Mode I Fatigue Crack Arrest in Tensile Steel Members Using Prestressed CFRP Plates

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Abstract

Numerous studies in the literature have shown that the strengthening of steel members using carbon fiber reinforced polymer (CFRP) composites can significantly extend the fatigue life of these structures. However, not enough attention has been focused on the potential of prestressed CFRP reinforcements for fatigue crack arrest in such members. In the current study, a simple analytical model is proposed to calculate the required prestressing level in the CFRP reinforcements in order to arrest the propagation of an existing fatigue crack in tensile steel members. Furthermore, a novel mechanical unbonded system is developed to anchor the high prestressing forces in CFRP reinforcements to the steel substrate using friction. A set of fatigue tests are performed on unstrengthened and strengthened precracked steel plates to verify the proposed model. The experimental results of the current study showed that the application of nonprestressed ultra-high modulus CFRP plates as externally bonded reinforcements can increase the fatigue life of precracked steel plates by a factor of 4.3. However, fatigue crack arrest is only possible when prestressed CFRPs of a certain prestressing level are used. Based on the analytical, numerical, and experimental results of the current study, it can be concluded that existing fatigue cracks in tensile steel members can be arrested using the proposed prestressed unbonded reinforcement system with the initial prestressing level calculated using the proposed model. In addition, some design recommendations are provided for fatigue crack arrest in practical cases.

Keywords: Steel structures, fatigue strengthening, crack arrest, carbon fiber reinforced polymer (CFRP), prestressed unbonded reinforcement (PUR)

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1. Introduction

A large number of steel structures worldwide are currently aging, and most of these structures, such as road and railway bridges, offshore structures, and communication towers, are subjected to fatigue loading. The increasing service loads and harsh environmental conditions make these structures even more vulnerable to fatigue failure. As a result, the fatigue strengthening of metallic structures has attracted much interest. Various techniques such as using bolted or welded cover plates to bridge existing cracks, overloading the structure to retard the fatigue crack propagation, as well as drilling stop holes at crack tips have been conventionally used to prolong the fatigue life of cracked metallic members [1]. For the last two decades, however, the unique advantages of carbon fiber reinforced polymer (CFRP) composites such as high corrosion resistance, light weight, high strength and elastic modulus, as well as excellent fatigue life, have made CFRP composites a well-accepted alternative for the static and fatigue strengthening of such structures [2,3].

Because several pioneer researchers have demonstrated the potential of CFRP composites in the fatigue strengthening of steel structures [3-9], a considerable number of studies have been conducted on mode I fatigue strengthening of steel plates using nonprestressed bonded CFRP reinforcements [10-18]. The existing literature on this subject mainly focuses on valuable experimental results with analytical or numerical models to predict the fatigue life of CFRP-strengthened steel plates. Furthermore, a few researchers took into account the effects of near-crack debonding of CFRP from a steel substrate [19-21].

Recently, strengthening of fatigue-sensitive or fatigue-damaged steel members with prestressed CFRP plates is becoming increasingly popular, because a reduction in the stress level that causes damage to the structure would be possible with prestressed reinforcements [7,22-28]. Although the aforementioned studies have demonstrated the advantages of prestressed CFRP reinforcements over nonprestressed ones, fewer attempts have been made to develop a model to calculate the required prestressing level in CFRPs for fatigue crack arrest [7,29,30].

1 The reason for this might be that adhesively bonded CFRPs have a limited bond capacity prior
2 to debonding from the substrate (i.e. steel/concrete) [31]; this capacity is severely affected by
3 the prestressing of the CFRP reinforcements [32]. Consequently, the premature debonding of
4 prestressed CFRP reinforcements should be avoided owing to the high interfacial and peeling
5 stresses generated in the end zones of the reinforcement plates. Thus, in almost all the above-
6 mentioned studies that deal with the strengthening of steel members with prestressed bonded
7 CFRP reinforcements, mechanical end-anchorage were used [7,25-27,29].

8 In 2015, Ghafoori [33] conducted extensive research on mode I fatigue strengthening of
9 steel beams using bonded and unbonded prestressed CFRP reinforcements with the intention
10 of preventing fatigue cracking. The research project resulted in different analytical models to
11 estimate the safety state of a steel member under fatigue loading as well as the required pre-
12 stressing level in CFRP reinforcements to prevent fatigue-crack initiation when strengthening
13 with prestressed reinforcement was deemed necessary [34,35]. Furthermore, a novel pre-
14 stressed unbonded reinforcement (PUR) system was developed by Ghafoori and Motavalli
15 [36] and was used to strengthen a 120-year-old railway metallic bridge in Switzerland [37]. It
16 was concluded by the authors that the proposed PUR system has certain advantages such as
17 ease of application, elimination of any surface preparation (which is required for bonded sys-
18 tems), and high performance of the system in terms of prestressing levels [36].

19 More recently, an innovative thermally activated shape memory alloy (SMA)/CFRP
20 patching system was developed by El-Tahan et al. [38] for the strengthening of fatigue-
21 sensitive steel members. This patching system generates compressive stresses in the steel after
22 the activation of SMA wires. Through a comprehensive experimental investigation, Zheng
23 and Dawood [39] proved that strengthening with the help of a prestressed SMA/CFRP patch-
24 ing system can lead to upgrading the fatigue detail from worse than an American Association
25 of State Highway and Transportation Officials (AASHTO) Category E detail to better than a
26 Category B detail. However, near-crack debonding was reported in all of the specimens

strengthened with CFRP and SMA/CFRP patches during the fatigue loading, which has a negative impact on the fatigue life improvement, but is unavoidable in adhesively-bonded reinforcements [39].

As it can be seen from the literature survey, some previous studies have reported fatigue crack arrest in prestressed CFRP-strengthened steel members. However, there exists no analytical model to predict the required prestressing level in CFRP reinforcements to achieve a complete crack arrest. In the current study, an analytical model is proposed to calculate the required prestressing level in CFRP reinforcements to arrest the propagation of an existing fatigue crack in a tensile steel member. To apply such a prestressing level in practical cases, a high performance PUR system has been developed. In order to verify the proposed analytical model, a set of fatigue tests has been performed on precracked steel plates with and without the proposed PUR system; the test procedure and experimental results are comprehensively discussed in this paper. Furthermore, a finite element (FE) analysis has been developed and the results have been compared to those obtained from the proposed analytical model. Lastly, some design recommendations are provided for the use of the proposed analytical model and the PUR system for fatigue crack arrest in practical cases.

2. Analytical Solution for Crack Arrest

The schematic of a tensile steel member under far-field fatigue loading with a ratio of $R = \sigma_{min}/\sigma_{max}$, is considered in Figure 1a. For the member strengthened using the PUR system (Figure 1b), by assuming that the acting stresses and mechanical clamps are far away from the crack (which is a reasonable assumption in practical applications), the loading ratio experienced by the crack can be expressed as follows:

$$R_r = \frac{\rho\sigma_{min} - \sigma_c}{\rho\sigma_{max} - \sigma_c} \quad (1)$$

where R_r is the loading ratio that the retrofitted member experiences, σ_c is the compression generated in the steel owing to prestressing, and ρ is the stiffness ratio with respect to the member after the strengthening and is calculated as follows:

$$\rho = \frac{A_s E_s}{A_s E_s + A_f E_f} \quad (2)$$

where A_s , A_f , E_s and E_f are the cross sectional areas and elastic moduli of the steel and CFRP reinforcements, respectively. On solving Eq. (1) for σ_c , we obtain the following:

$$\sigma_c = \frac{\rho}{1 - R_r} (\sigma_{\min} - R_r \sigma_{\max}) \quad (3)$$

In order to arrest the existing mode I fatigue crack in the assumed steel member, the following criterion should be fulfilled:

$$\Delta K_{I,eff} < \Delta K_{I,th} \quad (4)$$

where $\Delta K_{I,th}$ is the mode I threshold stress intensity factor (SIF) range. This value is a characteristic of the material and should be known or assumed while considering an adequate safety factor for the strengthening (refer to Section 6.1 for the detailed discussion). $\Delta K_{I,eff}$ is the effective mode I SIF range that accounts for the crack closure effect as follows:

$$\Delta K_{I,eff} = U \cdot \Delta K_I \quad (5)$$

where U is a factor less than unity and a function of the loading ratio R , and ΔK_I is the mode I SIF range, which can be generally expressed using Eq. (6). Further details regarding suitable crack closure models that can be used for mild steel are provided in Section 6.2. Nevertheless, it should be noted here that when the *arrest* of an existing fatigue crack is of interest, the initial R ratio, i.e. the load ratio prior to strengthening (and not R_r) should be considered in the selected crack closure model to estimate U (see Section 6.2). This is because the residual plastic deformation in the wake of an existing fatigue crack is the key parameter that controls the

magnitude of the crack closure effect. The size of the plastic zone, however, is a function of the initial loading ratio of the member, R . In other words, the existing fatigue crack has not propagated and will not propagate for R_r after strengthening owing to the fatigue crack arrest.

$$\Delta K_I = \Delta \sigma \cdot f(a, w) \quad (6)$$

where for the strengthened member (Figure 1b),

$$\Delta \sigma = \begin{cases} \rho(\sigma_{\max} - \sigma_{\min}) & R_r > 0 \\ \rho\sigma_{\max} - \sigma_c & R_r \leq 0 \end{cases} \quad (7)$$

and $f(a, w)$ is a geometry function that accounts for the half-crack length a and width of the steel member w . For a middle-cracked steel plate, which is also used in the experimental program of the current study, $f(a, w)$ can be estimated using Eq. (8) [40], while for a wider range of geometries, $f(a, w)$ is given in [41],

$$f(a, w) = \sqrt{\pi a \sec \frac{\pi a}{w}} \quad (8)$$

For clamped-end cases, the aforementioned expression, i.e., Eq. (8), is accurate to within 1% for $2a/w \leq 0.8$ [40]. On substituting Eqs. (5) to (7) into the main criterion in Eq. (4) and solving for R_r , we obtain the following:

$$R_r < \frac{\frac{\Delta K_{I,th}}{U\rho\sigma_{\max}f(a, w)} + R - 1}{\frac{\Delta K_{I,th}}{U\rho\sigma_{\max}f(a, w)}} \quad \text{for } R_r \leq 0 \quad (9)$$

where for design purposes the equality form of Eq. (9) can be used. On obtaining the maximum allowable R_r for crack arrest from Eq. (9), the minimum required compression in steel σ_c can be easily calculated from Eq. (3); subsequently, the minimum required initial prestrain in the CFRP reinforcements can be calculated using a previously developed analytical model [42], as:

$$\varepsilon_{pre} = \frac{\sigma_c A_s}{\rho A_f E_f} \quad (10)$$

As mentioned above, Eq. (9) is valid for $R_r \leq 0$. In the case of $R_r > 0$, $\Delta\sigma$ is a function of ρ , while it is independent of σ_c (see Eq. (7) and Figure 1b). This emphasizes that the strengthening of cracked steel members under very high R ratios can only decrease $\Delta\sigma$ by a factor ρ , which depends on the reinforcement stiffness and not on the prestressing force. Therefore, prestressing is an efficient solution for the fatigue strengthening of cracked steel members when $R_r \leq 0$ can be reached after strengthening. This is generally the case with steel structures, as steel members do not experience very high R ratios; this means that $R_r \leq 0$ after the cracked member is strengthened with prestressed reinforcements. It is also worth mentioning that the analytical formulation derived in this section is independent of the reinforcement material and/or prestressing technique. Thus, the aforementioned formulation can be used to estimate the required compression in a tensile steel member for an existing mode I fatigue crack to be arrested. Subsequently, a suitable reinforcement material and technique may be selected to provide the calculated compression force in the member, while considering the boundary conditions. In the current study, a PUR system consisting of normal-modulus (NM) CFRP plates and novel high-performance mechanical clamps has been used in the experimental program to verify the accuracy of the proposed analytical model.

3. Experimental Program

3.1. Test layout and specimen details

In order to evaluate the performance of the proposed analytical model to predict the required prestressing force for an existing fatigue crack to be arrested, a set of fatigue tests were performed on three precracked middle-tension (M(T)) steel specimens of dimensions $900 \times 150 \times 10$ mm (length $\times$ width $\times$ thickness). The three different specimens tested under fatigue loading are depicted in Figure 2. While the reference specimen had no external reinforcement (Figure 2a), nonprestressed bonded ultra-high-modulus (UHM) and prestressed unbonded

normal-modulus (NM) CFRP plates were used to strengthen the second and the third specimens, which are denoted as NPBR-UHM (Figure 2b) and PUR-NM (Figure 2c), respectively. The aim of having the NPBR-UHM specimen was to compare the performance of nonprestressed UHM CFRPs with prestressed NM CFRPs for the fatigue strengthening of cracked steel members and to evaluate the feasibility of crack arrest in each case. The details regarding the strengthening procedures used for each specimen are provided in the subsequent sections.

As shown in Figure 2a, all the steel specimens were cut so that the rolling direction of the steel plates was perpendicular to the loading direction, and 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 or crack arrest. An electrical discharge machine (EDM) was used to cut a through-thickness notch at the center of all the specimens, as illustrated in Figure 2a, 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 [40].

3.2. 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 unstrengthened 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 [43]. The stress-strain curves for all the samples are plotted in Figure 3, while the mechanical characteristics of the steel both parallel and perpendicular to the rolling direction are reported in Table 1. The experimental results showed no significant difference in the mechanical properties of the steel parallel or perpendicular to the rolling direction.

In order to strengthen the steel plate specimens, two different types of unidirectional CFRP plates were used. For the second specimen, four UHM CFRP plates of type Carbolam

THM 450-50 $\times$ 1.2 with measured cross-sectional dimensions of 25 $\times$ 1.5 mm (width $\times$ thickness) were used. For the third specimen, four NM CFRP plates of type S&P 150/2000 with measured cross-sectional dimensions of 25 $\times$ 1.4 mm (width $\times$ thickness) were used. The mechanical properties of the CFRP plates are provided in Table 2. Furthermore, in the NPBR-UHM specimen, a two-component epoxy adhesive of type Araldite 420 A/B was used to bond the UHM CFRP plates to the steel substrate. The ultimate tensile strength of the adhesive was obtained from three six-day samples (see Michels et al. [45] for the test procedure) and was determined to be 26.0 MPa. No auxiliary test was performed to determine the shear modulus G_a of the adhesive as part of the current study; however, a shear modulus of $G_a = 730$ MPa is proposed by the manufacturer for room temperature applications.

3.3. Fatigue precracking

The steel plate specimens were precracked prior to being strengthened with CFRP plates. 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 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 [40]. Consequently, based on the recommendations provided in ASTM E647-15 [40], a minimum precrack of 1.0 mm (on each side of the starter notch) is required for the designed M(T) specimens with the special machined notch depicted in Figure 2a. Table 3 presents the details of the fatigue precracking for all the specimens. It should be noted that 200,000 fatigue cycles in total with $\Delta\sigma = 75$ MPa and $R = 0.2$ were applied to each of the steel plates for fatigue precracking, and approximately 100,000 of those fatigue cycles were required for the crack to initiate from the EDM notch.

3.4. Strengthening techniques

3.4.1. Nonprestressed bonded reinforcement (NPBR)

After the fatigue precracking of the second specimen, the specimen was taken out of the fatigue machine to be strengthened with nonprestressed UHM CFRP plates. As it was intended to visually monitor the crack development with a travelling microscope to detect crack arrest, if any, two UHM CFRP plates were bonded on each side of the specimen away from the precrack tips (Figure 2b). To do so, the four bond areas were first sandblasted and carefully cleaned with acetone. Two $400 \times 25 \times 1.5$ mm (length $\times$ width $\times$ thickness) UHM CFRP plates were then immediately glued on one side of the specimen using the two-component epoxy adhesive. After curing for 24 h, the specimen was turned over and the other two UHM CFRP plates were bonded to the other side of the specimen as well. The entire sample was cured at room temperature for 7 days and, the adhesive thickness was then measured at three locations along each of the CFRP plates using a micrometer with a resolution of 0.01 mm. The adhesive thickness was found to be in the range of 0.04 to 0.11 mm.

3.4.2. *Prestressed unbonded reinforcement (PUR)*

The third specimen was also removed from the test setup, after fatigue precracking, to be strengthened with four prestressed NM CFRP plates as illustrated in Figure 2c. The strengthening configuration including the positions of the reinforcement plates for both the second and third specimens were the same, which allowed the results to be directly compared. As shown in Figure 2c, the prestressed NM CFRP plates were held on both sides of the steel plate specimen using mechanical clamps which work via friction. As it can be seen in Figure 4, 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. As the entire system functions with the help of friction, 3MTM diamond friction shims of grade 10 (3M Technical

1 Ceramics GmbH, Germany), were used between the CFRP plates and steel substrate to in-
2 crease the friction. Furthermore, because the normal force generated by the prestressed bolts
3 is transferred to the hard plates via the upper and lower clamp plates and causes high bending
4 stresses in those parts, the upper and lower clamp plates were manufactured from high-
5 strength steel M200 with a nominal yield strength of 1000 MPa.

6 As mentioned in Section 3.4.1, the CFRP plates were not intended to cover the crack
7 because the state of the crack was required to be visually monitored for any probable crack re-
8 initiation. Consequently, the PUR system in this study was designed and developed to hold
9 the four CFRP plates apart at the crack tips (Figure 2c). However, another configuration of the
10 PUR system has been previously designed and tested to anchor two 50×1.4 -mm (width $\times$
11 thickness) CFRP plates [42], which can be installed at the cracked zone of a tensile steel
12 member in practical cases. The advantage of the aforementioned PUR system is its relatively
13 simple installation owing to the lower number of mechanical parts and bolts (i.e. eight M12
14 bolts in total) involved [42]. It is also worth mentioning that a set of static and fatigue tests on
15 the unbonded mechanical clamps were performed to evaluate the ultimate capacity of the de-
16 veloped unbonded system. All the performed tests showed that even after 10 million fatigue
17 cycles, the designed system is capable of exhibiting the tensile capacity of the CFRP plates
18 before any slippage occurs. However, further details on this topic are beyond the scope of the
19 current paper.

20 3.4.3. *Prestressing setup and procedure*

21 To strengthen the precracked specimen using the developed PUR system, a special prestress-
22 ing setup was designed and assembled in order to simultaneously prestress four parallel CFRP
23 plates (Figure 5). To do so, the four CFRP plates were first placed in the specially designed
24 prestressing grips. Using a hydraulic jack, an average prestrain level of $5180 \mu\text{m/m}$ was gen-
25 erated in the CFRP plates. This value was slightly higher than the required value, i.e., 5040
26 $\mu\text{m/m}$, which was calculated based on the procedure described in Section 2 (Eq. (10)) consid-

ering $\Delta K_{I,th} = 100 \text{ N/mm}^{3/2}$ and $U = 1.0$ (refer to Section 4.1. and Section 6 for further explanation on the considered values). 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 2c. It should be noted that the procedure of strengthening of the third steel plate specimen using the PUR system was carried out in less than 2 h hours because, unlike bonded systems, no surface preparation or curing of adhesive are required when using unbonded mechanical clamps.

3.5. Instrumentation, test setup, and test procedure

A 1000-kN static/fatigue servo-hydraulic Schenck machine with an Instron controller was used for the fatigue precracking as well as fatigue testing of all the specimens until failure. All the tests were performed under the load-control condition with a load ratio of $R = 0.2$ and a frequency of 15 Hz. Figure 6 shows the test setup and the instrumentation used to monitor the specimens during the fatigue testing. Several $120\Omega \pm 0.30\%$ electrical foil strain gauges (HBM AG, Germany) were mounted on the specimens to monitor the evolution of strain in steel and CFRP plates during the tests. Strain gauges of type 1-LY61-6/120 were installed at the mid-width of both sides of the steel specimens at a distance of 52.5 mm from the specimen's mid-length; strain gauges of type 1-LY66-6/120 were used at the mid-length of all the CFRP plates. An MTS clip gauge (model 632.03C-20) with a gauge length of 12 mm was installed on all the steel specimens to monitor the crack mouth opening displacement (CMOD) during the fatigue loading.

A travelling microscope (Spindler & Hoyer, Germany) was installed on the lower grip of the testing machine (Figure 6), thus allowing the crack length to be visually measured with

a resolution of 0.01 mm. Furthermore, the beach marking technique was also incorporated in all the tests, both in the stages of fatigue precracking of the bare steel specimens as well as the fatigue testing of the strengthened specimens. Figure 7 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. It should be noted that in the fatigue precracking of all the specimens and fatigue tests of the first and second specimens, the values of $N_1 = 50,000$ and $N_2 = 25,000$ were used, while in the third fatigue test, 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.

4. Experimental Results and Discussions

4.1. Fatigue life extension and crack arrest

All the prepared steel specimens were tested under fatigue loading with a load ratio of $R = 0.2$ until failure. The applied fatigue stress range $\Delta\sigma$, the number of elapsed cycles until failure, and the fatigue life extension ratio are reported in Table 4. As can be observed in Table 4, the strengthening of the precracked steel-plate specimen using nonprestressed UHM CFRP plates extended the fatigue life by a factor of 4.3 compared to the reference unstrengthened specimen. On the other hand, using the PUR system with the calculated prestressing force based on the proposed analytical model led to the complete arrest of the existing crack in the PUR-NM specimen for $\Delta\sigma = 75$ MPa. 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 [40]. 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

1 verify the high performance of the proposed PUR system, the PUR-NM specimen was sub-
2 jected to 2.5 million fatigue cycles, with no crack extension detected.

3 As the existing crack in the PUR-NM specimen was fully arrested for $\Delta\sigma = 75$ MPa, the
4 loading range was increased by 20% to $\Delta\sigma = 91$ MPa for the same R ratio. The specimen was
5 then subjected to this higher fatigue-loading range for another 2.5 million cycles. Once again,
6 no crack extension was detected by the travelling microscope and no increase in CMOD was
7 detected by the clip gauge, thus confirming the crack arrest in the PUR-NM specimen for $\Delta\sigma$
8 $= 91$ MPa. The fatigue load was then increased to $\Delta\sigma = 105$ MPa (40% more than the initial
9 loading level) again. After approximately 300,000 fatigue cycles at this level, it was found
10 that the crack was re-initiated, resulted in complete failure of the steel plate after approximate-
11 ly 2,509,000 fatigue cycles. Consequently, the fatigue tests performed on the PUR-NM spec-
12 imen showed that using the PUR system resulted in complete crack arrest even for the 20%-
13 higher stress range, while the fatigue life of the cracked steel specimen that was strengthened
14 with the PUR system in the range of 140% of the initial stress was extended by a factor of 2.2
15 compared to the unstrengthened steel plate.

16 It should be mentioned that the prestress level used in the PUR system was initially cal-
17 culated so that the SIF range, experienced by the material in front of the crack after strength-
18 ening with the PUR system, would be equal to the assumed $\Delta K_{I,th} = 100 \text{ N/mm}^{3/2}$ for the stress
19 range of $\Delta\sigma = 75$ MPa. By increasing the stress range to $\Delta\sigma = 91$ and 105 MPa, the SIF range
20 experienced by the specimen was increased to 200 and 285 $\text{N/mm}^{3/2}$, respectively. As the
21 crack started to re-initiate in the fatigue stress range of $\Delta\sigma = 105$ MPa, it can be concluded
22 that $\Delta K_{I,th}$ for the utilized steel in this study was in the range of 200 to 285 $\text{N/mm}^{3/2}$. The same
23 order of $\Delta K_{I,th}$ for mild steel is reported in the study by Otsuka et al. [46] based on an exten-
24 sive experimental research on three grades of low carbon steel.

25 After the complete failure of all tested specimens, i.e. propagation of the crack through
26 the entire section of the steel plates, the specimens were removed from the test setup and a

1 Canon D70 digital camera with a resolution of 20.2 megapixels was used to capture high
2 quality images from the failed cross sections of the specimens, as shown in Figure 8. A
3 MATLAB toolbox was then used to read the beach marks and to plot the half-crack length a ,
4 against the elapsed number of fatigue cycles in Figure 9. As shown in Figure 9, the strength-
5 ening of an existing cracked steel plate with nonprestressed UHM CFRP plates can be a very
6 efficient technique to extend the fatigue life of such a tensile member as the $a-N$ curve shows
7 an approximately a linear behavior when the crack tip is beneath the CFRP plates. However,
8 crack arrest was only possible when the required prestressing force in the damaged member
9 was provided. The $a-N$ results presented in Figure 9 were used to obtain the crack growth rate
10 versus half-crack length ($da/dN-a$) plots shown in Figure 10. The figure shows that in the ref-
11 erence specimen, the crack growth rate rapidly increases by propagation of the fatigue crack.
12 However, in the specimen strengthened with nonprestressed UHM CFRP plates, the crack
13 growth rate initially increases for a few millimeters of crack extension and then gradually de-
14 creases when the crack propagates beneath the CFRP plates. The decrease in da/dN with the
15 increasing crack length is attributed to the ability of bonded CFRP plates to bridge the crack
16 as previously mentioned in [7]. However, after the crack propagates through the entire width
17 of the CFRP plates, the crack growth rate starts to rapidly increase until complete failure of
18 the specimen occurs. Careful inspection of Figures 9 and 10 reveals that an existing crack can
19 experience further propagation before the sudden failure of the remaining section when the
20 steel plate is strengthened with CFRP plates. This is because the stresses acting on the cracked
21 section are lower when the steel plate is strengthened with nonprestressed or prestressed
22 CFRPs, as the CFRP plates contribute to carrying the external load, especially when the crack
23 is relatively long.

24 The maximum CMOD of all the tested specimens during fatigue loading is plotted
25 against the elapsed number of cycles in Figure 11. Figure 11 illustrates that the CMOD- N
26 curve in the reference unstrengthened specimen exhibited a non-linear increasing trend until

complete failure of the specimen occurred. However, in the NPBR-UHM specimen, the CMOD first linearly increased with the number of cycles (until approximately 3.5 million cycles), which was followed by a sharp ascending branch until the propagation of the fatigue crack through the entire steel section (at approximately 4.0 million fatigue cycles). The fatigue loading was then continued until the complete failure of the specimen, which was a combination of CFRP debonding from the steel substrate and CFRP tensile rupture (Figure 12). It is worth mentioning that during the last 28,600 fatigue cycles, the entire tensile fatigue load was transferred to the UHM CFRP plates via the adhesive, because the entire section of the steel plate was cracked. The bond failure that occurred in the NPBR-UHM specimen demonstrates that the fatigue performance of the bond is of great importance and should be carefully considered when adhesively bonded reinforcements are used for fatigue strengthening of metallic members. On the other hand, Figure 11 shows that the CMOD in the PUR-NM 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.

The evolution of the maximum strain in the CFRP plates of the NPBR-UHM specimen with respect to the elapsed fatigue cycles is plotted in Figure 13. As shown in the figure, the tensile strain at the mid-length of the UHM CFRP plates slightly increased with the number of cycles until approximately 0.75 million cycles, when the crack reached the CFRP plates. Between 0.75 and 3.0 million fatigue cycles, the crack propagated beneath the 25-mm wide CFRP plates, while the strain in the CFRP plates was increasing. This ascending trend continued with a sudden increase in the CFRP strain at approximately 4.0 million cycles when the

entire steel section cracked (Figure 13). It should be noted that the value of the strain generated in the UHM CFRP plates after the complete failure of the steel plate was approximately 3000 $\mu\text{m/m}$ (0.3%). This value is very close to the ultimate elongation of the material at tensile rupture. As a result, a combined failure mode consisting of debonding and CFRP rupture could be expected in the NPBR-UHM specimen and was indeed observed (Figure 12).

As mentioned in Section 3.4.3, a special prestressing setup (Figure 5) was used to apply the required prestressing force in the NM CFRP plates to strengthen the third precracked steel plate using the PUR system. Figure 14 shows the strain history of the steel and CFRP plates during the prestressing process. First, all the four CFRP plates were prestressed using a hydraulic jack and the prestrain level was manually adjusted to the desired value with the help of a hydraulic valve (Figure 14). The prestressed CFRP plates were then anchored to the steel plate using mechanical clamps, and the load in the hydraulic jack was released to zero. This resulted in a slight decrease in the prestrain level of the CFRP plates owing to the compressive deformation of the steel, which based on Eq. (10), was considered to reach the required compressive strain of approximately 370 $\mu\text{m/m}$ in the steel plate specimen for the existing fatigue crack to be arrested (Figure 14). It is worth mentioning that, as shown in Figure 14, the strain level was not identical in all the four CFRP plates; obtaining an identical prestrain level in all the CFRP plates would be practically impossible as all the CFRP plates were prestressed together. However, the maximum difference in the final strain level in the different CFRP plates was less than 6%, which is deemed acceptable.

Figure 15 illustrates the evolution of the maximum strain in the prestressed CFRP plates of the PUR-NM 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. Firstly, this shows that no crack propagation occurred during the first two 2.5 million fatigue cycles for $\Delta\sigma = 75$ and 91 MPa, respectively, and sec-

only, 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 at approximately 7.5 million cycles (Figure 15).

4.2. Crack closure phenomenon

The term *crack closure* [47] refers to the phenomenon whereby the fracture surfaces of an existing fatigue crack come into contact during the unloading regime of a fatigue cycle and force is transferred across the crack [40]. It is generally well understood that crack closure can occur owing to one or more of the following phenomena [48,49]:

- 1) residual plastic deformation in the wake of the crack, which is also known as plasticity-induced crack closure or Elber mechanism,
- 2) a mismatch between the two crack surfaces caused by surface roughness asperities, crack branching, or undesired mixed-mode crack opening, and
- 3) crack surface oxidation, known as oxide-induced crack closure, usually associated with an aggressive environment.

Crack closure can occur while the applied force on the cracked member is above the minimum force in the fatigue cycle. As a result, upon reloading from the minimum force in a subsequent cycle, some increment in the loading must be applied before the crack is fully open and activated. Consequently, crack closure provides a mechanism in which the effective SIF range $\Delta K_{I,eff}$ experienced by the crack is lower than the applied value of ΔK_I (see Eq. (5)) [40]. Information regarding the magnitude of the crack closure is crucial to interpreting and predicting crack growth (or arrest) behavior [40,49]. An estimate of $\Delta K_{I,eff}$ can be obtained

experimentally by determining the minimum force at which the crack is fully open (opening force, P_o). Given the value of P_o in hand, it is possible to determine U (see Eq. (5)) as follows:

$$U = \frac{\Delta K_{I,eff}}{\Delta K_I} = \frac{K_{max} - K_o}{K_{max} - K_{min}} = \frac{P_{max} - P_o}{P_{max} - P_{min}} \quad \text{for } P_o > P_{min} \quad (11)$$

Owing to the importance of the crack closure effect, many experimental techniques have been introduced in the literature to determine the opening force and, subsequently, U [40]. In the current study, the compliance offset method which is comprehensively described in [40], was applied to near-crack-tip strain measurements to determine P_o . To do so, a special small strain gauge of type 1-LY61-3/120 (HBM AG, Germany), was mounted in the vicinity of the notch tip as illustrated in Figure 16. Load–strain diagrams for $N=1$ and 200,000 cycles obtained from the near-crack-tip measurements are plotted in Figure 17a. As shown in the figure, residual compressive strain was generated in the vicinity of the notch tip after the first cycle unloading; the unloading portion of the diagram is, however, linear because the crack had not initiated yet. At $N=200,000$ cycles, the near-crack-tip load–strain diagram exhibited a bilinear behavior both in the loading and unloading portions of the cycle. This bilinear behavior of the load–strain diagram clearly indicates the crack closure effect. P_o can be calculated based on the procedure describe in [40] using the compliance offset, defined as follows:

$$\text{Compliance offset} = \frac{C_o - C}{C_o} \times 100 \quad (12)$$

where C is the compliance defined as ε/P , and C_o is the open-crack compliance determined as the slope of the strain–load diagram over a span range of the upper 25% portion of the cyclic load. A plot of the load versus the compliance offset for the unloading portion at $N=200,000$ cycles is provided in Figure 17b, from which the opening force corresponding to the 2% compliance offset was determined to be $P_o=39.3$ kN. Consequently, $U = 0.9$ as calculated using Eq. (11) by substituting $P_o=39.3$ kN, $P_{max}=140.6$ kN, and $P_{min}=28.1$ kN.

In order to show the significance of the crack closure effect on the crack growth rate behavior, a - N plot data of the reference specimen presented in Figure 9 were used to construct the da/dN versus ΔK_I curve in Figure 18. It should be noted that the a - N curve results of the specimen during the precracking stage were excluded from the da/dN - ΔK plots in order to consider the stage II of crack propagation (Paris regime). Paris law parameters C and m for the steel used were determined both with and without the crack closure effect (see Figure 18). It is obvious that an accurate crack growth rate-estimation can be only achieved by using $\Delta K_{I,eff}$ (calculated from Eq. (5)) and applying the intrinsic Paris law parameters $m = 3.401$, and $C = 2.32 \times 10^{-14} \text{ mm/cycle}(\text{N/mm}^{3/2})^{-m}$.

4.3. State of holes in PUR system

As shown in Figure 19, several holes are required to be drilled in the steel plate for the installation of the PUR system, and the fatigue performance of these holes might be of concern. Consequently, strain gauges of type 1-LY61-3/120 were installed adjacent to the holes in order to monitor their state during the fatigue test of the PUR-NM specimen (see Figure 19b). It should be noted that holes of diameter 11 and 13 mm were drilled into the steel plate for M10 and M12 bolts, respectively (see Figure 19b). Thus, the prestressed bolts can be assumed to not be in contact with the inner surfaces of the holes during the fatigue loading.

Figure 20a illustrates the experimental load-strain behavior of the holes at fatigue cycle number $N = 2,500,000$. It can be seen from Figure 20a that holes 1 and 5 experienced higher strain levels in a loading cycle compared to the others, as they are less affected by the prestressing force generated in the steel using the CFRP plates (see Figure 19). Furthermore, holes 2 and 3 are in stiffer zones than the others because they benefit more from the additional stiffness provided by the CFRP and hard plates. It is evident from the load-strain behavior of the different holes in Figure 20a that holes 1 and 5 are the most fatigue-prone holes in the PUR system. Consequently, the evolution of the maximum strain in the vicinity of holes 1 and 5 with respect to the number of cycles was monitored during the entire fatigue testing of the

PUR-NM specimen, the results of which are provided in Figure 20b. It is apparent that any crack initiation and subsequent propagation from holes 1 and/or 5 will result in an increase in the measured strain levels in the vicinity of the holes. However, Figure 20b verifies that no crack was initiated from the holes because the maximum strain level in the vicinity of holes 1 and 5 was nearly constant until the failure of the steel plate occurred. In addition to the strain measurements, visual inspection of the holes after disassembling the PUR system confirmed that no crack initiated from the holes.

Experimental strain measurements in the vicinity of the most fatigue-prone holes, i.e. holes 1 and 5, were used in Figure 21 to compare the condition of holes with predictions from different constant life diagram (CLD) criteria. It should be noted that, as the experimental strain measurements were performed at a distance of 8.85 mm from the holes' center (see Figure 19b), the following formulation was used to estimate the stress at the holes' edges [50]:

$$\sigma_h = \frac{3E_s \varepsilon_{\exp}}{1 + \frac{1}{2} \left(\frac{a}{x}\right)^2 + \frac{3}{2} \left(\frac{a}{x}\right)^4} \quad (13)$$

where $\varepsilon_{\exp}$ is the experimental strain obtained from the strain gauges mounted in the vicinity of the holes, a is the hole radius ($a = 5.5$ mm in this case), and x is the distance between the hole center and strain gauge centerline ($x = 8.85$ mm in this case).

Figure 21 shows the experimental state of holes 1 and 5 in terms of mean stress ($\sigma_{m,h} = \frac{\sigma_{\max,h} + \sigma_{\min,h}}{2}$) and alternating stress ($\sigma_{a,h} = \frac{\sigma_{\max,h} - \sigma_{\min,h}}{2}$) compared to the Goodman and Gerber CLD criteria. Any point below an assumed CLD criterion represents an infinite fatigue life (no crack initiation/propagation) for the assumed metallic detail. Thus, it can be seen from Figure 21 that the predictions of the Gerber CLD criterion for all the three steps of loading correlated well with the experimental observations for holes 1 and 5 (i.e., no crack initiation). On the other hand, the Goodman criterion is considered to be more conservative as it predicts

an infinite fatigue life for the holes only under the initial loading level ($\Delta\sigma = 75$ MPa). Consequently, the experimental results verify that the fatigue endurance limit of the holes in the PUR system can be predicted using the Gerber CLD criterion; alternatively, the Goodman CLD criterion might be used for a conservative design. As a detailed discussion on different CLD criteria is beyond the scope of the current paper, readers may refer to [35,37] for a comprehensive background and further discussions regarding different CLD criteria and their performance in fatigue endurance limit determination in metallic structures.

5. Finite Element (FE) Modeling

5.1. Geometry, mesh, and boundary conditions

FE models of the reference and CFRP-strengthened steel specimens were created using ABAQUS 6.14-1 [51]. The geometries and dimensions used in the FE models were similar to those described in Section 3.1 for each specimen (Figure 2). However, owing to the fact that hydraulic grips were used to clamp the specimens in the fatigue-testing machine (Figure 6), the 150-mm steel plate extremities that were clamped inside the hydraulic grips were not considered in the FE models. First, the reference unstrengthened steel plate was modeled, and subsequently, a model for each of the NPBR and PUR cases was developed using the UHM and NM CFRP plates in the reference model and implementing the required interactions between the CFRP reinforcements and steel substrate. Owing to the symmetry of the specimen, only one-eighth of each specimen was modeled (as shown in Figure 22) to reduce the computational effort. The steel was modeled using 8-node linear brick elements of type C3D8R with reduced integration and hourglass control, while the CFRP was modeled using 20-node quadratic brick elements of type C3D20R with reduced integration. Furthermore, a very fine radial mesh was generated around the tip of the crack (Figure 22), while 6-node linear triangular prism elements of type C3D6 were used at the crack tip. The model of a CFRP-strengthened steel plate consisted of approximately 10,000 3D elements. The crack was modeled in ABAQUS by introducing the crack tip and crack extension direction, while a free boundary

condition was applied for the notch surface and the 1.0 mm precrack length as illustrated in Figure 22. A static uniform pressure of $\sigma_{max} = 93.7$ MPa was introduced at the end of the steel plate to simulate the maximum far-field tensile load during fatigue cycles.

5.2. Material behavior, interactions, and CFRP prestressing

Both the steel and CFRP were modeled as isotropic linear elastic materials, and the material properties were adopted in the models based on the performed auxiliary tests (described in Section 3.2). It should be noted that the Poisson ratio was considered to be 0.3 for both the steel and CFRPs. In the NPBR-UHM specimen, surface-to-surface tie constraints were used to model the adhesive bond of the UHM CFRP to the steel substrate. In this model, the entire length of the CFRP plate was tied to the steel by introducing the steel and CFRP as the master and slave surfaces, respectively. The tie constraint does not allow any relative displacement to occur between the CFRP and steel in the interaction plane, which is a simplifying assumption for modeling the adhesively bonded joints. However, as the main intention of the FE modeling in the current study was to investigate the effect of prestressing on the SIF experienced by the crack in the PUR system (and not precisely modeling the bond), this simplified approach was used. Valuable research studies that deal with different modeling aspects of bonded CFRP-strengthened steel plates, such as near-crack debonding, can be found in the literature [19-24]. For the PUR-NM specimen, only the 85-mm long end of the CFRP (which is equal to the length of the hard plates) was tied to the steel substrate, which reflects the behavior of the unbonded mechanically anchored CFRP-to-steel joint well in the friction-based PUR system used. A predefined stress field in the Y direction (see Figure 22) was introduced to the NM CFRP plate in the FE model of the PUR-NM specimen to simulate the desired prestressing force. During the initial step of analysis in ABAQUS, this predefined stress field was redistributed to obtain a force equilibrium in the entire model. This process reflects the release of the hydraulic jack prestressing force in the prestressing setup fairly well (see Figure 5); this

leads to compression in the steel as well as a prestressing loss in the CFRP reinforcement due to the shortening of the steel plate.

5.3. FE results

In all the FE models, the SIF experienced at the 1.0-mm fatigue precrack tip was calculated using J-integral in ABAQUS, and the results are plotted versus the external loading introduced to the models in Figure 23. Furthermore, the analytical procedure described in Section 2 was used to calculate the SIF versus the external load in all the three specimens, and the results are shown in Figure 23 for comparison with the obtained FE results. As can be observed, the predicted SIF using the proposed analytical model correlates well with the FE results for the reference unstrengthened specimen as well as for the NPBR-UHM and PUR-NM specimens. It should be mentioned that in the PUR-NM specimen, owing to the compression force generated in the steel by the prestressed unbonded CFRP plates, the SIF remains negative for a major portion of the external loading (see Figure 23). Although negative values of the SIF might be meaningless from the physical point of view, it shows that the crack tip is under compression because of the prestressing. Furthermore, careful inspection of Figure 23 reveals that upon applying the fatigue loading in the PUR-NM specimen, the ΔK_I experienced by the crack would be equal to the desired value for crack arrest ($\Delta K_{I,th} = 100 \text{ N/mm}^{3/2}$) for which the required prestressing level was calculated from the proposed analytical model.

Consequently, the simple analytical model proposed in Section 2 can be safely used to calculate the required prestressing force for an existing fatigue crack in a tensile steel member to be arrested. However, for more complicated configurations of steel cross sections, $f(a,w)$ in Eq. (8) cannot be analytically derived, which means that ΔK_I cannot be explicitly formulated. In such cases, the proposed FE modeling can be used to determine $f(a,w)$ for the unstrengthened member, and subsequently, the analytical procedure described in Section 2 can be used to calculate the required prestressing level in the CFRP reinforcements for crack arrest.

6. Design Recommendations

6.1. Threshold stress intensity factor (SIF) range

It is clear that in order to design a reliable strengthening system to arrest the propagation of an existing fatigue crack in a tensile steel member using prestressed CFRP plates, a fairly accurate estimation of the threshold SIF range ($\Delta K_{I,th}$) should be obtainable. $\Delta K_{I,th}$ can be determined for the material of interest by performing adequate fatigue tests based on existing guidelines such as ASTM E647-15 [40]. However, such tests are time-consuming and costly, while sample extraction can be unfavorable or even impossible in some practical cases. Furthermore, the existing literature shows a relatively large scatter in $\Delta K_{I,th}$ with characteristic values ranging from 126.5 N/mm^{3/2} [52] to 484.8 N/mm^{3/2} [53] for mild steel. Such a high scatter may be attributed to the fact that a variety of materials, specimen configurations and test protocols were used by different researchers. In addition, tests were conducted with different R ratios ranging from -1.0 [46] to 0.7 [52], and in most cases no information is provided by the researchers regarding the crack closure effect and probable residual stresses due to annealing and/or rolling of the steel. Consequently, a suitable value of $\Delta K_{I,th}$ should be carefully selected from the existing literature. However, in the case that no information is available regarding the material of the metallic member that is required to be strengthened, and performing a proper test is not feasible, a design value equal to $\Delta K_{I,th} = 100 \text{ N/mm}^{3/2}$ can be conservatively used for a safe strengthening design.

6.2. Crack closure effect

As comprehensively discussed in Section 4.2, the crack closure phenomenon has a significant effect on the determination of the crack growth rate and the prediction of crack arrest. It has also been proven in several studies that U (see Eq. (11)) is a function of the material as well as the loading ratio R [50]. A number of empirical models have been proposed in the literature to quantify the crack closure effect or to determine U ; Dilling [54] proposed the following empirical formulation for mild steel, which was then recommended by other researchers in the field such as [7,25,49]:

$$U = 0.69 + 0.45R; -1 \leq R \leq 0.33 \quad (14)$$

Moreover, based on an extensive experimental program on center-notched specimens of structural steel, Kurihara et al. [55] proposed the following empirical formulation that covers a wider range of R ratios:

$$U = \frac{1}{1.5 - R}; -5.0 \leq R \leq 0.5 \quad (15)$$

which, for $R \geq 0$, provides values similar to Dilling's model [54]. On substituting $R = 0.2$ in Eqs. (14) and (15), we obtain $U = 0.78$ and 0.77 as the predictions of the Dilling [54] and Kurihara et al. [55] models, respectively, for the mild steel used in the current study. Therefore, the aforementioned empirical models overestimate the crack closure effect by approximately 14% compared to the experimental result, $U = 0.9$ (see Section 4.2). It should be note that U is a material-dependent factor; however, there is no information available regarding the probable residual stresses caused by the rolling or annealing of the samples used for the calibration of the empirical models. Therefore, a difference of 14% between the experimentally obtained U and the predicted values is deemed to be acceptable; thus, the Dilling [54] or Kurihara et al. [55] models can be useful in obtaining an idea regarding the influence of the crack closure phenomenon. However, similar for obtaining $\Delta K_{I,th}$, the ideal approach for determining P_o and, subsequently, U for the material of interest would be performing standard tests as discussed in Section 4.2 using the real R ratio experienced by the steel member. In case of a lack of information or experimental data, $U = 1.0$ may be used for a conservative safe strengthening design.

6.3. Special considerations regarding PUR system

As comprehensively discussed in Section 4.3, the fatigue performance of the required holes, which must be drilled into the steel member in the proposed PUR system, might be of concern. Thus, in practical strengthening designs, the fatigue endurance limit of the most fatigue-prone holes has to be estimated using proper CLD criteria (see Section 4.3), and the infinite

fatigue life of the PUR system must be verified prior to its use. It should be noted here that in addition to the proposed PUR system in the current study, other configurations of the PUR system in which no hole is required to be drilled in the steel member have been developed and successfully tested [36,37,44,56,57]. Thus, based on the geometry and configuration of the fatigue-prone (fatigue-damaged) member, a suitable PUR system can be selected and used.

7. Conclusions

In the current study, a simple analytical model was proposed to calculate the required prestressing level in external strengthening reinforcements to arrest the propagation of an existing fatigue crack in a tensile steel member. A novel PUR system was then introduced to anchor the required prestressing forces in the CFRP plates to the steel substrate. Fatigue tests on precracked steel plate specimens strengthened with nonprestressed bonded UHM CFRP plates (NPBR-UHM specimen), and prestressed unbonded NM CFRPs (PUR-NM specimen) were conducted to evaluate the proposed analytical model and to verify the performance of the PUR system. Moreover, an FE simulation was performed to further investigate the reduction in the SIF range in precracked steel plates strengthened with the proposed PUR system. The analytical modeling, experimental results, and FE simulations presented in the current study allow the following conclusions to be drawn:

- Strengthening of the fatigue precracked steel plate with nonprestressed UHM CFRP plates increased the fatigue life of the member by a factor of 4.3 compared to the unstrengthened steel plate. However, crack arrest was only possible when prestressed CFRP reinforcements with a certain level of prestressing were used in the PUR-NM specimen. Thus, it can be concluded that the efficacy of the prestressing force in CFRP reinforcements is much higher than the stiffness effect of the reinforcement for fatigue strengthening of cracked steel members.

- The fatigue tests on the PUR-NM specimen verified that the proposed analytical model is capable of predicting the required prestressing level in CFRP reinforcements for an existing fatigue crack to be completely arrested. It is evident that the accuracy of the analytical model largely depends on the available estimation of the input variables (such as $\Delta K_{I,th}$ and U); hence, adequate recommendations for a safe design have been provided in the current study. It should be noted that the application of the proposed analytical model is not limited by the reinforcement material and/or prestressing technique.
- The experimental crack closure measurements that were performed in the current study using the compliance method for the near-crack-tip strain readings showed that the crack closure phenomenon had an influence of 30% on the crack growth rate estimations for the steel used. Thus, experimental results revealed that the crack closure phenomenon has a significant effect on the crack growth rate prediction and, subsequently, on the required prestressing level for a fatigue crack to be arrested.
- The SIF predicted using the proposed analytical model for the PUR-NM specimen fits well with the results of the performed FE model simulation. Consequently, the proposed simple analytical model can be safely used to calculate the required prestressing force in external reinforcements to reach a desired SIF range in a cracked tensile steel member. The proposed FE simulation can be used to determine the SIF of unstrengthened cracked members having complex steel cross-section configurations, and subsequently, the analytical model can be used to determine the required prestressing level in the external reinforcements for crack arrest.
- The experimental results proved the high performance of the developed PUR system for prestress strengthening of fatigue-cracked steel plates, and neither prestress losses nor fatigue crack initiation from the required holes in the steel plate were observed during 7.5 million fatigue cycles. Owing to the advantages of the developed PUR sys-

tem, such as the capability of carrying high prestressing forces and elimination of any surface preparation and curing process for adhesively bonded reinforcements, the system can be considered as a good alternative to the conventional bonded reinforcements for fatigue strengthening of damaged steel members. It should be noted that the infinite fatigue life of the proposed PUR system has to be verified using proper CLD criteria prior to its practical use.

- In practical strengthening projects intended to arrest the propagation of an existing fatigue crack in a tensile steel member, it is desired to determine the threshold SIF range ($\Delta K_{I,th}$) and take into account the effect of the crack closure phenomenon by performing adequate standard tests on the material of interest under the practical loading scenarios experienced by the member. However, as such tests are time-consuming and costly, and sample extraction can be unfavorable or even impossible in some cases, $\Delta K_{I,th} = 100 \text{ N/mm}^{3/2}$ can be assumed for a safe design calculation, while the crack closure phenomenon might be neglected to obtain a conservative result.

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Table 1. Mechanical properties of grade S355J2+N steel plates.

Specimen direction*	Elastic modulus (GPa)	Yield stress (MPa)	Ultimate strength (MPa)
Parallel, mean	205	421	526
CV** (%)	0.99	2.18	0.12
Perpendicular, mean	205	430	527
CV** (%)	0.12	1.12	0.25

* With respect to the rolling direction.

** Coefficient of variation based on five tests.

Table 2. Mechanical properties of CFRP plates.

Material	Type	Minimum tensile strength (MPa)	Elastic modulus (GPa)
NM CFRP	S&P 150/2000-50/1.4	2800	156 [42]
UHM CFRP	THM 450-50×1.2	1200	435 [44]

NM= Normal modulus; UHM= Ultra high modulus

Table 3. Notch length and precracking details of specimens before strengthening.

No.	Specimen label	Initial notch length (mm)	Precracking $\Delta\sigma$ (MPa)	Precrack length, $2a_0$ * (mm)
1	Reference	14.97	75	17.39
2	NPBR-UHM	14.97	75	16.85
3	PUR-NM	14.93	75	17.21

* Considering approximately 1 mm precrack in each side after 200,000 fatigue cycles.

NM= Normal modulus; UHM= Ultra high modulus

NPBR= Nonprestressed bonded reinforcement; PUR= Prestressed unbonded reinforcement

1 Table 4. Fatigue loading and fatigue life extension of tested specimens.

No	Specimen label	$\Delta\sigma^a$ (MPa)	Number of fatigue cycles to failure (million)	Fatigue life extension ratio
1	Reference	75	0.935	-
2	NPBR-UHM	75	4.028	4.3
3	PUR-NM	75	2.500 ^b	∞^c
4	PUR-NM ^d	91	2.500 ^b	∞^c
5	PUR-NM ^d	105	2.509	2.7

^a Applied on the unstrengthened cross section of steel.

^b Test stopped owing to fatigue crack arrest.

^c Crack was fully arrested.

^d $\Delta\sigma$ was increased in the same specimen.

2

Figure 1. (a) An assumed tensile steel member having a fatigue crack under far-field loading;
 (b) effect of strengthening of the assumed member using the proposed PUR system.

Figure 2. Specimen dimensions and notch details (all dimensions are in mm): (a) reference specimen; (b) nonprestressed bonded reinforcement with ultra-high modulus CFRPs (NPBR-UHM); (c) prestressed unbonded reinforcement with normal modulus CFRPs (PUR-NM).

Figure 3. Stress-strain behavior of S355J2+N steel: (a) parallel to the rolling direction; (b) perpendicular to the rolling direction.

Figure 4. Details of mechanical clamps.

Figure 5. Prestressing setup.

Figure 6. Test setup and PUR-NM specimen under fatigue loading.

Figure 7. Loading scenario for beach marking technique in fatigue tests.

(a)

(b)

(c)

Figure 8. Cross sectional view of failed specimens and beach marks: (a) reference specimen; (b) NPBR-UHM specimen; (c) PUR-NM specimen.

Figure 9. Half-crack length versus elapsed fatigue cycles for all the tested specimens under fatigue loading.

Figure 10. Crack growth rate versus half-crack length of tested specimens under fatigue loading.

Figure 11. Maximum crack mouth opening displacement (CMOD) versus the elapsed cycles for the tested specimens under fatigue loading.

Figure 12. Ultimate failure of NPBR-UHM specimen with CFRP rupture and debonding.

Figure 13. Evolution of maximum strain in nonprestressed UHM CFRP plates with respect to fatigue cycles (NPBR-UHM specimen).

Figure 14. Strain history of steel and CFRP plates in PUR-NM specimen during prestressing process.

Figure 15. Evolution of maximum strain in prestressed CFRP plates in response to fatigue cycles (PUR-NM specimen).

Figure 16. Microscopic view of the notch and crack tip and the mounted strain gauge to measure near-crack-tip strain for the compliance offset method.

(a)

(b)

Figure 17. Compliance offset method using near-crack-tip strain measurement: (a) load-strain behavior; (b) load-compliance offset diagram for the unloading regime at $N = 200,000$ (fatigue crack length of approximately 1 mm).

Figure 18. Paris' law parameters for the reference specimen and effect of crack closure phenomenon.

(a)

(b)

Figure 19. (a) PUR-NM specimen and the required holes in steel for the PUR system; (b) location of applied strain gauges in the vicinity of holes.

(a)

(b)

Figure 20. (a) Load versus strain in the vicinity of the holes in the PUR-NM specimen at $N = 2,500,000$; (b) evolution of maximum strain in the vicinity of the most fatigue-prone holes with respect to fatigue cycles.

Figure 21. Constant life diagrams (CLDs) for estimating the state of holes in PUR system (S_y = yield strength of steel, S_{ut} = ultimate strength of steel, and S_e = fatigue endurance limit in geometry and condition of use [37]).

Figure 22. Details of the FE model created in ABAQUS [51].

Figure 23. Comparison of FE and analytical results for the tested specimens.