Heat-activated SMA-CFRP composites for fatigue strengthening of cracked steel plates

Lingzhen Li ¹, Tao Chen ², Xianglin Gu ³, and Elyas Ghafoori ⁴

¹ Master Student, Key Laboratory of Performance Evolution and Control for Engineering Structures of Ministry of Education, Tongji University, Shanghai 200092, China; Department of Structural Engineering, Tongji University, Shanghai 200092, China.

² Professor, Key Laboratory of Performance Evolution and Control for Engineering Structures of Ministry of Education, Tongji University, Shanghai 200092, China; Department of Structural Engineering, Tongji University, Shanghai 200092, China. (Corresponding Author). E-Mail: t.chen@tongji.edu.cn

³ Professor, Key Laboratory of Performance Evolution and Control for Engineering Structures of Ministry of Education, Tongji University, Shanghai 200092, China; Department of Structural Engineering, Tongji University, Shanghai 200092, China.

⁴ Group leader, Empa, Swiss Federal Laboratories for Materials Science and Technology, Ueberlandstrasse 129, 8600 Duebendorf, Switzerland. ORCID: <http://orcid.org/0000-0002-4924-0668>. E-mail: elyas.ghafoori@empa.ch.

Abstract

There exist many studies on carbon fiber-reinforced polymer (CFRP) strengthening of cracked steel details (e.g. cracks in riveted or welded bridge connections). The majority of these studies have used CFRP sheets without prestressing. The efficiency of such systems for fatigue strengthening is often limited as the high strength of CFRP materials is not utilized under service loads. On the other hand, prestressing small CFRP sheets is very difficult and requires hydraulic jacks and mechanical clamps, which makes the strengthening process very complicated or even impossible. Against this background,

in this study, NiTi shape memory alloy (NiTi-SMA) wires and CFRP sheets were used to produce a heat-activated prestressed SMA-CFRP composite patch. This composite patch offers both the benefits of prestress of SMA and the high elastic modulus of CFRP. The proposed patch is relatively small ($300\text{ mm} \times 45\text{ mm}$) and can be prestressed, which makes it a good solution for strengthening of cracked bridge connections, e.g. welded connections. In this study, the composite patch was used to enhance the fatigue performance of central cracked steel plates. Because the SMA wires were small (1 mm in diameter), first 45 SMA wires were converted into a sheet of SMA strands and then embedded into multiple CFRP layers, forming a SMA-CFRP composite patch, which offers an easy manufacturing process. Eight central cracked steel plates were tested under cyclic loading. For the specimens strengthened by prestressed SMA-CFRP composites, the fatigue lives were extended to 2.7 times (with normal-modulus CFRP) and 6.0 times (with high-modulus CFRP), respectively. Finite element (FE) simulation was employed to better understand and interpret the test results. The decreased effective stress intensity factor (SIF) range was found to be the reason for prolonged fatigue life of the cracked specimens.

Keywords: fatigue strengthening, prestress, carbon fiber reinforced polymer (CFRP), shape memory alloy (SMA), SMA strand sheet, composite patch.

Introduction

Much emphasis has been put on the fatigue strengthening of steel structures by

employing carbon fiber reinforced polymer (CFRP), and good fatigue life enhancement has been observed (Chen et al. 2018d; Colombi et al. 2015; Colombi and Fava 2015; Liu et al. 2009a; Yu et al. 2014). However, the fatigue life extension is usually limited. The ideal result is an infinite fatigue life, which means that fatigue cracks stop propagating. To reach this goal, the amount of CFRP used for strengthening has to be increased, which is not economical, or the CFRP needs to be prestressed before strengthening, which has been studied, and crack arrest has been achieved (Hosseini et al. 2017, 2019b; Täljsten et al. 2009). Nevertheless, it is not easy to prestress CFRP in places with a concave surface and small operational space because it requires the hydraulic jack and a complex prestressing setup (Chen et al. 2018a; Emdad and Al-Mahaidi 2015; Huawen et al. 2010).

Over the past decades, a new type of smart metal, called shape memory alloy (SMA), has been used for prestressed-strengthening of civil structures (Schranz et al. 2019; Soroushian et al. 2001). For a traditional steel material, after it is tensioned beyond a limit (yield strain), it cannot return to its original shape, and the plastic deformation remains. However, for SMA, the "plastic deformation" (actually, phase-transferring deformation) disappears after heating to a specific temperature and cooling (Cladera et al. 2014; Ghafoori et al. 2017), and the SMA returns to its original shape. This is the so-called shape memory effect (SME). If this reversible deformation is restrained, recovery stress is generated in the SMA, which can be used for prestressed-strengthening of the structure. Prestressed SMA has been successfully employed in

strengthening, for example, to strengthen reinforced concrete beams (Shahverdi et al. 2016) and to confine the lateral deformation of concrete columns to increase the axial compression resistance (Gholampour and Ozbakkaloglu 2018; Tran et al. 2015).

Fatigue strengthening using Fe-SMA

Various types of SMAs can be used for prestressed-strengthening. Iron-based SMA (Fe-SMA) provides a high-recovery stress level with a relatively low price, which makes its application feasible in civil engineering. Recently, Fe-SMA strips were used to prestress steel structures under cyclic loading (Izadi et al. 2018a). More specifically, if the prestrained SMA is attached to steel structures and then heated, the contraction of the SMA will be accompanied by compression of the steel substrate, which can enhance the fatigue performance of the steel substrate.

Izadi et al. (2019, 2018b) developed an SMA system for the strengthening of small steel plates (1100 mm long, 150 mm wide and 10 mm thick) and large girders (300 mm high, 125 mm wide and 6.4 m long). It has been shown that the Fe-SMA could be prestressed up to about 430 MPa for an activation temperature of about 260 °C. Furthermore, the Fe-SMA patches have been used for the fatigue strengthening of cracked steel plates (Izadi et al. 2018a). The effects of loading frequency and multiple reactivation have been also studied. It has been shown that Fe-SMA strips could completely arrest fatigue crack in steel plates (Izadi et al. 2018a). Various mechanical anchors have been developed for connecting Fe-SMA strips to steel structures. These include friction

clamps (Izadi et al. 2018b) and nail-anchor systems (Fritsch et al. 2019). Finally, Hosseini et al. (2019a) conducted a comparative study between Fe-SMA and CFRP reinforcements for the prestressed-strengthening of metallic structures.

Ghafoori et al. (2017) and Hosseini et al. (2018) extensively studied the fatigue behavior and the recovery stress behavior of the Fe-SMA. It has been observed that the Fe-SMA achieves very good fatigue performance and has an endurance limit greater than its yield stress (Ghafoori et al. 2017). Furthermore, the elevated temperature behavior of the prestressed Fe-SMA has also been studied (Ghafoori et al. 2019). The results showed that the prestress level in the Fe-SMA decreased from 373 MPa to 178 MPa when an Fe-SMA member was subjected to fire exposure to 260 °C. To further increase the temperature to 318 °C, the recovery stress was significantly reduced to 2.5 MPa.

Fatigue strengthening using NiTi-SMA

Since discovered in 1962, due to their practical nature and stability, NiTi-SMAs have been widely studied (Mohd Jani et al. 2014; Wilkes and Liaw 2000), and they have been used in the aviation, automotive and biomedical fields etc. El-Tahan et al. (2015) and Dawood et al. (2015) studied the bond behavior of NiTi-SMA wires embedded in CFRP layers under monotonic loading. The test conducted by El-Tahan et al. (2015) revealed that there is an effective bond length of 51 mm above which the bond strength does not increase (the wire diameter is 0.77 mm). The test and simulation conducted by Dawood

et al. (2015) uncovered two debonding mechanisms: debonding without phase transformation and debonding after phase transformation. There is also a specific bond length to distinguish these two debonding forms; for SMA wires with different diameters, this bond length changes. El-Tahan and Dawood (2015) studied the fatigue behavior of NiTi-SMA wire. Under the mean stress of 290 MPa and stress amplitude of 40 MPa, the SMA wires survived after 2 million fatigue cycles. The fatigue life decreased as the mean stress or the stress amplitude increased. Jonnalagadda et al. (1997), Jiang and Kishi (2005), Lau et al. (2002), and Yuan et al. (2016) investigated the bond strength between NiTi-SMA wires and adhesive with various surface and shape treatments. Surface treatments, such as chemical etching and sandblasting, can improve the bond strength by 18% and 189%, respectively. Twisting and indentation can increase the bond strength by 5 and 8.58 times, respectively.

Compared to fatigue strengthening using Fe-SMA, only a few studies (Abdy et al. 2018; Zheng and Dawood 2017) have been done using TiNi-SMA. Abdy et al. (2018) and Zheng and Dawood (2017) bonded the heat-activated prestressed SMA-CFRP composite patches on cracked steel plates and tested the fatigue performance. In these works, one of the most challenging and time-consuming issues was the process to glue the SMA wires and the CFRP layers one by one onto the steel substrate. The current study aims to suggest a new fabrication technique, which substantially simplifies the manufacturing process of the SMA-CFRP patches. The manufacturing process proposed in the current study is straightforward, easy and, most importantly, the SMA-

CFRP patches can be manufactured in the laboratory. This ability increases substantially the speed of the strengthening procedure and can result in an enhanced quality of the patches (as they can be manufactured in the laboratory rather than onsite).

Strengthening using SMA-CFRP composite patches

Despite the fact that Fe-SMA has economic advantages, however, it is mainly in the form of plate and re-bar, which is not suitable for the current research. Therefore, NiTi-SMA wires were used in this study, and, hereinafter, all the SMA refer to NiTi-SMA. Fig. 1 displays a schematic process of strengthening using the heat-activated prestressed SMA-CFRP composite patches. First, SMA wires are prestrained, i.e. stretched and unloaded (see Fig. 1 (a) and (b)), and the residual deformation remains. Then, the prestrained SMA wires (in the current study, SMA wires were first formed into SMA strand sheet, more details are presented in “SMA strand sheet preparation”) and CFRP material are glued together to form the SMA-CFRP composite patches (Fig. 1 (c)). After the composite patches have been glued on the cracked steel plate, the SMA is heated to the target temperature (Fig. 1 (d)) and then cooled down to the room temperature (Fig. 1 (e)). Steps (d) and (e) are also known as activation, during which the prestrained SMA wires tend to shrink, but they are constrained to the steel plate. Therefore, the SMA is tensioned, and the steel plate goes under compression. Finally, cyclic loading is applied to the strengthened steel plate (Fig. 1 (f)).

Outline of the current study

In this study, the fatigue performance of cracked steel plates strengthened by SMA-CFRP composites was investigated. An easy fabrication process for the innovative SMA strand sheets and SMA-CFRP composites, which simplifies their on-site applications, was presented. A total of eight central cracked steel plates were tested under cyclic loading. One specimen was unstrengthened (i.e., a reference specimen); four were strengthened by the CFRP sheets; one was strengthened by the non-prestressed aluminium-CFRP (Al-CFRP, replacing non-prestressed SMA-CFRP) composite patches; and two were prestressed by SMA-CFRP composite patches. The fatigue strengthening efficiency was assessed by comparing the fatigue life improvement of each specimen. Finite element (FE) simulation was employed to better understand and interpret the test results. Stress intensity factor (SIF) range was calculated from the FE models and the reduced SIF range was found to be the reason for the extended fatigue lives. The proposed SMA-CFRP composites were found to be efficient in fatigue strengthening of cracked steel plates, as they could substantially enhance the fatigue lives.

Materials

Steel plate

All eight steel plates were of type Q345B (yield stress no less than 345 MPa, and partly deoxidized), with a dimension of 700 mm × 90 mm × 8 mm (see Fig. 2). A through-thickness hole with a diameter of 5 mm was cut by wire-electrode in the center of each

steel plate. Two slots, 2 mm long and 0.18 mm wide, were also cut by wire-electrode at the fringe of the center hole. The elastic modulus of the steel plates was 205.35 GPa, and the yield stress and ultimate tensile strength were 372 MPa and 538 MPa, respectively (Chen et al. 2018c).

CFRP and adhesive

Two types of CFRP sheets with a normal modulus of 230 GPa (UT70-30G, from Toray Industries, Inc., Tokyo, Japan) (Toray-Industries n.d.) and a high modulus of 640 GPa (FTS-C8-30, from NIPPON STEEL Chemical &Material Co., Ltd., Tokyo, Japan) (NIPPON-STEEL 2019) were used. Their elastic moduli are based on the actual fiber thickness. The corresponding tensile strengths were 3,400 MPa and 1,900 MPa, respectively, and their thicknesses were 0.167 mm and 0.143 mm, respectively. All of the CFRP sheets were cut into pieces measuring 300 mm × 45 mm. Structural adhesive (FR-E9P (ST), from NIPPON STEEL Chemical &Material Co., Ltd., Tokyo, Japan) (NIPPON-STEEL 2016) was used to bond the SMA strand sheets and CFRP sheets onto the cracked steel plates. Its elastic modulus and ultimate tensile strength were 3,227 MPa and 64 MPa, respectively. Hitherto, all material properties are listed in Table 1. Moreover, structural adhesive had a shear strength of 15.7 MPa, a Poisson's ratio of 0.4, and a glass transition temperature (T_g) of 84 °C, which was greater than the target activation temperature (approximately 70 °C). The material properties of CFRP and adhesive were provided by the manufacturers.

SMA strand sheet preparation

NiTi-SMA wires (C-901-60, from Beijing Jiye Technology Trade Co., Ltd., Beijing, China) with a diameter of 1 mm were utilized in this study. They had an austenite start temperature (A_s) of 47 °C, above which martensite starts transferring to austenite while prestress generates inside SMA; and an austenite finish temperature (A_f) of 55 °C, above which the material is 100% in austenite phase and no more prestress can be generated (Yuan et al. 2016). Furthermore, they had a martensite start temperature (M_s) of 17 °C, below which austenite starts transforming into martensite and prestress decreases; and a martensite finish temperature (M_f) of 7 °C, below which the material is 100% in martensite phase and no more prestress loss can happen (Yuan et al. 2016). The two elastic moduli were 32 GPa (martensite phase) and 90 GPa (austenite phase). The main properties of SMA are listed in Table 2.

For convenience, the authors fabricated SMA strand sheets which comprised several individual SMA wires. The fabrication process was carried out as follows (see Fig. 3):

- a. The as-received SMA coil was straightened and cut into segments with lengths of approximately 700 mm.
- b. Ten segments were laid out as a strip, and thin aluminum plates were bonded at the two ends of the strip using a fast-curing glue. The SMA wire length between the two aluminum ends was 600 mm.
- c. The SMA strips were polished with abrasive paper to remove the attached lubricant and to roughen the surface.

d. SMA strips were tensioned to the prestrain levels of 4%, 6% and 8% and then unloaded. The prestrain level of 6% showed the greatest recovery stress. More information will be presented later in this study. The SMA strips were prestrained using an MTS uniaxial testing machine with a displacement accuracy greater than 0.1 mm. As the free length of the SMA strip was 600 mm, the accuracy of the prestrain was greater than 0.02%.

e. The deformed SMA wires were cut into lengths of 300 mm for each segment.

f. The deformed SMA segments were connected using cotton strings with fast-curing glue to form SMA strand sheets.

Note that cotton strings and fast-curing glue did not provide strength but only connected the SMA wires. What really provided bond strength was the structural adhesive. Furthermore, the fast-curing glue only temporarily bonded SMA wires and thin aluminum plates together, and also did not provide strength. When the SMA strips were installed on the testing machine, the thin aluminum plates were squeezed by the clampers and got deformed, which generated friction and held SMA wires. Every SMA strand sheet consisted of 45 wires, hence, the dimensions were 300 mm × 45 mm. This process can be done in advance in the laboratory or factory. Thus, gluing SMA strand sheets on-site can be as easy as gluing CFRP sheets.

Thermo-mechanical behavior of SMA

The SMA strips shown in Fig. 3 (b) were employed to test the recovery stress, which

can be used to set prestress. The stress-strain and stress-temperature behaviors are presented in Fig. 4 (a) and Fig. 4 (b), respectively (Here, the prestrain level of 6% is used as an example). First, the SMA strip was tensioned at the room temperature to the strain level of 6% with a displacement rate of 5 mm/min (step i) and unloaded (step ii). The residual strain was approximately 5.4%. Then, the prestrained SMA strip was tensioned to approximately 30 MPa (step iii) to prevent the strip being slack during the activation process due to thermal expansion. Next, the SMA strip was heated to approximately 70 °C by a forced air gun (step iv), and the tensile stress in the SMA wires reached the maximum value of approximately 364 MPa. The difference between the maximum tensile stress and the initial tensile stress was called the maximum recovery stress (334 MPa). After cooling down to the room temperature (step v), the tensile stress in the SMA wires decreased to approximately 93 MPa; subtracting this value by the initial tensile stress yielded the residual recovery stress (63 MPa).

To optimize the prestress level, the authors tested the recovery stress of SMA wires with three different prestrain levels (4%, 6%, and 8%). The corresponding residual strains were 3.6%, 5.4%, and 6.2%, respectively. The relationship between the recovery stress and the prestrain level is shown in Fig. 5. The maximum recovery stresses were between 284 and 376 MPa at approximate 70 °C. When the specimens reached the room temperature, a remarkable recovery stress loss occurred, and the residual recovery stress remained between 20 and 63 MPa, which is much lower than that at high temperature. For NiTi-SMA, it was also observed by Abdy et al. (2018), Shin and Andrawes (2010),

and Choi et al. (2010, 2012) that the residual recovery stress (at room temperature) is lower than the maximum recovery stress (at high temperature). Here, only the residual recovery stress can be used, because in engineering applications the service temperature is usually around the room temperature. All SMA wires were then prestrained to 6%, and the corresponding residual recovery stress was 63 MPa.

Because all the SMA wires were already used, aluminum (Al) wires with an elastic modulus of 70 GPa (similar to the elastic modulus of the SMA) were used to replace the non-prestressed SMA wires. The authors' previous investigation (Li et al. 2019b) revealed that when using different materials for fatigue strengthening, if their tensile stiffnesses (cross section $\times$ elastic modulus) are similar, their fatigue lives are almost identical. Therefore, it is rational to replace the non-prestressed SMA-CFRP composite patches with Al-CFRP composite patches. Hence, the Al-CFRP strengthened specimen can be regarded as the non-prestressed SMA-CFRP strengthened specimen.

Specimen preparation

Fabrication

Before strengthening, the designated areas on the steel plates were first sandblasted to remove the oxides and to roughen the surface. Next, all material surfaces were cleaned by alcohol to remove dust and grease. Then, the two components of the epoxy adhesive were mixed together and brushed onto SMA strand sheets and CFRP sheets. They were then bonded together to form SMA-CFRP composite patches, which were then bonded

onto both sides of the cracked steel plates, as depicted in Fig. 6. The numerical investigations of Chue et al. (1994) and Dawood et al. (2007) revealed that the tapering edge of the adhesive on both ends of a composite patch can significantly reduce the peeling stress (approximately 15% and 60%, respectively) in the adhesive layer and thus decrease the possibility of debonding. Hence, a wedge fringe of adhesive (see Fig. 7) was made by laying a plastic membrane (when the adhesive was still liquid) on the adhesive outside the composite patch and forming a slope. To further decrease the probability of the plate end debonding in the prestressed specimens, mechanical clamps were placed at two ends of the composite patches. The above steps were conducted for SMA-CFRP strengthened specimens. For specimens without SMA strand sheets, the steps with SMA and mechanical clamps should be omitted.

All eight specimens are listed in Table 3. Here, U stands for the unstrengthened specimen, and NC and HC refer to specimens strengthened by normal- and high-modulus CFRP sheets, respectively. Two layers of CFRP were presented on each side. In addition, PS means that the SMA strand sheets (two layers on one side of a steel plate) were embedded in CFRP layers to offer prestress, and NA denotes that the non-prestressed aluminum strand sheets (one layer on each side) were embedded. Owing to the scattering nature, three HC specimens were tested, and they are denoted as “a”, “b” and “c”.

Prestressing

For the SMA-CFRP strengthened specimens, the strain gauges were attached to the steel plates and the composite patches in order to monitor the prestress level, as shown in Fig. 8 (a). Then, 703 glue, which is a single-component silicone rubber with good adhesion and sealing performance, was applied on the strain gauges to prevent water penetration into the strain gauges, as shown in Fig. 8 (b). The arrangement of strain gauges is depicted in Fig. 9, in which ε stands for a strain gauge. The strain gauges in brackets are those on the opposite side of the specimen. Here, a steel plate was used as a dummy for temperature compensation. The dummy steel plate (without inducing prestress) was placed in the same thermal environment as the real specimen in order to eliminate the temperature-induced expansion and contraction and to compensate the thermal effect on the strain gauge itself. Next, the SMA specimens were heated to approximately 70 °C using a water bath. The whole specimen was submerged in the water and the temperature was increased by an electrical heater and then cooled down to the room temperature by cold water. The process of the heating and cooling of the SMA is called activation process. The utilized activation process in this study is just for laboratory application, and there are other activation techniques for on-site activation of the SMA material (e.g., hot air, flames, infrared heating technique, etc). After cooling down to the room temperature, a final prestress level of approximately 63 MPa was achieved.

During the prestressing process, the strains were recorded approximately every 5 °C.

Setting specimen NC-PS as an example, Fig. 10 presents two of its typical strain-temperature curves. Here, the thermally induced strain was offset, and only the prestress-induced strain remained. Before activation, all six strain gauges were approximately zero, which means no prestress was applied. As the temperature started to increase, the SMA wires were tensioned, and the steel and CFRP were compressed. The compressive strain on the steel and CFRP first increased with the temperature, and then decreased with the temperature (prestress loss). After it returned to the room temperature, the average compressive strain measured in the steel plate was $103\ \mu\epsilon$, and the corresponding compressive force on steel plate was 15.3 kN. This means that prestress was successfully induced.

Fatigue test

All specimens were then tested in an MTS fatigue machine (see Fig. 11), applying a tension-tension sinusoidal fatigue loading with a frequency of 20 Hz and a stress ratio (the ratio of minimum stress on maximum stress) of 0.1 till final fracture. To correlate the crack length and the fatigue loading cycle, beach-marking loading regime was employed, as shown in Fig. 12. Here, high and low fatigue loading blocks, whose stress ranges were 160 MPa and 80 MPa on the unstrengthened cross-section, respectively, appeared alternatively. Fatigue cracks propagated relatively slowly with low stress ranges, leaving dark curves on the fracture surface, as depicted in Fig. 13. The fatigue life fraction of the low-range cycles was converted to that of the high-range cycles using Equation (1), which will be further explained in Appendix. A.

$$\frac{\Delta N_l}{\Delta N_h} = \left(\frac{\Delta \sigma_h}{\Delta \sigma_l} \right)^m \quad (1)$$

where ΔN_l and ΔN_h are the fatigue life fractions resulting from the low and high stress ranges, respectively. In addition, $\Delta \sigma_l$ and $\Delta \sigma_h$ represent the low and high stress ranges, respectively, and m is a parameter in Paris law for which it was recommended to use 3 (British Standards Institution 2005).

361

362 **FE simulation**

To better interpret the fatigue test results, FE simulation was conducted using ABAQUS. Stress intensity factor (SIF) around the crack tip was directly calculated from the FE simulation. The fatigue life was then determined based on the SIF range, as will explained in this section.

367

368 **FE modeling**

Fig. 14 presents a typical FE model with SMA-CFRP strengthening. The dimensions, and material properties were the same as described in section “Materials”. Beside that the wedge elements around the crack tip in the steel plate were defined by C3D6R element, steel plate and CFRP were modeled using C3D8R element. Adhesive and SMA wires were modeled using “Cohesive” and “Truss” elements, respectively. The interfaces between steel and adhesive so as between CFRP and adhesive were defined as “Tie”, which allowed no separation and slide between the two surfaces. Although the SMA wires were in reality embedded in CFRP layers, they were tied on the outer

surface of CFRP in FE model. The SIF calculated this way was only 0.1% lower than SMA being tied in the inner surface of CFRP, which can be ignored. The total thickness of a composite patch on one side of steel plate was approximately 4 mm. By subtracting the contribution of SMA strand sheets and CFRP sheets, the adhesive thickness was defined as 2 mm. To introduce the prestress in SMA, a decreased temperature field was induced in SMA wires in the FE model. Only the tensile load with high stress range was applied on the specimens. Due to the fact that most of the materials are in the linear elastic state, all the material in this study were defined linear elastic and linear elastic fracture mechanics (LEFM) was used to calculate SIF.

Fatigue life calculation

After the SIF corresponding to the different crack length was calculated using FE simulation, fatigue lives were integrated using the Paris law (Paris and Erdogan 1963), which is expressed as Equation (2).

$$\frac{da}{dN} = C \cdot (\Delta K_{\text{eff}})^m \quad (2)$$

where da/dN and ΔK_{eff} were the crack growth rate (in mm/cycle) and the effective SIF range, respectively. C and m were material constants, taken as 5.21×10^{-13} and 3, respectively (British Standards Institution 2005). The effective SIF range (ΔK_{eff}) was obtained using the following equations considering crack closure effect (Hosseini et al. 2017):

$$\Delta K_{\text{eff}} = U \cdot (K_{\text{max}} - K_{\text{min}}) \quad (3)$$

$$U = 0.69 + 0.45R, \quad -1 \leq R \leq 0.33 \quad (4)$$

where $K_{\max}$ and $K_{\min}$ were the maximum and minimum SIF in one loading cycle, respectively. R was the stress ratio.

Results and discussions

Fatigue life

Fatigue lives from experiment and FE simulation are shown in Table 3 and Fig. 15, in which HC is the average fatigue life of HC-a, -b and -c. The average fatigue life of these three specimens was 409,670 cycles, and the coefficient of variation (CoV) was 26.6%, which was deemed acceptable due to the scattering nature of fatigue. Fig. 16 presents the a - N curves of all specimens. HC-c is used to represent the average of HC-a, -b and -c, because its fatigue life (444,925 cycles) is the closest to their average life.

Compared to the unstrengthened specimen, normal- and high-modulus CFRP (non-prestressed) enhanced the fatigue lives by 2.4 times (NC) and 3.3 times (HC), respectively. The reason for the longer fatigue life was the decrease in the SIF range.

According to the Paris law, as expressed by Equation (2), fatigue crack growth rate decreases with a decrease in the SIF range. In comparison with the unstrengthened specimen, the effective SIF range was reduced approximately 14% and 22% by normal- and high-modulus CFRP, as depicted in Fig. 17. Therefore, the fatigue crack growth rates of these two specimens were reduced (see Fig. 18, HC-c is also used to represent HC-a, -b and -c), and as a result, their fatigue lives were prolonged substantially.

Similarly, the a - N curves (see Fig. 16) demonstrates that the fatigue cracks in these two

specimens propagated slower than that in the unstrengthened specimen. As the high-modulus CFRP had much greater modulus than the normal-modulus CFRP and they shared similar cross-sectional area, high-modulus CFRP carried greater portion of the load, leading to a more pronounced reduction of the SIF range. From this analysis, it can be concluded that the fatigue life of the HC specimen was greater than that of the NC specimen, which indicates that the high-modulus CFRP is much more efficient (than the normal-modulus CFRP) to be used in the SMA-CFRP composite patches.

Focusing on HC-NA and HC, the effective SIF range of HC-NA was only 3% lower than that of HC. The embedded non-prestressed aluminum wires achieved only 9% fatigue life improvement, and the a - N curves of HC-NA and HC almost overlap (see Fig. 16). This means non-prestressed aluminum wires are not efficient in fatigue strengthening, because the elastic modulus of aluminum (70 GPa) is relatively low compared with steel (205.35 GPa) and CFRP (640 GPa). Thus, the authors speculate that the fatigue life would not be prolonged much if non-prestressed SMA, which had similar elastic modulus to aluminum, was employed in the fatigue strengthening.

As shown in Fig. 17, in the two SMA-CFRP strengthened specimens, the prestressing applied by the SMA strand sheets could reduce the effective SIF range of NC-PS and HC-PS approximately 12% and 10%, respectively, compared to the non-prestressed ones (i.e. NC and HC). Hence, their a - N curves also moved to the right in comparison to the non-prestressed ones (see Fig. 16). The corresponding fatigue life extension ratio

(i.e. the ratio of the fatigue life of the strengthened specimen to that of the reference specimen) were 2.7 and 6.0, respectively, which were greater than the non-prestressed specimens (2.4 and 3.3). This indicates that the heat-activated prestressed SMA-CFRP composite patches are more effective than CFRP in the fatigue strengthening.

Further explanation for the fatigue strengthening mechanism of SMA-CFRP composite patch is described below. After the activation process, tensile stress was generated in SMA while steel plate and CFRP were in compression. When the specimen was loaded by the test machine, steel plate and CFRP were (1) tensioned to (roughly) zero-stress state (like unloading from the compressive state), and then (2) tensioned more with an open crack. In stage (1), a certain force was needed to tension CFRP and steel to the zero-stress state. Because steel plate was still in compression, the effective tensile force, which contributed to fatigue, was reduced. In stage (2), steel plate and CFRP were tensioned and CFRP carried a part of the load, so that the load carried by steel was further reduced. The effective tensile force carried by steel plate was twice reduced. As a result, the stress level around the crack was reduced twice (by CFRP and prestress, respectively), as depicted in Fig. 19. Thus, the effective SIF range around the crack tip in the steel plate was reduced twice. The outcome was that compared to unstrengthened specimen, the fatigue life was prolonged by bonded CFRP (specimens NC and HC), and it was further prolonged by prestress from SMA (specimens NC-PS and HC-PS).

It should be mentioned here that the effect of prestressed strengthening was limited by

the relatively low prestress level (63 MPa). If the residual prestress could reach 140 MPa (Abdy et al. 2018) and 400 MPa (Zheng and Dawood 2017), the FE simulation demonstrated that the fatigue life extension ratio of specimen NC-PS could be 6.3 (793,216 cycles) and 59 (7,384,636 cycles), respectively. In reality, the latter one is regarded as infinite fatigue life (more than 2 million cycles), which means the crack propagation is fully restricted by the SMA-CFRP strengthening system. For specimen HC-PS, this fatigue life extension would be even better.

It is concluded that the bonded strengthening can reduce the fatigue crack growth rate by decreasing the effective SIF range, thus prolong the fatigue life. The effective SIF range and crack growth rate can further be decreased by increasing the CFRP elastic modulus or applying prestressed SMA. If the prestress level is high enough, fatigue crack can be fully arrested. The combination of high-modulus CFRP and prestressed SMA has the best strengthening effect, which is recommended for engineering applications.

Failure mode

All failure modes are listed in Table 4. Steel plate fracture is not included because it appeared in every specimen.

All specimens strengthened by high-modulus CFRP, i.e. HC-a, -b and -c, failed with CFRP rupture; the one strengthened by normal-modulus CFRP, i.e. NC, showed CFRP

debonding and CFRP rupture, as shown in Fig. 20 (CFRP debonding and CFRP rupture happened almost simultaneously). These findings are in accordance with the previous study of some of the authors (Li et al. 2019b), which revealed: specimens strengthened by high-modulus CFRP are more prone to CFRP rupture, whereas specimens strengthened by normal-modulus CFRP tend to have adhesive failure, e.g. CFRP debonding.

The two SMA-CFRP strengthened specimens showed bonding failure, even though the surfaces of the SMA strand sheets were polished and cleaned. HC-PS failed with CFRP rupture and SMA strand sheet pull-out (see Fig. 21); and NC-PS failed with SMA strand sheet debonding (see Fig. 22). The Al-CFRP strengthened specimen, i.e. HC-NA, failed with CFRP rupture and aluminum strand sheet rupture; no bonding failure occurred. This means that the bonding of the aluminum wires to the adhesive was better than that of the NiTi-SMA to the adhesive. The reason could be that the surface of aluminum wires was rougher than SMA wires, thus, the mechanical interlock between aluminum wires and adhesive stronger than that between SMA wires and adhesive.

Although the edge of the adhesive was wedge shaped, debonding still occurred in two specimens with normal modulus, i.e. NC and NC-PS. However, the debonding did not originate from the junction of the adhesive wedge and the steel plate (Point 1 in Fig. 23), because the wedge edge of the adhesive decreased the stress concentration at the junction of the adhesive and the steel plate. Rather, there were two potential origins of

the debonding: the junction of the adhesive wedge and the composite patch (Point 2 in Fig. 23), and the adhesive around the crack in steel plate (Point 3 in Fig. 23). According to FE simulation, the stress level in the adhesive at these two points was relatively high. For the junction of the adhesive wedge and the composite patch (Point 2 in Fig. 23), the interface is subject to cyclic tension, which is prone to fatigue. Debonding could generate here and propagate to the crack in the steel plate. For the adhesive around the crack in steel plate (Point 3 in Fig. 23), it was similar to a double lap-shear joint (Fawzia et al. 2006). As the crack length increased, CFRP carried more force and the adhesive near the crack (Point 3 in Fig. 23) deformed more, which could lead to local debonding and eventually the composite debonding. Further research is needed to investigate the origin of the composite debonding.

For steel plates strengthened by SMA-CFRP composite patches, it can also be concluded that specimens with high-modulus CFRP are prone to CFRP rupture, while specimens with normal-modulus CFRP are more prone to composite debonding or inter-delamination.

Limitations in the current study

This study is one of the first studies that aim to demonstrate the potential of the SMA-CFRP composite patches for fatigue strengthening of cracked steel details. Therefore, there are many open questions and long way until the technology is ready for real on-site applications. Some of the limitations in this study, which could be considered in

future studies, are listed here: (1) The prestress level is not high enough when the temperature returns to the room temperature after the activation process. An SMA with high residual recovery stress and relatively low activation temperature is preferred. (2) The mechanical anchorage requires some space and limits the application of the proposed technique to complex details. A bonded anchorage with good loading capacity has to be developed. (3) Other types of activation methods have to be developed in order to facilitate the onsite activating process but also to ensure safety, reliability and quality of the work. (4) Long-term durability tests have to be conducted on the SMA-CFRP composite patches.

Conclusions

In this study, heat-activated prestressed SMA-CFRP composite patches, which comprised the newly developed SMA strand sheets and CFRP sheets, were used to improve the fatigue performance of cracked steel plates. The recovery stress of the NiTi-SMA wires was first tested. Then, the cracked steel plates were strengthened by CFRP and prestressed SMA-CFRP composites, and their fatigue performance was measured. To better interpret the strengthening mechanism, finite element simulation was conducted. The following conclusions could be drawn:

(1) The proposed SMA strand sheet developed in this study is easy to work with and can be used in engineering projects. Gluing SMA strand sheets is as convenient as gluing CFRP material.

(2) The effective stress intensity factor range around the crack tip was reduced 14% to

22% by bonding CFRP and 10% to 12% by applying prestressed SMA. As a result, the crack growth rate was decreased, leading to a prolonged fatigue life.

(3) Using normal-modulus CFRP and high-modulus CFRP, fatigue lives were extended by 2.4 and 3.3 times, respectively. Fatigue life was prolonged by 2.7 times by embedding prestressed SMA in normal-modulus CFRP, and by 6.0 times by embedding prestressed SMA in high-modulus CFRP. If higher prestress level was reached, better fatigue life extension (even infinite fatigue life) could be attained.

(4) Non-prestressed aluminum-CFRP (or non-prestressed SMA-CFRP) composite patches behaved similarly to non-prestressed CFRP in the fatigue strengthening, because the elastic modulus of aluminum (or SMA) was relatively low compared to CFRP and steel, and its effect in reducing effective stress intensity factor range could be ignored.

(5) For specimens strengthened by CFRP or SMA-CFRP, those with high-modulus CFRP tended to fail with CFRP rupture, while those with normal-modulus CFRP were more prone to fail with composite debonding. SMA itself showed bonding failure.

Appendix A. The equivalent loading number of cycles

To correlate the loading number of cycles with the crack length, the beach-marking loading regime is usually used. It contains alternating low and high stress ranges, as shown in Fig. 24 (a). Both low and high stress ranges contribute to the crack propagation life. Usually, only the high stress range (see Fig. 24 (c)) is used in numerical

simulation (Chen et al. 2018b; Li et al. 2019a) and theoretical calculation (Liu et al. 2009b, 2019; Yu et al. 2013). For the purpose of comparison with numerical simulation or theoretical calculation, the fatigue life fraction contributed by the low stress range (ΔN_l in Fig. 24 (a)) should be converted to that from the high stress range (ΔN_h in Fig. 24 (c)).

Based on the slope of the S - N curve, researchers (Aljabar et al. 2017; Chen et al. 2018c; Zhao et al. 2005) have conducted fatigue crack propagation life conversion by employing Equation (1). In those studies, the parameter m was the slope of the S - N curve. However, in the mechanical field, the S - N curve is usually used to evaluate fatigue crack initiation life. Nevertheless, Equation (1) can still be used to convert the fatigue crack propagation life. The theoretical explanation is summarized as follows.

The classical Paris law (Paris and Erdogan 1963) is expressed as:

$$\frac{da}{dN} = C \cdot (\Delta K)^m \quad (5)$$

where da/dN is the crack growth rate. C and m are material constants, and ΔK is the range of the stress intensity factor (SIF). Equation (5) can be re-written as:

$$\frac{dN}{da} = \frac{1}{C \cdot (\Delta K)^m} \quad (6)$$

For the half crack length developing from a_1 to a_2 , the loading number of cycles are:

$$\Delta N = \int_{a_1}^{a_2} \frac{1}{C \cdot (\Delta K)^m} \cdot da \quad (7)$$

The universal SIF range can be expressed as:

$$\Delta K = F \cdot \Delta \sigma \cdot \sqrt{\pi \cdot a} \quad (8)$$

where F is the correction factor for the finite plate width. $\Delta \sigma$ is the remote tensile stress range in the steel plate, and a is the half crack length.

Substituting Equation (8) into Equation (7) yields:

$$\Delta N = \frac{\gamma_1 \cdot \gamma_2}{(\Delta \sigma)^m} \quad (9)$$

where

$$\gamma_1 = \frac{1}{C \cdot F^m \cdot \pi^{m/2}} \quad (10)$$

$$\gamma_2 = \int_{a_1}^{a_2} \frac{1}{a^{m/2}} \cdot da \quad (11)$$

For certain a_1 and a_2 , the two parameters γ_1 and γ_2 are constant, therefore, ΔN is the function of $\Delta \sigma$ only. From the half crack length a_1 to a_2 , the loading number of cycles needed from the low and high stress ranges are expressed as:

$$\Delta N_l = \frac{\gamma_1 \cdot \gamma_2}{(\Delta \sigma_l)^m} \quad (12)$$

$$\Delta N_h = \frac{\gamma_1 \cdot \gamma_2}{(\Delta \sigma_h)^m} \quad (13)$$

where ΔN_l and ΔN_h are loading number of cycles needed from the low and high stress ranges, respectively. $\Delta \sigma_l$ and $\Delta \sigma_h$ represent the low and high stress ranges, respectively.

Dividing Equation (12) by Equation (13) yields:

$$\frac{\Delta N_l}{\Delta N_h} = \left(\frac{\Delta \sigma_h}{\Delta \sigma_l} \right)^m \quad (14)$$

which is exactly the same as Equation (1). Thus, this equation can be used to convert fatigue life fraction from the low stress range to that of the high stress range, vice versa.

Likewise, this equation can be used to convert the fatigue lives of different specimens

under different stress ranges, for the purpose of comparison or fatigue life estimation.

This is very similar to the function of the $S-N$ curve.

Interestingly, fatigue life conversion of crack initiation and crack propagation can be done using the same equation, even though the physics behind them is different. The reasons are summarized as follows. (1) Both the fatigue crack initiation and propagation lives are inversely proportional to the m th. power of the stress range. Moreover, (2) in Refs. (Aljabar et al. 2017; Chen et al. 2018c; Zhao et al. 2005), parameter m is the slope of the $S-N$ curve, which is usually chosen as 3 for the fatigue life less than 5×10^6 cycles (British Standards Institution 2005; EN 1993-1-9 2005; Zhao et al. 2005); The parameter m in the current study is the exponent in Paris law, ranging from 2.75 to 3.25 (British Standards Institution 2005; Hosseini et al. 2019b; Liu et al. 2009b; Yu et al. 2013), which is near 3. Furthermore, to evaluate the fatigue life of a specimen in comparison to that subject to another stress range, Equation (14) or Equation (1) can be directly used, without distinguishing the fatigue crack initiation and propagation lives.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgements

This work was financially supported by the National Natural Science Foundation of

China (NSFC Grant No. 51978509). NIPPON STEEL Chemical &Material Co., Ltd. is appreciated for donating materials used in this study. It is noted that all the names of the commercial products mentioned in this study are only stated for the sake of factual accuracy and shall not be interpreted as an endorsement of the products used.

References

- Abdy, A. I., Hashemi, M. J., and Al-Mahaidi, R. (2018). "Fatigue life improvement of steel structures using self-prestressing CFRP/SMA hybrid composite patches." *Engineering Structures*, Elsevier, 174, 358–372.
- Aljabar, N. J., Zhao, X. L., Al-Mahaidi, R., Ghafoori, E., Motavalli, M., and Koay, Y. C. (2017). "Fatigue tests on UHM-CFRP strengthened steel plates with central inclined cracks under different damage levels." *Composite Structures*, Elsevier Ltd, 160, 995–1006.
- British Standards Institution. (2005). *BS 7910, Guide to methods for assessing the acceptability of flaws in metallic structures*. BSI Standards Publication, 306.
- Chen, T., Gu, X. L., Qi, M., and Yu, Q. Q. (2018a). "Experimental Study on Fatigue Behavior of Cracked Rectangular Hollow-Section Steel Beams Repaired with Prestressed CFRP Plates." *Journal of Composites for Construction*, 22(5), 04018034.
- Chen, T., Hu, L., Zhang, N. X., and Yu, Q. Q. (2018b). "Boundary element analysis of fatigue behavior for CFRP-strengthened steel plates with center inclined cracks." *Thin-Walled Structures*, Elsevier Ltd, 125(December 2017), 164–171.
- Chen, T., Li, L., Zhang, N., Song, X., and Hidekuma, Y. (2018c). "Fatigue performance test on inclined central cracked steel plates repaired with CFRP strand sheets." *Thin-Walled Structures*, Elsevier Ltd, 130(May), 414–423.
- Chen, T., Wang, X., and Qi, M. (2018d). "Fatigue improvements of cracked rectangular hollow section steel beams strengthened with CFRP plates." *Thin-Walled Structures*, Elsevier Ltd, 122(September 2017), 371–377.
- Choi, E., Cho, S., Hu, J. W., and Park, T. (2010). "Recovery and residual stress of SMA wires and applications for concrete structures." *Smart Materials and Structures*, 19(9).
- Choi, E., Chung, Y.-S., Choi, D.-H., and DesRoches, R. (2012). "Seismic protection of lap-spliced RC columns using SMA wire jackets." *Magazine of Concrete Research*, 64(3), 239–252.
- Chue, C. H., Chang, L. C., and Tsai, J. S. (1994). "Bonded repair of a plate with inclined central crack under biaxial loading." *Composite Structures*, 28(1), 39–45.
- Cladera, A., Weber, B., Leinenbach, C., Czaderski, C., Shahverdi, M., and Motavalli, M. (2014). "Iron-based shape memory alloys for civil engineering structures : An

- overview.” *Construction and Building Materials*, Elsevier Ltd, 63, 281–293.
- Colombi, P., and Fava, G. (2015). “Experimental study on the fatigue behaviour of cracked steel beams repaired with CFRP plates.” *Engineering Fracture Mechanics*, 145, 128–142.
- Colombi, P., Fava, G., and Sonzogni, L. (2015). “Fatigue crack growth in CFRP-strengthened steel plates.” *Composites Part B: Engineering*, Elsevier Ltd, 72, 87–96.
- Dawood, M., El-Tahan, M. W., and Zheng, B. (2015). “Bond behavior of superelastic shape memory alloys to carbon fiber reinforced polymer composites.” *Composites Part B: Engineering*, Elsevier Ltd, 77, 238–247.
- Dawood, M., Guddati, M., and Rizkalla, S. (2007). “Bond Behavior of a CFRP Strengthening System for Steel Structures.” *Asia-Pacific Conference on FRP in Structures (APFIS 2007)*.
- El-Tahan, M., and Dawood, M. (2015). “Fatigue behavior of a thermally-activated NiTiNb SMA-FRP patch.” *Smart Materials and Structures*, IOP Publishing, 25(1), 15030.
- El-Tahan, M., Dawood, M., and Song, G. (2015). “Development of a self-stressing NiTiNb shape memory alloy (SMA)/fiber reinforced polymer (FRP) patch.” *Smart Materials and Structures*, IOP Publishing, 24(6), 065035.
- Emdad, R., and Al-Mahaidi, R. (2015). “Effect of prestressed CFRP patches on crack growth of centre-notched steel plates.” *Composite Structures*, 123, 109–122.
- EN 1993-1-9. (2005). *Eurocode 3: Design of steel structures. Part 1-9: Fatigue*. CEN, Brussels.
- Fawzia, S., Al-Mahaidi, R., and Zhao, X. L. (2006). “Experimental and finite element analysis of a double strap joint between steel plates and normal modulus CFRP.” *Composite Structures*, 75(1–4), 156–162.
- Fritsch, E., Izadi, M., and Ghafoori, E. (2019). “Development of nail-anchor strengthening system with iron-based shape memory alloy (Fe-SMA) strips.” *Construction and Building Materials*, Elsevier Ltd, 229, 117042.
- Ghafoori, E., Hosseini, E., Leinenbach, C., Michels, J., and Motavalli, M. (2017). “Fatigue behavior of a Fe-Mn-Si shape memory alloy used for prestressed strengthening.” *Materials and Design*, Elsevier Ltd, 133, 349–362.
- Ghafoori, E., Neuenschwander, M., Shahverdi, M., Czaderski, C., and Fontana, M. (2019). “Elevated temperature behavior of an iron-based shape memory alloy used for prestressed strengthening of civil structures.” *Construction and Building Materials*, Elsevier Ltd, 211, 437–452.
- Gholampour, A., and Ozbakkaloglu, T. (2018). “Understanding the compressive behavior of shape memory alloy (SMA)-confined normal- and high-strength concrete.” *Composite Structures*, Elsevier, 202(May), 943–953.
- Hosseini, A., Ghafoori, E., Motavalli, M., Nussbaumer, A., and Zhao, X. L. (2017). “Mode I fatigue crack arrest in tensile steel members using prestressed CFRP plates.” *Composite Structures*, Elsevier Ltd, 178, 119–134.
- Hosseini, A., Michels, J., Izadi, M., and Ghafoori, E. (2019a). “A comparative study between Fe-SMA and CFRP reinforcements for prestressed strengthening of

metallic structures.” 226, 976–992.

Hosseini, A., Nussbaumer, A., Motavalli, M., Zhao, X. L., and Ghafoori, E. (2019b). “Mixed mode I/II fatigue crack arrest in steel members using prestressed CFRP reinforcement.” *International Journal of Fatigue*, Elsevier, 127(March), 345–361.

Hosseini, E., Ghafoori, E., Leinenbach, C., Motavalli, M., and Holdsworth, S. R. (2018). “Stress recovery and cyclic behaviour of an Fe–Mn–Si shape memory alloy after multiple thermal activation.” *Smart Materials and Structures*, IOP Publishing, 27(2), 025009.

Huawen, Y., König, C., Ummenhofer, T., Shizhong, Q., and Plum, R. (2010). “Fatigue Performance of Tension Steel Plates Strengthened with Prestressed CFRP Laminates.” *Journal of Composites for Construction*, 14(5), 609–615.

Izadi, M., Hosseini, A., Michels, J., and Motavalli, M. (2019). “Thin-Walled Structures Thermally activated iron-based shape memory alloy for strengthening metallic girders.” *Thin Walled Structures*, Elsevier Ltd, 141(April), 389–401.

Izadi, M. R., Ghafoori, E., Motavalli, M., and Maalek, S. (2018a). “Iron-based shape memory alloy for the fatigue strengthening of cracked steel plates: Effects of re-activations and loading frequencies.” *Engineering Structures*, Elsevier, 176(February), 953–967.

Izadi, M. R., Ghafoori, E., Shahverdi, M., Motavalli, M., and Maalek, S. (2018b). “Development of an iron-based shape memory alloy (Fe-SMA) strengthening system for steel plates.” *Engineering Structures*, Elsevier, 174(August), 433–446.

Jang, B. K., and Kishi, T. (2005). “Adhesive strength between TiNi fibers embedded in CFRP composites.” *Materials Letters*, 59(11), 1338–1341.

Jonnalagadda, K., Kline, G. E., and Sottos, N. R. (1997). “Local displacements and load transfer in shape memory alloy composites.” *Experimental Mechanics*, 37(1), 78–86.

Lau, K. tak, Tam, W. yin, Meng, X. long, and Zhou, L. min. (2002). “Morphological study on twisted NiTi wires for smart composite systems.” *Materials Letters*, 57(2), 364–368.

Lee, I., Roh, J. H. O., Yang, S. M., and Han, J. H. (2005). “Shape and vibration control of smart composite structures.” *Advanced Composite Materials: The Official Journal of the Japan Society of Composite Materials*, 14(2), 121–130.

Li, L., Chen, T., and Zhang, N. (2019a). “Numerical analysis of fatigue performance of CFRP-repaired steel plates with central inclined cracks.” *Engineering Structures*, Elsevier, 185(February), 194–202.

Li, L., Chen, T., Zhang, N., and Hidekuma, Y. (2019b). “Test on fatigue repair of central inclined cracked steel plates using different adhesives and CFRP, prestressed and non-prestressed.” *Composite Structures*, Elsevier, 216(January), 350–359.

Liu, H. B., Al-Mahaidi, R., and Zhao, X. L. (2009a). “Experimental study of fatigue crack growth behaviour in adhesively reinforced steel structures.” *Composite Structures*, Elsevier Ltd, 90(1), 12–20.

Liu, H., Xiao, Z., Zhao, X. L., and Al-Mahaidi, R. (2009b). “Prediction of fatigue life for CFRP-strengthened steel plates.” *Thin-Walled Structures*, Elsevier, 47(10), 1069–1077.

- Liu, R., Chen, T., Li, L., and Tateishi, K. (2019). "A practical stress intensity factor formula for CFRP-repaired steel plates with a central crack." *Journal of Constructional Steel Research*, Elsevier Ltd, 162, 105755.
- Mohd Jani, J., Leary, M., Subic, A., and Gibson, M. A. (2014). "A review of shape memory alloy research, applications and opportunities." *Materials & Design (1980-2015)*, Elsevier Ltd, 56, 1078–1113.
- NIPPON-STEEL. (2016). *Test Report (in Japanese)*.
- NIPPON-STEEL. (2019). "Type and performance for CFRP material (in Japanese)." <https://www.nscm.nipponsteel.com/carbon/pdf/6_forca_tousheet_performance_20180922.pdf>.
- Paris, P., and Erdogan, F. (1963). "A Critical Analysis of Crack Propagation Laws." *Journal of Basic Engineering*, 85(4), 528.
- Schranz, B., Michels, J., Shahverdi, M., and Czaderski, C. (2019). "Strengthening of concrete structures with iron-based shape memory alloy elements: Case studies." *SMAR 2019 - Fifth Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures*, 1–8.
- Shahverdi, M., Czaderski, C., and Motavalli, M. (2016). "Iron-based shape memory alloys for prestressed near-surface mounted strengthening of reinforced concrete beams." *Construction and Building Materials*, Elsevier Ltd, 112, 28–38.
- Shin, M., and Andrawes, B. (2010). "Experimental investigation of actively confined concrete using shape memory alloys." *Engineering Structures*, Elsevier Ltd, 32(3), 656–664.
- Soroushian, P., Ostowari, K., Nossoni, A., and Chowdhury, H. (2001). "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*, 1770(1), 20–26.
- Täljsten, B., Hansen, C. S., and Schmidt, J. W. (2009). "Strengthening of old metallic structures in fatigue with prestressed and non-prestressed CFRP laminates." *Construction and Building Materials*, 23(4), 1665–1677.
- Toray-Industries. (n.d.). "Technical data sheet for Torayca cloth." <<https://www.torayca.com/en/download/pdf/cloth.pdf>>.
- Tran, H., Balandraud, X., and Destrebecq, J. F. (2015). "Improvement of the mechanical performances of concrete cylinders confined actively or passively by means of SMA wires." *Archives of Civil and Mechanical Engineering*, Politechnika Wroclawska, 15(1), 292–299.
- Tsoi, K. A., Schrooten, J., Zheng, Y., and Stalmans, R. (2004). "Part I . Thermomechanical characteristics of shape memory alloy composites." *Materials Science and Engineering A*, 368, 299–310.
- Wilkes, K. E., and Liaw, P. K. (2000). "Fatigue behavior of shape-memory alloys." *Jom*, 52(10), 45–51.
- Yu, Q. Q., Chen, T., Gu, X. L., Zhao, X. L., and Xiao, Z. G. (2013). "Fatigue behaviour of CFRP strengthened steel plates with different degrees of damage." *Thin-Walled Structures*, 69, 10–17.
- Yu, Q. Q., Zhao, X. L., Al-Mahaidi, R., Xiao, Z. G., Chen, T., and Gu, X. L. (2014).

808 “Tests on Cracked Steel Plates with Different Damage Levels Strengthened by
809 CFRP Laminates.” *International Journal of Structural Stability and Dynamics*,
810 14(06), 1450018.

811 Yuan, G., Bai, Y., Jia, Z., Hui, D., and Lau, K. tak. (2016). “Enhancement of interfacial
812 bonding strength of SMA smart composites by using mechanical indented method.”
813 *Composites Part B: Engineering*, Elsevier Ltd, 106, 99–106.

814 Zhao, X. L., Wilkinson, T., and Hancock, G. (2005). *Cold-formed tubular members and*
815 *connections*. Elsevier.

816 Zheng, B., and Dawood, M. (2017). “Fatigue strengthening of metallic structures with
817 a thermally activated shape memory alloy fiber-reinforced polymer patch.”
818 *Journal of Composites for Construction*, 21(4), 04016113.

Table 1. Material properties.

Material	Type	Yielding stress (MPa)	Ultimate tensile stress (MPa)	Elastic modulus (MPa)	Thickness (mm)
Steel	Q345B	372	538	205,350	8
CFRP	FTS-C8-30	N/A	1,900	640,000	0.143
	UT70-30G		3,400	230,000	0.167
Adhesive	FR-E9P (ST)		64	3,227	N/A

*Material properties of CFRP sheets and adhesive were provided by the manufacturers.

*Steel properties represent average values.

*Tensile strength of CFRP represents a characteristic value and the elastic modulus represents the average.

*Thickness of CFRP was measured on the actual cross-section area of carbon fibers.

Table 2. Material properties of SMA (Yuan et al. 2016).

M_f (°C) ^a	M_s (°C) ^b	A_s (°C) ^c	A_f (°C) ^d	E_M (GPa) ^e	E_A (GPa) ^f	σ_u (MPa) ^g	μ ^h
7	17	47	55	32	90	1000	0.21

^a Martensite finish temperature

^b Martensite start temperature

^c Austenite start temperature

^d Austenite finish temperature

^e Elastic modulus in martensite phase

^f Elastic modulus in austenite phase

^g Ultimate tensile stress

^h Poisson's ratio

Table 3. Specimen details.

Specimen symbol	CFRP	Prestress	Fatigue life (cycles)	
			Experimental	Numerical
U	N/A	N/A	124,847	177,107
NC	Normal		304,409	279,847
NC-PS	modulus	SMA	340,006	472,239
HC-a	High modulus	N/A	496,668	406,785
HC-b			287,418	
HC-c			444,925	
HC-NA			447,553	
HC-PS		SMA	751,980	729,817

Table 4. Failure modes.

Specimen symbol	Failure mode
U	N/A
NC	CFRP rupture & CFRP debonding
HC-a	CFRP rupture
HC-b	CFRP rupture
HC-c	CFRP rupture
HC-NA	CFRP rupture & Al strand sheet rupture
NC-PS	SMA strand sheet debonding
HC-PS	CFRP rupture & SMA strand sheet pull-out

Figure Captions

Fig. 1. Schematic processes of strengthening using SMA-CFRP composites: (a) non-deformed SMA wires, (b) prestrained SMA wires, (c) SMA-CFRP composite patch, (d) activation of prestress by heating, (e) cooling down process, and (f) strengthened specimen under cyclic loading.

Fig. 2. Steel plate and crack details (in mm, not to scale).

Fig. 3. The process of producing SMA strand sheet (in mm): (a) SMA segments with a length of 700 mm. (b) SMA wires glued with aluminum plates at two ends, (c) polishing of SMA wires with sand paper, (d) pre-straining of SMA wires, (e) prestrained SMA wires (with residual strain), and (f) SMA strand sheet, front and back sides.

Fig. 4. (a) Stress-strain relationship (tested by the authors), and (b) schematic view of stress-temperature curve (Abdy et al. 2018; Lee et al. 2005; Tsoi et al. 2004).

Fig. 5. Maximum and residual recovery stresses during activation process.

Fig. 6. Scheme of the SMA-CFRP strengthened specimen.

Fig. 7. Profile of SMA-CFRP strengthened specimen (mechanical clamps not presented).

Fig. 8. Strain gauges and mechanical clamps: (a) strain gauges uncovered and (b) strain gauges covered by water-proof glue.

Fig. 9. Arrangement of the strain gauges (in mm).

Fig. 10. Strains in specimen NC-PS during the activation process.

Fig. 11. Fatigue test set-up: (a) specimen strengthened by CFRP and (b) specimen

strengthened by the SMA-CFRP composite patches.

Fig. 12. Beach-marking loading regime with high stress range of 160 MPa and low stress range of 80 MPa.

Fig. 13. Beach marks of the specimens (the intervals on the ruler are 1 mm).

Fig. 14. FE model of SMA-CFRP strengthened specimen.

Fig. 15. Fatigue life comparison between experiment and FE simulation.

Fig. 16. a-N curves of specimens (experimental).

Fig. 17. Effective SIF range of specimens (numerical).

Fig. 18. Crack growth rates of specimens (experimental).

Fig. 19. Stress distribution in the steel plates in different specimens: (a) unstrengthened, i.e. U, (b) strengthened by high-modulus CFRP, i.e. HC, and (c) strengthened by high-modulus CFRP-SMA composite, i.e. HC-PS (half crack length $a = 12.5$ mm, only the middle part of the steel plate with approximately 400 mm length is shown).

Fig. 20. Failure mode of the NC specimen: (a) schematic view and (b) photo of the failed specimen.

Fig. 21. SMA strand sheet pull-out (HC-PS).

Fig. 22. SMA strand sheet debonding (NC-PS).

Fig. 23. Schematic view of the debonding formation in the specimen with normal-modulus CFRP.

Fig. 24. Fatigue life conversion: (a) beach-marking loading regime, (b) schematic view of beach marks on the fracture surface, and (c) the equivalent cyclic load with

only high stress range.

Fig. 1. Schematic processes of strengthening using SMA-CFRP composites: (a) non-deformed SMA wires, (b) prestrained SMA wires, (c) SMA-CFRP composite patch, (d) activation of prestress by heating, (e) cooling down process, and (f) strengthened specimen under cyclic loading.

Fig. 2. Steel plate and crack details (mm, not to scale).

Fig. 3. The process of producing SMA strand sheet (in mm): (a) SMA segments with a length of 700 mm. (b) SMA wires glued with aluminum plates at two ends, (c) polishing of SMA wires with sand paper, (d) pre-straining of SMA wires, (e) pre-strained SMA wires (with residual strain), and (f) SMA strand sheet, front and back sides.

Fig. 4. (a) Stress-strain relationship (tested by the authors), and (b) schematic view of stress-temperature curve (Abdy et al. 2018; Lee et al. 2005; Tsoi et al. 2004).

Fig. 5. Maximum and residual recovery stresses during activation process.

Fig. 6. Scheme of the SMA-CFRP strengthened specimen.

Fig. 7. Profile of SMA-CFRP strengthened specimen (mechanical clamps not presented).

Fig. 8. Strain gauges and mechanical clamps: (a) strain gauges uncovered and (b) strain gauges covered by water-proof glue.

Fig. 9. Arrangement of the strain gauges (in mm).

Fig. 10. Strains in specimen NC-PS during the activation process.

Fig. 11. Fatigue test set-up: (a) specimen strengthened by CFRP and (b) specimen strengthened by the SMA-CFRP composite patches.

Fig. 12. Beach-marking loading regime with high stress range of 160 MPa and low stress range of 80 MPa.

Fig. 13. Beach marks of the specimens (the intervals on the ruler are 1 mm).

Fig. 14. FE model of SMA-CFRP strengthened specimen.

Fig. 15. Fatigue life comparison between experiment and FE simulation.

Fig. 16. a - N curves of specimens (experimental).

Fig. 17. Effective SIF range of specimens (numerical).

Fig. 18. Crack growth rates of specimens (experimental).

Fig. 19. Stress distribution in the steel plates of different specimens: (a) unstrengthened, i.e. U, (b) strengthened by high-modulus CFRP, i.e. HC, and (c) strengthened by high-modulus CFRP-SMA composite, i.e. HC-PS (half crack length $a = 12.5$ mm, only the middle part of the steel plate with approximately 400 mm length is shown).

Fig. 20. Failure mode of the NC specimen: (a) schematic view and (b) photo of the failed specimen.

Fig. 21. SMA strand sheet pull-out (HC-PS).

Fig. 22. SMA strand sheet debonding (NC-PS).

Fig. 23. Schematic view of the debonding formation in the specimen with normal-modulus CFRP.

Fig. 24. Fatigue life conversion: (a) beach-marking loading regime, (b) schematic view of beach marks on the fracture surface, and (c) the equivalent cyclic load with only high stress range.