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Nailed iron-based shape memory alloy (Fe-SMA) strips for strengthening of steel members

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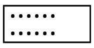
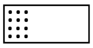
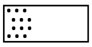
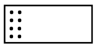
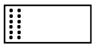
ABSTRACT: The paper presents the development of an iron-based shape memory alloy (Fe-SMA) retrofit system with end-nailed mechanical anchorages for strengthening of steel members. In the first step, a series of lap-shear tests was conducted to investigate the performance of different anchorage designs using a direct fastening method. To this end, a digital image correlation (DIC) system was used to monitor the slip behavior of the anchorage zone. In the second step, the optimized mechanical anchorage was then employed to strengthen a steel girder of 6.4 m in length with a pre-strained Fe-SMA strip that was applied externally. A four-point bending test setup was arranged accordingly. Infrared heating technique was used to heat up the Fe-SMA strip to maximum temperature of 160 °C, resulting in activation and therefore, induction of prestress. Finally, static and fatigue loadings for more than 2.5 million cycles were applied to assess the reliable performance of the proposed nailed Fe-SMA strengthening system. Laboratory testing revealed great mechanical properties of the anchorage regarding tensile capacity and slip. Applied pre-stress was fully maintained throughout fatigue loading.

1 INTRODUCTION

Ensuring satisfactory lifetime performance of steel structures is a challenging task due to unforeseen operational demands and structural degradation. Remedial measures build upon efficient strengthening methods with high applicability and reliability. Extensive research on strengthening methods with carbon fiber reinforced polymers (CFRP) has shown promising outcomes (Teng et al. (2012), Ghafoori et al. (2018), Ghafoori et al. (2018), and Zhao et al. (2007)). However, CFRP pre-stressing systems often require large and heavy equipment (e.g. hydraulic actuators) that make the application difficult or impossible for structures with low accessibility to the damaged detail. Iron-based shape memory alloys (Fe-SMAs) offer a simple pre-stressing procedure that is based on heating and therefore is not reliant on the use of hydraulic actuators (Izadi et al. (2017, 2018)). Recently, several researches have been founded by the authors on the application of the newly proposed pre-stressing systems that are based on the use of Fe-SMAs (Izadi et al. (2019, 2018, 2018), Hosseini et al. (2018), and Ghafoori et al. (2017)). Similar to the case of pre-stressed CFRP strengthening systems, different bonded and un-bonded anchorages are required to attach the Fe-SMA strips (Kianmofrad et al. (2017), Ghafoori et al. (2015), and Hosseini et al. (2017)). So far, different mechanical friction-based

Table 1. Lap-shear test matrix

Test No.	Nailing pattern	Test label	Number of nails	Number of nails per row	Number of rows	Staggered (S) or parallel (P)
1		2p12	12	2	6	P
2		4p12	12	4	3	P
3		4s12	12	4	3	S
4		6p12	12	6	2	P
5		4p8	8	4	2	S

anchorages were introduced for Fe-SMA strengthening applications (Izadi et al. (2019, 2017)). Herein, the current paper discusses the nail-based anchorage of external pre-stressed Fe-SMA reinforcements as a new retrofit system.

2 EXPERIMENTS

2.1 Lap-shear tests

Lap-shear tests were performed on Fe-SMA strips that were anchored to steel beams. The lap-shear tests were intended to study the effect of the different nailing patterns on the load-slip response of the anchorage systems. In the following, the most suitable anchorage was employed for flexural strengthening of steel girders with externally applied Fe-SMA strips.

2.1.1 Specimens and materials

Five Fe-SMA strips, provided by the company re-fer AG in Switzerland, were anchored to IPE 240 steel beam profiles using a direct fastening method. The Fe-SMA strips had dimensions of 100 × 1.5 mm (width × thickness) and lengths ranging from 410.4 to 470.4 mm. The mechanical properties of the Fe-SMA including initial elastic modulus, ultimate tensile strength and ultimate strain at failure were 160 GPa, 1000 MPa and 42 %, respectively. The yield point was arbitrarily defined as 0.2% plastic strain and the according yield stress ranged from 527 MPa to 538 MPa (Shahverdi et al. (2018)).

IPE 240 steel beams of grade 235JR with length of 1000 mm were used in the arranged test set up.

Additionally, X-R 14 P8 nails were used to fasten the Fe-SMA strip to the steel substrate. The nails were set with the fastener shooting tool of DX 450 (125%). Both the nails and the shooting tool were provided by the company Hilti AG, Germany. The nail had a total length of 16.8 mm, a shank length of 14 mm, and a diameter of 3.7 mm. The nails consisted of a CrMnMo alloy and had a tensile strength above 2000 MPa. The fastener has been designed for fastenings exposed to outdoor environments in mildly corrosive conditions (Hilti Deutschland AG Company (2016)).

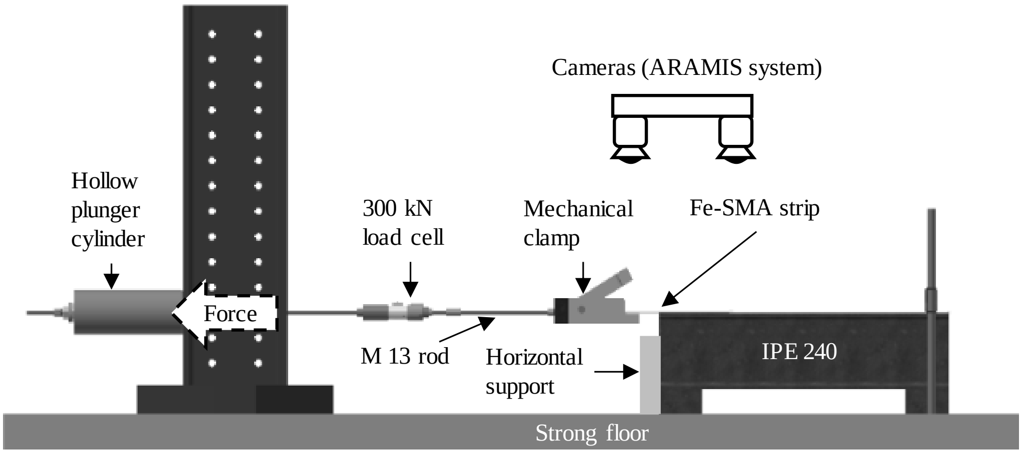


Figure 1. Schematic lap-shear test setup.

2.1.2 Test layout

Table 1 shows an overview of the test program and the general layout of the nailing patterns. The schematic assembly of the test setup is depicted in Figure 1. A steel I-profile (IPE 240) was vertically anchored to the strong floor and horizontally fixed by a support to prevent rigid-body movement of the whole assembly. An aluminum clamp which was connected to a high-strength (Grade 12.9) M13 threaded steel rod, gripped the Fe-SMA strip. 350 mm of free length between the gripping plate of the aluminum clamp and the first row of nails was maintained for each specimen to ensure an undisturbed stress distribution. A load cell with a capacity of 300 kN was installed, connecting the M13 steel rods of the clamp and a hollow plunger hydraulic cylinder. The hydraulic cylinder, operated by a manual pump and supported horizontally by a constraint steel column, was used to induce lateral force onto the system. A digital image correlation (DIC) system (ARAMIS by company GOM GmbH, Germany) was used to record the displacement field of the anchorage zone. The output fields were then analyzed to explain the slip behavior of the anchorages.

2.2 Four-point bending tests

Four-point bending tests were performed on a steel girder that had been reinforced by an externally applied Fe-SMA strip. The Fe-SMA strip was fastened to the steel beam’s bottom flange by the developed nail-based anchorage. To evaluate the system’s performance a set of static and fatigue tests were conducted on the retrofitted beam.

2.2.1 Specimens and materials

A pre-strained Fe-SMA strip with a residual strain of 3.1 %, provided by the company re-fer AG in Switzerland, with dimension of 4800 × 100 × 1.5 mm (length × width × thickness) was used. The mechanical properties of the Fe-SMA deviated from the ones of the lap-shear test, as the material was of a different production batch. The ultimate tensile strength, corresponding strain and strain at failure were 907 MPa, 31.2 % and 31.3 % respectively. The elastic modulus was 195 GPa and the 0.2 % yield strength 470 MPa. The material testing was conducted by re-fer AG. An INP 300 steel profile of grade S275JR, with length of 6400 mm, was used for the experiment. The beam had an average elastic modulus, yield strength, and ultimate strength of 203.3 GPa, 328 MPa, and 465 MPa, respectively.

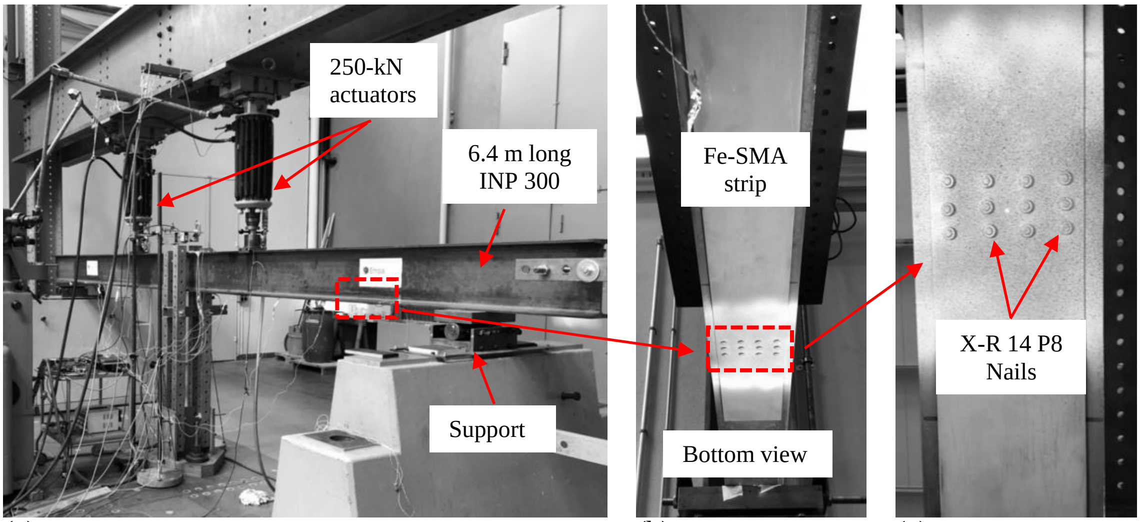
Table 2. Beam test matrix

Test No.	Activation temperature	Strengthening type	Loading type	Test label
1	N/A	Reference	Static	S_R
2	N/A	Non-activated	Static	S_NA
3	160 °C	Activated	Static	S_A
4	160 °C	Activated	Fatigue	F_A

2.2.2 Test layout

Three static tests and one fatigue test were conducted on the steel beam. Table 2 gives an overview of the experimental program. The series of static tests started with a reference test of the un-strengthened beam (S_R) and continued with the test of the beam, strengthened by a non-activated Fe-SMA strip (S_NA). Subsequently, a static test of the strengthened beam with the activated strip was performed (S_A). For all the static loading, a maximum load of 75 kN per actuator was applied during the tests. Once the last static test (S_A) was finished, the fatigue test (F_A) was conducted on the strengthened beam. 2.5 million cycles of loading with a frequency of 4.35 Hz were subjected to the system. The minimum and maximum loading were approximately 8 kN and 40.2 kN per actuator.

Figure 2 shows a photo of the arranged four-point bending test setup. The Fe-SMA strip was applied by placing it underneath the steel beam with the help of clamps and timber beams. X-R 14 P8 nails were set by the fastener tool DX 450(125%). The test setup consisted of the INP 300 steel profile installed as a simple beam with a span of 5300 mm. Two hydraulic cylinders of 250 kN force capacity and 1.8 m center to center distance were placed midway on top of the beam. The Fe-SMA strip was fastened to the bottom flange of the beam with a length of 4125 mm between its anchorages. Laser displacement sensors were installed in midspan of the beam. Several thermocouples were mounted on the Fe-SMA strip and the beam.



(a) (b) (c)

Figure 2. (a) Four-point bending test setup, (b) the Fe-SMA strip fastened to the steel I-profile, (c) the nail-based anchorage.

2.2.3 Activation

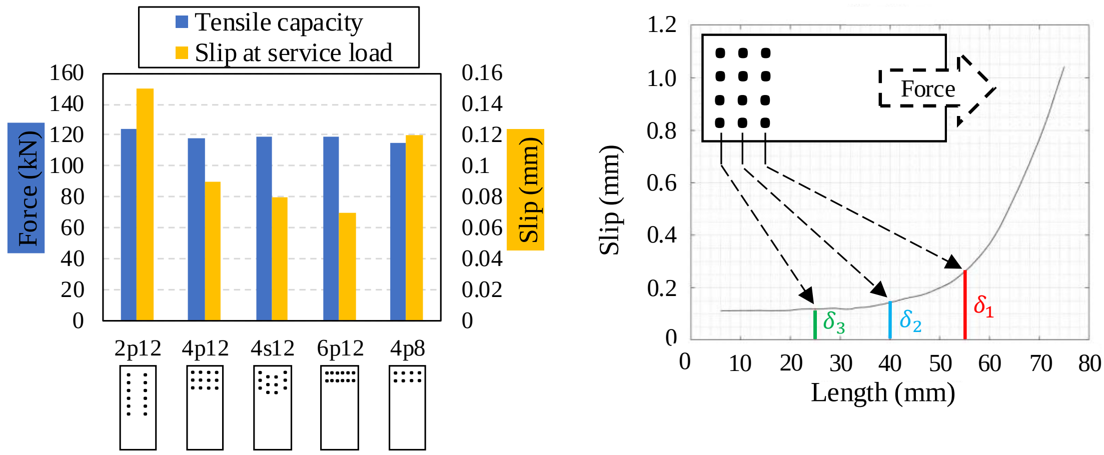
The Fe-SMA strip was heated to the maximum temperature of 160°C with an infrared heating unit, provided by re-fer AG, Switzerland. The activation temperature was monitored by the infrared heating unit's own temperature sensors and by the mounted thermocouples. An upward deflection of the system of 0.89 mm was reported after subsequent heating to 160°C and cooling to room temperature. Based on the deflection of the system the recovery stress was calculated to 223 MPa.

3 RESULTS AND DISCUSSIONS

3.1 Lap-shear tests

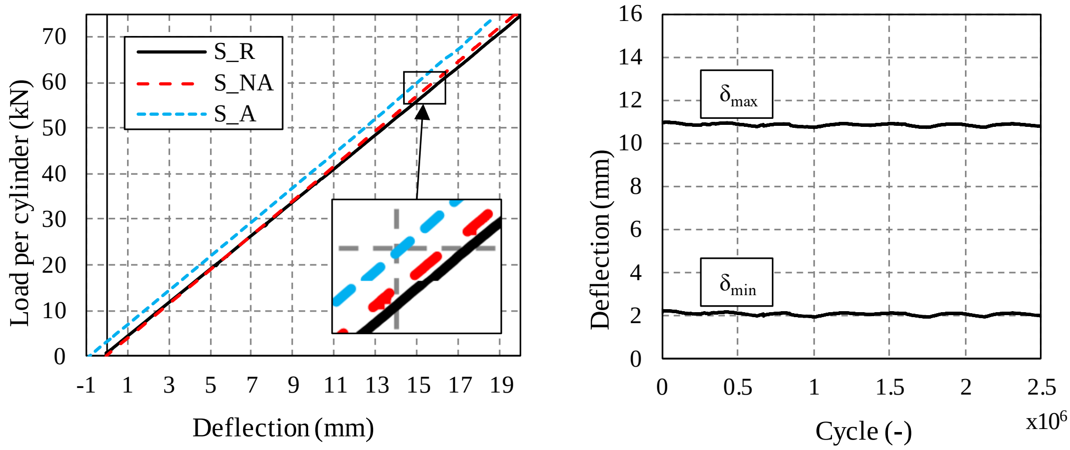
Figure 3a presents the results of the lap-shear tests regarding tensile capacity and slip at service load level of 75kN (equals to 500 MPa in Fe-SMA strip). The slip of the Fe-SMA strip to its steel substrate was compared at the position of the first nail row in mid-width. The test results demonstrate sufficient tensile capacity of all anchorage designs, ranging from 115.3 to 123.9 kN. The failure mode of all the specimens with twelve fasteners was rupture of the Fe-SMA strip at the reduced cross-section in the first row (the desired failure mode), whereas the anchorage with eight fasteners experienced shear failure of the nails. Therefore, twelve nails was found to be the optimal number of fasteners.

Slip of the anchorage at service load level delivered more disperse results ranging from 0.07 to 0.15 mm. Specimens 2p12 and 4p8 were sorted out, as they experienced significantly higher slip than the other designs. Testing of specimen 6p12 resulted in lowest slip but the design was deemed impractical as spacing of the nails was too narrow to ensure reliable application. Second lowest slip results were achieved by specimen 4s12. However, design 4p12 proved superior to its alternatives due to the combination of excellent tensile capacity, slip behavior, low complexity and short anchorage length. Figure 3b depicts the slip behavior of specimen 4p12 in longitudinal direction at maximum load level. The slip at the first (δ_1), second (δ_2), and third (δ_3) nail row was 0.25, 0.15, and 0.12 mm, respectively. The difference in experienced slip, from



(a) (b)

Figure 3. (a) Overview of the lap-shear test results: Tensile capacity and slip at service load level of 75 kN. (b) Slip of specimen 4p12 in longitudinal direction at maximum load level of 118.2 kN.



(a) (b)

Figure 4. Static and fatigue test results: (a) Load per cylinder versus mid-span beam deflection, (b) beam deflection versus load cycle.

second to third row, was only 0.03 mm. This indicates, that the designed number of nails is sufficient, as additional nail rows do not contribute to neither the tensile maximum capacity nor the slip behavior.

3.2 *Four-point bending tests*

The load-deflection behavior of the SMA-strengthened steel beam is depicted in Figure 4a. The slope of the load-deflection curve describes the stiffness of the system. It is shown that the reference beam (S_R) had the lowest flexural stiffness and that the stiffness of the non-activated beam (S_NA) and activated beam (S_A) was increased equally (i.e., equal slope of the curves). The increase of stiffness is attributed to the added cross-section of the Fe-SMA strip to the system. Nevertheless, the pre-stressing improves the load-carrying capacity of the beam significantly as the pre-stressed strips impose an upward maximum deflection of 0.89 mm gained by activation (an equivalent pre-stressing of 223 MPa in the activated Fe-SMA strip). It is worth to note that, at maximum load level, the strain in the bottom flange at mid-span is reduced from 880 µm/mm in the reference beam test to 808 µm/mm for the activated test. The Fe-SMA retrofitting system was examined upon fatigue behavior. Figure 4b presents the development of deflection with respect to the fatigue loading cycles. As seen from the evolution of the deflection, the strengthening system endured 2.5 million loading cycles without failure or significant loss in prestress. As the figure demonstrates, this is proved from the stability of the deflection curves (δ_{min}, δ_{max}) throughout the fatigue test, expressing the successful performance of the pre-stressing system.

4 SUMMARY AND CONCLUSIONS

A novel retrofit system for strengthening of steel structures with externally applied Fe-SMA strips was introduced. A nail-based mechanical anchorage was designed and tested in a series of lap-shear tests. An infrared heating technique was used for activation of the Fe-SMA and pre-stressing a steel beam. The strengthening system was successfully tested in a set of static and fatigue four-point bending beam tests. The proposed pre-stressed strengthening system offers a fast and easy installation. The main observations are presented in the following concluding remarks:

- The designed mechanical anchorage demonstrated excellent performance in terms of static tensile capacity and slip, while preserving low complexity and small size.
- A simple beam (INP 300) with a span of 5.3 m was successfully reinforced with the nail- anchored pre-stressed Fe-SMA strips. The pre-stressed strip induced a maximum upward deflection of nearly 0.9 mm that enhanced the steel beam's load-carrying capacity.
- The nail-based anchorage system performed successfully under fatigue loading as no loss in pre-stress was observed, indicating no slip and the stability of the anchorage during fatigue testing.

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