Iron-based shape memory alloy (Fe-SMA) for fatigue strengthening of cracked steel bridge connections

Mohammadreza Izadi ^{1,2*}, Masoud Motavalli ^{1,2}, Elyas Ghafoori ²

¹ School of Civil Engineering, University of Tehran, 16th Azar Street, Tehran, Iran

² Empa, Swiss Federal Laboratories for Materials Science and Technology, Überlandstrasse 129, 8600 Dübendorf, Switzerland

Abstract

Smart iron-based shape memory alloys (Fe-SMAs) are used in this study to retrofit fatigue-cracked riveted connections in steel bridges. The prestressed strengthening technique is found to be an effective approach to overcome fatigue-related damage in riveted connections. Because of the property of Fe-SMAs known as shape memory effect, these alloys can be prestressed without difficulty. The activated (i.e., prestressed) Fe-SMA strips (two 50-mm wide $\times$ 1.5-mm thick) are anchored to the flanges of a steel I-beam in either side of the connection. Thereafter, a test setup is specifically designed to examine the SMA-strengthened cracked double-angle connections. First, a static test is performed on the unstrengthened connection without any crack. Subsequently, two high-cycle fatigue (HCF) tests are conducted on a pre-cracked connection. The pre-cracked connection with no strengthening is subjected to fatigue loading with a load ratio of $R=0.1$. After practically $N = 2 \times 10^6$ loading cycles, the crack propagates up to 50% of the connection depth, whereas the fatigue crack growth rate gradually decreases because of the reduction in connection rigidity. Finally, the SMA-strengthened connection is

---

* Corresponding author. Structural Engineering Laboratory, Swiss Federal Laboratories for Materials Science and Technology (Empa), Überlandstrasse 129, CH-8600 Dübendorf, Switzerland. Tel.: +41 58 765 4872. Email addresses: mohammadreza.izadi@empa.ch, mohammadr.izadi@gmail.com

subjected to the HCF loading. It is observed that the fatigue life is substantially enhanced, and the fatigue crack is arrested by the activated Fe–SMA strips.

Keywords: Iron-based shape memory alloy (Fe–SMA); high-cycle fatigue (HCF); steel bridge connection; prestressed strengthening; fatigue crack

Nomenclature

L_s	stringer length	δ_{top}	top out-of-plane deformation of connection
L_c	cross-beam length	δ_{bot}	bottom out-of-plane deformation of connection
g	gauge distance	P_{min}	minimum applied external load
t	angle thickness	P_{max}	maximum applied external load
d	angle depth	σ_{min}^{mid}	minimum stress at midspan of stringer
M_p	secondary moment in connection	σ_{max}^{mid}	maximum stress at midspan of stringer
M_F	moment in fully fixed connection	Δ_{min}^{mid}	minimum deflection at midspan of stringer
α	degree of continuity	Δ_{max}^{mid}	maximum mid-deflection of stringer
R	stiffness ratio	M_{min}^-	minimum negative moment at connection
E_{st}	elastic modulus of stringer steel	M_{max}^-	maximum negative moment at connection
I_{st}	stringer moment of inertia	δ_{min}^{top}	minimum top deformation of connection
l_{st}	length of stringer	δ_{max}^{top}	maximum top deformation of connection
K_{st}	stringer flexural stiffness	ϵ_{min}^{SMA}	minimum strain in Fe–SMA strip
K_{rot}	rotational stiffness of connection	ϵ_{max}^{SMA}	maximum strain in Fe–SMA strip
E_{SMA}	elastic modulus of utilized Fe–SMA	K_I	mode-I stress intensity factor (SIF)
A_{SMA}	cross-sectional area of Fe–SMA strip	ΔK_I	mode-I SIF range
e	eccentricity	ΔK_{II}	mode-II SIF range
σ_r	recovery stress	ΔK_{III}	mode-III SIF range
$\Delta\sigma_r$	recovery stress change	$\Delta K_{I,th}$	mode-I threshold SIF range
M^-	negative moment on connection	ΔK_I^{top}	top crack mode-I SIF range
ϵ_{mid}^s	strain in bottom flange of stringer at midspan	ΔK_I^{bot}	bottom crack mode-I SIF range
Δ_{mid}	stringer deflection at midspan		

1. Introduction

Currently, the aging of existing railway and highway steel bridges has become a matter of apprehension among bridge proprietors; fatigue damage in various members of such bridges has resulted in insufficient load-carrying capacity and limited residual life. In a comprehensive study conducted by Haghani et al. [1], fatigue-vulnerable details in existing steel and composite bridges were identified and thereafter categorized. The study showed that the majority of

1 reported damage were caused by undesirable secondary effects, referred to as deformation-
2 induced cracking, in contrast with those that are load-induced. Generally, design codes and
3 standards provide considerably limited information on averting deformation-induced fatigue;
4 this has led to inadequate detailing. Consequently, the unintentional or ignored interaction
5 among different members through such detailing inadequacy has generated secondary stresses
6 that finally cause fatigue cracking in most details [2-5]. Extensive distortion-induced fatigue
7 cracking cases are reported in [2, 6, 7].

8 According to the studies in [1, 3, 4, 8, 9], there are two types of distortion-induced fatigue
9 cracking reported more prevalently (compared with the other details): first type is the
10 connections of cross-girders and stringers as well as the connections between cross-girders and
11 bottom chords, and the second type is the gap region in the cross-beam and diaphragm
12 connections. Both type of details face fatigue cracking in the connection angle/plate or an oval-
13 shape crack in the existing gap in the connection. In this study, the configuration of stringer-to-
14 floor beam is studied which represents the former type of the connections. The strengthening
15 system proposed in this study can be slightly changed and used for other types of connections.
16 In stringer-to-cross-girder connections, double angles that are riveted or bolted to the webs of
17 stringers and cross-girders are typically used. The general engineering practice is to design these
18 connections as simple connections. Although this assumption is satisfactory in the ultimate
19 limit-state design, undesirable deformation-induced fatigue cracking can occur in the service
20 limit state because of the semi-rigid connection behavior. This semi-rigidity partially restrains
21 the end rotation of the stringer; consequently, additional bending moments and secondary
22 stresses are generated in the connection. Figure 1 demonstrates the out-of-plane deformation of
23 the double-angle of the connection. As seen from the figure, owing to the stiffness of the
24 connection against the rotation, a secondary moment in the fillet of the angle and the tensile
25 stresses at the top of the connection are generated, which may result in fatigue cracking.

1.1. Strengthening solutions for fatigue-prone double-angle connections

Retrofitting of existing bridges can enhance their service lives and reduce the adverse impacts of demolition and reconstruction works on society, environment, and economy; eventually, an increase in sustainability is achieved [10]. Traditionally, two different retrofit techniques for the softening or stiffening of connections are employed to resolve the aforementioned problem of fatigue-cracked double-angle connections [11, 12]. In the first method, engineers have attempted to soften the connection by removing certain rivets/bolts and drilling holes around the crack tips to relieve the stresses [3, 12, 13]. In the second approach, the connections have been stiffened by welding/bolting additional elements to reduce or eliminate connection distortion [3]. Recent studies have demonstrated that these conventional retrofit methods are not always effective because reducing the stiffness of connections has resulted in larger deformations and certain amounts of damage in other components [13]. The welding of additional elements may also lead to additional fatigue cracks because of the residual stresses generated in the welded area; this renders the welded area itself prone to fatigue damage. Moreover, in some cases, the rivets are replaced by high-strength bolts; however, this technique does not repair the fatigue damage in the angles [14, 15]. On the other hand, it is presumed that the application of prestressed elements can be an effective method for strengthening bridge connections; this is because the stiffness of the connection is maintained and deformations are reduced.

The introduction of new materials, such as carbon-fiber reinforced polymers (CFRPs) and iron-based shape memory alloys (Fe-SMAs) with unique properties, overcomes the problems associated with conventional strengthening techniques [16-21]. The fatigue strengthening of various steel members with prestressed CFRP composites has already received considerable interest [18, 20, 22-24], whereas steel strengthening with prestressed (activated) Fe-SMAs has only been recently introduced [16, 21, 25]. With respect to all strengthening attempts with

1 prestressed CFRPs and Fe–SMAs, the latter is found to be considerably easier to prestress [16,
2 25]. Accordingly, in view of the complex geometric details involved in bridge riveted/bolted
3 connections, the prestressed Fe–SMA is deemed to be a suitable retrofit material to resolve the
4 fatigue-crack problem in double-angle connections.

5 **1.2. Activated Fe–SMAs as a strengthening solution**

6 Iron-based shape memory alloy materials have been developed and patented by the Swiss
7 Federal Laboratories for Materials Science and Technology (Empa), Switzerland. The static
8 tensile behavior and high-cycle fatigue behavior of the material in ambient temperatures for
9 outdoor civil structures have been studied in [16, 21, 26-28]. Moreover, the behavior of Fe–
10 SMA under corrosive environmental conditions [29-31] and its long-term durability and
11 stability [27, 32-36] have been investigated. Although there are a few studies on the corrosion
12 behavior of this alloy (e.g., [30]), further research on this topic is necessary. The material has
13 already been proved effective for prestressed strengthening applications because of its suitable
14 mechanical properties. In several studies, the Fe–SMAs have been employed for different post-
15 tensioning applications in concrete and steel structural elements [16, 21, 25, 37-39]. The
16 flexural, shear, and fatigue reinforcements of different structural members including plates,
17 beams, and columns have been fulfilled because of the so-called shape memory effect (SME)
18 of the material.

19 In several studies that were conducted by Izadi et al. [16, 21, 25] on different steel structural
20 members, activated Fe–SMA strips were used to enhance the load-carrying capacity and fatigue
21 performance. The pre-strained Fe–SMA strips were anchored and assembled via end
22 mechanical anchorages to steel beams and plates. Thereafter, to prestress the beams and plates,
23 the strips were electrically heated to the maximum target temperature. The response of Fe–
24 SMA to each step of strengthening (i.e., pre-straining, anchoring, activating, and external
25 loading) was examined; the successful application of SMAs on steel members was observed.

In a manner similar to that referred to as unbonded Fe–SMA strengthening system, which has been previously developed and introduced in [25, 40], the present research resolves the utilization of this retrofitting technique in the fatigue reinforcement of cracked double-angle connections. An innovative large-scale test setup is arranged for the static and fatigue testing of double-angle connections. Before mounting the retrofit system on the connection, static and fatigue loadings are performed. Connection behaviors, such as moment-rotation behavior (connection rigidity) and stress fields on the surface of angles, are investigated. Thereafter, crack propagation and damage development under fatigue loading in the angle of connection are investigated. In the final stage, the connection is strengthened with the unbonded Fe–SMA strengthening system and tested under fatigue loading for two million cycles. To comprehend the fatigue state of the connection before and after strengthening, finite element (FE) modeling is integrated. Finally, the effectiveness of the proposed retrofitting technique to delay the fatigue damage in double-angle connections is successfully demonstrated.

2. Fatigue performance of stringer-to-floor beam connections

Figure 2a shows a typical stringer-to-floor beam connection that exists in several in-service aged highway and railway bridges [41-45]. The out-of-plane distortion of the connection induces secondary stress concentrations in the connection. Bending and axial stresses in the angles and rivets/bolts are generated, respectively. The bending stress induces crack development in the fillet of the angle, whereas the axial stress initiates cracking in the junction between the rivet head and shank [3, 7, 14]. Both types of fatigue damage are generally located at the top (i.e., “tension” side) of the connection; nevertheless, there are also some cases where fatigue damage occurs at the bottom (i.e., “compression” side) of the connection [3, 46].

Al-Emrani [3] has demonstrated that the out-of-plane deformation is mainly affected by the bending stiffness of the outstanding leg. On the other hand, Wilson and Coombe [47] have

1 shown that the stiffness of the outstanding leg can be increased by either decreasing the rivet
2 gauge length (g) or increasing the angle thickness (t) (Figure 2b and 2c). In another study,
3 Wilson [48] suggested a design formula, $(g \geq \sqrt{\frac{Lt}{K}})$, where g is the gage distance, t is the angle
4 thickness, L is the length of the stringer, and K is a constant (8 for railway bridges)). The
5 American Railway Engineering and Maintenance-of-Ways Association (AREMA) [49] has
6 adopted the foregoing to ensure adequate flexibility in the outstanding leg and avoid fatigue-
7 related damage in the connection.

8 Similar to gage distance, which has a major contribution to fatigue cracking in the angles, it is
9 noteworthy that the clamping force mainly contributes to the rivet/bolt failure of the connection.
10 However, for high levels of clamping force, rivet/bolt failure is considerably less probable
11 because the axial stress range is substantially reduced [3, 14, 46]. Figures 2a and 2c, the main
12 parameters that affect the connection behavior are shown. As comprehensively explained by
13 the studies of Wilson [47, 48] and Guyer et al. [4], parameters such as stringer length (L_s), rivet
14 gage distance (g), angle thickness (t), and angle depth (d) mainly influence the connection
15 behavior.

17 **3. Large-scale testing program**

18 The experimental setup in this study is programmed to examine the fatigue damage
19 development in a bolted stringer-to-floor-beam connection and an SMA-based retrofit solution
20 to resolve the problem. Thereby, a framing configuration of the stringer-to-floor beam that
21 simulates the real floor system of bridges (i.e., particularly riveted railway bridges mostly
22 constructed in the early 1900s [3, 4]) is designed. The configuration consists of two stringers
23 connected to a cross beam via double-angle connections (Figures 2 and 3). The designed
24 stringer-to-floor beam system is then positioned in the loading frame, as shown in Figure 3. The

1 detailed description and design of the specimens, testing setup, and experimental procedure are
2 thoroughly explained in the subsequent sub-sections.

3 Moreover, Figure 3 shows the general scheme of the SMA-based strengthening system mounted
4 on the stringer-to-floor beam frame. The static and fatigue performance of the retrofit system
5 are discussed in [25, 40]. Izadi et al. [25, 40] conducted a series of static and fatigue tests on
6 the SMA-strengthened steel beam and connection; they utilized a flat prestressed unbonded
7 retrofit system (FPUR). The system was originally designed for the CFRP-strengthening of
8 steel girders [50] and reinforcing an old metallic bridge [51]. Subsequently, the efficiency of
9 the FPUR system was evaluated for the purpose of SMA-strengthening [25, 40]. As a brief
10 description, the retrofit system anchors two 50-mm wide activated (prestressed) Fe–SMA strips
11 to the top and bottom flanges of the steel I-beams. The system includes two anchoring clamps
12 that mechanically tie the Fe–SMA strips from both ends to the beam flanges. Compared with
13 the original application of the FPUR system, two thin friction shims and glass-fiber reinforced
14 polymer (GFRP) laminates are also embedded in between of the upper and lower clamping
15 plates inside the system for the SMA strengthening cases (see Figure 3b); further details on the
16 design and assemblage of different components of the system are found in [25, 40, 50]. More
17 information regarding the development of the FPUR system can be found in [50]. Along with
18 the results of the previous study on the development of the SMA-based FPUR system for
19 strengthening double-angle connections [40], the current study exploits the system for the
20 fatigue enhancement of the connection.

21 **3.1. Configuration of specimens**

22 Figure 4 shows the geometries and dimensions of the designed stringer and floor beam as well
23 as the detailing of the double-angle connection. As elaborated in Section 2, the most influential
24 parameters that affect the connection behavior are stringer length (L_s), connection thickness (t),

gage distance (g), and depth of connection (d). The scope and magnitude of these parameters are determined according to field observations [41, 52] and the standard code, AREMA [49].

The measurements of the typical stringer-to-floor beam decks of railway bridges [4, 41, 52] indicate that the stringer length ranges from 2.5 to 4.2 m; the minimum angle thickness of the connection is limited to 12 mm as specified in AREMA [49]. After determining the stringer length and angle thickness, the gauge distance (which does not conform with the design formula

proposed in AREMA [49] (i.e., $g \geq \sqrt{\frac{Lt}{K}}$)) is calculated. Finally, the ratio of the connection

depth to stringer depth and that of the stringer length to stringer depth (0.75–0.85 and 8–10

according to field measurements in [4, 41, 52], respectively) is used to determine the stringer

and angle depth; an M16 high-strength bolt with a 12.9-grade is employed. In this regard,

AREMA also limits the size of the bolt to a maximum of one-fourth of the width of the

outstanding leg. As explained in Section 2, the clamping force is the main factor in the fatigue

failure of bolts. Therefore, a considerable magnitude of pre-loading (clamping force) for M16

bolts (80 kN, which is equivalent to the applied torque of 180 Nm) is selected; this ensures that

the connection does not slip during static and fatigue loadings. On the other hand, the

investigation on the failure of the angle is primarily intended for retrofitting purposes. It is noted

that in order to reduce the residual stresses near the holes in the connection, all holes have to be

drilled in the same way and with a high precision.

For the fatigue tests (Section 4.2), a through-thickness notch (i.e., slot) is created at the top of

the connection in the angle fillet along the bolt centerline using electrical discharge machining

(EDM). The presence of the starter notch localizes and accelerates the onset of fatigue cracking

starting from the tip of the notch. The investigations on the SMA strengthening of the cracked

steel plate (with notch) in [16] and the finite element (FE) modeling of the connection in [40]

are employed to determine the geometry of the notch; Figure 4c shows the notch details.

3.2. Material characterization

Two different steel types are used for the steel beams (stringers and cross beams) and angles of connection: S235JR and S355JR, respectively. To characterize their material properties, tension tests are performed on three and two samples of steel beams and angles, respectively. The characterization tests are performed on 350-mm long samples according to DIN EN ISO 6892-1:2009 [53]. The obtained average values of the yield stress of steel beams and angles are 329 and 425 MPa, respectively. The properties of the steel utilized for different components of the test setup are summarized in Table 1.

In all the previous studies on the SMA strengthening of steel structures discussed in [16, 21, 25, 40], the Fe-SMA strips employed were 1.5 mm thick with variable widths and lengths of 50–100 mm and 500–5000 mm, respectively; in the current study, the strip width and length are 50 and 1000 mm, respectively. The static and fatigue behavior of this newly developed Fe-SMA at Empa, Switzerland, were thoroughly comprehended by the investigations reported in [16, 21, 54]: the initial elastic modulus, 0.2% yield strength, and recovery stress at 260 °C were found to be 160 GPa, 523 MPa, and 435 MPa, respectively [55]. Table 2 summarizes the reported mechanical properties from [55]. Additionally, thin friction foils [56] and glass fiber-reinforced polymer (GFRP) laminates [57] that are 0.1 and 0.2mm thick are employed, respectively. To provide sufficient friction between the steel and Fe-SMA substrates, friction shims are used. To ensure electrical insulation during the activation of the Fe-SMA strip, the GFRP plates are embedded in the retrofit system (details regarding the application and performance of these two parts in the SMA-based retrofit system are discussed in [21, 40]).

3.3. Test layouts

As shown in Figure 3, a stringer-to-floor beam test setup is designed to assess the fatigue strengthening of the cracked double-angle connection using the SMA-based retrofit system; Table 3 lists the connection test layout. In the first step, a static test is performed on the reference double-angle connection without strengthening (referred to C1_S_R). In the second step, a

high-cycle fatigue (HCF) test is performed on the notched connection without strengthening (denoted as C2_F_R); notch details are presented in Section 3.1. In the final step, the SMA-based system is mounted on the stringer-to-floor beam framing; the fatigue test performed on this new configuration is denoted as C3_F_A.

The main objectives of the static and fatigue tests on the connection without strengthening (i.e., tests C1_S_R and C2_F_R, respectively) are to study the local and global behaviors of the connection when subjected to static and fatigue loadings. The moment of the connection due to its semi-rigidity and the stress distribution in the fillet of the angle are investigated from the static test. The crack development when the notched connection is subjected to fatigue loading is investigated in the fatigue test. In the last test (C3_F_A) of the experimental program, the fatigue life enhancement of the connection with a fatigue pre-cracking and retrofitted with the activated SMA-based FPUR system is explored.

4. Experimental setup, instrumentations, and procedure

Two fatigue tests and one static test are performed using the test setup shown in Figure 3; the front view of the test setup is also shown in Figure 5a. Two hydraulic cylinders with a maximum static capacity of 250 kN are positioned with an axis-to-axis distance of 2.5 m; each cylinder is placed at the centerline of the stringer. The cylinders are actuated by a pulsator machine from Maschinenfabrik Alfred J. Amsler & Co., Switzerland. The test specimen is supported by four bearing supports, each placed under the ends of the stringers and floor beam (Figure 3).

The static and fatigue tests are conducted under load-controlled conditions using two 250-kN actuators. The static test is implemented with a maximum load of $P_{\max} = 75$ kN for each cylinder; this is equivalent to the maximum load applied in the fatigue tests, which are performed with minimum and maximum loads of $P_{\min} = 7.5$ kN and $P_{\max} = 75$ kN per cylinder, respectively. The fatigue load conforms with the minimum and maximum bending

stresses of $\sigma_{\min} = 13.3$ MPa and $\sigma_{\max} = 133.3$ MPa in the upper and lower flanges of the stringer beam without reinforcement (assuming that the stringer beam is simply supported from both ends), respectively. These stress levels are the maximum stresses experienced by the stringers to generate the maximum distortion effects on the connection (see more details in [3]). Figure 5 illustrates the different components and layout of the double-angle connection test setup along with other measurement points and sensors. During the static and fatigue loadings, the bending and axial strains are measured in the stringer, cross beam, and connection angle. Additionally, the midspan deflection of the longitudinal and transverse beams (stringers and cross beam, respectively) and the local deformation of the connection (connection rotation) are also recorded and measured.

Three strain gauges (SGb-1-3) of type 1-LY61-6/120, with a gauge factor of 2.05 and electrical resistance of $120 \Omega \pm 0.30\%$ (HBM GmbH company, Germany), are installed in the mid-width and mid-length of the bottom flanges of the stringers and cross beam. Moreover, five other strain gauges (SGb-4-8) with similar specifications are attached near the connection along the stringer depth at a distance of 150 mm from the cross-beam web. The strain gauges are used to measure the generation of strain during the static and fatigue tests. Nine strain gauges (SGa-1-9) of type 1-LY61-3/120 with the same electrical resistance but with a gauge factor of 1.99 (provided by HBM GmbH, Germany) are also mounted on the angle of the connection near the fillet. Furthermore, in the middle of the length and width of the two Fe-SMA strips, two 1-LY65-3/120 strain gauges, labeled as SGs-1 and SGs-2 (supplied by the same company), with a gauge factor of 2.01 and an electrical resistance of $120 \Omega \pm 0.30\%$ are installed. The ordering and numbering of measurement points are shown in Figure 5a and 5b.

Three OptoNCDT-ILD 2200 contactless laser displacement sensors (LDSs) with a measuring range of 100 mm (provided by Micro-Epsilon Messtechnik GmbH & Co. KG in Germany) are used to measure the midspan deflection of the stringer and cross beam (Figure 5a and 5b). Two

linear variable differential transformers (LVDTs) are also installed at the top and bottom of the connection to record the upper and lower deformation (rotation) of the connection, respectively.

4.1. Large-scale static test setup (test C1_S_R)

Figure 6 displays a photograph of the stringer-to-floor beam double-angle connection test setup. The midspan of the stringers is statically subjected by the actuators to the maximum load of 75 kN. During the static test, the strains and deflections read by the strain gauges and the displacement sensors, respectively, are analyzed to obtain the rotational behavior of the connection. The connection's moment-rotation curve and the corresponding moment developed because of the connection's flexural stiffness are obtained from the static test. Moreover, the static test results aid to comprehending the secondary bending stress distributions in the fillet of the connection angle.

4.2. Large-scale fatigue test setup

The effectiveness of the suggested retrofitting system is evaluated under two HCF loadings: on firstly the non-strengthened and secondly strengthened connection using tests C2_F_R and C3_F_A, respectively. The fatigue test is performed with load of approximately $\Delta P = 70$ kN and a load ratio of $R = 0.1$ (corresponding to stress range of $\Delta\sigma = 120$ MPa at the bottom flange of the stringer at midspan; no strengthening is applied, and a fully simple connection is assumed (Section 4)). The loading frequency of the pulsating machine employed is constant at 4.35 Hz. The fatigue tests are conducted for approximately maximum two million ($N = 2 \times 10^6$) loading cycles.

4.2.1. Fatigue test before strengthening (test C2_F_R)

Before mounting the retrofit system on the connection setup (Figure 3), the fatigue test is performed on the reference connection (with a notch at the top (Figure 4c)) without reinforcement to observe the crack development pattern and its effects on connection behavior.

To monitor crack propagation as well as visually control and observe the crack length in the connection angle, the test is temporarily halted every ~200 000 cycles.

4.2.2. Fatigue test after strengthening (test C3_F_A)

Following the fatigue test on the unstrengthened connection, the damaged connections are replaced with a new notched connection. Prior to the fatigue test, the connections have been pre-cracked to an initial length of approximately 1 mm from the bottom and top edges of the notch (Figure 4c). The pre-cracking simulates a real case of pre-cracked connection which in addition removes the residual stresses around the tip of the notch that are generated during the application of the EDM technique. Afterwards, the retrofit system is assembled on the pre-cracked connection and tested under the HCF loading with similar fatigue load levels in test C2_F_R (fatigue test on unstrengthened connection).

• Fatigue pre-cracking and strengthening with SMA-based reinforcement system

Figure 4 presents the details of the notch cut at the top of the connections. Subsequently, this notched connection is subjected to a fatigue test. The same load levels (as those in HCF loading) were used to pre-crack the connection from the notch tip. After approximately 50 000 load cycles, sharp 1-mm cracks are generated from the top and bottom edges of the notch. Thereafter, the SMA-based FPUR is mounted such that the pre-strained Fe–SMA strips pass over the top of connection and are anchored to the top flange of the stringers on each side of the connection (Figure 3); the strips are then activated (prestressed) to a maximum temperature of 260 °C. Figure 7 presents a photograph of the strengthened double-angle connection after the activation of the embedded Fe–SMA strips in the designed FPUR system [50]. The procedure for assembling the retrofit system on the double-angle connection configuration and its performance are comprehensively discussed in [25, 40].

• Fatigue test

Upon the completion of the pre-cracking and strengthening procedures, the fatigue load with the same load level as that applied to the unstrengthened connection ($\Delta\sigma = 120$ MPa with a stress ratio of $R = 0.1$) is applied on the strengthened connection. The fatigue crack growth after strengthening is monitored for $N = 2 \times 10^6$ loading cycles and compared with the crack advancement in the connection before strengthening.

5. FE simulation

As discussed in Section 2, the secondary bending stresses in the fillet of the angle because of the out-of-plane distortion of the connection can induce fatigue crack propagation. The crack propagates perpendicular to the direction of the maximum principal tensile stress (in this case, bending stress) along the depth of the connection. For the early stage of crack propagation, the bending stresses dominate the fatigue crack growth. Nevertheless, with some further crack propagation and with the presence of shear stresses, the combined effects of bending and shear stresses govern the crack scenario. However, the mechanisms for crack propagation is still based on maximum principal stress [58]. The fatigue crack growth is resolved by the mode-I stress intensity factor (SIF) range, $\Delta K_I = K_{I,max} - K_{I,min}$, at the tip of the crack during the early stages of propagation. In order to prevent crack propagation (full crack arrest), it is necessary for the SIF range (or corresponding tensile stress range in the vicinity of the crack tip) to be reduced to less than the Mode-I threshold SIF range ($\Delta K_{I,th}$) of the utilized steel (i.e., fatigue crack arrest condition). To this end, numerical simulations are implemented to evaluate the fatigue state of the pre-cracked connection before and after strengthening. The FE models of the connection without fatigue crack have already been created and validated with experimental results obtained from [40]. Section 6.1 also explains the tensile stress distribution in the angle of the non-cracked connection; the verified FE results are taken from [40].

Figure 8 displays the FE model of the pre-cracked connection strengthened with the SMA-based FPUR system. The materials utilized are isotropic linear elastic materials; their

corresponding mechanical properties are described in Section 3.2. Except for the crack tip with six-node linear triangular prism elements (C3D6), eight-node linear brick elements with reduced integration (C3D8R) are utilized to discretize different geometries (a minimum size of 2 mm in the connection and a maximum size of 50 mm in the beams). As shown in the figure, the element size around the crack tip is considerably refined to compute the stress/strain fields accurately. To calculate the SIF in ABAQUS, a contour integral analysis is incorporated into the model. Considering the symmetry of the specimen and to reduce computational time, only a quarter of the whole geometry is modeled. The boundary conditions are then assigned to the symmetric planes. In order to simulate the pre-stressing of the Fe–SMA strip and external applied load, two different static loading steps are defined in addition to the initial step. The pre-stressing, which is taken from the results of the activation tests (further details on the modeling of the prestressed Fe–SMA strips are found in [16, 40]), is first introduced in the initial step and thereafter redistributed in the first loading step. The external maximum static load is finally simulated in the second loading step by the equivalent static uniform pressure.

6. Experimental and numerical results and discussions

6.1. Large-scale static test results (test C1_S_R)

The static testing prior to fatigue loading is performed to obtain information on the flexural stiffness of the connection and the moment that is generated because of this stiffness. Figures 9a and 9b show the moment–rotation curve of the connection and the stringer-end moment developed on the connection for the applied static load, respectively. The magnitude of the moment is calculated from the measured bending strains at the middle of the stringer, whereas the rotation of the connection is derived from the top and bottom LVDTs (further details on the double-angle connection static behavior are found in [40]). Because of the semi-fixity of the connection, it is evident that the stringer has partial rigidity at the end where the moment is

generated, as shown in Figure 9. For the stringer, the so-called degree of continuity, α , is defined as [3] follows:

$$\alpha = \frac{M_p}{M_F} = \frac{3/2}{1+R}, R = \frac{3E_{st}I_{st}/l_{st}}{K_{rot}} = \frac{K_{st}}{K_{rot}} \quad (1)$$

where M_p is the moment generated in the connection, M_F is the moment if a fully fixed connection is assumed, R is the stiffness ratio, K_{rot} is the rotational stiffness of the connection, K_{st} is the flexural stiffness of the stringer, E_{st} is the elastic modulus of the stringer, I_{st} is the moment of inertia of the stringer, and l_{st} is the stringer length.

Table 4 lists the resulting behavioral parameters of the connection obtained from the static test. The parameters include rotational stiffness, degree of continuity, and stringer-end moment. As indicated by the table, the restraint induced at the stringer end from the connection is significant such that it produces a moment that is approximately 66% of that in an assumed fully continuous connection. The rotational stiffness of the connection subjected to the maximum load of 75 kN is estimated to be 6305 kNm/rad. As discussed in previous sections, the rotational stiffness of the double-angle connection is a function of the flexural stiffness of the outstanding leg along the gage length.

The rotational stiffness of the connection is calculated by the analytical model proposed by Wilson and Coombe [47]. In this model, the outstanding leg is assumed to be fixed along the bolt center line and angle fillet (with the translation at the angle fillet). Based on the model, the stiffness is estimated to be 6831 kNm/rad, which is in good agreement with the static test results. As illustrated in Figure 9a, the rotational behavior of the connection is non-linear (even to a small extent) although the measured strain values are below the yielding strain of steel. This may explain the occurrence of plastic deformation in certain areas in the connection with a local high-stress concentration; such areas include the vicinity of the angle fillet and around the holes. Because nonlinearity begins at the initial loading stage, this indicates that other (or additional)

factors, such as the pre-loading of bolts, existing tolerance, and small gaps between different components, could also contribute to the nonlinear behavior of the connection.

Figure 10 shows the stresses measured near the angle fillet along the depth of the connection. A significant portion of the connection deformation (or rotation) resulting from the rotation of the stringer end is restrained because of connection stiffness. As a result of the rigidity of the connection with respect to rotation, the connection depth is primarily subjected to tensile stresses (see Figure 10). The figure shows the tensile stress distribution along the depth; it can be observed that the upper part of the connection where the out-of-plane deformation reaches its maximum sustains higher tensile stresses. This highly stressed area at the top of the connection explains why fatigue cracks are triggered from this location of the double-angle connections. Moreover, it is observed that the secondary stresses generated are approximately identical in all the tests performed.

6.2. Large-scale fatigue test results

6.2.1. Fatigue crack growth before strengthening (test C2_F_R)

During the fatigue test on the unstrengthened notched connection, the crack length is periodically measured using an optical measurement device with a magnification factor of 30. The fatigue loading is halted every 200 000 cycles to measure the crack length. The fatigue crack development in the connection angle is shown in Figure 11; the crack initiates and propagates from the edges of the notch at the top of the connection. The growth rate of the crack is relatively rapid; however, with the decrease in the connection stiffness (that also reduces the critical tensile stresses in the angle fillet) because of the reduction in the flexural strength of the outstanding leg, the crack growth rate is reduced. Finally, after $N = 2.3 \times 10^6$ loading cycles, an 80-mm long crack up to the middle of the connection (approximately 50% of the connection depth) is observed. Figure 11 also illustrates that when the load cycle is one million and the crack length is 30 mm, the upper bolt of the connection fails. Despite the failure of the bolt, the

connection is still able to transfer the shear forces; until the bolt is replaced (by the end of 100 000 cycles after bolt failure), no crack growth is observed because of the significant reduction in the bending stiffness of the connection (Figure 12a). It is noteworthy that with the crack development, higher stress ranges are gradually induced on the bolt because the cracked part of the outstanding leg has become incapable of sustaining bending stresses. Moreover, the reduction in the bolt clamping force increases the applied stress ranges on the upper bolt; this causes fatigue damage to accumulate in the bolt.

The gradual reduction in the rotational stiffness of the connection is accompanied by the crack development in the double-angle connection (Figure 12a). This gradual decrease (or softening of the connection) is associated with a decrease in moment in the connection (or bending stresses in the fillet of the angle) and an increase in the connection rotation (upper and lower deformations, as shown in Figure 13a). Thus, this behavior causes a decrease in the fatigue crack growth rate, which is indicated by the gradual increase in the bending stress and vertical deflection in the middle of the stringer (Figures 12b and 13b). The crack extension in the connection angle during the different stages of crack propagation, the bending stiffness of the connection, bending moment in the connection, and bending stress in the bottom flange of the stringer are summarized in Table 5. With the growth of fatigue cracking in the connection angle after $N = 2 \times 10^6$ loading cycles, the degree of continuity is reduced from approximately $\alpha = 66\%$ to 52% , and the flexural stiffness of the connection is reduced from approximately 6300 to 4400 kNm/rad.

6.2.2. Fatigue crack growth after strengthening (test C3_F_A)

After assembling and activating the SMA-based retrofit system on the pre-cracked connection, the SMA-strengthened connection is subjected to two million cycles with frequency of 4.35 Hz. The static performance of the connection strengthened with the aforementioned SMA strengthening system is comprehensively described in [40]. Indeed, the out-of-plane distortion

of the connection, which is the major source of fatigue cracking in the double-angle connection, is substantially reduced. The retrofit system decreases the amount of stringer-end rotation by providing a reverse rotation relative to the original moment (with pre-stressing forces in the activated Fe–SMA strips) while it further “absorbs” some other amounts of rotation by providing additional stiffness (axial stiffness of the strip); further details regarding the performance of the proposed SMA-strengthening system are found in [40]. The minimum and maximum deformations at the top and bottom of the connection (i.e., $\delta_{\min}^{\text{bot}}$, $\delta_{\max}^{\text{bot}}$, and $\delta_{\min}^{\text{top}}$, and $\delta_{\max}^{\text{top}}$) when subjected to fatigue cycles before and after strengthening are shown in Figure 14. After the connection is strengthened and thereafter subjected to two million loading cycles, the fatigue crack does not propagate, which indicates the complete arrest of the crack. The top and bottom out-of-plane deformations of the connection during fatigue loading are constant, as shown in Figure 14; this also proves that the fatigue crack does not propagate (full arrest of the crack or infinite fatigue life) after connection strengthening.

Because of the complexity of connection geometry, the clip gauges could not be installed to measure the crack mouth opening for the purpose of detecting the crack arrest. Instead, in order to observe the near-field behavior of the crack, two small strain gauges are installed around the upper and lower tip of the notch (Figure 15). The evolution of the minimum and maximum strains (i.e., $\epsilon_{\min}$ and $\epsilon_{\max}$, respectively) versus the fatigue cycles for the two strain gauges is shown in Figure 15. In this figure, the minimum and maximum strains measured by the two strain gauges in connection without strengthening (test C2_F_R) decrease with fatigue loading; this phenomenon is attributed to the crack tip’s movement away from the two strain gauges. On the other hand, in the strengthened connection (test C3_F_A), the strain has no descending trend, and the strain levels measured by the two strain gauges are constant. In fact, the constant level of strains (except for strain increases during the early stages of fatigue loading cycles that result from the stress recovery reduction in the Fe–SMA) confirms the crack closure; this

constant strain level is also observed from the top and bottom deformations measured by the top and bottom LVDTs, respectively. Table 6 summarizes the test results of fatigue test C3_F_A.

Figure 16 shows the average minimum and maximum strains in the activated Fe–SMA strips against the loading cycles. During the two million loading cycles, the strain in the mid-length of the strip remains constant. A minimal increase in the strain level during the initial stages of fatigue loading is attributed to the stress recovery reduction [16, 26], which is approximately 37 MPa in the Fe–SMA strips. The stability of the strain level in the Fe–SMA during cyclic loading indicates that there is no slippage in the connection strengthened with the proposed retrofit system; it further indicates the satisfactory performance of the system during fatigue loading [25].

6.2.3. FE results

In order to observe a possible fatigue crack arrest, the mode-I SIF range (ΔK_I) is determined from the FE modeling. The built-in contour integral technique in ABAQUS FE package involves the J-integral calculation along the contour surrounding the crack tip. The final mode-I SIF is determined when J-integrals numerically converge. The calculated mode-I SIFs for different applied load levels are shown in Figure 17, where it can be observed that the mode-I SIF value for the cracks at the top and bottom of the notch (top crack and bottom crack, respectively) are reduced after the connection is strengthened. The SIF range values of the top crack are $\Delta K_I^{\text{top}} = 534$ and $271 \text{ N/mm}^{3/2}$ before and after strengthening, respectively; for the bottom crack, these are $\Delta K_I^{\text{bot}} = 521$ and $168 \text{ N/mm}^{3/2}$ before and after strengthening, respectively. As comprehensively explained in the previous sections, the tensile stresses on the critical cracked part of the connection are reduced after being strengthened with the SMA-based FPUR system. As a result, the SIF range is reduced to values that are lower than the threshold value of mild steel, i.e., $\Delta K_I \leq \Delta K_{I,\text{th}}$ (further information on threshold values can be found in

[59]); this proves the experimentally observed fatigue crack arrest. It is worth to note that based on the FE modeling, the value of mode-II and III SIFs (i.e., ΔK_{II} and ΔK_{III}) were approximately zero during the early stage of crack growth.

7. Summary and conclusions

This study demonstrates the effectiveness of the activated/prestressed iron-based shape memory alloy (Fe–SMA) strips for the fatigue retrofit of connections in steel bridges. The existing steel double-angle connections in riveted railway bridges are normally prone to fatigue cracking because of the semi-rigid behavior of the connection. The retrofit system includes activated/prestressed Fe–SMA strips that connect the top flanges of the two stringers on the sides of the connection. Two 50-mm wide $\times$ 1.5-mm thick Fe–SMA strips are inserted inside the end anchorage systems that are mounted on the top flange of the beams on each side of the connection. Thereafter, the strips are activated (prestressed) to a maximum temperature of 260 °C. A new stringer-to-floor beam double-angle connection test setup is specially designed to examine the performance of the proposed system. In the first step, a static test is performed on the connection without the strengthening system. The degree of continuity of the connection is $\alpha = 66\%$ of the corresponding moment of an assumed fully continuous connection. Thereafter, two fatigue tests are performed on the unstrengthened and strengthened connection. The fatigue crack growth is approximately 50% of the connection depth after $N = 2 \times 10^6$ loading cycles. In the succeeding step, the SMA-based retrofit system is mounted on the connection test setup and subjected to another $N = 2 \times 10^6$ loading cycles with the same load level. The conclusions derived from the study are as follows:

1. The rotational stiffness of the connection for a maximum static load of 75 kN (equivalent to the maximum load in the fatigue test) is 6305 kNm/rad; this results in a stringer-end moment of 15.5 kNm.

2. The fatigue test is applied to the pre-cracked unstrengthened connection with a stress range of $\Delta\sigma = 120$ MPa and a stress ratio of $R = 0.1$ in the bottom flange at midspan; a simply supported stringer is assumed. With fatigue crack growth in the connection angle after $N = 2 \times 10^6$ load cycles, the degree of continuity is reduced from approximately from $\alpha = 66\%$ to 52%, and the flexural stiffness of the connection is reduced from approximately from 6300 to 4400 kNm/rad.

3. The use of activated/prestressed Fe–SMA strips in the FPUR system results in a complete crack arrest at the top of the connection. The out-of-plane connection deformation (or stringer end moment of the connection), which is the major cause of fatigue cracking, is substantially reduced after strengthening.

Conflict of interest

The authors declare no conflicts of interest.

Acknowledgements

The authors gratefully recognize Zurich University of Applied Sciences (ZHAW), Winterthur, Switzerland (commissioned by State Secretariat for Education, Research, and Innovation (SERI)) for providing the mobility grant for the bilateral research collaboration with South Asia and Iran 2017–2019. The authors also thank the technicians of the Structural Engineering Research Laboratory of Empa, Switzerland for their exceptional support in performing the experiments. Furthermore, the authors acknowledge the support of Von Roll Deutschland GmbH for providing the GFRP laminates.

References

1. Haghani, R., M. Al-Emrani, and M. Heshmati, *Fatigue-prone details in steel bridges*. Buildings, 2012. **2**(4): p. 456-476.
2. Fisher, J.W., B. Yen, D. Wang, and J. Mann, *Fatigue and fracture evaluation for rating riveted bridges*. 1987.
3. Al-Emrani, M., *Fatigue in Riveted Railway Bridges-a study of the fatigue performance of riveted stringers and stringer-to-floor-beam connections*. 2002: Chalmers University of Technology.
4. Guyer, R.C. and J.A. Laman, *Distortion-induced stress investigation of double angle stringer-to-floorbeam connections in railroad bridges*. Engineering Structures, 2012. **38**: p. 104-112.
5. Aygül, M., M. Al-Emrani, Z. Barsoum, and J. Leander, *An investigation of distortion-induced fatigue cracking under variable amplitude loading using 3D crack propagation analysis*. Engineering Failure Analysis, 2014. **45**: p. 151-163.
6. Fisher, J.W., *Distortion-induced fatigue cracking in steel bridges*. 1990: Transportation Research Board.
7. Al-Emrani, M., B. Åkesson, and R. Kliger, *Overlooked secondary effects in open-deck truss bridges*. Structural engineering international, 2004. **14**(4): p. 307-312.
8. DePiero, A.H., R.K. Paasch, and S.C. Lovejoy, *Finite-element modeling of bridge deck connection details*. Journal of Bridge Engineering, 2002. **7**(4): p. 229-235.
9. Fisher, J., J. Jin, D. Wagner, and B. Yen, *NCHRP Report 336: Distortion Induced Cracking of Steel Bridges*. Transportation Research Board, National Research Council, Washington, DC (December 1990).
10. Ghafoori, E., *Editorial for special issue on Sustainable Metallic Structures*. Engineering Structures, 2019. **183**: p. 83.
11. Kuehn, B., M. Lukić, A. Nussbaumer, H.-P. Guenther, R. Helmerich, S. Herion, M. Kolstein, S. Walbridge, B. Androic, and O. Dijkstra, *Assessment of existing steel structures: recommendations for estimation of remaining fatigue life*. JRC Scientific and technical Report, 2008(43401).
12. Bowman, M.D., *Fatigue evaluation of steel bridges*. Vol. 721. 2012: Transportation Research Board.
13. Roeder, C.W., G.A. MacRae, K. Arima, P.N. Crocker, and S.D. Wong, *Fatigue cracking of riveted steel tied arch and truss bridges*. 1998.
14. Al-Emrani, M. and R. Kliger, *FE analysis of stringer-to-floor-beam connections in riveted railway bridges*. Journal of Constructional Steel Research, 2003. **59**(7): p. 803-818.
15. Roeder, C.W., G. MacRae, A. Leland, and A. Rospo, *Extending the fatigue life of riveted coped stringer connections*. Journal of Bridge Engineering, 2005. **10**(1): p. 69-76.
16. 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.
17. Hollaway, L. and J. Cadei, *Progress in the technique of upgrading metallic structures with advanced polymer composites*. Progress in Structural Engineering and Materials, 2002. **4**(2): p. 131-148.
18. Teng, J., T. Yu, and D. Fernando, *Strengthening of steel structures with fiber-reinforced polymer composites*. Journal of Constructional Steel Research, 2012. **78**: p. 131-143.
19. Ghafoori, E. and M. Motavalli, *Normal, high and ultra-high modulus carbon fiber-reinforced polymer laminates for bonded and un-bonded strengthening of steel beams*. Materials & Design, 2015. **67**: p. 232-243.
20. Ghafoori, E., M. Motavalli, J. Botsis, A. Herwig, and M. Galli, *Fatigue strengthening of damaged metallic beams using prestressed unbonded and bonded CFRP plates*. International Journal of Fatigue, 2012. **44**: p. 303-315.

21. 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.
22. Ghafoori, E. and M. Motavalli, *Lateral-torsional buckling of steel I-beams retrofitted by bonded and un-bonded CFRP laminates with different pre-stress levels: Experimental and numerical study*. Construction and Building Materials, 2015. **76**: p. 194-206.
23. Ghafoori, E. and M. Motavalli, *Innovative CFRP-prestressing system for strengthening metallic structures*. Journal of Composites for Construction, 2015. **19**(6): p. 04015006.
24. 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.
25. Izadi, M.R., E. Ghafoori, A. Hosseini, J. Michels, and M. Motavalli, *Thermally Activated Iron-Based Shape Memory Alloy for Strengthening Metallic Girders*. Thin-Walled Structures 2019. **141**: p. 389-401.
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. 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.
28. 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.
29. Lee, W., R. Partovi-Nia, T. Suter, and C. Leinenbach, *Electrochemical characterization and corrosion behavior of an Fe-Mn-Si shape memory alloy in simulated concrete pore solutions*. Materials and Corrosion, 2016. **67**(8): p. 839-846.
30. Michels, J., M. Shahverdi, C. Czaderski, and R. El-Hacha, *Mechanical Performance of Iron-Based Shape-Memory Alloy Ribbed Bars for Concrete Prestressing*. ACI Materials Journal, 2018. **115**(6): p. 877-886.
31. Hosseini, A., J. Michels, M.R. Izadi, and E. Ghafoori, *A comparative study between Fe-SMA and CFRP reinforcements for prestressed strengthening of metallic structures*. Construction and Building Materials (Accepted), 2019.
32. 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.
33. Lee, W., B. Weber, G. Feltrin, C. Czaderski, M. Motavalli, and C. Leinenbach, *Phase transformation behavior under uniaxial deformation of an Fe-Mn-Si-Cr-Ni-VC shape memory alloy*. Materials Science and Engineering: A, 2013. **581**: p. 1-7.
34. 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.
35. 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.
36. 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.
37. 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.

38. Shahverdi, M., C. Czaderski, and M. Motavalli, *Iron-based shape memory alloys for prestressed near-surface mounted strengthening of reinforced concrete beams*. Construction and Building Materials, 2016. **112**: p. 28-38.
39. Shahverdi, M., C. Czaderski, P. Annen, and M. Motavalli, *Strengthening of RC beams by iron-based shape memory alloy bars embedded in a shotcrete layer*. Engineering Structures, 2016. **117**: p. 263-273.
40. Izadi, M.R., E. Ghafoori, M. Motavalli, and S. Maalek, *On the Behavior of Fe-SMA Strengthened Steel Bridge Connection*. Scientia Iranica (submitted for publication), 2019.
41. Leighty, C.A., J.A. Laman, and G.L. Gittings, *Heavy axle study: impact of higher rail car weight limits on short-line railroad bridge structures*. Civil Engineering and Environmental Systems, 2004. **21**(2): p. 91-104.
42. Pipinato, A., C. Pellegrino, O. Bursi, and C. Modena, *High-cycle fatigue behavior of riveted connections for railway metal bridges*. Journal of Constructional Steel Research, 2009. **65**(12): p. 2167-2175.
43. Gocál, J., J. Vičan, R. Hlinka, and J. Jošt, *Laboratory tests of a typical fatigue prone riveted steel railway bridge structural detail*. Procedia Engineering, 2010. **2**(1): p. 1761-1766.
44. Imam, B.M., T.D. Righiniotis, and M.K. Chryssanthopoulos, *Numerical modelling of riveted railway bridge connections for fatigue evaluation*. Engineering Structures, 2007. **29**(11): p. 3071-3081.
45. Imam, B., T.D. Righiniotis, and M.K. Chryssanthopoulos, *Fatigue assessment of riveted railway bridges*. Steel Structures, 2005. **5**(5): p. 485-494.
46. Wang, D., *Fatigue behavior of mechanically fastened double angle shear connections in steel bridges*. Dissertation Abstracts International, 1990.
47. Wilson, W.M. and J.V.V. Coombe, *Fatigue tests of connection angles*. 1939, University of Illinois at Urbana Champaign, College of Engineering. Engineering Experiment Station.
48. Wilson, W. *Design of connection angles for stringers of railway bridges*. in *proceedings of the Forth-First Annual Convention*. American Railway Engineering Association. 1940.
49. Manual, A., *American Railway Engineering and Maintenance-of-Way Association*. 2006.
50. 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.
51. 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.
52. Laman, J.A. and R.C. Guyer, *Condition assessment of short-line railroad bridges in Pennsylvania*. Pennsylvania: The Thomas D. Larson Pennsylvania Transportation Institute. The Pennsylvania State University, 2010.
53. ISO, E., *6892-1. Metallic materials-Tensile testing-Part 1: Method of test at room temperature*. International Organization for Standardization, 2009.
54. Ghafoori, E., E. Hosseini, and J. Michels, *Stress recovery behavior of an Fe-Mn-Si-Cr-Ni-VC shape memory alloy subjected to high-cycle fatigue loading*.
55. 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.
56. Product Information, M.F.S.a.C., ESK Ceramics GmbH & Co. KG, Germany, <http://technical-ceramics.3mdeutschland.de>.
57. Laminates VETRONIT G11, V.R.D.G., D-86199 Augsburg, www.vonroll.com.
58. Hosseini, A., A. Nussbaumer, M. Motavalli, X.-L. Zhao, and E. Ghafoori, *Mixed mode I/II fatigue crack arrest in steel members using prestressed CFRP reinforcement*. International Journal of Fatigue, 2019.

59. 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.

Table 1. Mechanical properties of steel materials in various components of double-angle connection test setup.

Member	Standard profile	Steel grade	Elastic modulus (GPa)	Yield stress (MPa)	Ultimate stress (MPa)
Stringer	INP 240	S235JR	205.3	329	446
Cross beam	INP 300	S235JR	205.3	329	446
Angle	100 × 100 × 10	S355JR	209.3	422	563

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22

Table 2. Reported mechanical properties of utilized Fe–SMA strip [55].

Member	Cross-section (mm ²)	Stress recovery at T _a = 260 °C (MPa)	Elastic modulus (GPa)	0.2% Yield stress (MPa)	Ultimate stress (MPa)	Ultimate elongation (%)
Fe–SMA	50 × 1.5	435	160	523	980	45.2

Table 3. Test layout.

Test Label	Pre-cracked connection	Loading type	Strengthening ¹	Test Description
C1	No	Static	No	Reference (C1_S_R)
C2	Yes	Fatigue	No	Reference (C2_F_R)
C3	Yes	Fatigue	Yes	Activated Fe-SMA (C3_F_A)

¹SMA-based FPUR system includes two 50-mm wide and 1.5-mm thick Fe-SMA strips

In the table, C, S, R, F, and A denote connection, static, reference, fatigue, and activated, respectively.

Table 4. Behavioral parameters of double-angle connection subjected to a maximum static load of $P_{\max} = 75$ kN.

Rotational stiffness (kNm/rad)	Degree of continuity (%)	Stringer end moment (kNm)
6305	66.3	15.5

Table 5. Results of fatigue test on unstrengthened pre-cracked connection (test C2_F_R,
 $P_{\min} = 7.5 \text{ kN}$, $P_{\max} = 75 \text{ kN}$).

	M^- kNm	$\varepsilon_{\text{mid}}^s$ μ	K_{rot} kNm/rad	α %	Δ_{mid} mm	δ_{top} mm	δ_{bot} mm	Crack length (mm)	
$N = 1$	15.5	554	6305	66.3	2.85	0.33	0.26	$a_0 = 0$	
$N = 1.0 \times 10^6$	12.8	563	5410	60.1	3.05	0.4	0.28	$a_1 = 35$	
$N = 2.0 \times 10^6$	9.9	573	4454	52.6	3.15	0.45	0.59	$a_2 = 69$	

Fatigue test performed at room temperature; loading frequency: $f_r = 4.35 \text{ Hz}$

Table 6. Results of fatigue test on strengthened pre-cracked connection (test C3_F_A, $P_{\min} = 7.5 \text{ kN}$, $P_{\max} = 75 \text{ kN}$).

	Fatigue load		Stringer				Connection				Fe-SMA	
	$P_{\min}$	$P_{\max}$	$\sigma_{\min}^{\text{mid}}$	$\sigma_{\max}^{\text{mid}}$	$\Delta_{\min}^{\text{mid}}$	$\Delta_{\max}^{\text{mid}}$	$M_{\min}^-$	$M_{\max}^-$	$\delta_{\min}^{\text{top}}$	$\delta_{\max}^{\text{top}}$	$\varepsilon_{\min}^{\text{SMA}}$	$\varepsilon_{\max}^{\text{SMA}}$
	kN	kN	MPa	MPa	mm	mm	kNm	kNm	mm	mm	%	%
C4_F_A ¹	7.5	75	8.3	102	0.26	2.35	-8.1	5.9	-0.03	0.18	1.25	1.33

¹ Complete fatigue crack arrest achieved after strengthening with SMA-based FPUR system

(a)

(b)

Figure 1. (a) Schematic drawing of the stringer-to-floor beam connection under end-moment loading. (b) Deformed shape of the double-angle detail and the corresponding generated distortion-induced secondary effects in the angle.

Figure 2. (a) Typical stringer-to-floor beam double-angle connection: L_s is stringer length, L_c is cross beam length, and d is depth of connection angle. (b) Side view of connection. (c) Cross-sectional view across top rivet/bolt center line: g is gage distance, and t is angle thickness.

1

2

3

Figure 3. (a) General assembly of stringer-to-floor beam system in a loading frame with corresponding end bearings. (b) Magnified view of SMA-based retrofit system including embedded friction shims and GFRP laminates; refer to [25, 40, 50] for further details on SMA-based FPUR system.

4

5

6

Figure 4. (a) Designed geometry of stringer (longitudinal beam) and cross beam (transverse beam) in stringer-to-floor beam test setup. (b) Design details of double-angle connection. (c) Details of 1-mm wide notch. All units are in mm.

1
2
3
4
5

Figure 5. (a) Front view of connection test setup showing locations of strain gauges and laser displacement sensors (LDSs) (Figure 2). (b) Strain gauges installed near connection along stringer depth and on connection angle; LDS at midspan of cross beam; the linear differential variable transformer (LVDT) at top and bottom of connection.

6
7
8

1
2
3
4
5
6
7

Figure 6. Components of double-angle connection test setup: two 250-kN cylinders, strain gauges, LDSs, and LVDTs.

8
9
10
11
12
13
14

Figure 7. Double-angle connection strengthened with proposed SMA-based FPUR system and end-mechanical anchorage systems clamped the activated Fe–SMA strips at both ends.

Figure 8. FE simulation of stringer-to-floor beam cracked double-angle connection with mounted SMA-based FPUR system.

1
2
3
4
5
6
7
8
9

(a) (b)
Figure 9. (a) Moment-rotation behavior of double-angle connection. (b) Moment-load curve derived from bending stress measurements at mid-length of stringer during static test.

10
11
12
13
14
15

Figure 10. Flexural stresses along depth of connection angle for three different load levels: $\frac{P_{\max}}{3} = 25 \text{ kN}$, $\frac{2P_{\max}}{3} = 50 \text{ kN}$, and $P_{\max} = 75 \text{ kN}$; FE modeling results extracted from [40] are also displayed with experimental results.

Figure 11. Fatigue crack development in double-angle connections.

(a)

(b)

Figure 12. (a) Reduction in rotational stiffness of double-angle connection with fatigue crack development; (b) subsequent increase in bending stress in bottom flange of stringer at midspan.

Figure 13. (a) Minimum and maximum deformations at top and bottom of connection followed by a decrease in rotational stiffness. (b) Minimum and maximum midspan deflections of stringer during fatigue loading.

Figure 14. Out-of-plane deformation of double-angle connection before and after strengthening.

Figure 15. Evolution of minimum and maximum strains ($\epsilon_{\min}$ and $\epsilon_{\max}$, respectively) measured by strain gauges attached near fatigue crack tip before and after strengthening.

Figure 16. Evolution of minimum and maximum average strains in activated/prestressed Fe-SMA strips versus number of loading cycles.

Figure 17. Calculated mode-I SIF (K_I) for 1-mm long pre-cracks at top and bottom of notch (top and bottom cracks, respectively) before and after strengthening.