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Fatigue strengthening of cracked steel plates using prestressed unbonded CFRP reinforcements

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ABSTRACT: Fatigue strengthening of existing steel structures is of great importance and has attracted lots of interest recently. Apart from the conventional strengthening technique, i.e. utilizing bulky and heavy steel plates and its disadvantages, carbon fiber reinforced polymer (CFRP) composites have exhibited a great potential to be used as external reinforcements in strengthening of steel structures. As a result, during the last two decades, considerable research studies have been done to further investigate static and fatigue behavior of CFRP-strengthened steel members under different loading configurations. Nevertheless, very limited investigations can be found in the literature on the performance of prestressed CFRP plates for fatigue strengthening of cracked steel members; while, it is obvious that using prestressed reinforcements is more effective than non-prestressed ones. Consequently, the main intention of the current study is to show the capability of fatigue crack arrest in steel plates using a novel prestressed unbonded reinforcement (PUR) system, including high performance mechanical clamps. This paper presents a set of fatigue tests on precracked steel plates with and without the PUR strengthening that has been performed. Based on the obtained experimental results it can be concluded that utilizing the proposed PUR system with a certain prestressing level, an existing fatigue crack in a steel member can be completely arrested.

1 INTRODUCTION

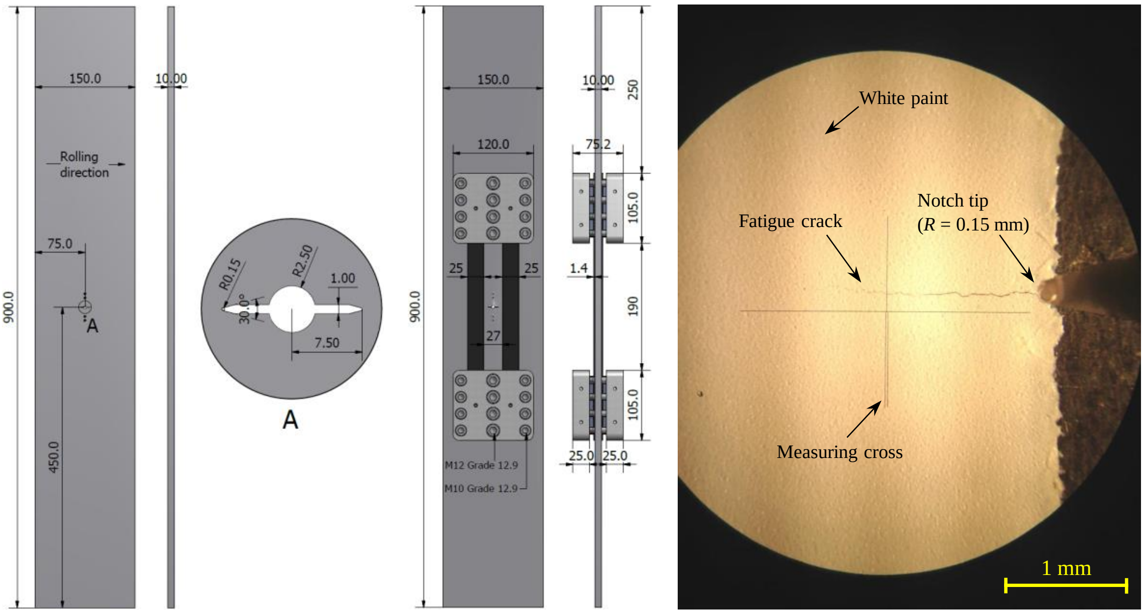
Several pioneer researchers have demonstrated the potential of carbon fiber reinforced polymer (CFRP) composites in the fatigue strengthening of existing steel structures (see Zhao and Zhang 2007; Zhao 2013). The existing literature on this subject mainly includes experimental results with analytical or numerical models to predict the fatigue life of CFRP-strengthened steel plates. Furthermore, in case of adhesively-bonded CFRP reinforcements, a few researchers took into account the effects of near-crack debonding of CFRP from a steel substrate (Colombi et al. 2003; Zheng and Dawood 2016). The strengthening of fatigue-sensitive or fatigue-damaged steel members with prestressed CFRPs is more advantageous due to the fact that a reduction in the tensile stress level that causes damage to the structure would be possible with prestressed reinforcements (Bassetti 2001; Ghafoori et al 2015a; Ghafoori et al. 2015b). Although experimental studies have demonstrated the certain advantage of prestressed CFRP reinforcements over nonprestressed ones, fewer attempts have been made to use prestressed bonded CFRPs in practical cases (for example see Koller et al. 2012). The reason is attributed to the fact that a bonded CFRP reinforcement can carry a limited tensile force before debonding failure occurs (Fernando 2010). This limited bond capacity, however, can be significantly reduced by prestressing the reinforcement, leading to the undesirable premature debonding of the prestressed CFRP reinforcements from the steel substrate under transient service loads.

In the current study, a prestressed unbonded reinforcement (PUR) system has been developed as an alternative to the conventional prestressed bonded reinforcement (PBR) technique for fatigue strengthening of cracked tensile steel members. The system is consisted of prestressed normal modulus (NM) CFRP plates, which are anchored to the cracked steel member using two sets of high performance mechanical clamps. The fatigue performance of the developed PUR system and its capability in fatigue crack arrest in steel plates have been evaluated through a set of fatigue tests on precracked steel plate specimens, conducted as a part of an ongoing research project on the fatigue strengthening of metallic members using CFRP plates at the Swiss Federal Laboratories for Materials Science and Technology (Empa) in collaboration with the Swiss Federal Institute of Technology Lausanne (EPFL), and Monash University in Melbourne.

2 EXPERIMENTAL PROGRAM

2.1 *Fatigue test specimens*

Fatigue tests were performed on two precracked middle-tension (M(T)) steel plate specimens; one without any external strengthening as the reference specimen (Figure 1a), and the other one with the proposed PUR system (Figure 1b).



(a) (b) (c)

Figure 1. Specimen dimensions and notch details (all dimensions are in mm); (a) reference specimen; (b) PUR specimen; (c) microscopic view of the notch and fatigue crack in the reference specimen.

As shown in Figure 1a, the steel specimens were cut so that the rolling direction of the steel plates was parallel to the crack propagation path. This was done to minimize the potential effects of residual stresses (at the microscopic level) due to the rolling process of steel on the experimental results of crack propagation. An electrical discharge machine (EDM) was used to cut a through-thickness notch at the center of all the specimens, as illustrated in Figure 1a, prior to the fatigue precracking. The notch was designed based on the recommendations provided by the American Society for Testing and Materials (ASTM) E647-15.

2.2 Material properties

The utilized steel was of grade S355J2+N with a nominal yield strength of 355 MPa. After the completion of the first fatigue test on the reference specimen, 10 standard tensile samples of diameter 6.00 mm were manufactured from the specimen and tensile tests performed on each according to DIN EN ISO 6892-1:2009. Elastic modulus, yield and ultimate strength of the utilized steel along the rolling direction were obtained to be 205 GPa, 421 and 526 MPa, respectively. Note that the experimental results showed no significant difference in the mechanical properties of the steel parallel or perpendicular to the rolling direction.

For strengthening of the PUR specimen, four NM CFRP plates of type S&P 150/2000 with measured cross-sectional dimensions of 25 × 1.4 mm (width × thickness) were used. The nominal tensile strength of the CFRP plate is 2800 MPa based on the manufacturer's catalogue, while the elastic modulus was obtained to be 156 GPa (Hosseini et al. 2016).

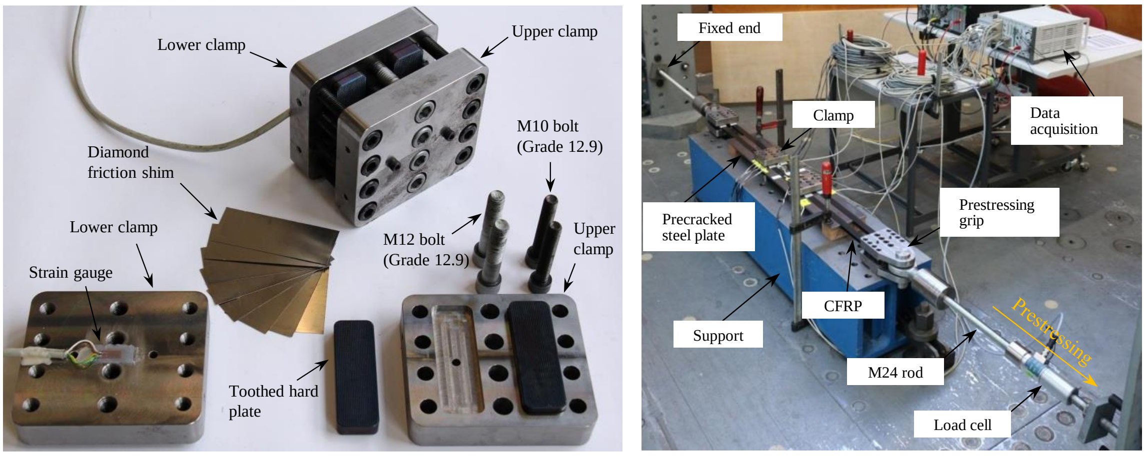
2.3 Fatigue precracking

The second steel plate specimen was precracked prior to being strengthened with the PUR system. The purpose of precracking is to provide a sharpened real fatigue crack of adequate size and straightness that ensures the following: a) the effect of the machined starter notch and related residual stresses are removed from the specimen stress intensity factor (SIF) calibration, and b) the effects caused by the change in the crack front shape or precrack load history on the subsequent crack growth rate data are eliminated (ASTM E647-15). Consequently, based on the recommendations provided in ASTM E647-15, a precrack of approximately 1.1 mm, on each side of the starter EDM notch was created. This was done by applying a total number of 200,000 fatigue cycles with $\Delta\sigma = 75$ MPa and $R = 0.2$, from which approximately 100,000 fatigue cycles were required for the crack to initiate from the EDM notch. Note that the precrack length was visually measured using a travelling microscope (Spindler & Hoyer, Germany) with a resolution of 0.01 mm (see Figure 1c).

2.4 PUR system

2.4.1 Mechanical clamps

As shown in Figure 1b, the prestressed NM CFRP plates were held on both sides of the second precracked steel plate specimen using mechanical clamps which work via friction. As it can be seen in Figure 2a, each set of the designed clamps consists of four toothed hard plates with a hardness of HRC 58(-60) on the Rockwell scale, which press the CFRP plates against the steel substrate using a compression force. This force is generated in the upper and lower clamp plates by fastening a set of M10 and M12 bolts. In total, eight M10 and four M12 high-strength (grade 12.9) bolts are used in each of the clamp sets that are tightened with torques of 54 and 160 N·m, respectively, to generate a total prestressing force of 518 kN per clamp set.



(a) (b)

Figure 2. (a) Different parts of the developed mechanical clamps; (b) prestressing setup.

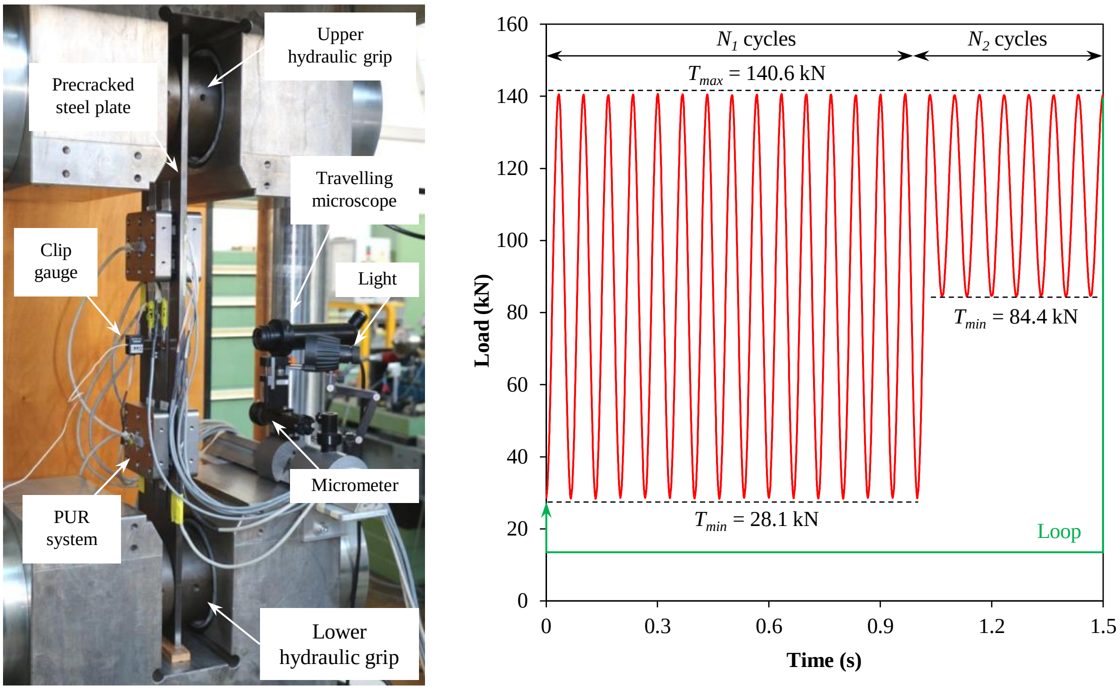
As the entire PUR system functions with the help of friction, 3M^{TM} diamond friction shims of grade 10 (3M Technical Ceramics GmbH, Germany), were used between the CFRP plates and steel substrate to increase the friction. Furthermore, because the normal force generated by the prestressed bolts is transferred to the hard plates via the upper and lower clamp plates and causes high bending stresses in those parts, the upper and lower clamp plates were manufactured from high strength steel M200 with a nominal yield strength of 1000 MPa. It should be mentioned that in the current study, the CFRP plates were not intended to cover the crack because the state of the crack was required to be visually monitored for any probable crack re-initiation. Consequently, the PUR system in this study was specially designed and developed to hold the four CFRP plates apart at the crack tips (Figure 1b), which is not necessary in practical cases.

2.4.2 Prestressing setup

To strengthen the precracked specimen using the developed PUR system, a special prestressing setup was designed and assembled in order to simultaneously prestress four parallel CFRP plates (Figure 2b). To do so, the four CFRP plates were first placed in the specially designed prestressing grips. Using a hydraulic jack, an average prestrain level of 5180 µm/m was generated in the CFRP plates. This value was obtained based on an analytical calculation of the mode I SIF range ΔK_I in the PUR specimen, to be less that the mode I threshold SIF range $\Delta K_{I,th}$ (considering $\Delta K_{I,th}$ = 100 N/mm$^{3/2}$). The aforementioned prestrain value in the CFRP plates corresponded to a load level of 110.8 kN, which was monitored using a 300 kN load cell along with all the strain gauges on the CFRP plates and the steel specimen upon prestress force release. Immediately after prestressing the CFRP plates, the high-strength bolts of the mechanical clamps were tightened with the required torque using a digital torque meter. The prestressing force in the cylinder was then released to zero and the CFRP plates were cut from both sides of the mechanical clamps to realize the final configuration depicted in Figure 1b.

2.5 Fatigue test setup

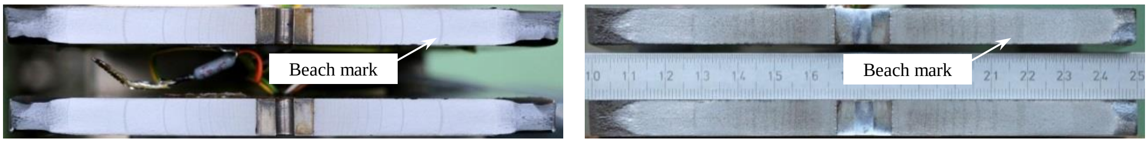
A 1-MN static/fatigue servo-hydraulic Schenck machine with an Instron controller was used for the fatigue testing of the specimens until failure. Tests were performed under the load-control condition with a load ratio of R = 0.2 and a frequency of 15 Hz. Figure 3a shows the test setup and the instrumentation used to monitor the specimens during the fatigue testing.



(a) (b)

Figure 3. (a) Fatigue test setup; (b) loading scenario for beach marking technique in fatigue tests.

Beach marking technique was incorporated in the fatigue tests, both in the stages of fatigue precracking as well as the fatigue testing of the specimens. Figure 3b illustrates the typical loading scenario for beach marking, where the fatigue test (or fatigue precracking) starts with N_1 cycles at the desired mean and stress range and continues with N_2 cycles, during which the maximum fatigue load was kept constant but the loading ratio was increased from 0.2 to 0.6. This leaves a visible mark along the crack front to determine the crack length after the complete failure of the specimen (see Figure 4). It should be noted that in the fatigue testing of the reference specimen as well as precracking the second specimen, the values of N_1 = 50,000 and N_2 = 25,000 were used, while in the fatigue testing of the PUR specimen, the values used were N_1 = 100,000 and N_2 = 50,000. Herein, only summations of the N_1 cycles are considered in number of the applied cycles on the specimens.



(a) Reference specimen (b) PUR specimen

Figure 4. Cross-sectional view of the failed steel plate specimens and beach marks.

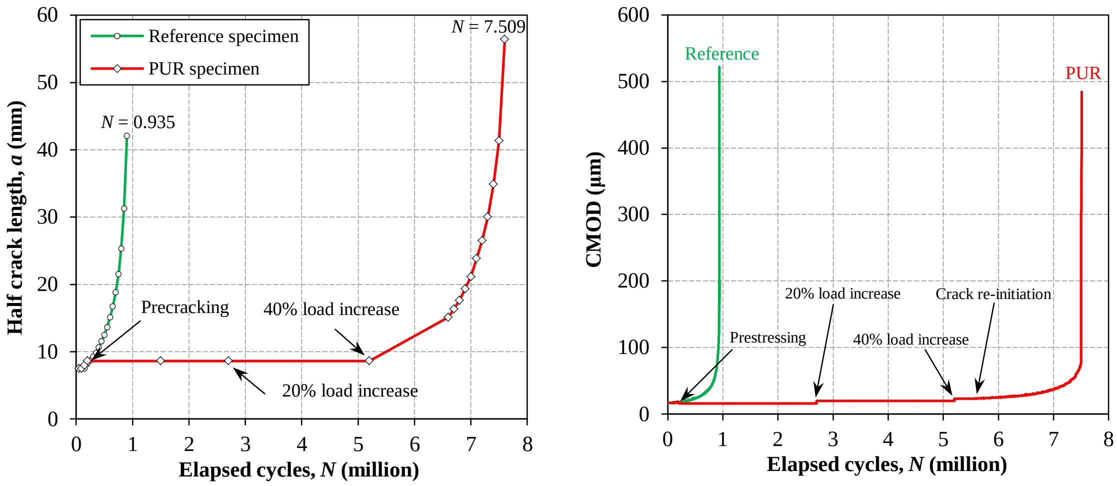
3 RESULTS AND DISCUSSIONS

3.1 *Fatigue crack arrest*

The reference specimen was tested under fatigue loading with a fatigue stress range of $\Delta\sigma$ = 75 MPa, and a load ratio of R = 0.2 until failure at N = 0.935 million cycles. Fatigue loading with the same conditions (i.e. $\Delta\sigma$ = 75 MPa, and R = 0.2) was first applied on the PUR specimen, and a complete crack arrest was observed for 2.5 million fatigue cycles at that stress range. It should be noted here that an operational definition of crack arrest can be considered as a fatigue crack growth rate of 10^{-10} m/cycle or less (ASTM E647-15). Consequently, considering the resolution of the travelling microscope used for the crack-length measurements, i.e., 0.01 mm, at least 100,000 fatigue cycles were required to verify the crack arrest. However, in order to strongly prove the complete arrest of the existing crack and to verify the high performance of the proposed PUR system, the PUR specimen was subjected to 2.5 million fatigue cycles, with no crack extension detected.

As the existing precrack in the PUR specimen was fully arrested for $\Delta\sigma$ = 75 MPa, the loading range was increased by 20% to $\Delta\sigma$ = 91 MPa for the same R ratio. The specimen was then subjected to this higher fatigue-loading range for another 2.5 million cycles. Once again, no crack extension was detected by the travelling microscope confirming the crack arrest in the PUR specimen for $\Delta\sigma$ = 91 MPa. The fatigue load was then increased to $\Delta\sigma$ = 105 MPa (40% more than the initial loading level) again. After approximately 0.3 million fatigue cycles at this level, it was found that the crack was re-initiated, resulted in complete failure of the steel plate after 2.509 million fatigue cycles. Consequently, the fatigue tests performed on the PUR specimen showed that using the PUR system resulted in complete crack arrest even for the 20% higher stress range, while the fatigue life of the cracked steel specimen that was strengthened with the PUR system in the range of 140% of the initial stress was extended by a factor of 2.2 compared to the unstrengthened reference steel plate. Considering the compression in steel plate due to the prestressing force in CFRP plates, $\Delta K_{I,th}$ for the utilized steel can be estimated to be in the range of 200 to 285 N/mm$^{3/2}$ (corresponding to $\Delta\sigma$ = 91 and 105 MPa, respectively) using linear elastic fracture mechanics (LEFM) calculations.

After the complete failure of the tested specimens, i.e. propagation of the crack through the entire section of the steel plates, the specimens were removed from the test setup and a Canon 70D digital camera with a resolution of 20.2 megapixels was used to capture high quality images from the failed cross sections of the specimens (Figure 4). A MATLAB toolbox was then used to read the beach marks and to plot the half-crack length a, against the elapsed number of fatigue cycles N, in Figure 5a, which provides a better understanding about the fatigue performance of the PUR specimen compared to the reference unstrengthened one.



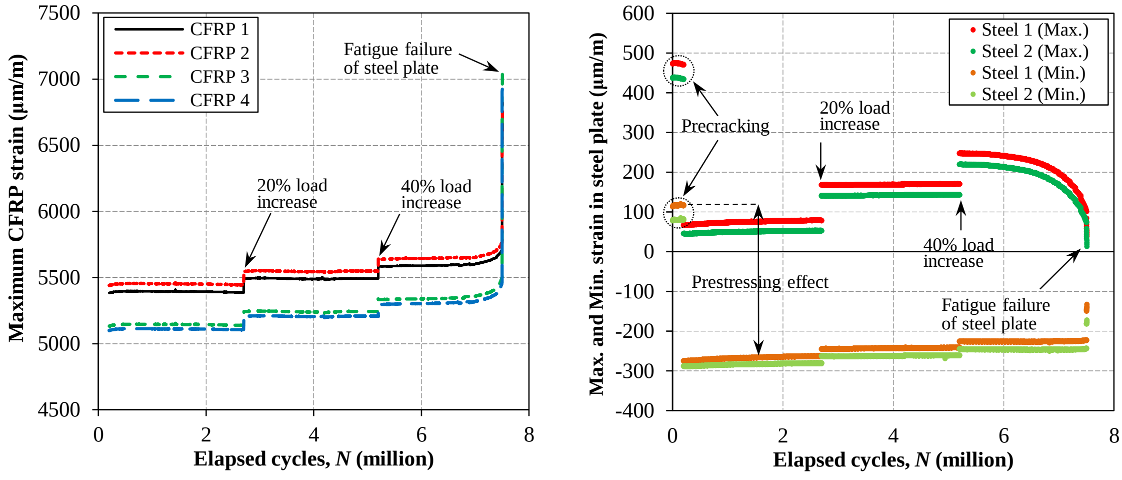
(a) (b)

Figure 5. Experimental results: (a) a–N curves; (b) maximum crack mouth opening displacement (CMOD) versus the elapsed cycles.

The maximum crack mouth opening displacement (CMOD) of the tested specimens during fatigue loading is plotted against the elapsed number of cycles in Figure 5b. The figure illustrates that the CMOD–*N* curve in the reference unstrengthened specimen exhibited a non-linear increasing trend until complete failure of the specimen occurred. On the other hand, Figure 5b shows that the CMOD in the PUR specimen was constant for the two sets of 2.5 million fatigue cycles with slight jumps when the fatigue stress range $\Delta\sigma$ increased from 75 to 91 MPa (at 2.7 million fatigue cycles) and later to 105 MPa (at 5.2 million fatigue cycles), respectively. Having a constant CMOD over the elapsed fatigue cycles strongly confirms that the fatigue crack was completely arrested for the fatigue stress ranges of $\Delta\sigma$ = 75 and 91 MPa. With a 40% increase in the fatigue stress range to $\Delta\sigma$ = 105 MPa, the crack again began to propagate, which resulted in the CMOD increasing until the complete failure of the steel plate.

3.2 Evolution of strain in CFRP and steel plates in PUR specimen

Figure 6a illustrates the evolution of the maximum strain in the prestressed CFRP plates of the PUR specimen with respect to the elapsed fatigue cycles. It can be seen from the figure that, during the fatigue cycles, the maximum strain in the prestressed CFRP plates remained constant for the first two 2.5 million cycles with a sudden increase at 2.7 million cycles due to the 20% increase in load amplitude. This proves that the proposed PUR system experienced no slippage during fatigue loading as no reduction in prestrain level was observed. On increasing $\Delta\sigma$ from 91 to 105 MPa after 5.2 million cycles, a second sudden increase in the CFRP strain levels is observed owing to the increase in load, and the strain in the CFRP plates then started to increase with the number of cycles owing to the crack propagation. A sudden jump in the strain was observed when the crack finally propagated through the entire steel section (Figure 6a). Furthermore, the evolution of the maximum and minimum strain in the steel plate in response to the fatigue cycles is plotted in Figure 6b. As it can be seen from the figure, applying the PUR system on the precracked steel plate considerably reduced the strain level in steel. In other words, prestressing of the cracked steel plate reduced the tensile portion of fatigue loading, while this reduced tensile portion of load resulted in ΔK_I values less than $\Delta K_{I,th}$ for $\Delta\sigma$ = 75 and 91 MPa. Increasing $\Delta\sigma$ by 40%, however, reinitiated the fatigue crack, and resulted in a gradual reduction of measured strain values in steel. Note that the strain gauges were applied at the mid-width of both sides of the steel plate at a distance of 52.5 mm from the specimen's mid-length.



(a) (b)

Figure 6. (a) Evolution of maximum strain in prestressed CFRP plates in response to fatigue cycles; (b) evolution of maximum and minimum strain in steel plate in response to fatigue cycles (PUR specimen).

4 SUMMARY AND CONCLUSIONS

In the current study, a novel PUR system was introduced for strengthening of fatigue-cracked tensile steel members with prestressed CFRP plates. The experimental results proved the high performance of the developed PUR system as the existing fatigue crack in the PUR specimen was completely arrested even for the 20% higher stress range, compared to the initial stress range on the reference specimen. Furthermore, neither slippage of the mechanical clamps nor prestress losses in CFRP plates was observed during 7.5 million fatigue cycles. Consequently, owing to the advantages of the developed PUR system, such as the capability of carrying high prestressing forces to arrest an existing fatigue crack, and elimination of any surface preparation and curing process for bonded solutions, the system can be considered as a good alternative to the conventional bonded reinforcements for fatigue strengthening of damaged steel members.

5 ACKNOWLEDGMENTS

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