Development of nail-anchor strengthening system with iron-based shape memory alloy (Fe-SMA) strips

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Abstract

This work discusses the development process of a direct fastening technique for strengthening steel members using iron-based shape memory alloy (Fe-SMA) strips. First, several lap-shear tests were performed to examine the efficiency of five nail-anchor systems in terms of load-carrying capacity, slippage, and convenience of installation. To this end, 3D optical digital image correlation (DIC) measurements (using an ARAMIS system) and numerical simulation were conducted. Different failure modes including tensile rupture of the strips, shear rupture of the nails, and/or sliding of the strips were observed and discussed. The optimum nail-anchor system was then determined. This system has a very short anchorage length of approximately 50 mm and only 12 nails (i.e., 3×4). Second, to demonstrate the efficiency of the proposed system, a steel I-beam was strengthened with the selected nail-anchor system and activated using an infrared heating (IRH) technique. The SMA-strengthened beam was subjected to static

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and then high-cycle fatigue loadings with a loading ratio of $R = 0.2$ for 2.5 million cycles without any failure or damage, indicating reliable performance of the system. Owing to the larger coefficient of thermal expansion of the Fe-SMA material compared to that of steel, it was observed that a decrease and increase in the environmental temperature resulted in an increase and decrease of the pre-stress level in the Fe-SMA strip, respectively (i.e., an inverse correlation).

Keywords: Iron-based shape memory alloy (Fe-SMA); direct fastening; nailing anchorage; strengthening; steel beam; pre-stressing.

1. Introduction

Operational demands not reckoned with during the initial design of civil structures cause remedial challenges during the service life of these structures. The increase in service loads, exposure to harsh environmental conditions, and aging make the steel structures susceptible to structural degradation. To address these problems and maintain the performance of steel structures, efficient repairing methods are required. Traditionally, steel structures were strengthened by replacement or by attaching additional steel structural members (such as steel plates). Recently, carbon-fiber-reinforced polymers (CFRPs) have emerged as a new structural material [1-4]. The strengthening technique, particularly with pre-stressed CFRP composites, effectively enhances the performance of steel structures [5-8]. However, the use of heavy hydraulic actuators and cylinders hinders and occasionally stalls the pre-stressing procedure. The unavailability of affordable and applicable pre-stressing solutions calls for the development of new methods using smart materials [9-15].

1.1. Shape memory alloys (SMAs) in civil engineering applications

SMAs are metallic materials that exhibit a beneficial property, the so-called shape memory effect (SME). The SME enables the material to recover its initial shape after permanent

deformation when it is subjected to a predefined temperature. The SME was initially discovered by Buehler and Wiley [16] in NiTi-based SMAs (also called Nitinol SMAs). Nitinol SMAs have various applications in medical instruments [17], aerospace and automotive industries [18, 19], and couplings and fasteners [20, 21]. However, their application in the domain of civil engineering was hindered by their production costs [21]. An iron-based shape memory alloy (also called Fe-SMA) was developed at the Swiss Federal Laboratories for Materials Science and Technology, Empa, Switzerland [22]. This newly developed Fe-SMA with a cost-effective manufacturing process has applications in civil engineering structures. A novel Fe-SMA with the composition Fe–17Mn–5Si–10Cr–4Ni–1(V,C) and highly potential mechanical properties has been recently presented [23-27]. Since then, Fe-SMAs have been used for strengthening steel [10, 28-32] and concrete [33] structures. Till the present, the most common technique for fastening Fe-SMA strips to civil structures has been direct fastening using nail-anchor systems. Thus, more research is required to optimize the size, geometry, and capacity of the anchors.

1.2. Fe-SMA strengthening of steel structures

Studies on Fe-SMA strengthening of steel structures are in a pioneering stage as few works are available in the literature. Izadi et al. [10, 34, 35] developed an Fe-SMA strengthening system for steel plates with a new friction-based clamping system (i.e., a mechanical anchor). Thermal activation with a maximum temperature of 260 °C was achieved by electrical resistive heating (ERH). It resulted in recovery stresses of 350–400 MPa. The activated (pre-stressed) Fe-SMA yielded a maximum compression of -74 MPa in the steel member. A series of static tensile tests were run. They revealed an enhanced performance of the retrofitted specimens. This Fe-SMA strengthening technique has also been applied for fatigue strengthening of cracked steel plates. It resulted in a remarkable fatigue life improvement and also an arrest of fatigue crack propagation in some cases [28].

In addition to and in conjunction with the studies on SMA strengthening of steel plates, Izadi et al. [29] adapted a specially designed so-called flat pre-stressed un-bonded reinforcement

(FPUR) system for flexural strengthening of a steel girder with activated Fe-SMA strips. The Fe-SMA strips were activated to maximum temperatures of 100, 160, and 260 °C, resulting in recovery stresses of 161, 328, and 431 MPa, respectively, and compressive stresses of -10.7, -21.9, and -28.8 MPa, respectively, in the bottom flange of the girder. The retrofitted steel beam was then subjected to static and fatigue four-point bending tests. The tests indicated a substantial increase in the static and fatigue performance of the steel girders [29].

In this study, the procedure to develop, model, and test a nail-anchor system for Fe-SMA strips is explained. In the first step, a set of lap-shear tests with various nailing patterns was conducted in order to optimize the geometry of the nail-anchor system. In the next step, the optimized nailing pattern was selected to anchor pre-strained Fe-SMA strips to a steel beam. Thermal activation of the Fe-SMA strips induced pre-stress in the system. A static and a fatigue four-point bending test were performed to assess the behavior of the nailed SMA-strengthened beam. In addition, 3D digital image correlation (DIC) measurements and numerical simulations were conducted to obtain the full-field strain/stress distribution in and near the anchorage zone. The nail-anchor system is proposed as an anchorage system that is convenient to install, cost-effective, and reliable performance under static and fatigue loadings. The main aim of this study is to develop an effective anchor system for Fe-SMA strips rather than to demonstrate the efficiency of Fe-SMA materials when used for strengthening purposes. The latter has already been studied by the authors elsewhere (e.g., [29]).

2. Test plan, materials, setups, and instrumentations

A series of tests was executed to examine the application of the nailing anchorage for strengthening a steel structure (here, a steel beam) with Fe-SMA strips. In the first step, lap-shear tests were conducted in order to compare and evaluate the responses of five nailing patterns. A monotonic static load was applied to the whole connection until failure of the anchorage. The tensile rupture of the strips, shear rupture of the nails, and/or sliding of the strips

were the failure modes. Several parameters such as the load-carrying capacity, slippage, and geometry of the anchorages were considered in the evaluation. In the next step and after the lap-shear tests, beam tests were conducted using a four-point bending test-setup in order to observe the performance of the designed nail-anchor system (when used on large-scale beams). The strengthening procedure involved anchoring the pre-strained strips to the bottom flange of the beam (with the selected anchorage pattern), activating the strips through the IRH technique, and finally performing the static and fatigue loadings.

2.1. Materials

IPE 240 steel beam of type S235JR and INP 300 steel profile of type S275JR (with nominal yield stresses of 235 and 275 MPa, respectively) were used for the lap-shear and four-point bending experiments, respectively. The lengths of the steel beams utilized for the lap-shear and four-point bending tests were 1000 and 6400 mm, respectively. The average elastic modulus and yield strength of INP 300 were 203.3 GPa and 328 MPa, respectively [29, 36].

All the Fe-SMA strips had a width of 100 mm and thickness of 1.5 mm. Different batches of Fe-SMA strips were used for the lap-shear and the four-point bending tests. The mechanical properties of the Fe-SMA strips in the lap-shear tests, namely, the initial elastic modulus, ultimate tensile strength, and ultimate failure strain, were 160 GPa, 1000 MPa, and 42%, respectively [33]. The Fe-SMA strip used in the four-point bending experiment had an initial elastic modulus of 195 GPa, ultimate tensile strength of 907 MPa, and ultimate failure strain of 31.3%. The length of the Fe-SMA strips in the lap-shear tests were in the range of 410 to 470 mm (depending on the anchorage length), whereas the length of the Fe-SMA strip in the four-point bending test was 4800 mm.

X-R 14 P8 fasteners [37], provided by Hilti AG, Switzerland, were used for anchoring the Fe-SMA strips to the steel substrate. The nails have a total length of 16.8 mm, shank length of 14 mm, and diameter of 3.7 mm. They have a conical outline and a polyethylene washer attached to the shaft. The nails are designed for application in mildly corrosive conditions and are made

of a CrMnMo alloy with a tensile strength of over 2000 MPa. The X-R P8 nail is not limited by the steel substrate's thickness (flange thickness) up to a steel yielding strength of 500 MPa. Figure 1b shows the nail's measurements and depicts it from different perspectives. Hilti powder-actuated direct fastening tool DX 450 (125%) [37], provided by Hilti AG, Switzerland, was used for setting the X-R nails on the steel substrates. Figure 1a shows a photo of the fastening tool. The tool can be operated using cartridges of the type Kal. 6.8/11M red & yellow. It features a cartridge power regulation system to adjust the setting power. The DX 450 (125%) used in this study was equipped with a small base plate and a 125% piston guide.

2.2. Lap-shear tests

Figure 2 shows the scheme of the lap-shear test setup with different components. In order to fasten the Fe-SMA strips to the substrate, different patterns of the nailing were tested. Table 1 presents the general layouts of the specimens in the lap-shear tests. Prior to the tests, three likely failure modes of the anchorage were identified as follows: bearing failure of the Fe-SMA, shear failure of the nails, and rupture of the Fe-SMA strip. Bearing failure occurs when the stress on the bearing causes either the deck or the substrate to yield. Shear failure occurs when the shear stress on a nail is higher than its shear resistance. However, rupture of the Fe-SMA strip (fracture along the first row of nails) is defined as the ultimate as well as desired failure mode, as the force level of rupture of the Fe-SMA strip cannot be exceeded. Further details on the failure modes of each nail-anchor test will be explained in Section 4.1.2.

The Fe-SMA strips were anchored to an IPE 240 steel beam with different anchorage patterns. Subsequently, the Fe-SMA strips were fixed to an aluminum clamp with two high strength M10 bolts fastened with a torque of 180 Nm. A hydraulic cylinder (connected to the aluminum clamp) and a manual pump were then operated to apply a horizontal force on the whole assembly, as shown in Figure 2b. The Fe-SMA strips were pulled till the failure of the anchorage systems. A 300 kN load cell was used between the hydraulic cylinder and aluminum clamp to monitor the load. In addition to the tests, a series of FE simulations were conducted to

optimize the arrangement and spacing between the nails of the anchorage designs. This optimization process has been explained in Section 3.1.

The slip of the anchorages is described by the displacement of the Fe-SMA strip relative to the steel substrate. In order to measure the load-slip behavior of the designed anchorages as well as the longitudinal displacement field of the anchorage zone, a non-contact optical 3D digital image correlation (DIC) system known also as “ARAMIS system” (provided by GOM GmbH, Germany) was used [38]. To ensure effective image processing by the DIC system, a random black and white pattern was sprayed onto the measured area (i.e., nail-anchor zone). The DIC system identifies the measurement surface using two digital cameras (with four megapixel resolution) mounted and calibrated on a frame, as shown in Figure 2a. The first image in the measurement zone represents the un-deformed (reference) state. During the test, more images are recorded at different load levels. The images are then compared with the reference digital image. Finally, the displacements and deformations of the measured zone can be calculated.

2.3. Four-point bending static and fatigue tests

2.3.1. Test layouts

The optimal anchorage pattern was selected based on the lap-shear tests (i.e., anchor system of S1_4p12) and used to anchor the Fe-SMA strip on an INP 300 steel beam. To evaluate the behavior of the novel strengthening system, four-point bending static and fatigue tests were conducted on the retrofitted steel beam with the externally nailed Fe-SMA strip.

Table 2 overviews the arranged static and fatigue test plan. Totally, four tests were conducted on a steel beam. The first reference test was on the un-strengthened beam (labelled as S1_R). Then, the test on the strengthened beam with the non-activated Fe-SMA strip (test S2_NA) was conducted. Subsequently, the Fe-SMA strip was activated, and the beam was exposed to another static load (i.e., test S3_A). Finally, after the third static test, the fatigue test (i.e., test S4_F_A) was conducted on a configuration of the system similar to that of the activated static test, as indicated in Table 2.

The static tests were performed up to a maximum loading of 75 kN per actuator. This load level corresponds to approximately 60% of the yield strength of the reference steel beam (without strengthening). This load level was selected as it represents the upper limit of the service load levels on similar steel bridge girders [36, 39, 40]. The main aim of the proposed retrofit system is to achieve fatigue strengthening of girders under service loads. Meanwhile, the fatigue response of the strengthened steel beam with the activated nail-anchored Fe-SMA was tested under the minimum ($F_{\min}$) and maximum ($F_{\max}$) loads of 8 kN and 40.2 kN per actuator, respectively, for $N = 2.5 \times 10^6$ load cycles. The fatigue load range was adopted from a study conducted on an identical four-point bending test setup, albeit with different anchorage systems for anchoring the Fe-SMA strips [29]. The load level simulates the service loads applied on a 19th century roadway metallic bridge [36, 39, 40].

2.3.2. Test setup configuration and instrumentation

Figure 3a shows the INP 300 steel beam that was used in a simply-supported setup with a span length of 5300 mm. Two hydraulic actuators with a load capacity of 250 kN and an axis-to-axis distance of 1800 mm were used to perform the four-point bending tests. Figure 3b, shows an additional sketch of the test setup, including the dimensions and positioning of the measurement devices. Strain gauges of types 1-LY61-6/120 and 1-LY66-6/120, provided by HBM GmbH, Germany, were attached on the mid-span of the steel beam and mid-length of the Fe-SMA strip, respectively. The strain gauges were used to record the strain of the steel beam's top and bottom flanges as well as of the Fe-SMA strips. In addition, a laser displacement sensor (LDS) was used to determine the beam's mid-span deflection.

2.3.3. Activation of the nailed Fe-SMA strip

Until now, Fe-SMAs have been activated with various heating techniques/tools such as induction heating coils [26], electrical resistance heating (ERH) [28, 29], heating tapes [13], and gas burning torch [13]. An IRH technique provided by the Company re-fer AG, Switzerland, was selected for activating the Fe-SMA strip in the present study. The IRH unit

1 incorporated infrared radiative heating rods embedded inside two trays of reflective mirror
2 plates. The IRH unit was approximately 1700 mm long (with an effective heating length of
3 1500 mm) and 200 mm wide, as shown in Figure 4. As the length of the IRH unit was shorter
4 than that of the Fe-SMA strip length, the whole length of the Fe-SMA strip was activated
5 segmentally and in a step-wise order. As illustrated in Figure 3b, the pre-strained Fe-SMA strip
6 was heated in three activation segments (segments I, II, and III) sequentially using the IRH
7 technique.

8 Twelve thermocouples (TCs) (eight on the Fe-SMA strip and four on the steel bottom flange)
9 were used to monitor the temperatures during the activation procedure. The TCs were placed
10 longitudinally every 50 and 100 cm along the Fe-SMA strip and steel beam, respectively. The
11 positions are depicted in Figure 3b. In addition, an infrared (IR) camera (Testo 885-
12 Wärmebildkamera by Testo SE & Co. KGaA in Switzerland) was set up facing the beam from
13 the side to record the temperature along the steel surface and depth during the activation
14 process. In addition, the DIC system was installed under the nail-anchor zone in order to record
15 the displacements of the anchorage and steel beam during the activation process. Figure 4
16 exhibits the DIC system, IR camera, and IRH unit during the activation process of the Fe-SMA
17 strips in the beam test setup. The mounted strain gauges and LDSs, as described in Section
18 2.3.2, were also used to monitor the strains and mid-span deflection during the activation
19 process.

21 **3. FE simulations**

22 The magnitude of the pre-stress level (i.e., recovery stress) in the Fe-SMA strip cannot be
23 measured directly using strain gauges. This is because the strain applied to the Fe-SMA has a
24 phase transformation origin rather than a mechanical source. Therefore, the pre-stress level in
25 the Fe-SMA after the activation process can be determined only by a back-calculation of the

1 strain readings from the strain gauges attached to the steel beam. In this study, the FE model
2 served as an effective tool for estimating the pre-stress level in the Fe-SMA strips.

3 The FE simulations for modeling the lap-shear and the four-point bending tests were conducted
4 using ABAQUS[®]/CAE 6.11 [41]. The numerical analysis was performed in the linear elastic
5 regime. The lap-shear test models included three material types: steel, Fe-SMA, and nails. All
6 the materials were modeled as isotropic linear elastic materials based on the mechanical
7 behavior (with a Poisson's ratio of 0.3) described in Section 2.1.

8 **3.1. Lap-shear tests**

9
10 A series of parametric studies was performed to investigate the effects of different geometric
11 parameters on the longitudinal and transversal stress distribution in the Fe-SMA strip. The
12 spacing of the nails along the length and width of the strip (P1, P2, and P3) and the distances
13 of the nails from the edges of the strip (e1 and e2) were determined as the most important
14 geometric variables, as shown in Figure 5a. Finally, a total of six nailing patterns were selected
15 and modeled.

16 Excluding the nailing patterns, the geometries used in the FE models were identical to those
17 described earlier for the laboratory tests. Eight-node linear brick elements with reduced
18 integration and hourglass control (C3D8R) were used for modeling all the parts including the
19 IPE 240 steel beam, Fe-SMA strip, and nail. A general mesh size of 2 mm was assigned for
20 both the steel beam and Fe-SMA strip. Meanwhile, a global mesh size of 0.7 mm was assigned
21 for the nail. The steel bottom surface was assigned a fixed boundary condition to prevent
22 displacements and rotations so as to represent the laboratory test conditions. The normal
23 interaction between the different surfaces was simulated by a “hard” contact, whereas the
24 tangential interaction was assumed to be a “penalty” friction with a friction coefficient of 0.3.
25 There are two different contact areas within the connection zone. The first one is between the
26 bottom surface of the Fe-SMA strip and the steel substrate and the second one is between the

shank of the nail and the surface of the hole inside the Fe-SMA strip and the steel flange. The hard interaction (in order to prevent penetration of surfaces) and penalty interactions (in order to introduce friction between surfaces) were defined for both of the contact areas. Figure 5b demonstrates the load transfer mechanisms via these two contact areas. A uniform pressure of 100 MPa at the ends of the strip was defined to simulate the external loading.

3.2. Four-point bending tests

The FE models of the un-strengthened and strengthened beam equivalent to the four-point bending experiment (explained in Section 2.3) were constructed. First, the reference beam test S1_R was modeled. Subsequently, the second beam test S2_NA, which involved a strengthened beam with a non-activated Fe-SMA strip, was modeled. The model of test S2_NA was constructed by incorporating the Fe-SMA strip to the reference beam model. Finally, a pre-stressing was added to the Fe-SMA strip to model the S3_A beam test. Figure 5c shows an FE model of the SMA-strengthened beam.

Given the assembly's symmetry, only one-fourth of each test was modeled. Two symmetric planes, along the mid-length and mid-width of the SMA-strengthened beam, were defined. The corresponding boundary conditions were then assigned to the defined planes, as shown in Figure 5c. In the region of the bearing (simply) supports, the vertical displacement (y-direction) as well as the rotation around the longitudinal and vertical axes (z- and y-axis) were prevented.

A linear brick element with reduced integration (C3D8R) was used to model all the geometries including the Fe-SMA strips and steel beam. Two mesh sizes of 20 and 10 mm were applied to model the steel beam and Fe-SMA strips, respectively. The external loading was simulated by assigning a uniform pressure in the actuator's location on the top flange of the steel beam. The value of the pressure was equivalent to that of the maximum static load (75 kN per cylinder). The defined pressure was then incrementally increased to the corresponding maximum load.

A surface-to-surface tie constraint was used to couple the anchorage regions in which the Fe-SMA strip was anchored to the beam bottom flange, as shown in Figure 5c. This constraint ties two distinct surfaces so as to prevent relative displacement between them.

3.3. Determination of Fe-SMA pre-stress level using FE model

In order to model the pre-stressing in the Fe-SMA strips, a pre-defined stress field with a certain magnitude was assumed to be in the Fe-SMA strip (in the z-direction) in the initial step of the simulation. In the subsequent step, the predefined stress was redistributed such that the equilibrium condition was fulfilled in the whole model. The redistribution of pre-stressing caused tensile and compressive strain fields in the top and bottom flanges of the steel beam, respectively. In this case, the compressive deformation of the beam often causes a partial loss of the initial pre-stress in the Fe-SMA strip. The results of the strains in the top and bottom flange of the steel beam were then compared with test measurements from the strain gauges attached on the top and bottom of the beam, respectively. The strains on the top and bottom flange of the steel beam are shown by "Top SG Steel" and "Bot SG Steel" in Figure 3, respectively. If the results of the FE model and the experiments do not match, a new pre-defined stress field is assumed for the Fe-SMA strip, and FE model is solved again to obtain the strains in the top and bottom flange of the beam. This iterative process has to be conducted until the results of the FE and experiments match. The last pre-defined stress field in the Fe-SMA strip is then the actual pre-stress level in the Fe-SMA.

For the problem in this study, the iterative process resulted in a pre-stress level of 235 MPa in the Fe-SMA strip. In addition, the compressive deformation of the beam caused a partial loss of the strip pre-stress of approximately 11 MPa.

4. Experimental and numerical results and discussions

4.1. Lap-shear tests

4.1.1. Numerical parametric study

As described in Section 3.1, five geometric parameters ($P1$, $P2$, $P3$, $e1$, and $e2$; see Figure 5a) were considered in order to optimize the design of the nail-anchor systems. Table 3 presents the layout of the parametric studies. The Von Mises stresses along the length of the strip near the holes for the parametric models 4p12_20_15_12 and 4p12_15_15_12 are presented in Figure 6a. The spacing of the nailing rows, $P1$, was different in these two models; $P1 = 15$ mm for the model 4p12_15_15_12 (indicated by blue in Figure 6a); and $P1 = 20$ mm for the model 4p12_20_15_12 (indicated by red in Figure 6a). Both models experience local peaks of stresses at the vicinity of the holes in the Fe-SMA strips. The critical stress at the first nailing row, which ultimately results in anchorage failure at higher loads (see Section 4.1.2), remains identical for both models. However, for the second and third rows, the model with the shorter row spacing ($P1 = 15$ mm) experiences higher stresses than that with the longer row spacing ($P2 = 20$ mm). Thus, it can be concluded that the design of 4p12_15_15_12 is preferable as it achieves higher participation of the second and third nailing rows in the transference of the load to the fasteners and substrate, while maintaining the anchorage load capacity.

Figure 6b shows the Von Mises stress distributions along a line adjacent to the holes in the first nailing row in the Fe-SMA strips for the lap-shear models 4p12_20_15_12, 4p12_20_25_125, and 4p12_20_20_20. The row spacing ($P1$) was maintained constant, whereas the transverse spacing of the nails ($P2$ and $P3$) and the distance from the nails to the edge of the strip ($e2$) were different. The model 4p12_20_15_12 was designed in order to prevent the fasteners from being set near the fillet of the web of the steel beam. This resulted in unequal spacing along the width. From Figure 6b, the minimum stress (near the edge and the middle of the strip) and maximum stress (near the inner and outer holes) ranged from 63 to 85 MPa and 212 to 236 MPa, respectively.

The design shown in Figure 6b for 4p12_20_20_20 involved a different approach. Here, the distances $P2$ and $e2$ between the fasteners and edges were equal. This resulted in minimum

stresses ranging from 69 to 77 MPa at the edges and the middle of the strip area. Meanwhile, the maximum stresses near the inner and outer holes ranged from 209 to 241 MPa. Moreover, Figure 6b shows the results of the third design of 4p12_20_25_125. The spacing was adjusted by reducing the edge distance, e_2 . The results revealed minimum stresses ranging from 72 to 79 MPa at the middle areas and edges and maximum stresses ranging from 220 to 225 MPa at the inner and outer nailing holes. The nailing pattern 4p12_20_25_125 resulted in approximately identical values for the minimum and maximum stresses along the width of the Fe-SMA strip. Therefore, the distances P_2 , P_3 , and e_2 of this model were adopted for the design approach. Figure 7 depicts the results of the two design approaches using two nails per row. The nailing pattern of 2p12_15_33_33 had equal distances for P_2 and e_2 ($= 33$ mm), whereas the distances $P_2 = 50$ mm and $e_2 = 25$ mm were used for 2p12_15_50_25. The results revealed a maximum stress of 300 MPa for both models. Nevertheless, the stresses along the width of the Fe-SMA strip for 2p12_15_50_25 exhibited a homogeneous minimum stress distribution. Therefore, the distances P_2 and e_2 of this model were adopted for the design approach wherein two nails per row were used.

4.1.2. Test results

Figure 8a illustrates the load–slip curves of the different nailing anchorages resulted from the lap-shear tests. The slip presented in the diagram is based on the relative displacement of the anchorages and steel substrate. Moreover, Figure 8b presents the bar chart results of the lap-shear tests with regard to the maximum tensile capacity and the slippage at the service load level of 75 kN ($= 500$ MPa in the Fe-SMA strip). As the load–slip curves in Figure 8a reveal, the anchorages with higher numbers of nails per row experienced less slippage. The maximum tensile capacity ranged from 115 to 124 kN. Unlike the tensile capacity, the slip at the service load level of 75 kN exhibited higher scatter in the results. The maximum slippage was 0.15 mm for the lap-shear test S3_2p12. It is noteworthy that the anchorage with only eight fasteners experienced shear failure of the nails. As the failure mode changed from rupture of the Fe-SMA

strip (the desired failure) to shear failure upon the reduction in the number of nails, the optimal number of nails was observed to be 12.

The least slippage occurred for the test S4_6p12. However, in practice, setting the nails in this configuration requires substantial caution, complicating the assembling process. The test S2_4s12 yielded the second best results with regard to the slip and the anchorage length. Nevertheless, the design of the test S1_4p12 resulted in the most optimum results in terms of tensile capacity, slip behavior, practicability (i.e., minimum complexity in the application of the nailing pattern), and the short anchorage length. The design of test S1_4p12 was finally selected as the most suitable nail-anchor system for application in the four-point bending tests.

The nail-anchor system in this study was developed for Fe-SMA strips of width 100 mm. However, this methodology can be used for Fe-SMA strips of smaller or larger widths also. For example, for an Fe-SMA strip of width 50 mm, only six nails can be used. This implies three rows of nails (see Table 1) with two nails in each row (i.e., 3×2). The anchorage length of approximately 50 mm will remain unaltered for different widths of the Fe-SMA strips (only the number of nails per row varies with the width).

Meanwhile, the nail-anchor system in this study has been developed for steel members; this concept can be adopted for strengthening concrete members. Nevertheless, the type of the nails and the nailing pattern are yet to be optimized for concrete members. More studies are required on this topic.

4.1.3. Validation of FE modeling

In order to validate the FE results, the slippage curves obtained from the FE modeling were compared with those from the lap-shear tests. The model 2p12_15_50_25 and experiment S3_2p12, which exhibit similar geometrical properties, were used for this comparison. The comparison is based on the behavior in the elastic region at a load level equivalent to 100 MPa (that was used in the FE modeling). The highest tensile stress that occurred in the FE model was 328 MPa. This is significantly lower than 0.2% and 0.01% of the yield strength of the

utilized Fe-SMA [33]. Note that the optimization of the nail-anchor system was based on the linear elastic FE modeling. The FE model presented in this study does not take into account the possible plasticity near holes in the Fe-SMA strips and was just used as a simple engineering tool to compare different nail-anchor designs. However, in this study, the lap-shear tests were performed up to failure to determine the ultimate capacity of the system and to study the non-linear behavior of the nail-anchor system. From Figure 9a, the numerical simulation reveals a slippage approximately 0.002 mm higher than that from the test results. However, the characteristic of a gradual increase in slippage along the anchorage length as revealed by the FE model agrees well with the experimental results. In addition, Figure 9b depicts the in-plane displacement along the length of the strip during the lap-shear test of S3_2p12. As is evident, the maximum slippage occurs near the first nailing row. It is worth noted that the slippage has been calculated by subtracting the displacement profile of the middle of the Fe-SMA strip from that of the steel substrate.

4.2. Four-point bending test results

4.2.1. Activation test results

The temperature history of the Fe-SMA strip and INP 300 steel beam during the activation of the segments is plotted in Figure 10. The whole activation process (i.e., heating and subsequent cooling down to room temperature) took approximately 3.5 h. During the activation process of each segment, a rapid temperature increase in the Fe-SMA area and a more gradual temperature increase in the adjacent steel beam were observed. As shown in Figure 10, throughout the activation process of segments I and II, the area of segment III was marginally heated as well. This is owing to the overlap of segment III with segments I and II (see Figure 2b). Furthermore, Figure 11 shows the temperature distribution along the depth of the steel beam for segment III, obtained from the infrared camera at the maximum activation temperature. After the activation procedure was completed (and all the segments were cooled down to the room temperature in approximately 2.5 h), an upward deflection of 0.89 mm was observed in the mid-span of the

beam. Then, a recovery stress of 223 MPa was calculated based on the recorded mid-deflection for the activation temperature of 160 °C. However, the pre-stressing generated in the Fe-SMA strip was 100 MPa less than the recovery stress of the Fe-SMA as obtained from the material characterization tests [29, 33]. This is explained by considering the heating technique (IRH), which caused a thermal expansion of the parent structure (here, the steel beam) during the heating of the Fe-SMA strips. The thermal expansion of the base member induces tensile stresses in the strips during the activation process. This hinders the completion of the martensite-to-austenite reverse phase transformation. The latter has been proven to be the main reason for the reduced recovery stress in this test [30, 42].

4.2.2. Static test results

Figure 12a shows the load–deflection behavior of the steel beam reinforced with the externally nail-anchored Fe-SMA strip. From this figure, the slope of the load–deflection curve of the reference beam S1_R is the lowest, implying that Fe-SMA reinforcement enhances the stiffness of the strengthened beam. In addition, the non-activated test S2_NA and activated test S3_A improved the stiffness identically, revealing the negligible effect of the pre-stressing in increasing the system’s stiffness. However, the deflection was significantly reduced for the SMA-activated test S3_A owing to the initial upward deflection of 0.89 mm caused by the activation.

Figure 12b depicts the development of the strain in the bottom flange of the steel beam. At the maximum load level, the strain in the bottom flange decreased from 880 $\mu\text{m}/\text{mm}$ for the un-strengthened beam test to 864 and 808 $\mu\text{m}/\text{mm}$ for the non-activated and activated tests, respectively. The strain reduction is larger for the SMA-activated beam test. This explains the positive effect of the pre-stressing. Figure 12b also displays the FE results of the load–strain relation of the bottom flange. It agrees well with the laboratory tests. The black curve in this figure represents the reference steel beam test of S1_R.

4.2.3. Fatigue test results

After the static tests, the pre-stressed beam was subjected to fatigue loading with a loading frequency of 4.35 Hz for 2.5 million cycles. Figure 13 displays the evolution of the minimum and maximum strains in the beam bottom flange as a function of the number of cycle loads. This figure shows that the stresses were stable throughout the cyclic tests. This indicates that no slippage or substantial pre-stress loss in the Fe-SMA occurred. This result also reveals the reliable performance of the new nail-anchor system under high-cycle fatigue loading regime. The minimum and maximum strains in the beam bottom flange were approximately 60 and 450 $\mu\text{m}/\text{mm}$, respectively. The strain level fluctuated during the cyclic loads. The reason for these strain fluctuations is explained in the following.

Figure 14 shows the strain of the Fe-SMA strip during the cyclic loading. The minimum strain of the Fe-SMA ranged between 31420 and 31470 $\mu\text{m}/\text{mm}$, whereas its maximum strain ranged between 31070 and 31115 $\mu\text{m}/\text{mm}$. Both the minimum and maximum strain curves describe a distinct wavy pattern that follows a day–night rhythm. Although the temperature in the lab was controlled to approximately 25 °C, it appears that even a marginal temperature variation could affect the pre-stress level in the Fe-SMA strips. When the temperature decreases at night, the strain of the Fe-SMA strip increases. During the daytime, the temperature increases, and the strain decreases. This implies that the readings were influenced by the variations in the lab temperature.

In Figure 14, linear trend lines are added for the strains that occurred during different temperature ranges (23.4–23.5 °C, 24.4–24.5 °C, and 25.4–25.5 °C). These horizontal trend lines demonstrate that there was no loss in pre-stress owing to the cyclic loading and that the wavy pattern in the strain readings can be explained by the difference in the coefficient thermal expansions (CTE) between the steel and Fe-SMA strip. Steel material exhibits a CTE in the range of around $11\text{--}13 \times 10^{-6} \text{ K}^{-1}$, while experimental results performed by Hosseini et al. [43] demonstrated that the thermal expansion behavior of the Fe-SMA is quite similar to that of other austenitic steels and a CTE of approximately $14.9 \times 10^{-6} \text{ K}^{-1}$ was experimentally determined for this alloy at ambient

temperature. More details about difference between the CTE of steel and Fe-SMA can be found in [43, 44]. Based on this background, when the temperature decreases during the night, the strains increase owing to the relatively larger CTE of the Fe-SMA material than that of steel. Thus, it can be concluded that the mismatch in the CTE between steel and Fe-SMA materials is responsible for the fluctuations in the strains during day- and night-time.

4.2.4. Fatigue state of the nail-anchor zone

The nail-base anchor system presented in this study requires drilling of holes in the steel beam. The anchors are placed near the two ends of the beam (i.e., near the supports), where there are minimum bending moments and therefore the tensile stresses in the beam bottom flange are low. The latter reduces the chance of initiation of fatigue cracks from the holes in the steel beam. Nevertheless, it is recommended to use the proposed nail-anchor system for structures that are not subjected to pronounced cyclic loads (e.g., buildings). In case, the system is used for strengthening of structures under sever cyclic loads (e.g., steel bridges), the safety of drilled holes against fatigue cracking has to be first checked. The procedure of design against fatigue crack is briefly explained in this section.

In order to ensure a reliable performance of the anchorage zone under cyclic loading, the fatigue state of the holes in the Fe-SMA strips (created by nailing) was examined. The constant life diagram (CLD) model, which was proposed by Ghafoori et al. [26] for predicting the Fe-SMA fatigue limit at different stress ratios, was employed. In order to determine the state of stress around the holes of the anchorage zone, the Fe-SMA strip was considered as a thin element subjected to uniaxial stresses. Stress concentration factors (SCFs) were used [45] to simulate the stress increase near the holes. The sensitivity of the material to notches was then taken into account by converting the theoretical SCF into the fatigue SCF [46]. Further details regarding the CLD technique for Fe-SMA materials are provided in [26].

The far-field stresses of the Fe-SMA strip at the minimum and maximum fatigue loads ($P_{\min} = 8.0$ kN and $P_{\max} = 40.2$ kN, respectively) were obtained from the FE model of the beam.

Subsequently, the nominal stress along the first nailing row was calculated. The resulting alternating stress and the mean stress are determined as follows:

$$\sigma_a = \frac{\sigma_{\max} - \sigma_{\min}}{2} \times \frac{b \times t}{(b - 4 \times d) \times t} = 31.7 \text{ MPa} \quad (1)$$

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2} \times \frac{b \times t}{(b - 4 \times d) \times t} = 310.7 \text{ MPa} \quad (2)$$

where σ_a is the alternating stress, σ_m is the mean stress, $\sigma_{\min}$ is the minimum far-field stress, $\sigma_{\max}$ is the maximum far-field stress, b is the Fe-SMA strip width, t is the Fe-SMA strip thickness, and d is the nail diameter. The alternating stress was then multiplied by the fatigue SCF (= 2.3, resulting in $\sigma_a = 73 \text{ MPa}$), while the mean stress was kept unchanged.

The CLD model proposed by Ghafoori et al. [26] for Fe–Mn–Si shape memory alloys is shown in Figure 15. The calculated alternating and mean stress of the anchorage zone is then compared with the proposed criteria. The stress state is denoted by point "A" in Figure 15. It is inside the safe zone and thus, predicts that no fatigue cracks would be initiated under a high fatigue loading regime. This theoretical prediction (based on the CLD approach) matches well with the results of the fatigue test on the beam, as the SMA-strengthened beam survived more than 2.5 million cyclic loadings without fatigue cracks. This also implies that the current pre-stress level of 223 MPa could be increased (up to 310 MPa) without imposing risk on the fatigue safety of the retrofitting system (as the point would still be inside the safe zone determined by the CLD approach [26]).

5. Summary and conclusion

In this study, a new nail-anchor system (as a direct-fastening technique) was developed and tested for clamping Fe-SMA strips to steel substrates. The technique is simple and reduces the time and cost of strengthening works. In the first step of this work, a series of lap-shear tests was conducted to investigate the response of five nail-anchor systems. In the next step, the optimized nail-anchor system was used for strengthening a steel beam. In order to demonstrate

the effectiveness and performance of the developed nail-anchor system, a series of static and fatigue tests were conducted in a four-point bending beam test setup. Furthermore, the Aramis DIC system and FE modeling were used for 3D measurements of the full-field displacements of the nail anchor zones. The following remarks were drawn from the presented study:

1. Different failure modes were observed in the SMA-to-steel nailed joints: tensile rupture of the strips, shear rupture of the nails, and/or sliding of the strips. The most optimized nail-anchor system was determined to be that with a very short anchorage length of approximately 50 mm and only 12 nails (3×4 nails), which demonstrated a remarkable structural performance in terms of low slippage and high tensile capacity. The proposed nail-anchor system offers a straightforward installation procedure as the nails can be set rapidly and conveniently with the proposed direct fastening tool.

2. The mechanism of the stress transfer between the Fe-SMA strip and the beam has been discussed. The numerical and test results indicated that the first line of the nails in the nail-anchor system (i.e., closest to the middle of the strip) is the most critical detail of the anchor, as the nails in this line transfer the greatest portion of the stresses between the strip and the beam.

3. The results of the static and fatigue loading (with load ratio of $R = 0.2$) on the SMA-retrofitted beam exhibited the reliable performance of the proposed system, as no significant pre-stressing loss or anchorage failure were observed in the system during 2.5 million fatigue cycles.”

4. The results of the high-cycle fatigue tests (with more than 6 days of lab cyclic tests) showed a small (but non-negligible) change of the pre-stress level in the Fe-SMA strip as a result of the daytime and nighttime temperature variations in the laboratory. Given the relatively larger CTE of the Fe-SMA material (i.e., $14.9 \times 10^{-6} \text{ K}^{-1}$) than that of steel (i.e., $11\text{--}13 \times 10^{-6} \text{ K}^{-1}$), a decrease and increase in the environmental temperature results in an increase and decrease of the Fe-SMA pre-stress level, respectively (i.e., an inverse correlation).

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References

1. Zhao, X.L. and L. Zhang, *State-of-the-art review on FRP strengthened steel structures*. Engineering Structures, 2007. **29**(8): p. 1808-1823.
2. Teng, J.G., Yu, T., Fernando, D., *Strengthening of steel structures with fiber-reinforced polymer composites*. Journal of Constructional Steel Research, 2012. **78**: p. 131-143.
3. Ghafoori, E. and M. Motavalli, *Normal, high and ultra-high modulus CFRP laminates for bonded and un-bonded strengthening of steel beams*. Materials and Design, 2015. **67**: p. 232–243.
4. Shaat, A., D. Schnierch, A. Fam, and S. Rizkalla. *Retrofit of steel structures using fiber-reinforced polymers (FRP): State-of-the-art*. in *Transportation research board (TRB) annual meeting*. 2004.
5. Ghafoori, E. and M. Motavalli, *Flexural and interfacial behavior of metallic beams strengthened by prestressed bonded plates*. Composite Structures, 2013. **101**: p. 22-34.
6. Hosseini, A., E. Ghafoori, M. Motavalli, A. Nussbaumer, and X.-L. Zhao, *Mode I fatigue crack arrest in tensile steel members using prestressed CFRP plates*. Composite Structures, 2017. **178**: p. 119-134.
7. Kianmofrad, F., E. Ghafoori, M.M. Elyasi, M. Motavalli, and M. Rahimian, *Strengthening of metallic beams with different types of pre-stressed un-bonded retrofit systems*. Composite Structures, 2017. **159**: p. 81-95.
8. Huawen, Y., C. König, T. Ummenhofer, Q. Shizhong, and R. Plum, *Fatigue Performance of Tension Steel Plates Strengthened with Prestressed CFRP Laminates*. Journal of composites for construction, 2010. **14**(5): p. 609-615.
9. Soroushian, P., K. Ostowari, A. Nossoni, and H. Chowdhury, *Repair and strengthening of concrete structures through application of corrective posttensioning forces with shape memory alloys*. Transportation Research Record: Journal of the Transportation Research Board, 2001(1770): p. 20-26.
10. Izadi, M., E. Ghafoori, A. Hosseini, M. Motavalli, and S. Maalek. *Development of anchorage systems for strengthening of steel plates with iron-based shape memory alloy strips*. in *Fourth Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures (SMAR 2017)*. 2017.
11. Czaderski, C., M. Shahverdi, R. Brönnimann, C. Leinenbach, and M. Motavalli, *Feasibility of iron-based shape memory alloy strips for prestressed strengthening of concrete structures*. Construction and Building Materials, 2014. **56**: p. 94-105.

12. Zheng, B. and M. Dawood, *Fatigue strengthening of metallic structures with a thermally activated shape memory alloy fiber-reinforced polymer patch*. Journal of Composites for Construction, 2016. **21**(4): p. 04016113.
13. Rojob, H. and R. El-Hacha, *Self-Prestressing Using Iron-Based Shape Memory Alloy for Flexural Strengthening of Reinforced Concrete Beams*. ACI Structural Journal, 2017. **114**(2): p. 523.
14. IZADI, M., M. MOTAVALLI, and E. GHAFOORI, *Smart SMA-based system for fatigue strengthening of cracked metallic bridge connections*.
15. FRITSCH, E., M. IZADI, and E. GHAFOORI, *Nailed iron-based shape memory alloy (Fe-SMA) strips for strengthening of steel members*.
16. Kumar, P. and D. Lagoudas, *Introduction to shape memory alloys*, in *Shape memory alloys*. 2008, Springer. p. 1-51.
17. Bogdanski, D., M. Köller, D. Müller, G. Muhr, M. Bram, H.P. Buchkremer, D. Stöver, J. Choi, and M. Eppe, *Easy assessment of the biocompatibility of Ni–Ti alloys by in vitro cell culture experiments on a functionally graded Ni–NiTi–Ti material*. Biomaterials, 2002. **23**(23): p. 4549-4555.
18. Van Humbeeck, J., *Non-medical applications of shape memory alloys*. Materials Science and Engineering: A, 1999. **273**: p. 134-148.
19. Jani, J.M., M. Leary, A. Subic, and M.A. Gibson, *A review of shape memory alloy research, applications and opportunities*. Materials & Design (1980-2015), 2014. **56**: p. 1078-1113.
20. Janke, L., C. Czaderski, M. Motavalli, and J. Ruth, *Applications of shape memory alloys in civil engineering structures—overview, limits and new ideas*. Materials and Structures, 2005. **38**(5): p. 578-592.
21. Cladera, A., B. Weber, C. Leinenbach, C. Czaderski, M. Shahverdi, and M. Motavalli, *Iron-based shape memory alloys for civil engineering structures: An overview*. Construction and building materials, 2014. **63**: p. 281-293.
22. Dong, Z., U.E. Klotz, C. Leinenbach, A. Bergamini, C. Czaderski, and M. Motavalli, *A Novel Fe-Mn-Si Shape Memory Alloy With Improved Shape Recovery Properties by VC Precipitation*. Advanced engineering materials, 2009. **11**(1-2): p. 40-44.
23. Lee, W., B. Weber, G. Feltrin, C. Czaderski, M. Motavalli, and C. Leinenbach, *Stress recovery behaviour of an Fe–Mn–Si–Cr–Ni–VC shape memory alloy used for prestressing*. Smart Materials and Structures, 2013. **22**(12): p. 125037.
24. Leinenbach, C., H. Kramer, C. Bernhard, and D. Eifler, *Thermo-Mechanical Properties of an Fe–Mn–Si–Cr–Ni–VC Shape Memory Alloy with Low Transformation Temperature*. Advanced Engineering Materials, 2012. **14**(1-2): p. 62-67.
25. Leinenbach, C., W. Lee, A. Lis, A. Arabi-Hashemi, C. Cayron, and B. Weber, *Creep and stress relaxation of a FeMnSi-based shape memory alloy at low temperatures*. Materials Science and Engineering: A, 2016. **677**: p. 106-115.
26. Ghafoori, E., E. Hosseini, C. Leinenbach, J. Michels, and M. Motavalli, *Fatigue behavior of a Fe-Mn-Si shape memory alloy used for prestressed strengthening*. Materials & Design, 2017. **133**: p. 349-362.
27. Ghafoori, E., M. Neuenschwander, M. Shahverdi, C. Czaderski, and M. Fontana, *Elevated temperature behavior of an iron-based shape memory alloy used for prestressed strengthening of civil structures*. Construction and Building Materials, 2019. **211**: p. 437-452.
28. Izadi, M., E. Ghafoori, M. Motavalli, and S. Maalek, *Iron-based shape memory alloy for the fatigue strengthening of cracked steel plates: Effects of re-activations and loading frequencies*. Engineering Structures, 2018. **176**: p. 953-967.

29. Izadi, M., A. Hosseini, J. Michels, M. Motavalli, and E. Ghafoori, *Thermally activated iron-based shape memory alloy for strengthening metallic girders*. Thin-Walled Structures, 2019. **141**: p. 389-401.
30. Hosseini, E., E. Ghafoori, C. Leinenbach, M. Motavalli, and S. Holdsworth, *Stress recovery and cyclic behaviour of an Fe–Mn–Si shape memory alloy after multiple thermal activation*. Smart Materials and Structures, 2018. **27**(2): p. 025009.
31. Izadi, M., M. Motavalli, and E. Ghafoori, *Iron-based shape memory alloy (Fe-SMA) for fatigue strengthening of cracked steel bridge connections*. Construction and Building Materials, 2019. **227**: p. 116800.
32. Izadi, M., E. Ghafoori, M. Motavalli, S. Maalek, and A. Hosseini. *Shape memory alloy (SMA) strips for fatigue strengthening of cracked steel plates*. in *Proceedings of the ninth international conference on fibre-reinforced polymer (FRP) composites in civil engineering (CICE 2018)*. 2018.
33. Shahverdi, M., J. Michels, C. Czaderski, and M. Motavalli, *Iron-based shape memory alloy strips for strengthening RC members: Material behavior and characterization*. Construction and Building Materials, 2018. **173**: p. 586-599.
34. Izadi, M., E. Ghafoori, A. Hosseini, M. Motavalli, S. Maalek, C. Czaderski, and M. Shahverdi. *Feasibility of iron-based shape memory alloy strips for prestressed strengthening of steel plates*. in *the fourth International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures (SMAR 2017)*. 2017.
35. Izadi, M., E. Ghafoori, M. Shahverdi, M. Motavalli, and S. Maalek, *Development of an iron-based shape memory alloy (Fe-SMA) strengthening system for steel plates*. Engineering Structures, 2018. **174**: p. 433-446.
36. Hosseini, A., E. Ghafoori, M. Motavalli, A. Nussbaumer, X.-L. Zhao, and R. Al-Mahaidi, *Flat prestressed unbonded retrofit system for strengthening of existing metallic I-Girders*. Composites Part B: Engineering, 2018. **155**: p. 156-172.
37. *Direct Fastening Technology Manual 2015*. www.hilti.com, May 2015.
38. Al-Zubaidy, H., R. Al-Mahaidi, and X.L. Zhao, *Experimental investigation of bond characteristics between CFRP fabrics and steel plate joints under impact tensile loads*. Composite Structures, 2012. **94**(2): p. 510-518.
39. Hosseini, A., E. Ghafoori, R. Al-Mahaidi, X.-L. Zhao, and M. Motavalli, *Strengthening of a 19th-century roadway metallic bridge using nonprestressed bonded and prestressed unbonded CFRP plates*. Construction and Building Materials, 2019. **209**: p. 240-259.
40. Ghafoori, E., A. Hosseini, R. Al-Mahaidi, X.-L. Zhao, and M. Motavalli, *Prestressed CFRP-strengthening and long-term wireless monitoring of an old roadway metallic bridge*. Engineering Structures, 2018. **176**: p. 585-605.
41. ABAQUS, C., *Version 6.11, 2011*. Hibbitt, Karlsson and Sorenson Inc., Providence, Rhode Island, USA.
42. Lee, W., B. Weber, and C. Leinenbach, *Recovery stress formation in a restrained Fe–Mn–Si-based shape memory alloy used for prestressing or mechanical joining*. Construction and Building Materials, 2015. **95**: p. 600-610.
43. Hosseini, E., E. Ghafoori, C. Leinenbach, M. Motavalli, and S.R. Holdsworth, *Stress recovery and cyclic behaviour of an Fe–Mn–Si shape memory alloy after multiple thermal activation*. Smart Materials and Structures, 2018. **27**: p. 025009.
44. Hosseini, A., J. Michels, M. Izadi, and E. Ghafoori, *A comparative study between Fe-SMA and CFRP reinforcements for prestressed strengthening of metallic structures*. Construction and Building Materials, 2019. **226**: p. 976-992.
45. Pilkey, W.D. and D.F. Pilkey, *Peterson's stress concentration factors*. 2008: John Wiley & Sons.

46. Budynas, R. and J. Nisbett, *Stress in pressurized cylinders*. Shigley's Mechanical Engineering Design, 9th ed. McGraw-Hill, New York, 2011: p. 3-14.

Table 1. Specimen layouts for the lap-shear tests.

Specimens	Total number of nails ¹	Number of nails per row	Number of rows	Staggered (S) / Parallel (P)	Test label ²	Scheme of nailing pattern	Experimental results	
							Tensile capacity (kN)	Slippage ³ (mm)
S1	12	4	3	P	S1_4p12		118.2	0.09
S2	12	4	3	S	S2_4s12		118.8	0.08
S3	12	2	6	P	S3_2p12		123.9	0.15
S4	12	6	2	P	S4_6p12		118.9	0.07
S5	8	4	2	P	S5_4p8		115.3	0.12

¹ The nails were of type X-R 14 P8 for corrosive environment with a tensile strength of over 2000 MPa (provided by the Hilti AG, Switzerland).

² In the test labels (SX_YpZ), the first identifier (X) indicates the test number, the second one (Y) indicates the number of nails per row, and the third one (Z) indicates the total number of nails.

³ Slippage is for a service load of 75 kN (equivalent to a tensile stress of 500 MPa in the Fe-SMA strip).

Table 2. Overview of the four-point bending beam tests.

Specimens	Strengthening type ¹	Activation temperature (°C)	Loading type ²	Load level (kN)	Test label
S1	Reference	-	Static	75	S1_R
S2	Non-activated	-	Static	75	S2_NA
S3	Activated	160	Static	75	S3_A
S4	Activated	160	Fatigue	8.0–40.2	S4_F_A

¹ In this table, R, N, A, and F denote Reference, Non-activated, Activated, and Fatigue, respectively.

² The static and fatigue test were conducted at room temperature. The fatigue test was run with a loading frequency of 4.35 Hz and a load ratio of 0.2.

Table 3. The layouts for different geometries adopted for the parametric study using FEM*.

Parametric model No ¹ .	Number of nails per row	P1 (mm)	P2 (mm)	P3 (mm)	e1 (mm)	e2 (mm)	Parametric label ²	Scheme of nailing pattern	Geometric variables
P1	4	15	15	46	25	12	4p12_15_15_12
P2	4	20	15	46	25	12	4p12_20_15_12
P3	4	20	25	25	25	12.5	4p12_20_25_12.5
P4	4	20	20	20	25	20	4p12_20_20_20
P5	2	15	50	-	25	25	2p12_15_50_25
P6	2	15	33.3	-	25	33.3	2p12_15_33_33

* All the Fe-SMA strips had a width of 100 mm and a thickness of 1.5 mm.

¹. For all the models, the total number of nails were 12, which were parallel (and not staggered).

². In the parametric labels (Xp12_Y_Z_W), the first identifier (X) indicates the number of nails per row, the second one (Y) indicates the geometric parameter P1, the third one (Z) indicates the geometric parameter P2, and the fourth one (W) indicates the geometric parameter e2.

(a)

(b)

(c)

Figure 1. (a) Hilti DX 450 (125%) nail setting tool, (b) X-R 14 P8 nail with its measurements, (c) 12 nails applied to an Fe-SMA strip.

1
2
3
4
5

Figure 2. Lap-shear test setup with 3D digital image correlation (DIC) measurement system:
(a) photograph of test setup, (b) schematic view of test setup with different components.

6
7
8
9
10

Figure 3. Four-point bending test setup with different components. (a) Shooting nails with direct fastening tool, final bottom view of anchorage zone, and photograph of test setup; (b) Schematic view of four-point bending test setup with different measurement equipment and the three segments for activation using IRH unit.

Figure 4. Aramis DIC system for 3D measurement of full-field displacement of nail-anchor zone, IRH unit for radiative heating of Fe-SMA strip, and IR camera for recording surface temperature along beam depth.

Figure 5. (a) Schematic views of FE modeling for lap-shear tests with particular attention on anchorage zone and boundary conditions; (b) Interaction forces between contact areas within the connection zone; (c) Schematic views of FE modeling for four-point bending tests with two symmetric planes.

(a)

(b)

Figure 6. FEM stress distribution for static load of 100 MPa (far-field tensile stress): (a) along the length of strip for configurations 4p12_15_15_12 and 4p12_20_15_12, (b) along the width of strip for configurations 4p12_20_15_12, 4p12_20_25_125, and 4p12_20_20_20 (see Table 3).

Figure 7. FEM stress distribution along the width of strip for static load of 100 MPa (far-field tensile stress) for models 2p12_15_50_25 and 2p12_15_33_33.

(a)

(b)

Figure 8. (a) Load-slip behavior of all nail-anchor systems up to failure. (b) Tensile capacity and slippage at service load level of 75 kN (= 500 MPa in the Fe-SMA strip) (see Table 1 also).

(a)

(b)

Figure 9. (a) Slippage along anchorage length from FE model for 2p12_15_50_25 and lap-shear test of S3_2p12 (at load level equivalent to 100 MPa). (b) Test measurements of full-field longitudinal displacements from DIC system for the mentioned lap-shear test of S3_2p12 (at onset of failure).

Figure 10. Temperature history of Fe-SMA strip and bottom flange of steel beam during activation of the three segments.

Figure 11. Temperature gradient along depth of steel I-beam during activation process. The infrared camera was used from the side of the beam on segment I: (a) normal photo of steel I-beam and (b) temperature distribution along beam depth at the maximum temperature of 160 °C.

Figure 12. (a) Load versus mid-span deflection and (b) load versus strain in bottom flange of beam at mid-span including the corresponding FE simulations.

Figure 13. The minimum and maximum strain development in bottom flange of steel beam during fatigue loading for test S4_F_A (see Table 2).

Figure 14. The minimum and maximum strain development in Fe-SMA strip during the fatigue loadings for test S4_F_A. The figure also shows the linear trend lines for the strains under different temperature ranges.

Figure 15. Fatigue state of the holes in nail-anchor zone of Fe-SMA strips determined using CLD methodology [26]. Point A shows the state of the calculated maximum stress in the nail-anchor zone, which is inside the safe (blue) zone.