ_r^{bs}	recovery stress before the static test
P_{min}	applied minimum external load	σ_r^{as}	recovery stress after the static test
P_{max}	applied maximum external load	$\Delta\sigma_r$	recovery stress reduction
R	applied load ratio	σ_b	stress in bottom flange of the steel beam
$\Delta\sigma$	bending stress range	σ_t	stress in top flange of the steel beam
σ_{max}	maximum bending stress	Δ_{mid}	mid-span deflection
σ_{min}	minimum bending stress	T_a	activation temperature
f_r	loading frequency	ϵ_{SMA}	strain in the Fe-SMA strip
N	number of fatigue cycles	σ_{SMA}	stress in the Fe-SMA strip
ϵ_b	strain in bottom flange of the steel beam	$\Delta\epsilon_{SMA}$	strain change in the Fe-SMA strip
σ_{pre}	prestressing level	$\Delta\sigma_{SMA}$	stress change in the Fe-SMA strip
E_{st}	steel elastic modulus	σ_{min}^{SMA}	minimum stress of the Fe-SMA in fatigue loading
E_{SMA}	Fe-SMA elastic modulus	σ_{max}^{SMA}	maximum stress of the Fe-SMA in fatigue loading
A_{st}	the steel beam cross-sectional area	$\sigma_{min}^{st,b}$	minimum stress of bottom flange in fatigue loading

A_{SMA}	the Fe-SMA strip cross-sectional area	$\sigma_{max}^{st,b}$	maximum stress of bottom flange in fatigue loading
S_{st}	elastic section modulus of the steel beam	Δ_{min}^{mid}	minimum mid-span deflection in fatigue loading
e	eccentricity	Δ_{max}^{mid}	maximum mid-span deflection in fatigue loading
σ_r	recovery stress		

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2 **1. Introduction**

3 Retrofitting of steel structures with prestressed carbon-fiber reinforced polymers (CFRPs) is
4 already investigated in both experimental and practical-scale applications. Lateral-torsional
5 buckling (LTB), fatigue, and flexural strengthening of different metallic members including
6 metallic beams, plates, and columns were demonstrated in the majority of existing studies [1-
7 5]. Different bonded and un-bonded techniques were developed to anchor prestressed CFRP
8 composites to the parent steel structures [4, 6-8]. Additionally, novel SMA-CFRP hybrid
9 patching systems have been recently developed which eliminate the necessity of having me-
10 chanical fixtures [9, 10]. With respect to all the retrofit techniques, prestressed un-bonded ret-
11 rofit (PUR) systems were recently shown as more effective [11, 12]. The girders of some
12 highway and railway steel bridges were recently retrofitted with the proposed un-bonded pre-
13 stressed techniques [13, 14]. Furthermore, different shapes and configurations of the pre-
14 stressed un-bonded systems were designed and tested to cope with geometrical complexities
15 that typically exist in steel structures [15, 16]. In order to prestress the CFRP laminates, heavy
16 hydraulic jacks with sufficient operating space are necessary. The overall procedure of pre-
17 stressing is generally difficult and even impossible in some cases due to difficulties associated
18 with the installation of prestressing tools such as hydraulic actuators. In order to overcome the
19 problem, a new advanced material termed as a shape memory alloy (SMA) is introduced to
20 reduce effort and time involved in prestressing.

21 It is worth noting that current market prices of available Fe-SMA are approximately two to
22 three times higher than the ones of slag applied CFRP strips. In addition to material prices, it
23 is mandatory to include labor costs in the overall price estimation. In this respect, the applica-

tion of a prestressed Fe-SMA strip requires less time than for conventional composite laminates or fabrics, as for instance, substantial surface preparation and epoxy adhesive mixing is not necessary anymore. Long-term application of prestressed Fe-SMA strips will be also comparable to current installations of slag applied CFRP strips. Prestressed CFRP strips require even more work upfront, resulting in very high end costs. Furthermore, fire protection is a crucial point. Composite material might require extensive protection against fire due to the low glass transition temperature of the resin; whereas, Fe-SMA can be treated as conventional steel and hence treated the same way in case a fire protection is to be installed [17].

1.1. SMAs in Civil Engineering

Specifically, SMAs are advantageous in terms of their application in civil engineering industry due to favorable features including shape memory effect (SME) and superelasticity. The SME property corresponds to the capability of the mechanically deformed SMAs to recover the primary un-deformed shape (shape or strain recovery) via heating [18-20]. Conversely, the latter is the ability of the material to undertake large deformations and recover the primary shape via unloading (without heating). Given the superelastic feature of the SMAs, different types of SMA-based dampers are developed to retrofit structures for earthquake resistance. The seismic applications of SMAs in civil engineering constructions are addressed in [21-23]. However, the SME property is mostly used in post-tensioning of the SMA reinforcement [18, 24, 25]. The material is pre-deformed at ambient temperature and attached to a parent steel structure. The reinforcement is then heated to a maximum activation temperature with a subsequent self-cooling process in air. During the activation process (i.e., heating followed by cooling), a prestress is developed via the SME. Given that the SMA is fixed to the parent structure, shape recovery is restricted, and thus a recovery stress (prestress) is generated in the SMA. Specifically, nickel-titanium (i.e., Nitinol) as well as iron-based SMAs (Fe-SMAs) are two well-known types of SMAs that are currently used in various engineering domains. The

former is employed in applications including small medical instruments, mechanical and aerospace structures, and recently used in hybrid patching techniques in combination with CFRP [25-28]. Nevertheless, the latter is proven as more promising in prestressing applications.

1.2. Retrofitting of civil structures with thermally activated Fe-SMA

The use of Fe-SMAs in large-scale civil engineering applications is increasing due to several advantages such as low components costs compared to Nickel-Titanium-based alloys, process of manufacturing, stability of recovery stresses, and acceptable elastic modulus [18, 29, 30]. Studies on the recovery stress behavior [31], durability of the recovery stress subjected to different temperature histories [19, 32, 33], fatigue [34], relaxation, creep behavior (an approximate prestressing loss of 14% over 50 years) [35, 36], and corrosion [37] showed the appropriateness of Fe-SMAs to be used as prestressing elements in civil structures. The first application of the Fe-SMAs commenced at Swiss Federal Laboratories for Materials Science and Technology (Empa), Switzerland. Researchers at Empa developed a composition of the Fe-SMA, Fe-17Mn-5Si-10Cr-4Ni-1(V,C), with the goal of applying it for structural prestressing purposes [38]. Michels et al. [36] performed a series of small- and large-scale static and cyclic tests on concrete bars and beams that were strengthened with thermally activated Fe-SMA bars and strips. It was shown that the ultimate load capacity of concrete slabs was enhanced by prestressed Fe-SMAs. The Fe-SMAs (in the form of bars and strips) can also be applied to the metallic structures as prestressing elements to enhance their behavior in terms of static and fatigue strength.

Along the prestressed retrofitting of concrete members with Fe-SMAs, strengthening of the steel structures was demonstrated by Izadi et al. [39, 40]. The Fe-SMA strips with different configurations were employed to retrofit steel tensile members (e.g., steel plates). Subsequently, the retrofitted elements were tested under a series of static and fatigue loadings. In a manner similar to prestressed un-bonded CFRP reinforcements, mechanical clamping systems

1 were utilized to anchor the Fe-SMA reinforcements to the steel structures. The un-bonded
2 techniques facilitated the activation procedure of the Fe-SMAs, conducted with an electrical
3 resistive heating (ERH) method.

4 The current study deals with the application of Fe-SMAs on steel structures as already de-
5 scribed in [39, 40]. To the best of the authors' knowledge, this is the first investigation to ad-
6 dress the benefit of Fe-SMA strips in strengthening a large-scale steel I-beam. An un-bonded
7 strengthening system with mechanical end-anchorage was employed to fix the two Fe-SMA
8 strips to the bottom of the steel beam. Activation tests with different maximum temperatures
9 were performed to produce different prestressing levels. A series of static and fatigue four-
10 point bending tests were performed on a SMA-strengthened steel beam. The effects of the ac-
11 tivations and the corresponding static and fatigue tests on behavior of the Fe-SMA reinforce-
12 ments as well as the steel beam were then examined. Finally, the application of prestressed
13 un-bonded Fe-SMA strips was proved successfully relative to static and fatigue loadings.

15 **2. Development of anchorage systems for Fe-SMA strips**

16 **2.1. Anchorage system for steel plates**

17 Indeed, a proper clamping system is needed to anchor the Fe-SMA reinforcements to the par-
18 ent steel member for the strengthening solution. As previously mentioned, bonded and un-
19 bonded solutions have already been designed for the case of prestressed CFRP composites.
20 However, among the existing systems, the un-bonded ones are more durable against environ-
21 mental conditions (like elevated temperatures or humidity) or fatigue problems compared
22 with the bonded systems [11]. Izadi et al. [39] suggested different un-bonded systems to
23 strengthen steel plates with Fe-SMA strips. Izadi et al. [39, 40] evaluated the Fe-SMA
24 strengthening of steel members with the proposed un-bonded systems during each step of the
25 strengthening procedure including assembly, activation, and external loadings. The anchorage

1 systems included different components. Friction foils were utilized to enhance the friction. To
2 provide the electrical insulation, glass-fiber reinforced polymer (GFRP) laminates were in-
3 corporated. Pre-loaded bolts and steel clamping plates were, moreover, utilized to generated
4 normal pressure over the Fe-SMA strip. The results of laboratory tests indicated the success-
5 ful joint of SMA-to-steel using such un-bonded mechanical anchorage systems.

6 **2.2. Anchorage system for steel beams**

7 In the current study, a flat prestressed un-bonded retrofit system (FPUR) that is already de-
8 veloped at Empa to anchor prestressed CFRP strips to the flange of steel I-beams [13] is
9 adapted for an application with Fe-SMA strips. Figure 1 schematically depicts the un-bonded
10 SMA-strengthened steel beam with the FPUR system. The prestressing procedure is different
11 for Fe-SMA strips (i.e., hydraulic actuators are not required), and thus the installation of the
12 FPUR system for SMA strengthening of a steel I-beam is slightly different when compared to
13 the original application [13]. Evidently, in case when Fe-SMA strips are used, the developed
14 prestressing system (see [13] for further details) is not required. However, similar to un-
15 bonded systems for steel plates, it is necessary to incorporate GFRP laminates and friction
16 foils into the system (see Figure 1). As shown in Figure 1, two prestrained Fe-SMA strips are
17 anchored from both ends inside the fixed clamps. Initially, the end clamps were fixed to the
18 beam bottom flange. Subsequently, the prestrained strips were sandwiched in the clamps us-
19 ing sets of prestressed M10 and M16 bolts. Further details on the design of the FPUR system
20 and how the different parts are assembled together can be found in [13].

22 **3. Experimental program**

23 The experimental procedure was planned to demonstrate the Fe-SMA strips application for
24 the flexural retrofit of steel I-beams relative to static and fatigue loadings. Figure 1 schemati-
25 cally shows a steel beam which is strengthened with Fe-SMA strips. Table 1 displays a sum-

mary of the test layout. All the tests were carried out on a steel profile of INP300 with a length of 6.4 m. Static tests were performed in three stages on the SMA-strengthened steel beam with different activation temperatures corresponding to 100, 160, and 260 °C (denoted as B3-1_A_100, B3-2_A_160, B3-3_A_260; see Table 1). Different activation temperatures were employed to achieve different levels of prestressing in the strips. Additionally, an un-strengthened reference steel beam was statically tested. In order to assess the prestressing effect in the Fe-SMA strips and steel beam, a specimen strengthened with non-activated strips were also included in the test layout. In the second stage, a high cycle fatigue (HCF) test was performed on the beam wherein the Fe-SMA strips were activated with the maximum activation temperature of 260 °C (see Table 1; denoted as B4_A_260). In the following subsections, the material properties of the Fe-SMA strips, steel I-beam profile, GFRP laminates, friction foils, measurement setup, and experimental procedure are given.

3.1. Utilized material properties

For all the static and fatigue tests, an INP300 steel beam of type S275JR with a nominal yield strength of 275 MPa was used. INP300 profile has web and flange thickness of 10.8 and 16.2 mm, respectively, while its flange width is 125 mm, and depth of the section is 300 mm. Mechanical properties of the steel beam were characterized by performing tensile tests on two coupon samples of 350 mm in length in accordance with ISO 6892-1:2009 [41]. The yield strength, ultimate strength, and elastic modulus of the steel were found to be 328 MPa, 465 MPa, and 203.3 GPa, respectively. The mechanical properties of the utilized steel are given in Table 2.

The roll of Fe-SMA strips (with composition of Fe–17Mn–5Si–10Cr–4Ni–1(V,C)) was provided by re-fer AG Company (Switzerland) with a 1.5 mm in thickness and 100 mm in width. The Fe-SMA strip with a length of approximately 5000 mm was subsequently cut along its length into two 50-mm wide strips. Tensile behavior of Fe-SMA until failure and activation

experiments along with cyclic behavior of the alloy are reported in [34, 39, 42]. Table 3 presents the Fe-SMA mechanical properties including recovery stress at different activation temperatures. The approximate ultimate tensile strength of 980 MPa, ultimate elongation of 45.2%, and initial elastic modulus of 160 GPa were determined [42]. Figure 2a shows the recovery stress versus temperature curves for three different maximum heating temperatures corresponding to 120, 160, and 195 °C [42]. Additionally, in Figure 2b, the stress–strain curves of the Fe-SMA strips during prestraining and after activation (to a strain of 1% after activation) for the three mentioned maximum temperatures are shown [42].

In order to increase the friction between the steel substrate and the Fe-SMA strip, grade-10 diamond friction shims [2] were used. Furthermore, electrical insulation of the Fe-SMA from the steel components during the activation process via resistive heating was done by using bi-directional GFRP laminates, provided by Von Roll Deutschland GmbH. According to the manufacturer’s catalogue, the utilized GFRP laminates had a shear strength and modulus of elasticity of 30 MPa and 24 GPa, respectively [1]. The GFRP laminates type was G-11 glass fabric bonded with epoxy resin (with a temperature index of 180 °C) [1].

3.2. Test setup and instrumentation

The beam test setup is shown in Figure 3. Prior to each static and fatigue test, the SMA-strengthened steel beam was (re)activated except for the static tests for B1 and B2 (which were prepared without activated Fe-SMA strips). All the static and fatigue tests were conducted by using two hydraulic actuators with maximum static capacity of 250 kN that were actuated by an Amsler pulsator machine with a constant frequency of 4.35 Hz. The center-to-center distance between the actuators corresponded to 1.8 m while, the distance of each actuator to the center line of support corresponded to 1.75 m.

Two 1-LY61-6/120 strain gauges (labeled as SG1 and SG2, see Figure 3), HBM AG Company, Germany, were installed on the mid-span of the steel I-beam. Strain gauge SG1 was

mounted at the mid-width of the bottom flange, while strain gauge SG2 was attached on the top flange. Two 1-LY66-6/120 foil strain gauges, provided by HBM AG (Germany), were also attached at the mid-width of the Fe-SMA strips at the mid-span (labeled as SG3 and SG4, as shown in Figure 3). The measurement points and the corresponding numbering and locations are schematically shown in Figure 3. Additionally, in order to measure mid-span deflection of the beam, a laser displacement sensor was installed on the mid-length of the top flange of the beam (see Figure 3).

During the activation tests, the Fe-SMA strips were equipped with three Type K thermocouples on each strip labeled as SMA1-T1 to SMA1-T3 and SMA2-T1 to SMA2-T3. Two Type K thermocouples of Steel-T1 and Steel-T2 were also attached near one of the anchorages and in the middle of the steel beam (see Figure 3). The temperature distribution along the strips and the steel beam was monitored by the mounted thermocouples.

3.3. Test procedure

Efficiency of Fe-SMA strengthening for a real-scale steel I-beam was investigated using sets of static and HCF (with a load ratio of $R = 0.2$) tests. Static and fatigue tests were conducted under a four-point bending test setup with a load-controlled condition (see Figure 3 and 4). Static loading was applied up to a maximum force of $P=75$ kN per cylinder, and this corresponded to a bending stress level equal to 60% of the yield strength in the top and bottom flanges of the unstrengthened beam. The fatigue test was performed with minimum and maximum loads of $P_{\min}=8.0$ kN and $P_{\max}=40.2$ kN, respectively, per cylinder. The fatigue load corresponded to minimum and maximum bending stresses of $\sigma_{\min}=21.6$ MPa ($=0.2 \times 0.33F_y$) and $\sigma_{\max}=108.2$ MPa ($=0.33F_y$), respectively, in the flanges of the reference beam. It is worth mentioning that this load level simulates the service loading of a real road-way metallic bridge [13]. A photo of the four-point bending test setup is presented in Figure 4.

Prior to each static and fatigue test, the (re)activations were performed to prestress the Fe-SMA strip as shown in Figure 4. Initially, an INP300 beam (B1, namely a reference steel beam without strengthening) was subjected to static loading. Afterwards, the steel beam was reinforced with prestrained Fe-SMA strips (i.e., B2, namely a steel beam strengthened with non-activated Fe-SMA strips) and subjected to another static loading. Subsequently, other beam tests of B3-1 to B3-3 (static tests on a steel beam strengthened with activated Fe-SMA strips) and B4 (fatigue test on a steel beam strengthened with activated Fe-SMA strips) were performed in the testing setup. Details on the procedures of the activation, static, and fatigue tests are presented in the following subsections.

3.3.1. Activation process of the Fe-SMA strips

The non-activated Fe-SMA strips were activated after the static test of B2. Each activation (re-activation) was then followed by static and/or fatigue tests. Figure 4 shows the activation test setup. The activation of the strips was performed with the electrical power supply that provided required electrical current to heat up the Fe-SMA strips in each test. A custom-designed electrical power unit provided by re-fer AG, Switzerland, was used for the ERH. Further details of the activation procedure using the ERH technique are provided in [39].

The two Fe-SMA strips were connected by a copper plate, and thus they were collectively heated (i.e., in series as shown in Figure 4). The Fe-SMA strips were heated to different activation temperatures approximately corresponding to 100, 160, and 260 °C. Different electrical voltages and currents corresponding to 27.8V/200A, 42.07V/300A, and 56.1V/400A were applied to reach activation temperatures of 100, 160, and 260 °C, respectively. When the mounted thermocouples on the Fe-SMA strips (SMA1-T1 to SMA1-T3 & SMA2-T1 to SMA2-T3) showed that the average temperature reached the target value, the power supply was manually turned off. All the activation processes were assumed as completed once the temperatures of the Fe-SMA strips returned to the room temperature. Additionally, the

mounted thermocouples on the steel beam (Steel-T1 and Steel-T2) were used to monitor any possible change of the steel beam temperature. The strains in the bottom and top side of the beam (measured by strain gauges SG1 and SG2, respectively, see Figure 3) were then used to determine the Fe-SMA recovery stress and corresponding bending stresses in the bottom and top flanges of the steel beam in the mid-span. Additionally, an infrared camera (testo 885-Wärmebildkamera, provided by Testo SE & Co. KGaA in Switzerland) was placed under the beam during the activation process to measure the surface temperature of the bottom side of the steel beam during heating and cooling to room temperature.

3.3.2. Static and fatigue four-point bending tests

First, the reference beam (B1) was statically tested. Afterward, the retrofit system was mounted on the beam and test B2 was performed.

After the second static test (test B2), the Fe-SMA strips were re-activated and three static tests were carried out on the steel beam strengthened this time with activated Fe-SMA strips corresponding to tests B3-1, B3-2, and B3-3 as presented in Table 1. After the first activation to a temperature of 100 °C, the beam was subjected to a monotonic static loading of 75 kN per cylinder (i.e., test B3-1). Later, for test B3-2, the strips were re-activated (i.e., a second activation) to a temperature of 160 °C and again the static loading was conducted to the same maximum load. Lastly, a final re-activation (this time to a temperature of 260 °C) was performed (corresponding to the third activation or a second re-activation). Subsequently, the beam was again subjected to static loading up to 75 kN per cylinder.

In addition, in order to evaluate the effectiveness of the strengthening system on the steel beam under HCF loading, beam test B4 was performed (see Table 6). For the fatigue test, after the end of the static test B3-3, the strips were re-activated again to a temperature of 260 °C. The test was conducted under load-controlled condition with a constant load range of ap-

proximately $\Delta P = 32$ kN and a load ratio of $R = 0.2$. The cyclic test was performed up to $N = 2 \times 10^6$ cycles with a frequency of $f_r = 4.35$ Hz.

4. Experimental results and discussions

4.1. Results of activation tests

As described in Section 3.3.1, the activation of the Fe-SMA strips was conducted with resistive heating. Figure 5 shows the temperatures for test B3-1 recorded over time via the thermocouples attached on the Fe-SMA strips (thermocouples of SMA1-T1 to SMA1-T3 & SMA2-T1 to SMA2-T3 in Figure 3) and on the steel beam (thermocouples of Steel-T1 and Steel-T2 in Figure 3) throughout the process of activation. In the same figure, the mid-span displacement versus the time is also shown. In order to reach an activation temperature of 100°C , a heating step of 60 s in duration was applied. As shown in Figure 5, the beam deformed downwards at the beginning. This was due to thermal expansion effect of Fe-SMA, which was expected during the early stage of the heating step for the Fe-SMA [31]. However, after a very short time, the shape memory effect became dominant and compensated the thermal expansion. The related prestressing led to a displacement in the other direction, and the beam then deformed upwards.

The measured compressive strains in the bottom flange of the steel beam (SG1 in Figure 3, ε_b) after the end of heating and cooling process (i.e., activation) was used to estimate the prestressing level in the Fe-SMA reinforcements. In test B3-1 with an activation temperature of 100°C , a recovery stress of $\sigma_r = 161$ MPa and bending strain and stress of (in the beam bottom flange) $\varepsilon_b = -53$ $\mu\text{m/m}$ and $\sigma_b = -10.7$ MPa, respectively, were achieved. Additionally, as shown in Figure 5, an upward mid-span displacement of $\Delta_{\text{mid}} = -0.7$ mm was reached after the activation. It should be noted that reduction of recovery stress owing to steel beam deformation during activation process was considered in the final determined recovery stress. Ta-

ble 4 summarizes the activation tests results including the final recovery stress, σ_r , and the beam bottom flange stress, σ_b , after the end of activation for all tests. The strain, ε_b , which indicates the compression level of the bottom flange after the activation is also included in the table.

Figures 6 and 7 represent the same curves as explained above for tests B3-2 and B3-3. Generally, the behavior was similar to that in test B3-1. The mid-span uplifts after the end of activation were approximately $\Delta_{mid} = -1.7$ and -2.2 mm for the aforementioned tests. For tests B3-2 and B3-3, the approximate duration of heating steps were 30 and 60 s to reach an activation temperature of 160 and 260 °C, respectively, and recovery stresses of $\sigma_r = 328$ and 431 MPa, respectively, were achieved. Further strain–stress analysis on the development of recovery stress can be found in [39].

In order to control the electrical insulation, the temperatures on the steel beam (by the thermocouples of Steel-T1 and Steel-T2) were also monitored (as shown in Figure 5-7). The insulation method (i.e., use of the GFRP laminates) was proved to be successful as the temperature on the steel beam was observed approximately constant during the activation process.

4.2. Results of static four-point bending tests

After each activation, the INP300 beam was subjected to a quasi-static four-point bending load until 60% of the yield bending stress of the steel beam with no strengthening (75 kN per cylinder). The applied external load versus strain in the bottom flange of the steel beam as well as the load–deflection of the beam for tests B1, B2, and B3-1 to B3-3 are shown in Figure 8. The anchorage system was originally designed to carry the full capacity of two CFRP plates (approximately 400-kN load) [13], and thus no failure occurred in the clamping system during the static tests. The possible failure mechanisms included the rupture or slippage of the Fe-SMA strips inside the system [13, 39].

From Figure 8a that shows the load–deflection of the beam, the stiffness of the SMA-strengthened beam exceeds that for the reference steel beam (i.e., B1), which displays the effect of added reinforcement elements (here the Fe-SMA strips stiffness, the reduction of 1 mm in mid-deflection of the beam which is equivalent to approximately 5% increase in the slope of the load-deflection curve). As shown in Figure 8a, the curves for the beam strengthened with activated Fe-SMA strips are nearly identical with the non-activated ones (i.e., equal stiffness), thereby indicating that the stiffness of the strengthened beam is not affected by the activation/prestressing procedure. Figure 8b shows the load–strain diagram of the beam bottom flange. With increases in the prestressing level (by activating to higher temperatures), the compressive strain/stress in the steel beam bottom flange increases.

Furthermore, Figure 8b shows that strengthening of the beam with the non-activated strip does not significantly reduce the bending strains. The reduction of stress in non-activated strengthened beam is 6% compared with the reference unstrengthened beam. However, activation of the strips significantly reduces the strain/stress level in the beam bottom flange by applying the prestressing force. As shown in Table 5, for tests B3-1, B3-2, and B3-3 with activation temperatures corresponding to 100, 160, and 260 °C, stress reductions of 11, 16, and 19.5%, respectively, were observed in the bottom flange of the steel beam. Furthermore, as depicted in Figure 8b, the bottom flange of the steel beam in test B3-3 was in compression up to a load of approximately 11 kN per cylinder. The observation implies that in case of the presence of a (fatigue) crack in the bottom flange of the steel beam, the crack is under compressive stress, and thus is not active for the load less than 11 kN. The values of the stresses in the steel beam bottom flange (σ_b) together with the mid-span deflection of the beam (Δ_{mid}) at a maximum static load of $P=75$ kN are given in Table 5.

Figure 9a depicts the average strain response of the strips. All the load–strain responses of the non-activated and activated tests are parallel to each other irrespective of the prestressing level. This explains that the contribution of the Fe-SMA strips is not affected by the prestressing

force. Therefore, the use of Fe-SMA strips can be more beneficial by providing higher prestressing levels (higher activation temperature), since higher prestressing levels lead to a pronounced reduction of the bending stresses in the steel beam (see Figure 8).

Figure 9b demonstrates the stress-strain response of the activated Fe-SMA in B3-1 to B3-3 tests. The figure shows the response of Fe-SMA during different stages of strengthening including the procedure of the prestraining, the process of activation, and the static loading. A magnified view is, moreover, illustrated in Figure 9c for the activation process as well as for the static loading up to 75 kN per cylinder. As shown in Figure 9c, the higher activation temperature, the larger is the strain reduction of the Fe-SMA owing to the deflection of the beam.

It should be mentioned that the compressive strain levels in the bottom flange of the beam and in the Fe-SMA strips are assumed to be equal, and thus $\epsilon_{\text{SMA}} = \epsilon_{\text{b}}$. Therefore, from Table 4, for tests B3-1 to B3-3, with activation temperatures of 100, 160, and 260 °C, approximate strain reductions of $\epsilon_{\text{SMA}} = -53, -108, \text{ and } -142 \mu\text{m/m}$, respectively, were assumed in the Fe-SMA. For all the activated tests, an elastic modulus of 160 GPa is observed, indicating the similar early elastic response compared to the as-received material [42] (see Figure 2). Furthermore, as shown in the curves, the Fe-SMA behaves linearly within the serviceable scope of strains experienced by Fe-SMA strips. The linear behavior can be then assumed for simulation of Fe-SMA material in finite element (FE) modeling under service loads [39].

Table 5 also presents the results of the static tests after unloading. The Fe-SMA exhibited recovery stress reduction in the first loading cycle and for activation temperatures of 100, 160, and 260 °C (corresponding to tests B3-1 to B3-3), the corresponding recovery stresses of $\sigma_{\text{r}}^{\text{bs}} = 161, 328, \text{ and } 431 \text{ MPa}$ were reduced to $\sigma_{\text{r}}^{\text{as}} = 116, 250, \text{ and } 346 \text{ MPa}$, respectively, after unloading. This reduction is deemed to be the result of a phase transformation from γ -austenite to ϵ -martensite (i.e., a forward transformation in the Fe-SMA due to mechanical loading) [40]. Further discussions regarding this phenomenon can be found in [19, 34, 35].

4.3. Results of fatigue four-point bending tests

Table 6 summarizes the fatigue test results for test B4. The development of minimum and maximum stresses in the Fe-SMA strip and the bottom flange (i.e., $\sigma_{\min}^{\text{SMA}}$, $\sigma_{\max}^{\text{SMA}}$, $\sigma_{\min}^{\text{st,b}}$, and $\sigma_{\max}^{\text{st,b}}$) as a function of number of fatigue cycles are also shown in Figure 10. The stresses are shown for minimum and maximum loads of $P_{\min}=8.0$ kN and $P_{\max}=40.2$ kN, respectively, per cylinder.

Due to compressive stresses applied by activated Fe-SMA strips (as shown in Figure 10), the minimum and maximum tensile stresses in the beam bottom flange are reduced to $\sigma_{\min}^{\text{st,b}} = -12$ MPa and $\sigma_{\max}^{\text{st,b}} = 69$ MPa during fatigue loading (see also Table 6). From Figure 10, stresses in the activated Fe-SMA did not significantly change during $N = 2 \times 10^6$ cycles, thereby indicating the absence of slippage in the proposed un-bonded system. The latter implies that the previously developed mechanical anchorage system [13] can be also used for fatigue strengthening of steel I-beams using Fe-SMA strips. It is worth mentioning here that, for real applications of the Fe-SMA strips for fatigue strengthening of steel structures, the stability of the prestressing in Fe-SMA strips needs to be further investigated for various applied strain/stress ranges, as already performed for the small-scale applications of prestressed Fe-SMA strips [39, 40].

5. Summary and concluding remarks

The study presented the development of a novel un-bonded SMA retrofit system for strengthening steel I-beams. To this end, a (friction-based) mechanical anchorage system was used to reinforce an INP300 steel profile by anchoring two activated (prestressed) Fe-SMA strips with dimensions of 50×1.5 mm² (width $\times$ thickness). Unlike conventional prestressing systems, the proposed SMA-retrofit system does not need any hydraulic jack for prestressing, which results in an easy and cost-effective prestressing approach. In order to demonstrate the

efficiency and reliability of the proposed system, a set of static and fatigue four-point bending tests were performed to study the static and fatigue performance of both Fe-SMAs and a real-scale SMA-strengthened steel I-beam (here INP300 steel profile). Following remarks were drawn from the study:

1. A new configuration of mechanical clamping system was designed for anchoring the prestressed (thermally activated) Fe-SMA reinforcements to a steel I-beam. In order to facilitate the electrical activation of the strips, GFRP laminates for the purpose of electrical insulation was incorporated in the system. The retrofit system offered a fast installation as no surface preparation and curing treatment, which are necessary for bonded anchorage systems, are required during assemblage.

2. The Fe-SMA strips were prestressed with different activation temperatures (using the electrical resistive heating technique), which resulted in different prestressing levels (i.e., recovery stresses). The prestressing levels in the Fe-SMAs for the activation temperatures of 100, 160, and 260 °C were approximately 160, 330, and 430 MPa, respectively. The value of prestressing level in the Fe-SMA members could be adjusted by the activation temperature. Furthermore, it was shown that the Fe-SMA members could be re-activated for multiple times to higher temperatures (than the initial activation temperatures in order to achieve higher prestressing level). These interesting features add to the adaptability, versatility and novelty of the proposed retrofit system.

3. The activation test results exhibited maximum upward deflections of $\Delta_{mid} = -0.7, -1.7,$ and -2.2 mm for INP300 steel beam for the activation temperatures of 100, 160, and 260 °C, respectively. The maximum bending stress for different activation temperatures in the bottom flange of the beam was reduced by approximately 10–20% for a maximum static load equivalent to 60% of the yield bending stress of the steel beam with no strengthening (this corresponded to a maximum load of 75 kN per cylinder in a four-point bending test setup).

4. HCF tests with a load range of $\Delta P = 32$ kN and a load ratio of $R = 0.2$ was performed on the steel beam strengthened by the Fe-SMA strips with the maximum prestressing level of 430 MPa (with an activation temperature of 260 °C). After applying $N = 2 \times 10^6$ cycles, neither slippage of the mechanical clamping system nor any Fe-SMA prestress loss were observed. The results of the static and cyclic tests in the study verified the performance and reliability of the proposed SMA-retrofit system for strengthening metallic girders.

Appendix A. Stresses in the top flange of the steel beam

Figure A1 shows the stresses in the top and bottom flanges of the beam at the mid-span during the static and fatigue tests for all the strengthened beams as well as the unstrengthened reference steel beam. As shown in Figure A1a, for $P = 0$ kN, as the prestressing is generated in the Fe-SMA strip, the strain in the top and bottom flange are tension and compression, respectively. However, a careful inspection of Figure A1 indicates that when the prestressing increases in the Fe-SMA strips, the strain in the bottom flange is affected more considerably when compared to the strain in the top flange. This mechanism agrees also with that is described in [43]. Hence, if the prestressing level in the Fe-SMA strip increases from 161 MPa (for the case of $T_a = 100$ °C) to 431 MPa (for the case of $T_a = 260$ °C), then the higher prestressing level causes a larger portion of the cross-section under compression. The values of bending stresses in the top and bottom flanges for the mentioned activation temperatures are calculated based on Equations A1 and A2 as follows:

$$\sigma_b = \frac{\sigma_r \times A_{SMA} \times e}{S_{st}} + \frac{\sigma_r \times A_{SMA}}{A_{st}}, \quad \sigma_b(100 \text{ °C}) \approx 10 \text{ MPa} \quad \sigma_b(260 \text{ °C}) \approx 28 \text{ MPa} \quad (A1)$$

$$\sigma_t = \frac{\sigma_r \times A_{SMA} \times e}{S_{st}} - \frac{\sigma_r \times A_{SMA}}{A_{st}}, \quad \sigma_t(100 \text{ °C}) \approx 4 \text{ MPa} \quad \sigma_t(260 \text{ °C}) \approx 10 \text{ MPa} \quad (A2)$$

where σ_b denotes the stress in the bottom flange of the steel beam after activation, σ_t denotes the stress in the top flange of the steel beam after activation, σ_r denotes the recovery stress, A_{SMA} denotes the cross-sectional area of the strip, A_{st} denotes the cross-sectional area of the

steel beam, e denotes the eccentricity of the mid-thickness of the Fe-SMA strip from the mid-depth of the steel beam, and S_{st} denotes the elastic section modulus of the steel beam. Figure A1b depicts the evolution of minimum and maximum stresses in the top and bottom flanges during the cyclic test at the maximum prestressing level (i.e., activation temperature of 260 °C in test B4_A_260).

Acknowledgements

The first author thanks the Swiss Federal Commission for Scholarships for Foreign Students (FCS) for providing a Swiss Government Excellence Scholarship for the academic year 2016–2017 (ESKAS No. 2016.1007) to support the project. The mobility grant for bilateral research collaboration with the South Asia and Iran 2017-2019 funded by ZHAW (Zürcher Hochschule für Angewandte Wissenschaften, Winterthur, Switzerland) is also acknowledged. The authors thank the technicians of the Structural Engineering Research Laboratory of Empa, Switzerland, for their exceptional support in performing the experiments. Furthermore, the authors acknowledge support from Von Roll Deutschland GmbH for providing GFRP laminates.

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Table 1. Overview of the test plan.

Test label	Activation temperature (°C)	Strengthening type ¹	Loading type
B1	N/A	Reference, no strengthening, (B1_R)	Static
B2	N/A	Non-activated (B2_NA)	Static
B3-1	100	Activated (B3-1_A_100)	Static
B3-2	160	Activated (B3-2_A_160)	Static
B3-3	260	Activated (B3-3_A_260)	Static
B4	260	Activated (B4_A_260)	Fatigue

¹Two Fe-SMA strips with width and thickness of 50 and 1.5 mm, respectively, are used.
In the table, B, R, N, and A denote beam, reference, non-activated, and activated, respectively.

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Table 2. Mechanical properties of the steel beam with grade S275JR.

Elastic modulus (GPa)	yield stress (MPa)	Ultimate strength (MPa)
203.3	328	465

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Table 3. Mechanical properties of the as-received Fe-SMA strips [42].

Elastic modulus (GPa)	Recovery stress $T_a = 100, 160 \text{ and } 260 \text{ }^\circ\text{C}$, (MPa)	0.2% yield stress (MPa)	Ultimate strength (MPa)	Ultimate elongation (%)
160	210, 335, 435	523	980	45.2

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Table 4. Details of the activation tests results.

Test label	T_a (°C)	σ_r^{bs} (MPa)	ϵ_b ($\mu\text{m}/\text{m}$)	σ_b (MPa)	Δ_{mid} (mm)
B3-1_A_100	100	161	-53	-10.7	-0.7
B3-2_A_160	160	328	-108	-21.9	-1.7
B3-3_A_260	260	431	-142	-28.8	-2.2

Table 5. Details of the static tests results (for maximum static loading of P=75 kN).

Test label	σ_b (MPa), (% ¹)	Δ_{mid} (mm)	σ_r^{as} (MPa)	$\Delta\sigma_r$ (MPa), (% ²)
B1	200	20.6	N/A	N/A
B2_NA	188 (6%)	19.6	N/A	N/A
B3-1_A_100	178 (11%)	18.8	116	45 (28%)
B3-2_A_160	168 (16%)	17.9	250	78 (24%)
B3-3_A_260	161 (19.5%)	17.4	346	85 (20%)

¹Percentage of stress reduction in the beam bottom flange when compared to that in the reference unstrengthened beam.

²Percentage of recovery stress loss after static loading when compared to the initial recovery stress.

For all the tests, the static loading is performed at room temperature.

Table 6. Details of the fatigue tests results.

Test label	Fatigue load ¹					Fe-SMA		Steel			
	P _{min} (kN)	P _{max} (kN)	σ _{min} (MPa)	σ _{max} (MPa)	Δσ (MPa)	σ _{min} ^{SMA} (MPa)	σ _{max} ^{SMA} (MPa)	σ _{min} ^{stb} (MPa)	σ _{max} ^{stb} (MPa)	Δ _{min} ^{mid} (mm)	Δ _{max} ^{mid} (mm)
B4_A_260	8.0	40.2	21.6 (≡ 0.2 × 0.33f _y)	108.2 (≡ 0.33f _y)	≅ 85	≅440	≅500	-12	69	-0.1	8.4

¹Fatigue load levels are calculated based on the bending stresses in the bottom and top flange of un-strengthened steel beam under the four-point bending load.

For all the tests, the Fe-SMA strips were activated to T_a=260 °C.

For all the tests, the fatigue loading was performed at room temperature with a load ratio of R = 0.2 and loading frequency of f_i=4.35 Hz.

Figure 1. Un-bonded SMA-strengthened steel beam with the FPUR system (for more details refer to [13]).

Figure 2. (a) Stress–temperature curve during heating and cooling for three different maximum temperatures corresponding to 120, 160, and 195 °C. (b) Uniaxial deformation response of the Fe-SMA at room temperature during prestraining to 2% and after activation to an additional tensile load (equivalent to 1% strain) [42].

Figure 3. Static and fatigue four-point bending test setup with arrangements of the measurement points.

Figure 4. Components of the four-point bending test setup including the 250-kN actuator, power supply for activation, and end mechanical anchorages.

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Figure 5. Activation of B3-1: displacement at mid-span during the first 50 min and corresponding temperatures in the Fe-SMA strips.

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Figure 6. Re-activation of B3-2: displacement at mid-span during the first 50 min and corresponding temperatures in the Fe-SMA strips.

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Figure 7. Re-activation of B3-3: displacement at mid-span during the first 50 min and corresponding temperatures in the Fe-SMA strips.

Figure 8. Behavior of SMA-strengthened beams subjected to the static four-point bending test. (a) load-deflection behavior, (b) load-strain behavior.

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Figure 9. Response of Fe-SMAs in tests B2, B3-1, B3-2, and B3-3: (a) load-strain behavior, (b) stress-strain behavior of the activated Fe-SMA during pretraining, unloading, activation, and static loading (c) enlarged details of the activation and static loading to a maximum load of 75 kN.

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Figure 10. Evolution of $\sigma_{\min}$ and $\sigma_{\max}$ in the activated Fe-SMA and bottom flange of the beam with respect to the number of fatigue cycles for $P_{\min}=8.0$ kN and $P_{\max}=40.2$ kN

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Figure A1. Stresses in the top and bottom flanges at the beam mid-span, (a) during static tests and (b) fatigue test of B4_A_260