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FATIGUE BEHAVIOR OF STEEL PLATE GIRDERS STRENGTHENED USING CFRP PLATES

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ABSTRACT

In this paper, the fatigue performance of strengthened steel plate girders with CFRP strips was investigated using numerical models. The cracked plate girders were strengthened by different reinforcement configurations at high damage level of web plate. The research confirmed that the strengthening by CFRP strips leads to a significant increase in fatigue life and a reduction in crack propagation, especially the strengthening for both flange and web. Moreover, the study proposed V-Shape strengthening system by CFRP strips around the crack in the web plate. Consequently, the results demonstrated that U-shape strengthening system with prestressed CFRP has the best efficiency for fatigue strengthening. On the other hand, the fatigue analysis based on stress life method was performed by using S-N curve to predict the actual total fatigue life for the steel plate girder without initial damage. Therefore, the results showed that the fatigue damage of plate girders starts to appear at maximum loading ($0.5P_y$). Furthermore, the load capacity and the age at which the strengthening should start were studied as parameters. Finally, the results concluded that an early repair for plate girders is more efficient in improving the fatigue performance, especially when the bridge is subjected to heavy loads.

Keywords: Fatigue behavior, Cracked steel plate girders, CFRP strips, SMART crack growth method, S-N curve.

1 INTRODUCTION

High fatigue loads cause great stresses on the beams, leading to the appearance of fatigue cracks that reduce durability of beams. Therefore, it is required to repair this damaged steel elements by using the development strengthening methods. So, the previous research studied this requirement of efficient repair techniques with CFRP on fatigue life of strengthened elements as Colombi and Fava. [1] strengthened cracked steel beams by two layers of CFRP reinforcement to increase fatigue life and reduce crack propagation. Besides, Colombi, et al. [2] investigated that completely covering with CFRP for cracked elements was more effective than partially covering. Colombi and Fava. [3] added the studying of strain distribution in CFRP strips and value of stress intensity factor (SIF) at crack tip [1]. Furthermore, Kim and Harries. [8] showed that the fatigue life of strengthened beams was significantly affected by the stress range while the damage propagation wasn't affected by the stress range up to 60% fatigue life. Whereas, Islam, et al. [37] showed the strengthening for beams with higher slenderness of web gave better fatigue performance. It is found a review for Kamruzzaman, et al. [17] used different types of CFRP reinforcement including (HM, HS, UHM and the effect of the load application angle with various initial crack length was studied by Chen, et al. [16] on improving the fatigue life of strengthened specimens with CFRP. In addition, the number of layers was increased with used different configuration of CFRP by Yue, et al. [18] for giving more efficient in the strengthened crane girder. Li, Anbang, et al. [35] showed the corrosion degree and

CFRP stiffness affected on fatigue mode. The effect of inclined angle of crack including (10o to 90o) was considered to study fatigue behavior of strengthened steel plate at mixed tension and shear loading by Aljabar, et al [26]. The objective of the study of research for Deng, et al. [13] was giving an integrated closed-form solution to determine the interfacial stresses of strengthened steel beams with CFRP plates. It is found the importance of studying the fatigue performance at different crack length, so Hmidan, et al. [6] showed that the effect of degree of fatigue damage for strengthened cracked steel beams was significant on load capacity and the repaired beams serviceability. Besides, the study at different initial crack lengths for Yu, et al. [4] conducted that the early strengthening with CFRP was more efficient in pooling the total fatigue life. Furthermore, Aljabar, et al. [27] studied the effect of inclined angle of crack with two different damage levels to improve the fatigue performance under mixed mode (tension & shear) crack propagation. In addition, Yu, et al. [29] showed that the fully coverage for crack at various initial damage level was more effective strengthening than double sided partially coverage for central notched steel plate. Due to using of different FRP composite plates significantly affected on the fatigue crack growth, Wu, et al. [5] investigated the fatigue behavior of reinforced cracked steel beams using different types of CFRP material including (HM, HS) CFRP and (SW-BFRP), welded steel plate. Besides, Jiao, et al. [24] showed that the fatigue performance of strengthened steel beams with CFRP plates was more improved than that of strengthened with CFRP sheets. For predicting the effectiveness of different CFRP configurations on the real cracked elements, Lepretre, et al. [25] used steel specimens including mild steel from old structures and wrought iron plates from the dismantling of an old riveted railway bridge. The effectiveness of strengthening with CFRP was studied in two cases of central notched plate and edged notched plate by Wang, et al. [28]. Furthermore Ghafoori, et al [9] used two mechanisms including mechanism 1 by increasing stiffness and mechanism 2 by applying pre-stress force to study their effect on mean stress and stress ratio. Consequently, the strengthening by prestressed CFRP has proven its significant efficiency in repairing cracked steel elements, Hosseini, et al. [21] investigated fatigue tests on strengthened steel beams by prestressed CFRP at different pre-stress level for calculation of required minimum pre-stressing to arrest the fatigue crack. Besides, the effect of bonded adhesive system and un bonded with prestressing CFRP was studied by Ghafoori, et al. [22]. In addition to the fatigue life increased and the fatigue crack was completely arrested at prestressing level 20% were concluded by Ghafoori, et al. [23]. The comparing between two strengthening system on fatigue life including non-prestressed bonded and prestressed unbonded was performed by Hosseini, et al. [10]. While Deng, et al. [33] showed combining the (SMA) alloy with (CFRP) was able to achieve the prestressed strengthening technique. Therefore, the mechanical clamping system was proposed by Hosseini, et al. [30] to fix CFRP plates instead of using adhesive layer. Besides, Yu and Wu. [19] showed that the using of mechanical anchorage schemes for fixing the CFRP layer were efficient in fatigue crack strengthening. In addition to the application of extra mechanical anchorage, Yu and Wu. [20] used two types of adhesives including (Araldite 420& Sikadur30) to compare between their efficiency. So Teng, et all. [12] used three different lengths of CFRP to predict the debonding failures occurred for repaired cracked steel beams. But Zheng, et al. [31] used other parameters including the maximum magnitude of the applied far-field stress(σf), the interfacial stiffness(k), the interfacial shear strength($\tau 0$) and the energy release rate(G) to predict the size and shape of the debonding region. Where Yashar, et al. [34] demonstrated the fatigue crack growth affected by debonding of CFRP. Hmidan, et al. [14, 15] predicted the correction factor (Y) to calculate the (SIF) for strengthened cracked W-Shape girders by using some parameters depend on the CFRP area ratio and crack depth ratio. The fatigue behavior influenced by the presence of CFRP reinforcement with welded elements. So, Wu, et all. [7] studied a negative effect of welded steel joints on the efficiency of CFRP reinforcement in increasing fatigue life. Besides, Wang, et all. [11] performed the fatigue test on strengthened welded corrugated steel web with tension flange by CFRP and shot peening at different stress range. Also, Lewei et al. [36] demonstrated the strengthening of butt-welded steel plates decreased stress concentration and thus crack propagation. Previous research focused on studying the fatigue behavior of repaired standard rolled sections of beams with CFRP at bottom flange only. In practice, there is a need to simulate the fatigue behavior of the real built-up plate girders even initially cracked or not, and strengthened or not.

Therefore, the present study at first covered the previous research gaps by evaluating different methods of strengthening for bottom flange and web of cracked steel plate girders. Moreover, parametric study was carried out to figure out the most important parameters that affect fatigue performance of these girders. On the other hand, previous research also focused on studying the improvement for the fatigue performance of damaged steel beams using strengthening with CFRP plates. Without measuring this improvement resulting from the reinforcement in the fatigue performance by the original performance of the beams without initial damage. So, the present study carried out fatigue analysis to predict the actual total fatigue life for the steel plate girder without initial damage. The finite element method was used to perform the fatigue analysis.

2 FINITE ELEMENT MODEL VERFICATION

In this paper, the simulation was conducted using ANSYS workbench. The accuracy of the present finite element models was examined by comparing with the experimental and analytical results that performed by [1] and [3]. The objective of finite element simulation was to investigate the effectiveness of the reinforcement of cracked steel beams on the fatigue performance. ANSYS workbench is a well-known computational software for simulation of engineering structures using finite element method. The new version of ANSYS R19.0 implements a new feature known as Smart Crack Growth, to perform the analysis of the stress intensity factor (SIF), crack propagation and number of cycles. The fatigue analysis was performed using the Paris' law equation under constant amplitude loading. Based on the Paris' law, the fatigue lifetime was predicted according to:

$$\frac{da}{dN} = C\,\Delta K^{m} \qquad (1)$$

where da/dN is the crack propagation rate as a function of the number of cycles, C and m are experimental testing constant for materials and ΔK is the range of SIFs through the life cycle. As shown in Table (1), C and m parameters were used for the steel type S275Jo as in [3].

Table 1. Estimated fatigue crack growth parameters for steel S275Jo.

Parameters	Values
C	2.669×10^{-14}
m	3.307

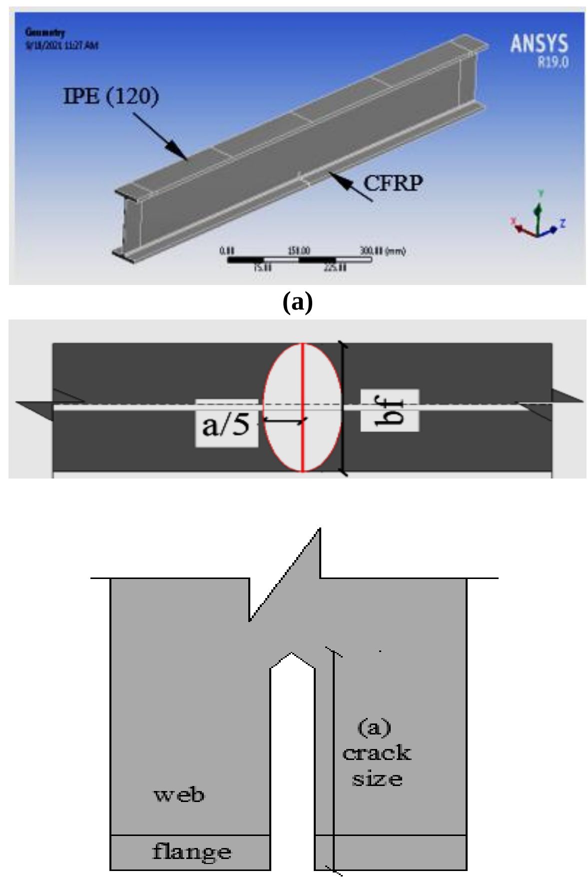
2.1 Finite Element Analysis

The experimental study showed that the hydraulic actuator test machine was used to perform the fatigue test under constant amplitude cycling loads with different frequencies. In addition, the load of the actuator was distributed to the tested beams using spreader beam at two points of loading. So, the all simulation beams were subjected to four-point flexural loading. The un-strengthened beams were tested under fatigue loading range $P = 6{\sim}15\ kN$ and other beams were tested under $P = 28{\sim}70\ kN$ with load ratio $R = 0.4$ which is the ratio between the minimum load and the maximum load. The model was conducted using a cracked steel beam (IPE 120) of steel grade S275J0 and a span length (L=1000mm). Besides, the initial 20 mm long and 2.5 mm width crack that was created at midspan of the beam. Then the bottom side of flange was strengthened with one layer of CFRP strip that had 60 mm width and 800 mm length. The experimental study [1] also showed that two identical specimens (B3 and B4) were used in the case of reinforcement with single layer of CFRP. The present three-dimensional finite element model included two geometries. The first one represents the steel cross section and the other represents the CFRP reinforcement. These geometrics were modelled using SOLID187 element [39, 40, 41] which is a higher order 3-D, 10-node element and well suited to model irregular meshes, as shown in Fig.1(a). Both the steel and the CFRP reinforcement were modelled as linear elastic isotropic material. Besides, the properties of the model materials were considered from [1] and [2] as shown in Table (2).

Table 2. Material properties of model geometries.

Material	Young's modulus (GPa)	Poisson's ratio
Steel	208	0.3
CFRP	210	0.3
Epoxy	4.5	0.3

The contact between the bottom flange and the CFRP reinforcement was modelled using "bonded contact" type. In this way, the material properties of the adhesive layer were not included in the model. Debonding area was modelled in the finite element which was assumed to be elliptical shape based on the experimental evidence of [1] and [2].



(a)

(b)

Figure 1: (a) The 3D finite element for the geometry and (b) debonding area close to the crack region.

As shown in Fig.1(b), the major axis of the ellipse was set to be equal to the width of the tension flange (b_f), while the minor axis was supposed to be equal to $2a/5$ where a is the crack size. The SMART used tetrahedron mesh [39, 40, 41], as shown in Fig.2, for both the steel beam and CFRP layer. The size of the mesh around the crack plays a major role in performing correct simulation for the fatigue crack growth results. Therefore, it was necessary to carry out a special mesh around the crack. Thus, the present study designed two forms of the mesh around the crack. The first, a mesh around the crack tip only as Fig.2(a) with two different mesh sizes including coarse mesh size, fine mesh size to show the effect of mesh size on the calculated number of cycles (N). The second, a mesh around the entire crack region as shown in Fig2(b) with fine mesh size. Fig. 3 shows that number of cycles using fine mesh size in the two forms of the mesh around the crack is closer to the counterfort experimental results than that obtained by using the coarse mesh size.

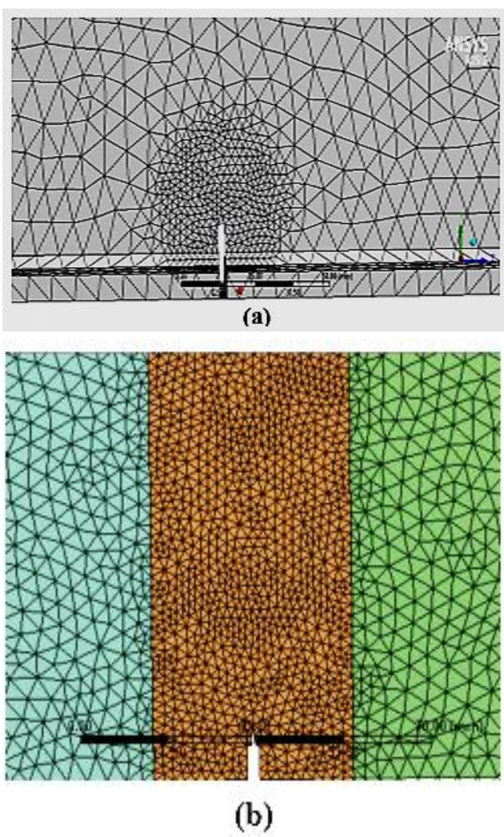


Figure 2: (a) Tetrahedron mesh and detail of mesh around the crack tip only and (b) detail of the mesh around the entire crack region.

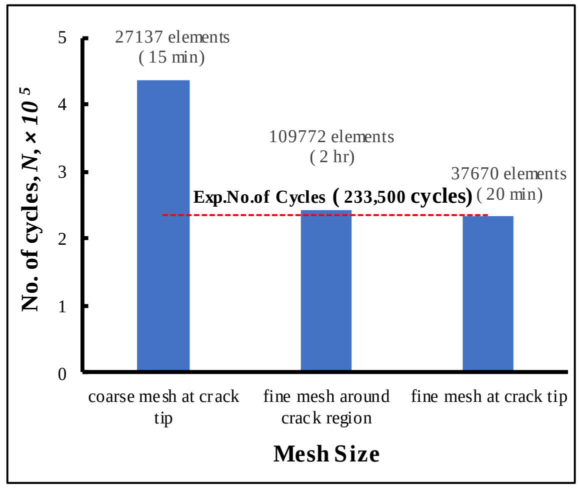


Figure 3: Effect of mesh size.

While, Fig.3 shows based on number of elements that using the fine mesh size around the crack tip only reduces the solution time significantly and gives more accurate results than using fine mesh around the entire crack region. Based on the results of Fig.3, the fine mesh size around crack tip is the best mesh to use for this simulation of the fatigue crack growth. Furthermore, determining the value of the maximum crack-growth increment for the model with special mesh around crack tip led to more precise value of the stress intensity factor at crack tip. Consequently, the simulation produced fatigue crack growth curves which is very similar to that of the corresponding experimental results.

2.2 Validation of Finite Element Analysis

From the results, it could be realized that there is a good agreement between previous experimental, analytical results and present finite element analysis. The finite element model was capable to predict the crack path which is very similar to that of the experimental one as shown in Fig.4.

Figure 5 shows the crack propagation curves which is the relationship between the number of cycles and the crack length for the un-strengthened cracked steel beam. The present finite element model shows a very good agreement with both experimental [1] and analytical [3] results. Figure 5 also shows that when the fatigue crack grew to a final crack size, a_f = 60 mm, the number of the present FE cycles reached the same number of both the experimental and the analytical cycles that were 233,500 duty cycles. In addition, Figure 6 shows the crack propagation curves for strengthened cracked steel beam using CFRP reinforcement layer. Thus Figure 6 shows that the present finite element model was very close to one of the two identical experimental specimens for [1] that was specimen (B3) and was very similar to the analytical results [3]. Finally, it could be concluded that the present 3-D finite element model can accurately simulate the fatigue behavior.

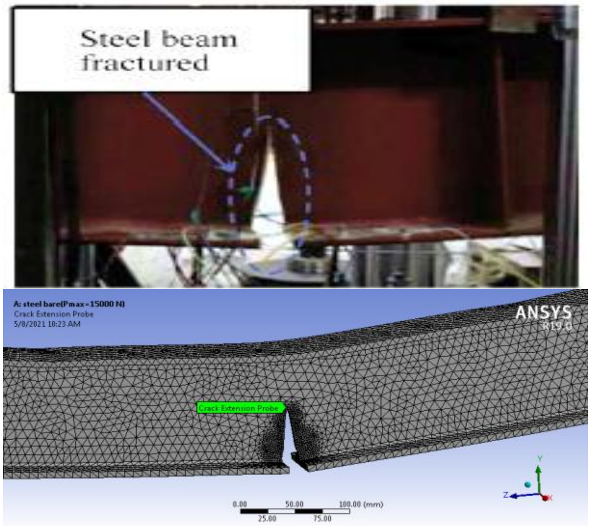


Figure 4: Agreement between the FE simulation and the experimental crack path.

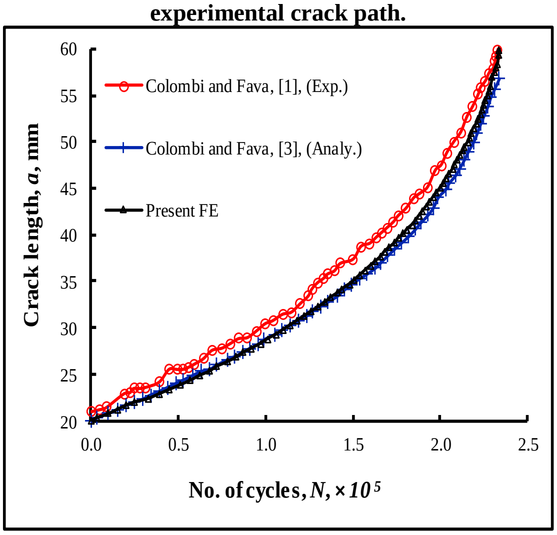


Figure 5: The crack propagation curves for the steel beam without CFRP under loading ($P = 6\sim15\ kN$).

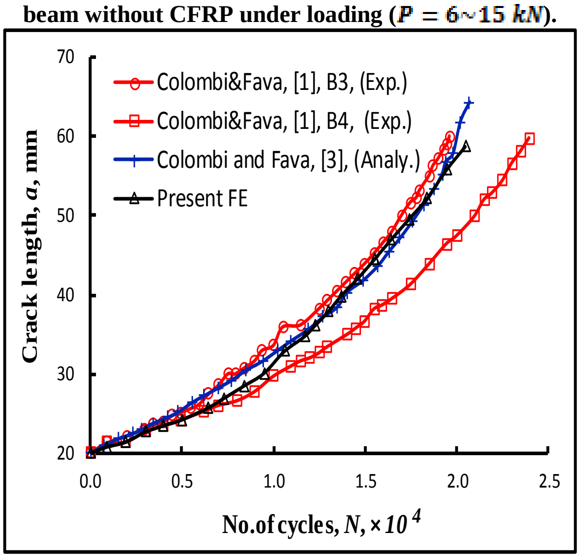


Figure 6: The crack propagation curves for single reinforcement layers under ($P = 28\sim70\ kN$).

3 THE PARAMETRIC STUDY

3.1 Specimens Description

The major focus of this research is on the fatigue behavior for cracked steel plate girders repaired with CFRP and to simulate the reality. To do so, the plate girder was supposed to be part of a major roadway bridge that its cross-section is shown in Fig. 7. Also, a parametric study was carried out to investigate the main parameters affecting the behavior of such plate girders. In addition, the parametric study investigated different strengthening systems using CFRP strips for both web and bottom flange of cracked steel plate girder. The dimensions of the plate girders were considered similar for all the specimens. The girder had a span ($L = 20\ m$) with two applied point loads at ($L/3$ and $2L/3$) as shown in Fig.8(a). The girder cross section as shown in Fig.8(b) was deduced from the design equations according to the Egyptian code. All girders were notched by initial crack with 2 mm width and initial depth (a_0) equals to 0.25 of web depth ($a_0 = h_w/4$). A 2 mm tip was added to the crack depth to generate more stress concentration to induce the vertical fatigue crack propagation in the web. The initial notch details are shown in Fig.8(c).

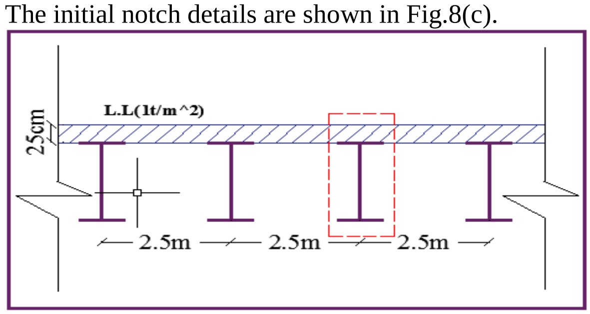


Figure 7: Cross-section of roadway bridge.

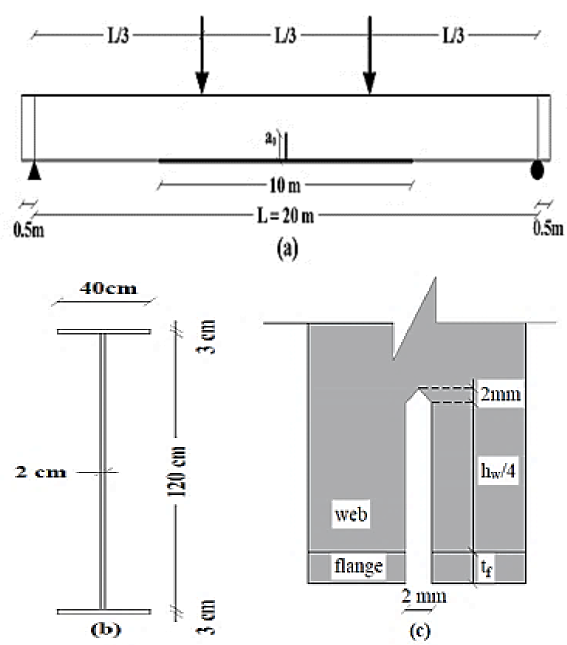


Figure 8: Specimen geometry: (a) beam geometry, (b) beam section and(c) crack details (not to scale).

3.2 Properties of Materials

All The plate girders were made of steel S355Jo, in addition, tested mechanical properties and fatigue crack parameters (C, m) of the steel according to [32] are shown in Table (3). For strengthening the specimens, the UT70-30 CFRP strips with JH-01 structural adhesive was used. The mechanical properties of the used CFRP strips and the adhesive material according to [18] are shown in Table (4).

Table 3. Material mechanical property and fatigue crack parameters of steel.

Properties	Values
Elastic modulus	$210\ MPa$
Poisson ratio	0.3
C	2×10^{-15}
m	3.605

Table 4. Material properties of CFRP strips and structural adhesive.

Properties	CFRP	Structural adhesive
Elastic modulus	245 GPa	2.50 GPa
Poisson's ratio	0.30	0.35
Tensile strength	4306 MPa	40.96 MPa
Thickness	0.167 mm	---

3.3 Fatigue Loading

The steel plate girders were subjected to constant amplitude cyclic load. The maximum applied load, P_{max}, was equal to 10% of the yield load. The yield load was calculated from yield stress law $F_y = M_y/Z$,based on the properties of the deduced cross section and the resulted moment value from the loading case for the girder as in Fig.8(a). While the adopted loading ratio $R = P_{min}/P_{max} = 0.1$. Where it was found that this loading ratio of 0.1 is commonly used in fatigue testing for steel members that strengthened with CFRP. This is for ease of comparing performance between un-strengthened and strengthened specimens as shown in most previous research. So, the used fatigue crack parameters (C, m) of the steel grade in Table (3) were set at this loading ratio as in [32].

3.4 Patch Configuration

Different configurations of the CFRP reinforcement were proposed to study the fatigue performance of the strengthened cracked steel plate girders. Therefore, the parametric study proposed strengthening system using the CFRP strips around the crack in web of cracked steel plate girder as well as the strengthening system at bottom flange. Four horizontal reinforcement configurations with CFRP for both flange and web with a length 10 m and a height up to half the depth of the web ($h_w/2$) were used. First (method) configuration was made using separate strengthening for both flange and web with CFRP. While the second method used continuous U-Shape strengthening for both web and flange. The third method used U-Shape strengthening for flange only. Finally, the last method used separate prestressed CFRP strengthening as shown in Fig. 9. The prestressing level of 20% of the tensile strength of CFRP according to [23, 25, 10] was applied. This prestressing level, mentioned in most of the previous research, is the best value because it was able to significantly reduce cyclic fatigue crack propagation and may lead to its arrest. Besides, it was suggested to use V-shape web-strengthening around the crack including single and double system as well as the bottom flange strengthening as in Fig.10. Therefore, an opening was made through the web plate to allow the CFRP layer to pass through it. The opening is 10 cm away from the crack position and CFRP layer is 2.50 m length and 25 cm width. Then, the horizontal reinforcement configurations for both flange and web as in Fig. 9 were added to double V-shape strengthening around the crack as shown in Fig.11. So as to study the influence for the application of V-shape strengthening system around the crack with the horizontal strengthening for both flange and web on the fatigue life and crack growth rate.

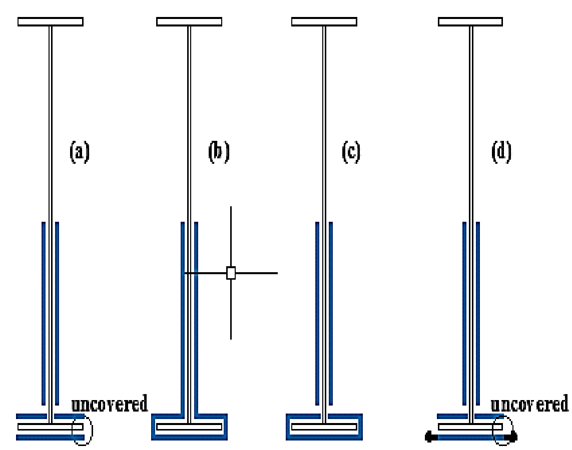


Figure 9: Methods of plate girder strengthening: (a) separated strengthening for flange and web with CFRP, (b) U-Shape strengthening for flange and web together, (c) U-Shape strengthening for flange only and (d) separate strengthening with prestressed CFRP.

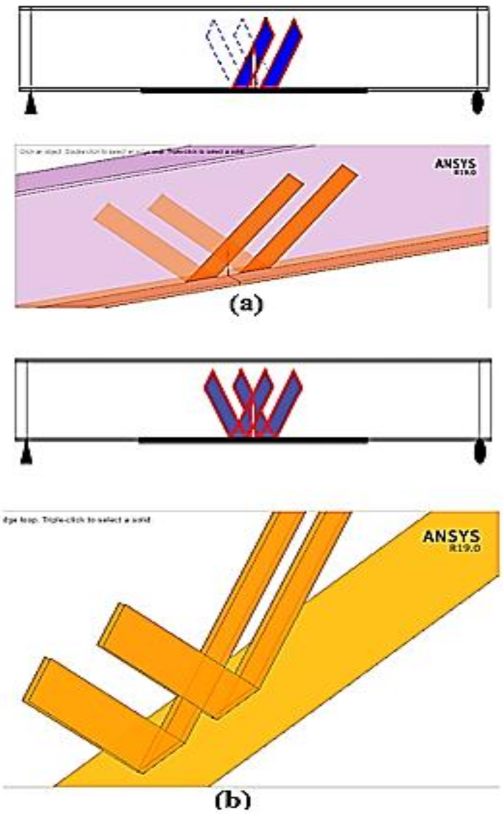


Figure 10: Inclined web strengthening (a) single V-shape strengthening (b) double V-shape strengthening.

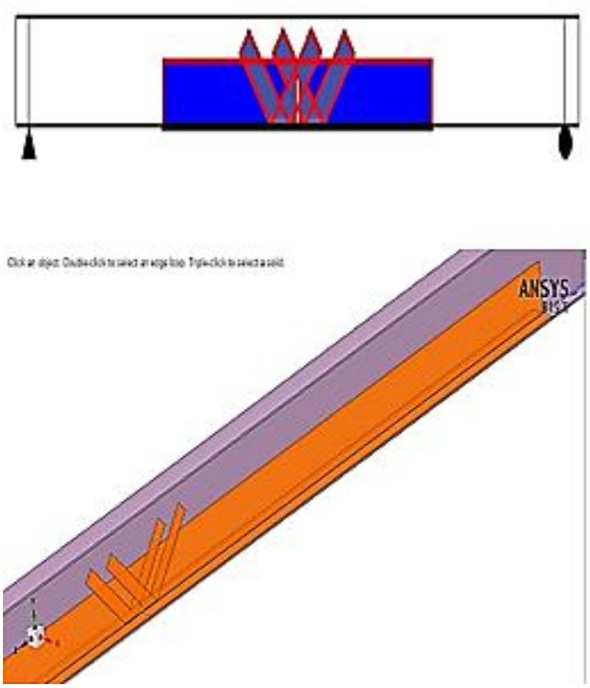


Figure 11: Strengthening with combined double V-shape strengthening around the crack and the horizontal strengthening system.

3.5 Patch Configuration

3.5.1 Geometry and Mesh

A three-dimensional finite element model made of 3-D SOLID187 element to simulate the model geometries. The steel plate girders and CFRP reinforcement layer were modelled as shown in Fig.8. In addition, the special mesh around crack tip was used as indicated in the finite element model verification. Crack definition and fatigue crack growth analysis and loading.

The initial crack was defined using the singularity-based SMART approach. Pre-meshed crack [39, 40] was applied to define initial crack by selecting the crack front, top and bottom faces of the crack and the crack coordinate system. Stress intensity factor, SIF, was defined for the fracture parameters. The number of contours for solution was set to 10. These were indicated to “loops” through the mesh around the crack tip that are used to estimate SIF by integrating the crack tip region strain energy [39, 40]. The life cycle, LC, method was used for fatigue analysis with a maximum crack-growth increment of 5.0 mm. The simulation was performed under applied fatigue loading $P_{max} = 102.5\ kN$ with load ratio $R = 0.1$.

3.5.2 Material Model and Interface Behavior

Both the steel and the CFRP reinforcement were modelled as linear elastic isotropic material, and their properties are shown in Table (4). Debonding area was modelled in the finite element which was assumed to be elliptical shape as previously shown in the previous section of finite element model verification.

3.5.3 Results and Discussion

In this section, the finite element study discusses the effectiveness of strengthening by CFRP strips for both flange and web of the cracked steel plate girders. By comparing the fatigue behavior of un-strengthened and strengthened steel girders using CFRP strips, the strengthening leads to a significant increment of the fatigue life and reduction of the crack propagation. The strengthening for bottom flange of the cracked specimens by CFRP strips significantly prolonged the fatigue life by four times that for the un-strengthened specimens as shown in Fig.12. Then, the V-shape strengthening system was added to the bottom flange strengthening system to add more improvement to the fatigue performance. Therefore, the strengthening by V-shape was presented by two configurations including single and double layer around the crack in the web plate of the specimens as shown in Fig.10. It was observed that using the double V-shape strengthening of web along with the bottom flange strengthening increased the fatigue life by five times more than the un-strengthened ones as shown in Fig.12.

Whereas there is a slight improvement in the final fatigue life of the strengthened specimens by single V-shape system with the bottom flange strengthening system over the one with the bottom flange strengthening only as in Fig.12. This is probably, due to the inclination angle of strengthening as well as the effective tensile force of CFRP sheet for single V-shape strengthening system that was bridging the crack opening can cover a little part of the crack cross section. In contrast, in the double V-shape strengthening system, the effective tensile force can cover a larger part of the crack cross section. Then, the horizontal strengthening for the flange and the web together was performed by four reinforcement configurations with CFRP as in Fig. 9.

The comparison of four reinforcement configurations with CFRP showed that the configuration (c) was more effective in reducing the crack length and increasing the fatigue life than both (a) and (b) configurations as shown in Fig.13. This is because of the fully coverage for side faces of the bottom flange that bridge the fatigue fracture initiation. Besides, the configuration (c) did not generate any significant stress component at the strengthening connection point between the web and the flange as in configuration (b) which leads to an increased possibility the debonding of adhesive. Moreover, the configuration (d) that strengthened with prestressed CFRP had the best fatigue strengthening efficiency as result prestressing can provide higher compression stresses. Then the results showed that the fatigue life improved by 60 times than that of the un-strengthened specimens.

Fig.14 and Fig.15, exhibit that adding the double V-shape system around the crack to the horizontal strengthening systems has an insignificant improvement of fatigue life for cracked plate girders. Furthermore, all the results of the improvement ratio for fatigue life using different the strengthening systems are reported in Table (5). Based on these observations, the vertical web strengthening for web with U-shape system is more effective than the inclined web strengthening with V-shape system around the crack. So that, the U-shape strengthening system leads to more stress bridging at the section where the crack is located. Consequently, the widening of crack opening reduces, and fatigue life extends.

Table 5. Improvement ratio for the fatigue life using different strengthening systems comparing with un-strengthened one.

Girder type	Fatigue life	Percentage Increase of fatigue life
Without strengthening	1×10^4	-------
With lower flange only strength. sys.	3.75×10^4	375%
With Lower flange with single V-shape strength. sys.	3.93×10^4	393%
With Lower flange with double V-shape strength. sys.	4.56×10^4	456%
With U-shape strength. sys.	3.49×10^5	3390%
With Prestressed CFRP strength. sys.	5.8×10^5	5700%

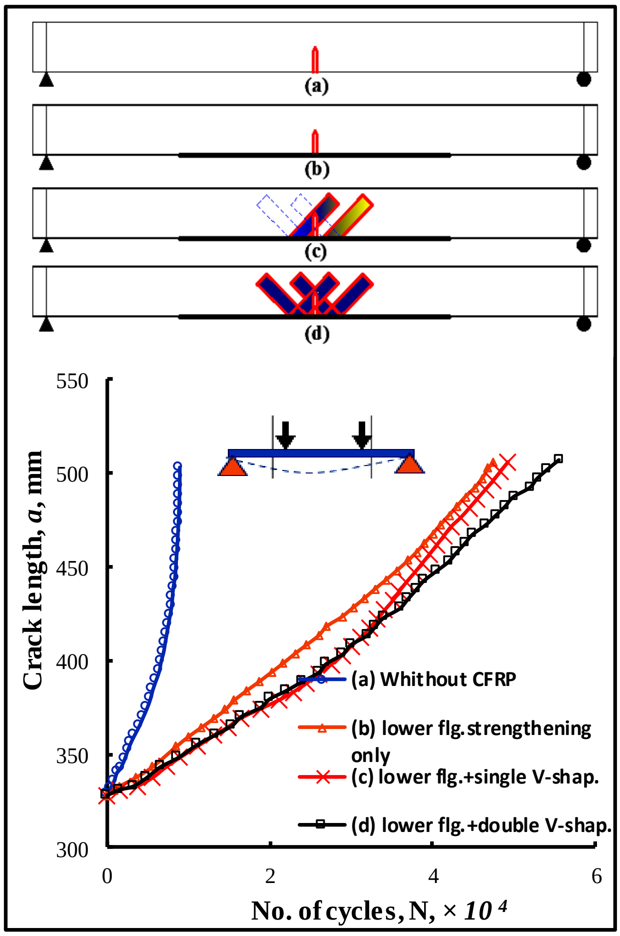


Figure 12: Fatigue crack growth results: crack propagation curves for the bottom flange and V-shape strengthening system.

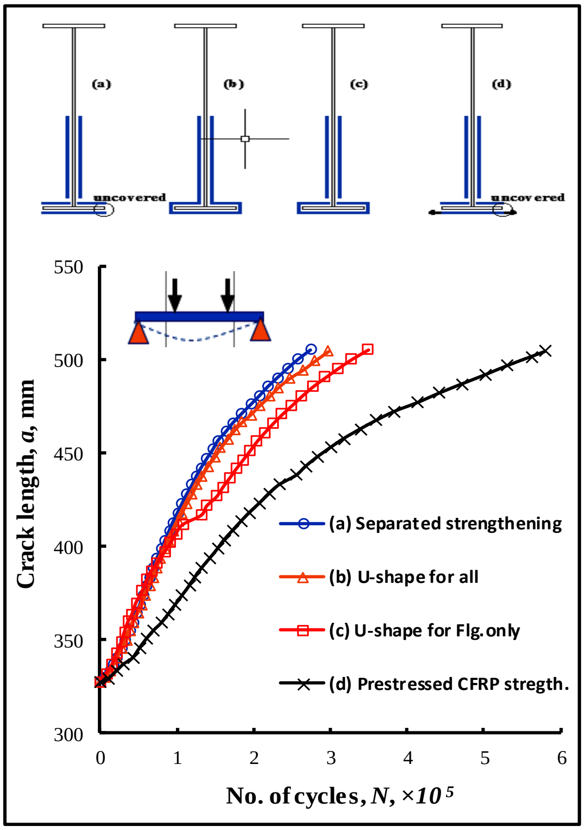


Figure 13: Fatigue crack growth results: crack propagation curves for U-shape strengthening systems.

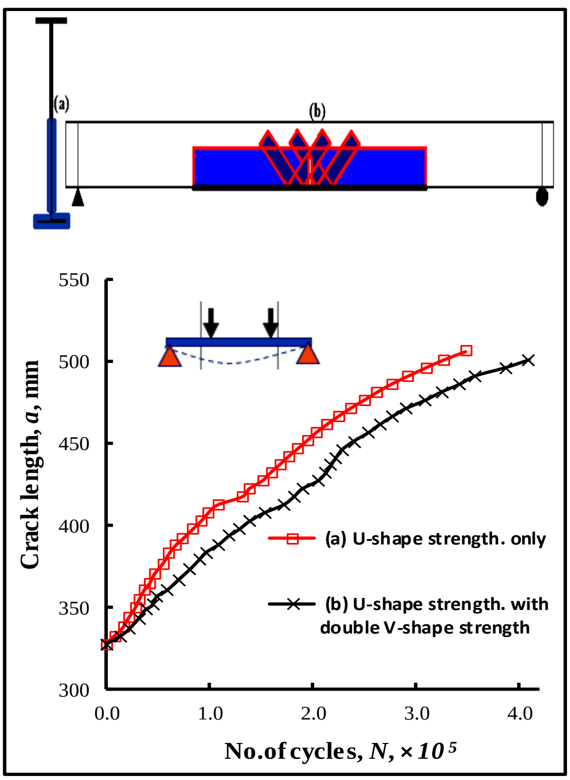


Figure 14: Fatigue crack growth for to U-Shape strengthening system for flange with\without double V-shaped system for web.

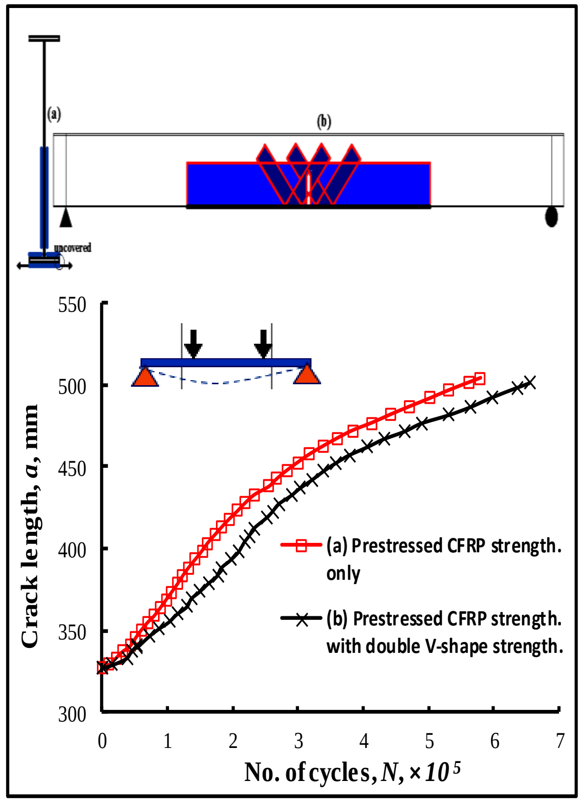


Figure 15: Fatigue crack growth for separated strengthening system with prestressed CFRP with\without double V-shape system for web.

4 FATIGUE ANALYSIS OF INITIALLY UNDAMAGED PLATE GIRDERS

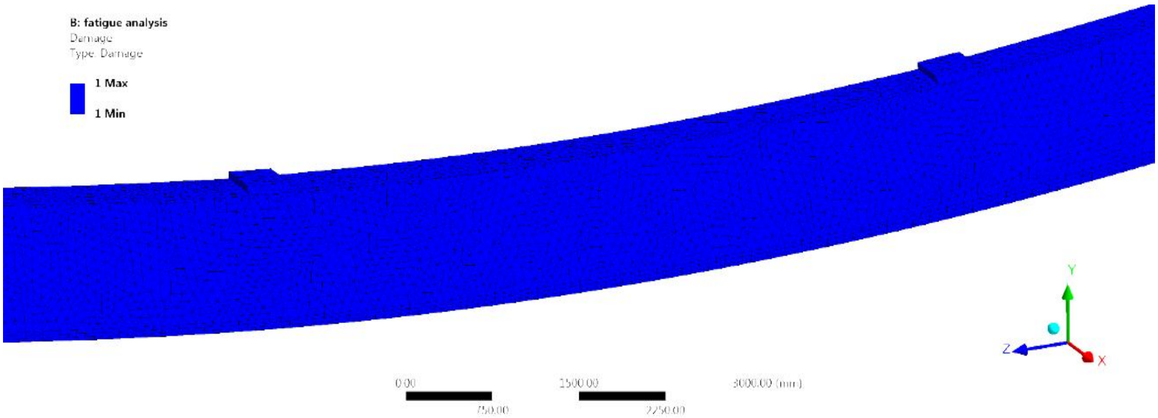
On the other hand, the fatigue analysis based on stress life method was performed using S-N curve that plots nominal alternating stress (S) versus number of cycles to failure (N) for able to predict the total actual fatigue life for the steel plate girders without initial damage. Consequently, the life of strengthened damaged steel plate girders was compared to the life of initially undamaged steel girders to predict the influence of different configurations of the strengthening on the improvement in the total fatigue life. Furthermore, the fatigue analysis was conducted at various values of the maximum load which represents a percentage of the yield load (P_y) to study the effect of increasing the load capacity on the total fatigue life. Figure 16 shows the calculated finite element values of the fatigue damage indicator, where, when it is greater than one it indicates that the failure occurs before the design life is reached. The following equation explains this fatigue damage indicator:

$$Fatigue\ Damage = \frac{Design\ Fatigue\ Life}{Actual\ Fatigue\ Life} \quad (2)$$

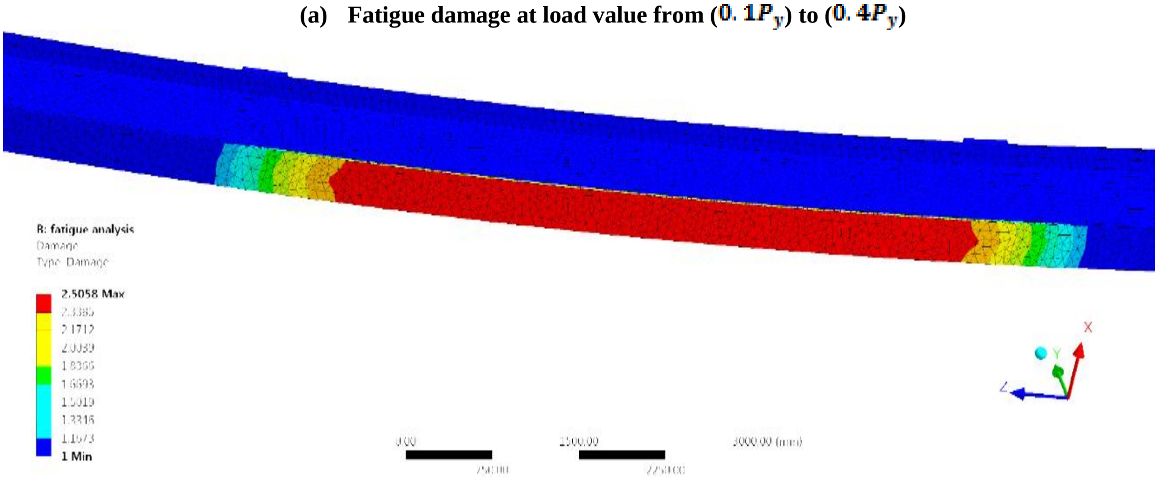
In addition, Fig.16 shows that the fatigue damage occurs at maximum moment location, and this confirms that the suggested location of initial crack at the girder's mid-span was correct. Moreover, it is observed that the fatigue damage started to appear at maximum loading ($0.5P_y$). However, the finite element calculations for the life of steel girders without initial damage were produced using log-log interpolation for the S-N curve [38]. Besides, the FE software S-N curve of the steel was modified by the Soderberg mean stress correction method for stress life fatigue analysis. Because the S-N test data are often obtained from applying the fully reversed constant amplitude cyclic loading with zero mean stress but, the actual applied cyclic loading was with stress ratio and thus mean stress values exist. The following equation [38] represents the Soderberg line as:

$$\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_y} = \frac{1}{N} \qquad (3)$$

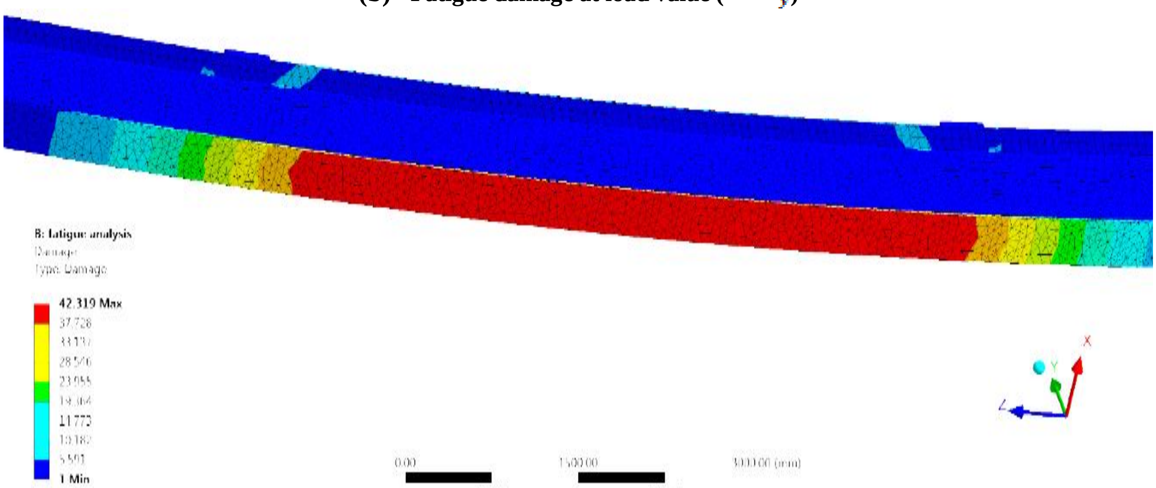
Where σ_a is alternating stress, σ_m is the mean stress, S_e is the endurance limit of material that represents the stress level below which the material does not fail and can be cycled infinitely, S_y is yield strength of material, and N is factor of safety. The fatigue life contour as Fig.17 shows the number of cycles that the steel girder can withstand before fatigue failure. In addition to the fatigue life, contour shows that in a Stress Life analysis with constant amplitude, if the equivalent alternating stress is lower than the lowest alternating stress defined in the S-N curve, the life at that point is (10^6) will be used. Therefore, Fig.17 shows the maximum life cycles are 10^6 and the minimum life cycles are represented by (red region). Based on these observations, the FE calculations confirmed that at the same maximum loading ($0.5P_y$) the fatigue lives are reduced comparing with the value of design life. Moreover, Figure 18 shows that the rate of the fatigue damage at different design cycles, N, 500,000 and 1,000,000. The rate of change of the fatigue damage rapidly increases for maximum loading values greater than ($0.5P_y$). Also, Fig.19 shows that when the maximum loading increased from ($0.5P_y$) to ($0.7P_y$) the fatigue lives dramatically decreased. Then, the life of initially undamaged steel girder was compared to the life of strengthened girders with different configurations of CFRP sheets at maximum loading ($0.1P_y$). Consequently, the results showed that the strengthening with U-shape CFRP system improving the life to approximately 40% of the total life of girder without initial crack whereas, the strengthening system with prestressed CFRP improving the life to approximately 60% of the total design life as shown in Fig.20. On the other hand, when the maximum loads on the girder are heavy, almost reaching the design load, the fatigue behavior should be investigated. Thus, the fatigue behavior has been studied at respectively high values of maximum loads ($0.4P_y$) and ($0.6P_y$). In addition, the age at which the strengthening starts can affect the fatigue behavior was also studied. So that, the damage level was considered to obtain the best strengthening efficiency. Two methods were herein used, in the first one, the number of cycles, N, were computed at low damage levels of the web plate to express the early repairing for the damaged plate girders. While in the second method, the number of cycles were calculated at high damage levels of the web plate to express the late repairing for the damaged plate girders. Figure 21 shows that the number of cycles of un-strengthened plate girders at maximum loading ($0.4P_y$) significantly reduced after damage level (0.03). Whereas Fig. 22 also shows that number of cycles of un-strengthened plate girders at maximum loading ($0.6P_y$) significantly reduced after damage level (0.02). In addition, it could be observed that the number of cycles of un-strengthened plate girders at high damage levels in both cases of loading whether at ($0.4P_y$) or ($0.6P_y$) was significantly reduced as shown in Figs. 23 and 24. For strengthened specimens at loading ($0.4P_y$), it was observed that the strengthening of damaged steel plate girders with U-shape CFRP was more efficient whether at low or at high damage levels of web plate as shown in Figs. 25 and 27. While at loading($0.4P_y$), the results showed that the strengthening with U-shape CFRP was more efficient at low damage levels only as shown in Figs. 26 and 28. Finally, the results confirmed that an early repair (at a/h_w = 0.01 or 0.02) for plate girders is more effective in improving the fatigue performance, especially when the bridge was carrying heavy loads. So, early repair is highly recommended. Furthermore, the Egyptian specification recommended to inspect the bridges annually. Whereas the finite element study showed that cracks are likely to occur approximately after 10 years at maximum loading ($0.6P_y$) and load ratio (R = 0.1). Based on the Egyptian specification the least design life is 50 years at a rate of 500,000 cycles for major roadway bridges. Thus, the current study affirms the necessity of periodic follow-up for the bridge inspection from the early ages of the bridge life as shown in Fig.29. Also Fig. 29 confirms the effectiveness of early strengthening under heavy loading ($0.6P_y$) where early strengthening at a/h_w = 0.01, leads to increase of the life almost up to the design period (50 years).



(a) Fatigue damage at load value from ($0.1P_y$) to ($0.4P_y$)

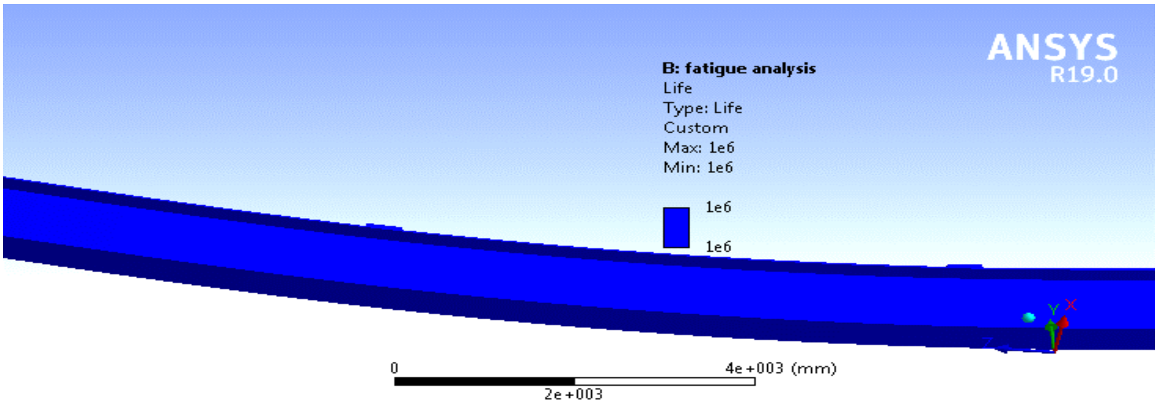


(b) Fatigue damage at load value ($0.5P_y$)

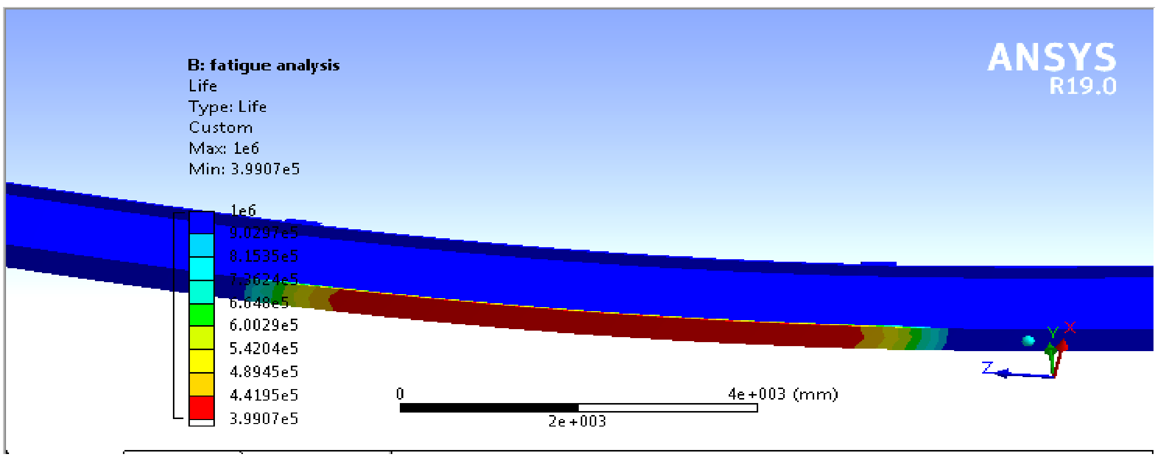


(c) Fatigue damage at load value ($0.7P_y$)

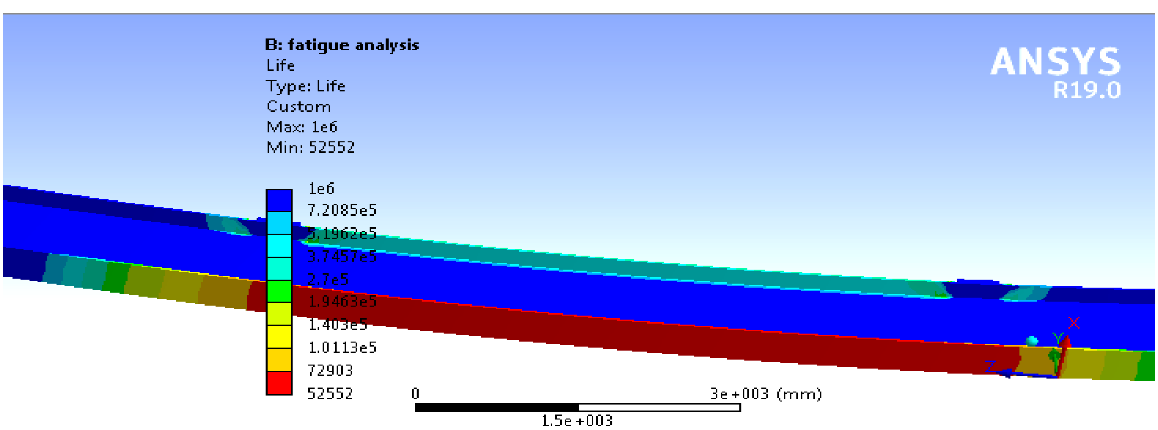
Figure 16: Finite element calculations of the fatigue damage of initially uncracked steel plate girders at various maximum loading values.



(a) Variable life at load value $(0.1P_y)$ to $(0.4P_y)$



(b) Variable life at load value $(0.5P_y)$



(c) Variable life at load value $(0.7P_y)$

Figure 17: Finite element calculations of the variable fatigue life of initially uncracked steel plate girders at various maximum loading values.

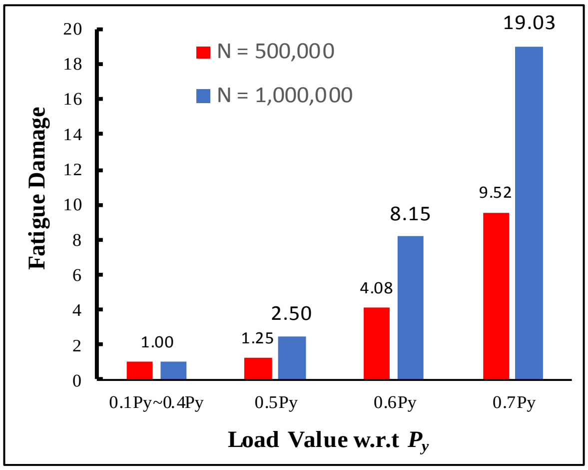


Figure 18: Effect of maximum load value on the fatigue damage of initially uncracked steel plate girders.

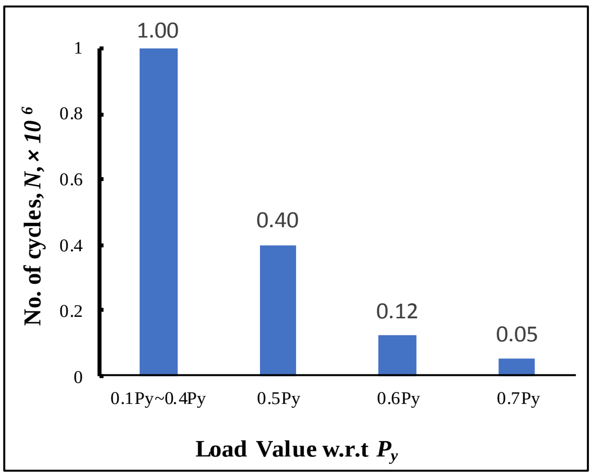


Figure 19: Effect of maximum load value on the fatigue life of initially uncracked steel plate girders.

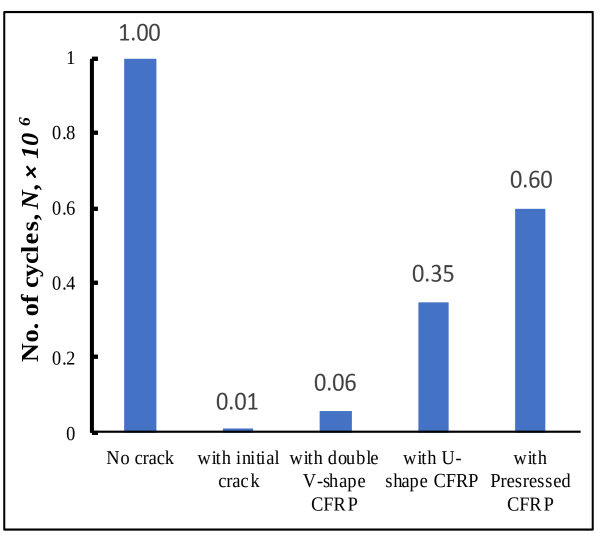


Figure 20: Comparison between the life of initially undamaged steel girder and the life of strengthened girders with different configurations of CFRP sheets at loading $0.1P_y$.

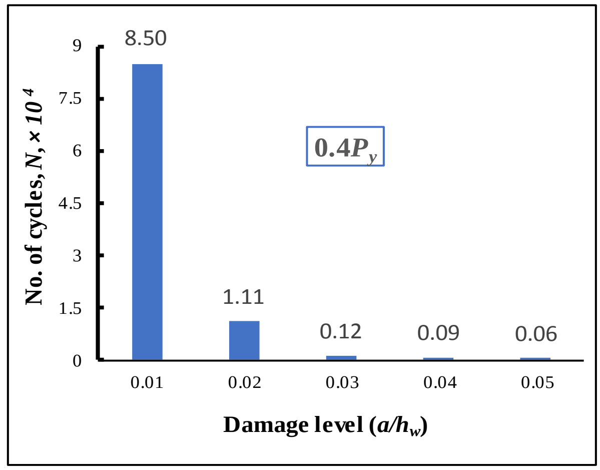


Figure 21: The fatigue life of un-strengthened girders at low damage levels of the web plate at load ($0.4P_y$).

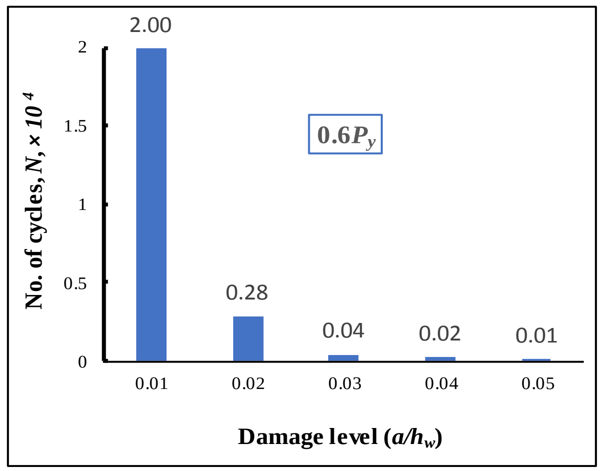


Figure 22: The fatigue life of un-strengthened girders at low damage levels of the web plate at load ($0.6P_y$).

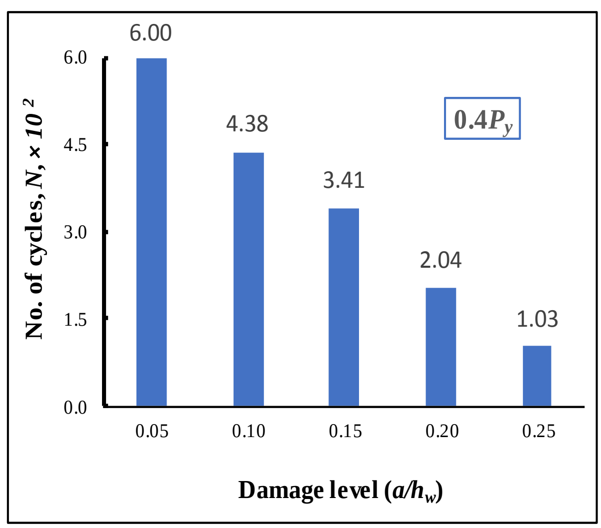


Figure 23: The fatigue life of un-strengthened girders at high damage levels of the web plate at load ($0.4P_y$).

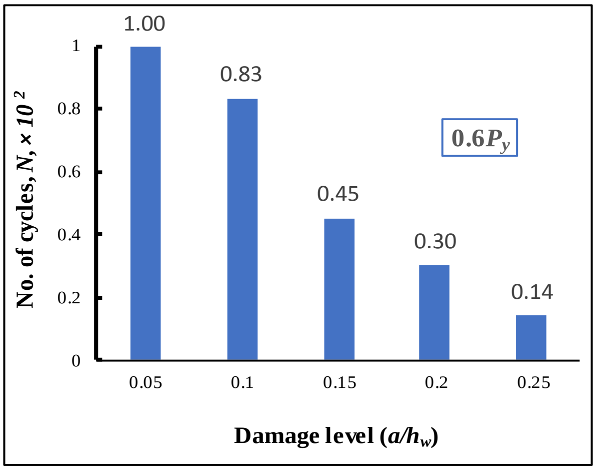


Figure 24: The fatigue life of un-strengthened girders at high damage levels of the web plate at load ($0.6P_y$).

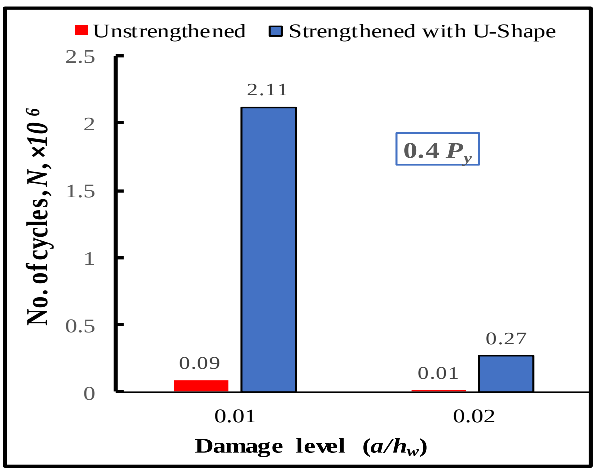


Figure 25: Comparison between the life of un-strengthened and the life of U-shape strengthened girders at load ($0.4P_y$) with low damage levels.

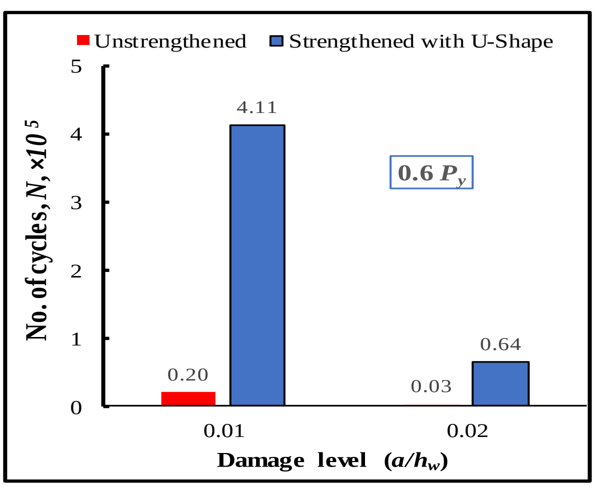


Figure 26: Comparison between the life of un-strengthened and the life of U-shape strengthened ones at load ($0.6P_y$) with low damage levels.

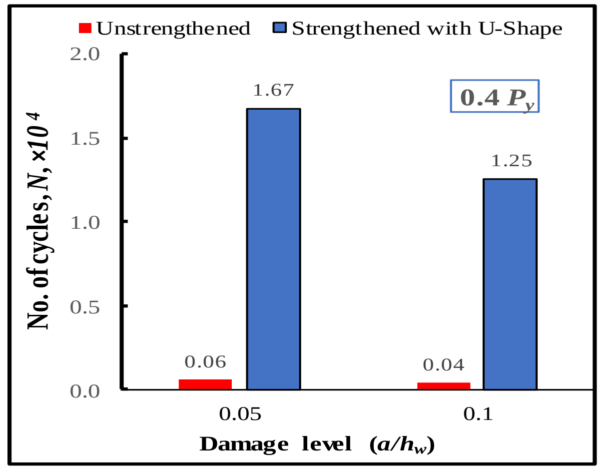


Figure 27: Comparison between the life of un-strengthened and the life of U-shape strengthened girders at load ($0.4P_y$) with high damage levels.

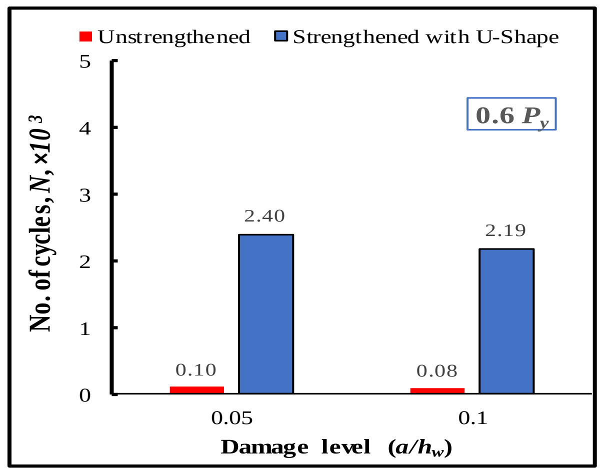


Figure 28: Comparing the life of un-strengthened to the life of U-shape strengthened ones at load ($0.6P_y$) with high damage levels.

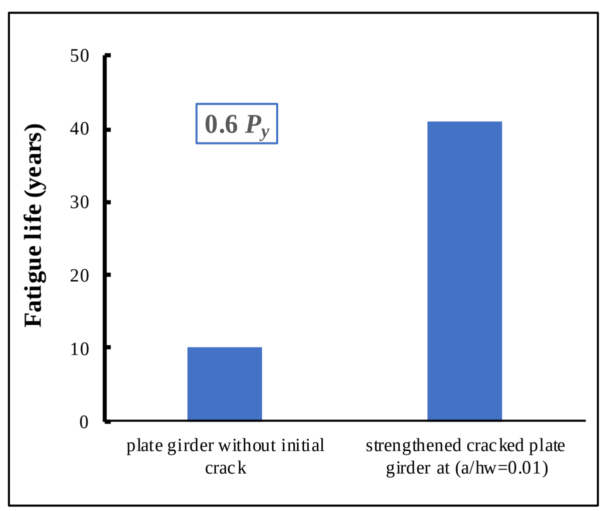


Figure 29: Fatigue life with years for the plate girder without initial crack and for strengthened plate girder with initial crack (a/h_w=0.01).

5 CONCLUSION

This paper discusses the fatigue performance of the strengthened steel plate girders by using CFRP strips. On this basis, the finite element models were conducted with different proposed reinforcement configurations using CFRP strips for both web and bottom flange of cracked steel plate. In addition, some parameters were considered to evaluate the fatigue performance such as loading capacity and initial damage level. Consequently, the following conclusions can be drawn from the present study:

- The fatigue performance for the strengthened cracked steel plate girders with CFRP strips significantly reduces the crack propagation and extends the fatigue life.
- The fatigue life of strengthened specimen using strengthening system for bottom flange only with CFRP strips can be increased up to 375% over un-strengthened girder. While adding the single V-shape strengthening system of web along to the bottom flange strengthening gave a slight improvement in the final fatigue life over the one with the bottom flange strengthening only.
- However, adding the double V-shape strengthening system of web along with the bottom flange strengthening was more effective as, it increased the fatigue life by 456%.
- The horizontal strengthening for both flange and web specially when U-shape strengthening system is used for flange only improves the fatigue life by 3390%.
- It is obvious that the use of prestressing with U-shape strengthening system could achieve the best efficiency of strengthening, as it can provide higher compression stresses. Then the fatigue life of strengthened specimen using an (20%) prestressed CFRP could increase by 5700%.
- Based on these results, the vertical web strengthening by U-shape system is more effective than the inclined web strengthening by V-shape system around the crack.
- The fatigue damage of initially undamaged plate girders starts to appear at maximum load capacity ($0.5P_y$). Consequently, the actual fatigue life of plate girders is reduced comparing with the value of design life at the same load capacity ($0.5P_y$).
- At high loading ($0.6P_y$), it is obvious that the strengthening with U-shape CFRP was obviously efficient at low damage levels only. So, an early repair is recommended for plate girders especially when the bridge is subjected to heavy loads.

6 RECOMMENDATION FOR FUTURE WORK

The following recommendations are suggested for future research in this area;

- The effect of various stress ratios should be investigated.
- The influence of different environmental conditions should be studied on the strengthening bridge steel plate girders to find the real fatigue behavior.
- Investigate the effect of using CFRP sheets on fatigue performance not only in strengthening the cracked steel girders but also in enhancing the uncracked steel girders.

REFERENCES

[1] Colombi, Pierluigi, Giulia Fava, "Experimental study on the fatigue behaviour of cracked steel beams repaired with CFRP plates." Engineering Fracture Mechanics 145 (2015): 128-142.

[2] Colombi, Pierluigi, Giulia Fava, and Lisa Sonzogni. "Fatigue crack growth in CFRP-strengthened steel plates." Composites Part B: Engineering 72 (2015): 87-96.

[3] Colombi, Pierluigi, and Giulia Fava. "Fatigue crack growth in steel beams strengthened by CFRP strips." Theoretical and Applied Fracture Mechanics 85 (2016): 173-182.

[4] Yu, Qian Qian, et al. "Fatigue behaviour of CFRP strengthened steel plates with different degrees of damage." Thin-Walled Structures 69 (2013): 10-17.

[5] Wu, Gang, et al. "Experimental study on the fatigue behavior of steel beams strengthened with different fiber-reinforced composite plates." Journal of Composites for Construction 16.2 (2012): 127-137.

[6] Hmidan, Amer, Yail J. Kim, and Siamak Yazdani. "CFRP repair of steel beams with various initial crack configurations." Journal of composites for construction 15.6 (2011): 952-962.

[7] Wu, Chao, et al. "Fatigue tests on steel plates with longitudinal weld attachment strengthened by ultra-high modulus carbon fibre reinforced polymer plate." Fatigue & Fracture of Engineering Materials & Structures 36.10 (2013): 1027-1038

[8] Kim, Yail J., and Kent A. Harries. "Fatigue behavior of damaged steel beams repaired with CFRP strips." Engineering Structures 33.5 (2011): 1491-1502.

[9] Ghafoori, Elyas, et al. "Fatigue design criteria for strengthening metallic beams with bonded CFRP plates." Engineering Structures 101 (2015): 542-557.
[10] Hosseini, Ardalan, et al. "Mode I fatigue crack arrest in tensile steel members using prestressed CFRP plates." Composite Structures 178 (2017): 119-134.
[11] Wang, Zhi-Yu, Qing-Yuan Wang, and Yong-Jie Liu. "Evaluation of fatigue strength improvement by CFRP laminates and shot peening onto the tension flanges joining corrugated steel webs." Materials 8.8 (2015): 5348-5362
[12] Teng, J. G., D. Fernando, and T. Yu. "Finite element modelling of debonding failures in steel beams flexurally strengthened with CFRP laminates." Engineering Structures 86 (2015): 213-224.
[13] Deng, Jun, Yonghui Jia, and Hengzhong Zheng. "Theoretical and experimental study on notched steel beams strengthened with CFRP plate." Composite Structures 136 (2016): 450-459.
[14] Hmidan, Amer, Yail J. Kim, and Siamak Yazdani. "Stress intensity factors for cracked steel girders strengthened with CFRP sheets." Journal of Composites for Construction 19.5 (2015): 04014085.
[15] Hmidan, Amer, Yail J. Kim, and Siamak Yazdani. "Correction factors for stress intensity of CFRP-strengthened wide-flange steel beams with various crack configurations." Construction and Building Materials 70 (2014): 522-530.
[16] Chen, Tao, et al. "Experimental study on mixed-mode fatigue behavior of center cracked steel plates repaired with CFRP materials." Thin-Walled Structures 135 (2019): 486-493.
[17] Kamruzzaman, Mohamed, et al. "A review on strengthening steel beams using FRP under fatigue." The Scientific World Journal 2014 (2014).
[18] Yue, Qing-Rui, et al. "Research on fatigue performance of CFRP reinforced steel crane girder." Composite Structures 154 (2016): 277-285.
[19] Yu, Qian-Qian, and Yu-Fei Wu. "Fatigue strengthening of cracked steel beams with different configurations and materials." Journal of Composites for Construction 21.2 (2017): 04016093.
[20] Yu, Qian-Qian, and Yu-Fei Wu. "Fatigue retrofitting of cracked steel beams with CFRP laminates." Composite Structures 192 (2018): 232-244.
[21] Hosseini, Seyed Mahdi, et al. "Fatigue crack arrest in steel beams using FRP composites." Engineering Failure Analysis 127 (2021): 105397.
[22] Ghafoori, Elyas, et al. "Fatigue strengthening of damaged metallic beams using prestressed unbonded and bonded CFRP plates." International Journal of Fatigue 44 (2012): 303-315.
[23] Ghafoori, Elyas, A. Schumacher, and M. Motavalli. "Fatigue behavior of notched steel beams reinforced with bonded CFRP plates: Determination of prestressing level for crack arrest." Engineering Structures 45 (2012): 270-283.
[24] Jiao, Hui, Fidelis Mashiri, and Xiao-Ling Zhao. "A comparative study on fatigue behaviour of steel beams retrofitted with welding, pultruded CFRP plates and wet layup CFRP sheets." Thin-Walled Structures 59 (2012): 144-152.
[25] Lepretre, Emilie, et al. "Fatigue strengthening of cracked steel plates with CFRP laminates in the case of old steel material." Construction and Building Materials 174 (2018): 421-432.
[26] Aljabar, N. J., et al. "Effect of crack orientation on fatigue behavior of CFRP-strengthened steel plates." Composite Structures 152 (2016): 295-305.
[27] Aljabar, N. J., et al. "Fatigue tests on UHM-CFRP strengthened steel plates with central inclined cracks under different damage levels." Composite Structures 160 (2017): 995-1006.
[28] Wang, Hai-Tao, Gang Wu, and Jian-Biao Jiang. "Fatigue behavior of cracked steel plates strengthened with different CFRP systems and configurations." Journal of Composites for Construction 20.3 (2016): 04015078.
[29] Yu, Qian-Qian, et al. "Tests on cracked steel plates with different damage levels strengthened by CFRP laminates." International Journal of Structural Stability and Dynamics 14.06 (2014): 1450018.
[30] Hosseini, Ardalan, et al. "Prestressed unbonded reinforcement system with multiple CFRP plates for fatigue strengthening of steel members." Polymers 10.3 (2018): 264.
[31] Zheng, B., and M. Dawood. "Debonding of carbon fiber–reinforced polymer patches from cracked steel elements under fatigue loading." Journal of Composites for Construction 20.6 (2016): 04016038.
[32] Seitl, Stanislav, et al. "Comparison of the fatigue crack propagation rates in S355 J0 and S355 J2 steel grades." Key Engineering Materials. Vol. 784. Trans Tech Publications Ltd, 2018.

[33] Deng, Jun, et al. "Fatigue behaviour of notched steel beams strengthened by a self-prestressing SMA/CFRP composite." Engineering Structures 274 (2023): 115077.
[34] Doroudi, Yashar, et al. "Behavior of cracked steel plates strengthened with adhesively bonded CFRP laminates under fatigue Loading: Experimental and analytical study." Composite Structures 266 (2021): 113816.
[35] Li, Anbang, et al. "Fatigue behavior of corroded steel plates strengthened with CFRP plates." Construction and Building Materials 314 (2022): 125707.
[36] Tong, Lewei, Qitong Yu, and Xiao-Ling Zhao. "Experimental study on fatigue behavior of butt-welded thin-walled steel plates strengthened using CFRP sheets." Thin-Walled Structures 147 (2020): 106471.
[37] Islam, Md Shariful, and Md Abdul HASİB. "Effect of Slenderness Ratio on Fatigue Life of CFRP Strengthened Steel I-Beam." International Journal of Engineering and Applied Sciences 12.2 (2020): 70-77.
[38] Browell, Raymond, and Al Hancq. "Calculating and displaying fatigue results." Ansys Inc 2 (2006).
[39] Fageehi, Yahya Ali, and Abdulnaser M. Alshoaibi. "Numerical simulation of mixed-mode fatigue crack growth for compact tension shear specimen." Advances in Materials Science and Engineering 2020 (2020).
[40] Alshoaibi, Abdulnaser M., and Yahya Ali Fageehi. "Numerical analysis of fatigue crack growth path and life predictions for linear elastic material." Materials 13.15 (2020): 3380.
[41] Alshoaibi, A. M., A. B. G. Abdulrahman, and A. F. Yahya. "Three-dimensional simulation of crack propagation using finite element method." Int. J. Eng. Adv. Technol 9 (2019): 892-897.

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