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Smart SMA-based system for fatigue strengthening of cracked metallic bridge connections

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ABSTRACT: In this study, a new retrofit system is proposed to enhance the load-carrying capacity of double-angle connections in aged railway steel bridges. The double-angle connections between the stringers and the cross beams are normally prone to fatigue cracking owing to semi-rigid (not simple) behavior of the connection. The retrofit system includes activated Fe-SMA strips that pass over the top of the connection. Two Fe-SMA strips of 50 × 1.5 mm (width × thickness) are sandwiched inside the end anchorage systems that are mounted on the top flange of the beams in each side of the connection. The strips are then activated (pre-stressed) to maximum temperature of 260 °C. A new stringer-to-floor beam double-angle connection test setup was specially designed to examine the performance of the proposed system. Initially, a static test was performed on the connection without strengthening system. Therefore, the local and global response of the connection were studied. In the next step, two high cycle fatigue (HCF) tests were performed on the non-strengthened and strengthened connection in a stringer-to floor beam framing in the test setup. It was observed that the fatigue life was enhanced substantially using the activated (i.e. pre-stressed) Fe-SMA strips. The activated Fe-SMA strips reduce tensile stresses (due to the reduction of moment on the connection) in the critical cracked detail in the steel connection, which is beneficial for fatigue life.

1 INTRODUCTION

The majority of railway and highway steel bridges are aging that make these structures vulnerable to fatigue damages (Kuehn et al. (2008), Teng et al. (2012), Al-Emrani (2002)). Fatigue damaged details are even more deteriorated in corrosive environmental conditions or when subjected to increased service loads. Various geometries and details are reported with respect to fatigue cracking. Haghani et al. (2012) reveals a study that report a wide-range of the most fatigue-prone details in steel bridges. Among the reported damaged detailing, the connections between the main girders of the bridges with transversal beam (also called cross beam or floor beam) or the latter one with the longitudinal beam (also called stringer) are categorized as one of the prevailing fatigue damaged details (Al-Emrani et al. (2004), Al-Emrani (2009, 2003)). These so-called stringer-to-floor beam double angle connections were normally designed as pin connections. The simple connection, however, in practice behaved in a semi rigid manner, inducing fixity moment on the connection. The undesirable fixity moment, therefore, generated unpredicted secondary stress in the angle of connection which was the main source behind fatigue cracking in the double angle connections (Fisher (1990), Imam et al. (2007), Guyer et al. (2012)). Traditionally, remedial solutions for tackling fatigue-related problems in double angle connection involve adding or welding extra steel elements (i.e., stiffening the connection) or removing the bolts to reduce the rigidity of the connection. However, the proposed strengthening solutions were not always efficient as they made other structural problems in the bridges (Roeder et al. (2005), Al-Emrani (2002)). Nowadays, emerge of a new smart material of iron-based shape memory alloy (Fe-SMA), developed recently at Empa, Switzerland overcomes the problems related to conventional remedial measures. The Fe-SMA strips or rods with unique property of so-called shape memory effect (SME) propose an easy pre-stressed technique that could be operated easily for the mentioned connection. Along the several studies that have been performed by the authors on SMA strengthening of the steel structures (Izadi et al. (2017, 2018)), the current study presents a pre-stressed Fe-SMA strengthening system that improve the fatigue performance of the mentioned fatigue damages in double-angle steel connections.

2 EXPERIMENTAL PROCEDURE

2.1 Materials

To assess the Fe-SMA-bsed strengthening solution, a special test setup was arranged. The test setup included two steel beam of INP 240 that were connected to the middle steel beam of INP 300. Both steel beams were of grade S235JR with nominal yielding stress of 235 MPa. The webs of the longitudinal beams (INP 240, as stringer) were connected to the web of the transversal beam (INP 300, as cross beam) via four angles of 100×100×10 mm. The type of the angles were of grade S355JR with nominal yielding stress of 355 MPa. In the strengthening system, two Fe-SMA strips of 50×1.5 mm (width×thickness) were employed. The Fe-SMA material had initial elastic modulus of 160 GPa with ultimate strength of 980 MPa. The 0.2% yielding stress of 523 MPa was also reported for this batch of Fe-SMA.

2.2 Experimental test layouts

A set of static and fatigue tests were performed within the framework of the current study. Table 1 represents the general layout of the performed tests. Initially, a static load was applied on the designed stringer-to-floor beam test setup. The static test was aimed to determine the connection fixity as well as the stress distribution on the angle of the connection. Then after, a fatigue test was carried out on the un-strengthened connection to understand how the fatigue crack behaves. Finally, the connection was retrofitted with the proposed strengthening system (see Section 2.3) and once again tested under the same fatigue loading.

Table 1. Double-angle connection tests layout.

Test No.	Loading type	Strengthening[1]	Test Label[2]
C1	Static	No	C1-S-R
C2	Fatigue	No	C2-F-R
C3	Fatigue	Yes	C3-F-A

1. The strengthening system includes two activated Fe-SMA strips that are anchored on the top flange of the stringer from both sides of the connection.

2. C, S, F, R, and A refer to Connection, Static, Fatigue, Reference, and Activated.

2.3 Stringer-to-floor-beam double-angle connection test setup

Figure 1 shows the specially designed stringer-to-floor beam test setup with the mounted SMA-based retrofit system. The setup included four bearing supports, each under the longitudinal and transversal beam ends, to provide the simple supports. The end roller bearings under the stringers had distance of 5 m relative t each other, while the end-roller bearings of the cross beam was placed with a distance of 1.5 m. The actuators with maximum static capacity of 250 kN were located in the mid-span of the stringers. The actuators were supplied by a pulsator machine from Maschinenfabrik Alfred J. Amsler & Co., Switzerland.

The idea of the proposed SMA-based retrofit system was primarily originated from the SMA strengthening of steel girders with the same system (Izadi et al. (2018), Hosseini et al. (2018)). The system was called flat pre-stressed un-bonded retrofit (FPUR) system. The application of the SMA-based FPUR system was then modified for the case of connection strengthening. The activated Fe-SMA strips were anchored from each side of the connection on the top flange of the stringer beam. Both end-anchorages was mechanically attached to the top flange the beam, while the strips were sandwiched in between of the upper and lower clamping plate of the anchorage.

2.4 Experimental procedure and instrumentation

The fatigue loading was performed between the minimum and the maximum load of 7.5 and 75 kN, respectively. The fatigue load levels generate a bending stress range of 120 MPa with stress ratio of 0.1 in the bottom flange of the stringer, assuming the simply behaving double-angle connection. The static load was, therefore, carried out equivalent to the maximum load of 75 kN to realize the local and global response of connection in the designed test setup until the experienced maximum fatigue load (a load of 75 kN).

Accordingly, several measuring sensors were attached near and far away the connection. Three strain gauges with gauge factor of 2.05 were attached in the mid-length of the stringer and cross beam. Several strain gauges (with gauge factor of 2.05) were attached along the depth of the stringer near the connection. To observe the strain development on the connection, strain gauges with gauge factor of 1.99 were put in the fillet of the angle along the depth. For the retrofitted

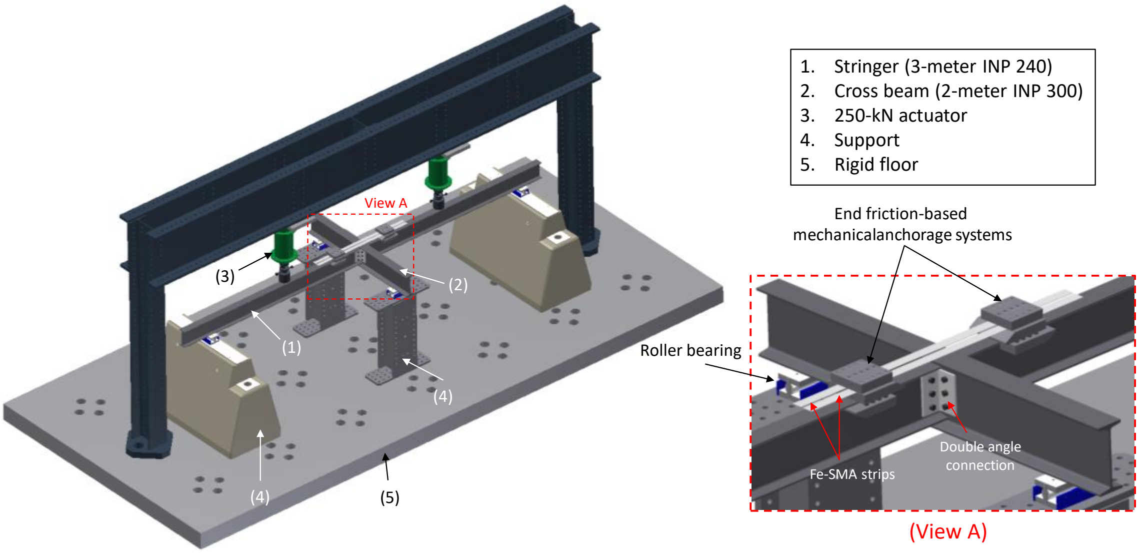


Figure 1. Stringer-to-floor beam double-angle connection test setup with the mounted SMA-based FPUR system.

connection, the Fe-SMA strips were also equipped with two strain gauges of 2.01 in gauge factor. Linear variable differential transformers (LVDTs) were placed on the bottom and top of the connection to monitor the connection rotation. Laser displacement sensors (LDSs) were, additionally, used in the mid-span of the beam to record the deflection of the beam.

3 RESULT AND DISCUSSIONS

3.1 Static test on the un-strengthened connection (test C1_S_R)

Before mounting the retrofit system on the stringer-to-floor beam framing, the static test was performed to gain information on the rigidity of the connection. The resulted end-moment due to the fixity of the connection for different load levels is shown in Figure 2. Table 2, moreover, reports, flexural stiffness, degree of continuity (ratio of the resulted end-moment over the calculated moment assuming the fully fixed connection), and stringer end-moment. The static results reveal a noticeable amount of the connection fixity that explain the reason behind fatigue cracking in the double-angle connection in existing railway and highway bridges. The rotational stiffness of 6305 kNm/rad induces an approximately 66% of the assumed fully-fixed connection. As studied in previous researches (Al-Emrani (2002), Guyer et al. (2012), Gocal et al. (2010), Wilson (1940)), the rotational stiffness of the double angle connection is influenced by the flexural stiffness of the outstanding leg of the connection. The flexural behavior of the outstanding leg depends on the distance between the bolt/rivet center line and the fillet of the angle (also called gauge distance). This implies that the smaller the gauge distance, the more is the rotational stiffness of the connection. Indeed, for connection with not sufficient gauge distance, the resulted end-moment induced secondary bending stresses through the thickness of the angle, a maximum stress of 225 MPa (due to the limited space, the strain measurements of the connection angle is not reported in this study). The bending stresses causes then the fatigue crack initiation.

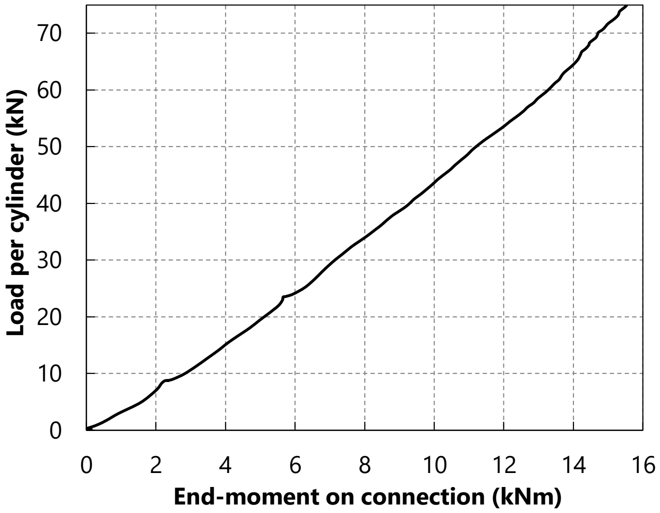
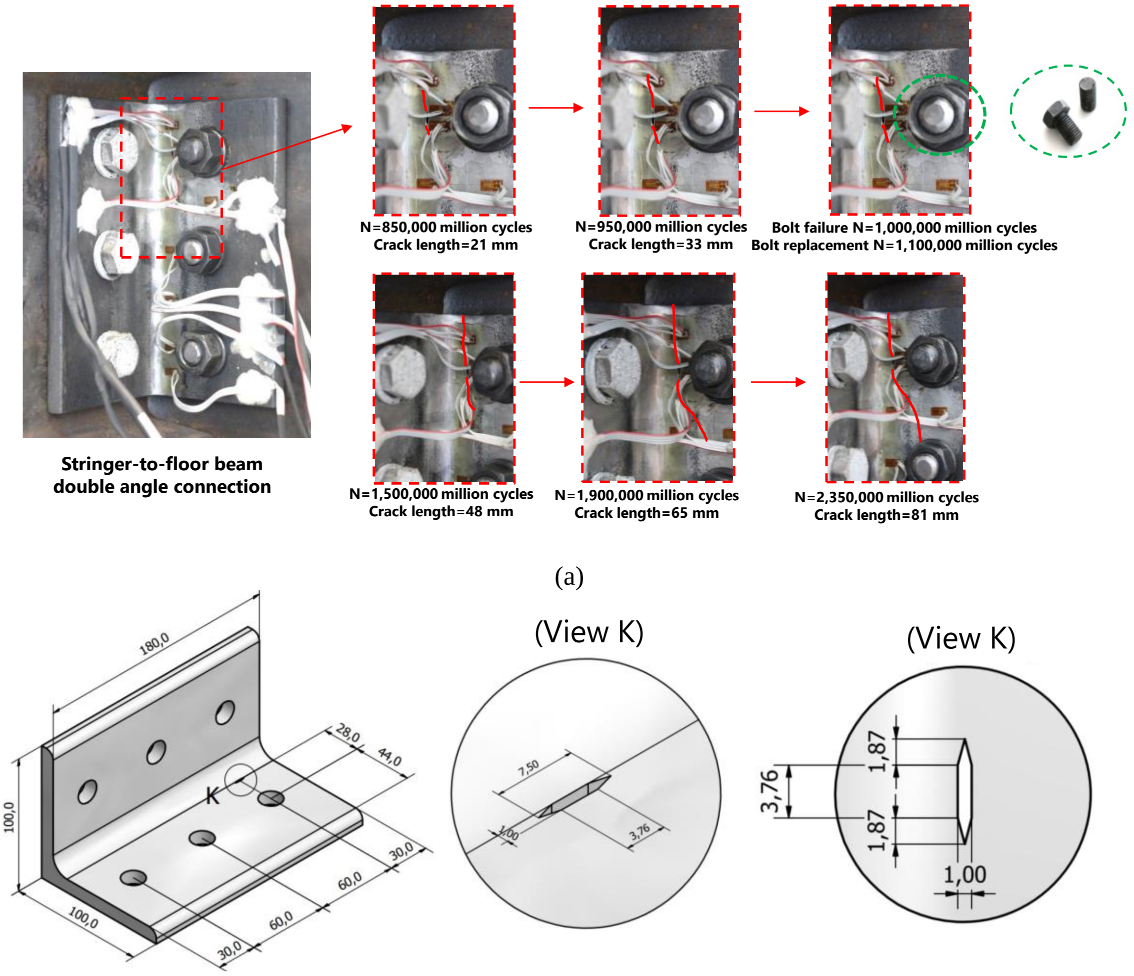


Figure 2. Resulted end-moment of the connection versus applied static load.

Table 2. The resulted connection parameters from the static test.

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



(a)

(b)

Figure 3. (a) Fatigue crack propagation in stringer-to-floor beam double-angle connection; (b) The geometry of notch cut at the top of the connection, units are in mm.

3.2 *Fatigue test on the un-strengthened connection (test C2_F_R)*

The fatigue test was conducted to study the fatigue crack propagation in the angle of the connection. Before starting the fatigue test, the top of the connection in the angle fillet (the critical part where normally damages are reported) was notched to accelerate the initiation and localization of the fatigue cracking. The details of the notch are shown in Figure 3b. The fatigue test was stopped in each approximate 200,000 loading cycles and the crack length and direction was visually controlled and measured. Figure 3a displays the fatigue crack growth (FCG) scenario during the fatigue test. As seen from Figure 3a, the fatigue crack after around $N = 2.3 \times 10^6$ loading cycles occupied half of the connection depth (equivalent to the approximate length of 80 mm). After around one million cycle and after the crack reaches the length of around 30 mm, the top bolt was failed. However, after 100,000 loading cycles, the bolt was replaced. During the fatigue test, as the crack propagates, the stiffness of the connection was reduced that resulted to the reduction of crack propagation rate. The reduction in the rotational stiffness was substantial when the bolt was failed, resulting almost no crack propagation anymore. Though, with bolt replacement, the crack started to propagate again.

3.3 Fatigue test on the strengthened connection (test C3_F_A)

After a comprehensive study on the static and fatigue behavior of the connection, the stringer-to-floor beam double-angle connection was retrofitted with the SMA-based FPUR system. The Fe-SMA strips were activated (pre-stressed) to the maximum temperature of 260 °C, resulting in the pre-stressing (or recovery stress) of 435 MPa in the strips. The pre-stressed strips applied a reverse moment on the connection and therefore reduced the portion of the undesirable negative moment that was produced due to rigidity of the connection. Figure 4 depicts the moment-load diagram of the connection after strengthening. After the activation, the fatigue test was initiated for two million cycles. This time and after the strengthening, the crack did not propagate as visually observed. However, to carefully detect the cracking behavior, the outward and inward deformation of the connection from the top and bottom LVDTs, respectively, were compared before and after strengthening. Figure 5 illustrates the outward and inward deformation of the connection. As seen from the figure, the connection out-of-plane deformation became constant

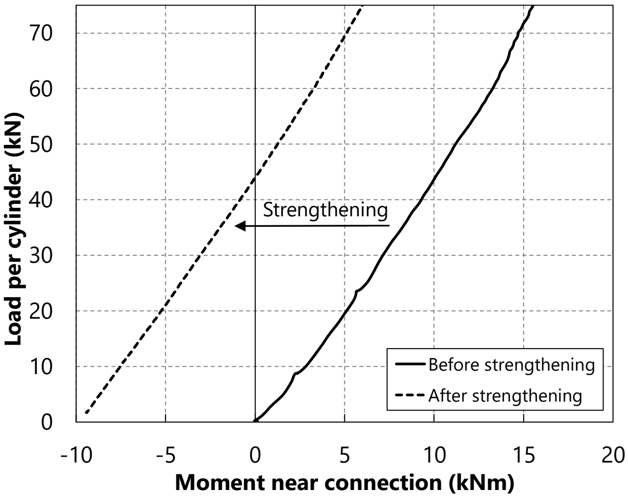


Figure 4. Moment versus applied load before and after strengthening.

during the fatigue test, proving no crack propagation after retrofitting.

4 SUMMARY AND CONCLUSIONS

In the current study, a series of static and fatigue tests on the un-strengthened and strengthened stringer-to-floor beam double-angle connections were conducted. Double-angle connections in existing highway and railway steel bridges are susceptible to cracking owing to the aging of the bridges. The un-predicted semi rigidity of the connection was explained the reason behind the fatigue cracking of the connection. Therefore, initially, a static test was performed to extract the behavioral parameters of the connection (such as rotational stiffness, end-moment, nonlinearity of the connection). Then after, a fatigue test was done to examine the crack propagation in the angle of connection. Finally, to tackle the fatigue cracking, the connection was reinforced with the SMA-based retrofit system and subjected to another fatigue loading. The following findings were extracted from the study:

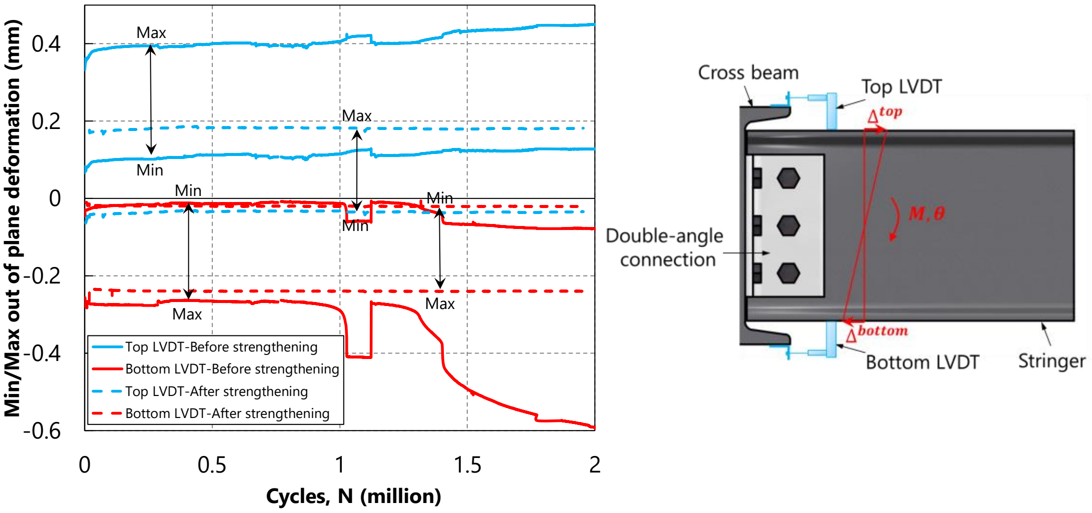


Figure 5. Minimum and maximum out-of-plane deformation of the connection under fatigue loading.

- Stringer end-moment that is equivalent to 66% of the connection assuming fully-fixed connection.
- Fatigue crack growth for approximately half of the depth of the angle of the connection after around $N = 2.3 \times 10^6$ loading cycles.
- No further fatigue crack propagation (i.e., fully fatigue crack arrest) after strengthening the connection with the activated Fe-SMA strips.

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