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Improving the Performance of Steel Beams by using Carbon Fiber Reinforced Polymer: A Review

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Abstract: *In latest years, the application of carbon fiber reinforced polymer (CFRP) composites for strengthening structural elements has become one of the efficient options to meet repair due to fatigue cracking, corrosion or the increasing cyclic loads. Therefore, the aim of this survey is to explore the existing carbon fiber reinforcing polymer (CFRP) techniques used for strengthening structural steel elements that are damaged due to fatigue. The current survey also deals with the researches that studied the efficiency of using (CFRP) in strengthening steel beams and rehabilitating (reestablishing) damaged ones. It also reviews the researches that used the finite element method (FEM) to evaluate the performance of steel beams strengthened by CFRP.*

Keyword: Steel beams, Carbon fiber reinforced polymer, strengthening steel beams, rehabilitation damaged steel beams, fatigue, Finite element method.

تحسين أداء العتبات الفولاذية باستخدام البوليمرات المدعّمة بألياف الكربون: مقال مراجعة

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المستخلص

في السنوات الاخيرة، أصبحت تطبيقات مركبات البوليمرات المدعّمة بألياف الكربون (FRP) لتقوية العناصر الانشائية واحدة من الخيارات الكفوءة لتحقيق صيانة تلك العناصر من الشقوق الناجمة عن الكلل (أو التآكل) أو من تزايد الأحمال الدورية. من أجل ذلك فأن هذه الدراسة الاستعراضية تهدف الى استكشاف تقنيات البوليمرات المدعمة بألياف الكربون المتوفرة لحد الآن والمستخدمة في تقوية العناصر الانشائية الفولاذية المتضررة من الكلل. تتناول الدراسة الحالية أيضاً البحوث التي تتحرى عن كفاءة استخدام البوليمرات المدعّمة بألياف الكربون (CFRP) في تقوية العتبات الفولاذية وإعادة تأهيل المتضررة منها. تستعرض الدراسة أيضاً البحوث التي تتناول استخدام طريقة العناصر المحددة (FEM) لتقييم أداء العتبات الفولاذية المقوّاة بالبوليمرات المدعّمة بألياف الكربون (CFRP).

الكلمات المفتاحية: عتبات فولاذية، البوليمرات المدعّمة بألياف الكربون، تقوية وإعادة تأهيل الدعامات الفولاذية، الكلل، طريقة العناصر المحددة.

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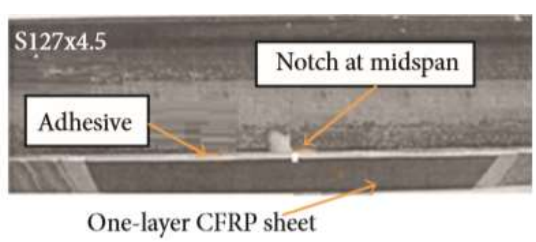
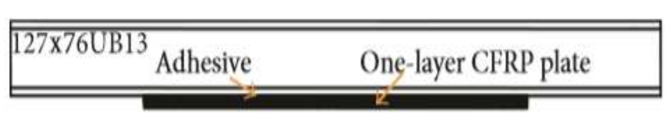
1. Introduction.

CFRP (Carbon Fiber Reinforced Polymers) are widely utilized in different aspects. FRP is an energy absorption tool used for numerous structural purposes such as crack obstruction in steel buildings and in bridges. Lately, the use of FRP for strengthening steel structures has significantly increased. Various techniques are existing for strengthening steel structures which need a considerable time and cost. FRP possesses good corrosion resistance, high strength, light weight, and adequate for enhancing the level of investment [1]. For the purpose of enlarging the fatigue strength of damaged steel girders, the application of fiber reinforced polymer compounds is considered as a hopeful technique which presents an encouraging replacement to conventional approaches like steel lamination [2]. Other FRPs were conventionally used in reestablishing concrete structures [3]. Latest strengthening schemes in the U.S., Australia, China, Iraq and many countries revealed that there is a large prospects for utilizing carbon fiber reinforced polymer (CFRP) to modify steel structural members [4,5,6]. Lately, an Iraqi study aimed to improve the effectiveness of CFRP installation by using the Technique of Carbon Fiber Confinement by a Steel Plate (CFCSP) [7].

2. Strengthening of Steel Beams by using Carbon Fiber Reinforced Polymers.

The elastic modulus, geometry, tensile strength, and arrangement of fiber reinforced polymers (FRP) components and adhesively bonded joints play a significant role in the aspect of fatigue resistance and the permanence of strengthened bridge girders and steel beams. Several investigators have examined steel beams strengthened with various fiber reinforcing polymer mechanisms and displayed their fatigue performance comparison. Table (1) displays an outline for the strengthening methods of steel beams with CFRP components.

Table 1: Method of strengthening steel beams

Specimen references	Material properties and dimensions	Figures
Steel beams : S127×4.5 reinforced with CFRP sheet [4]	Steel beams length = 1220mm $E = 194.4\ kN/mm^2$ fy = 336.4 MPa; 330.9MPa. CFRP Dim. = (300 x 76 x1.27)mm $E = 144\ kN/mm^2$; Fu = 2137MPa. Epoxy (1: 1) mix of (bisphenol based) resin and (poly-ethylene poly-amine) hardener.	
Steel beams : 127x76UB13 strengthened by CFRP plate [8].	Steel beams length = 120cm, E = 205 GPa Fu = 275MPa. CFRP thickness = 3mm, length = 40cm Epoxy(SikaDur[31]Normal) E = 8 GPa, G = 2.6 GPa, fu = 29.7MPa, thickness = 0.3mm.	

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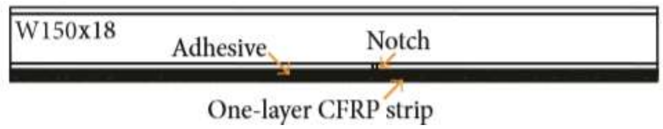
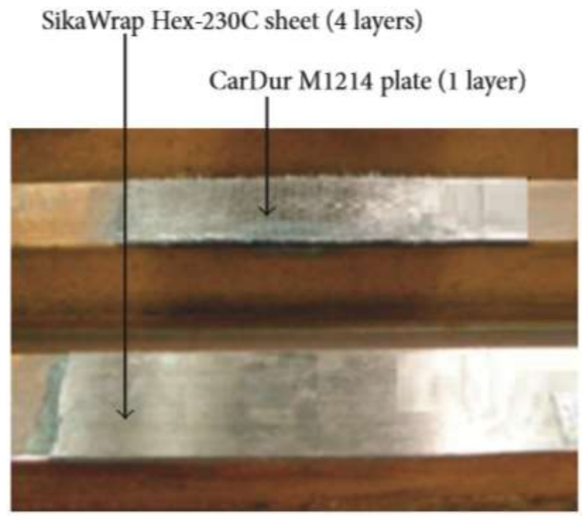
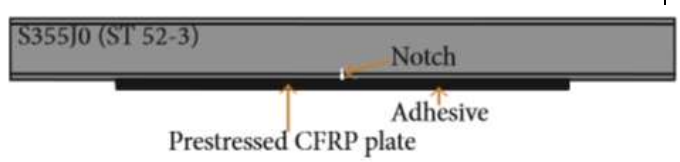
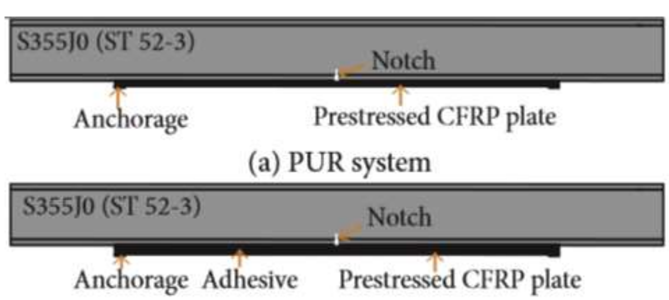
Steel beams W150x18 repaired with strips of CFRP[9]	Steel beams length = 183cm, E = 200 ken/mm^2, f_y = 393MPa. *CFRP* Dimensions : 50 x 1.4mm, E = 155 GPa, fu = 2.8GPa. Epoxy E = 4.5 GPa, fu = 25MPa, thickness = 1mm.	
Steel beams : 150UB14, notched, Grade 400, modified with welding, CFRP composites [10] .	Steel beams dimension: (L140 × W7.5 × H15) cm, E = 207.4 GPa, fy = 411.6 MPa , f_u. = 541.3MPa . CFRP : (1) Sika CarboDurM1214 pultruded plates; thickness=1.4mm, E = 210 GPa, F_t = 2.4GPa, (2) SikaWrap Hex-230 C woven sheets; thickness=0.13mm for each ply, E = 230 GPa, f_u = 3.45 GPa. Epoxy : (1)Sikadur − 330 (2) Araldite R 420	
Steel beams : S355J0 bonded with 20% pre-stressed CFRP plates [11] .	Steel beam*s* Dimensions:110 × 12 × 6.5cm, E=210 GPa, f_y = 355MPa. CFRP Dimensions: 910 × 50 × 1.2mm (S512) E = 165 GPa, fu = 3.10GPa, Pre − stressing level = 20% of the CFRP ultimate strength = 632MPa. Araldite(2015)adhesive : E = 1.75 GPa,	
Steel beams : S355J0 (ST 52 − 3) strengthened using 30% (a) pre-stressed un-bonded CFRP plates. (b) bonded CFRP plates [12].	Steel beams: Dimensions: (110 × 12 × 6.5)cm ,E = 210 GPa, fy = 355MPa CFRP: Dimensions: 910x 50 x 1.2 mm (S512), E = 160 GPa, fu = 3.10GPa, Pre − stressing level = 30% of the CFRP ultimate strength. Araldite2015adhesive: E = 1.75 GPa	(a) PUR system (b) PBR system

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Moreover, Wu *et al.* [13] examined 8 synthetically destructed H-350×175 steel beams, including a single non strengthened beam and 7-strengthened by welded steel, BFRP − SW (Basalt FRP)steel wire, HM − CFRP (high modulus CFRP), and HS − CFRP (high strength CFRP) plates by utilizing Normal epoxy adhesive “Sikadur-30”. The arrangement of the plates used in the reinforcing mechanism made by Wu *et al* .[13] is displayed in Fig.(1). An anchorage system has been incorporated at the end of the fibrous strengthened composite plates and under the concentrated load. The SW − BFRP is one of the best reinforcing materials from the view point of (cost: performance) ratio and the HM − CFRPs have the best efficient strengthening implementations [13].

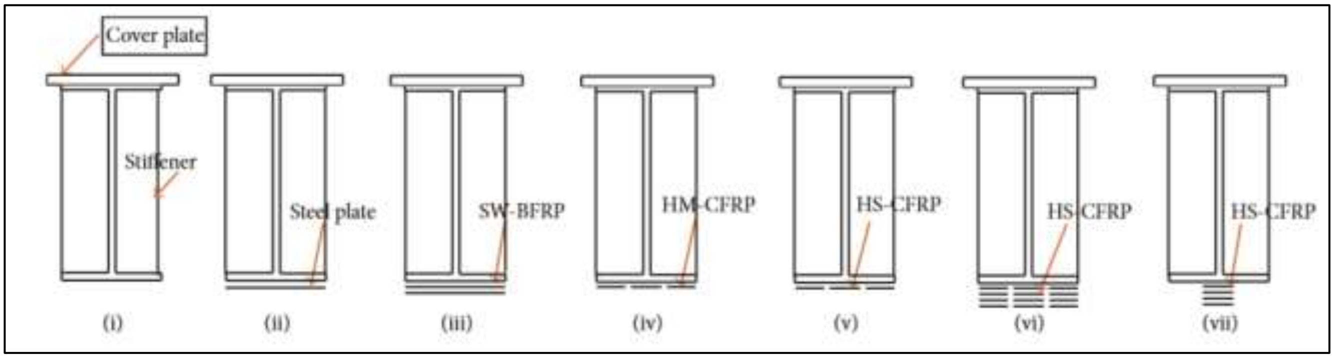

Figure 1: Strengthening technique with plate configuration [13].

Basalt FRP (BFRP) components reveal artificial benefits in strengthening structures and seismic repair, they are considered as unprecedented structural materials [14,15]. Nevertheless, the comparatively low elastic modulus of BFRP might not fulfill the stiffness requirements of some structural elements. Thus, to get better performance, SW (steel wires) BFRP could be manufactured from hybridizations of CFRPs or steel wire (SW) with BFRP [14,16]. A 3-continuous spans (64×7.92)m girder bridge of which its girders were reinforced by external post tensioned rods of CFRP [17] . The anchorage system was fastened to the steel girder web with bolts . The suggested pre stressed unrestrained reinforcement system (PUR) [12] could be utilized as a substituent to adhesively binded FRP reinforcements , especially when there is interest in the water effect, humidity , large climate temperature , and large cyclic loads on the adhesive between fiber reinforced polymer and steel.

Vatandoost [18] have utilized pre-stressed(CFRP)laminates for examining the fatigue performance of five steel beams (W310 × 74) shaped, in which some of the pre stressing CFRP laminates had been attached to the upper surface of the tension (bottom) flange , and the other pre-stressed plates had been bonded to the cover plate . A pre-stress fiber reinforced polymer component spot is highly proposed to magnify the efficiency of the adhesively binded spot on the steel element [19] and fatigue strength [20] . Pre stressing FRP system introduced by European Master of Public Administration (E.M.P.A.) was utilized for the strips of CFRP for subjecting a direct tensile force against the steel frame external reaction by jack lifting. Vatandoost & others [18,21,22,23] debated more details related to the pre stressing process .

Latterly, the carbon flex, which is carbon fiber hybrid polymeric matrix composite (CFHMC) reinforcing mechanism had been introduced by Zhou & Attard [24], that is a carbon fibrous based component made by the latter hybrid matrix mechanism containing amino based polymeric components to give substantial high-strength sustainability and substantial damping of the carbon fiber strip. Latterly, several researches [24,25,26] have signaled a huge potential of carbon flex as a reinforcing material and hence to prohibit excessive damage or tragic failure .

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Most of fatigue problems emerge from inexact fabrication or scant detailing, rather than inexact selection of materials [27]. Schnerch and others [5,28] reports have indicated that the binding mechanism of FRP reinforced steel structures differs from concrete structures. Besides, large binding stresses take place in steel structures to satisfy the strengthening demands [29]. Any breach of fabrication allowances could unpredictably alter the fatigue behavior and cause a quite fatigue life dispersion [23] .

Steel structures behave quite different from concrete structures during damage. The test results have also revealed that a large magnitude of adhesive stresses occur in steel structures (Schenerch *et al.*, 2005) [30]. The usage of bolted steel plates for confining the end of FRP was implemented by Motavalli & Czaderski. Buildings´ shear walls in the mentioned study were rehabilitated using GFRP and constrained CFRP laminates. Using FRP as anchor or a single additional steel plate can basically decrease stresses at the ends (Motavalli & Czaderski , 2007) [31].

Narmashiri *et al.*[32], have concentrated on the influence of the usage of bolted steel strips as end anchors applied to 4 steel beams for rupture test and 3-D simulations and nonlinear static analyses using ANSYS software signals 24% increment in bearing capacity of confined steel beams as compared with the reference (un strengthened) steel beams. Moreover, the outcomes have revealed that end anchors of CFRP strip with small spacings of bolts is more efficient (Narmashiri et al. , 2010) [32].

Sweedan *et al.* [33] have studied the role of longitudinal connection of anchored steel edges with fiber reinforced polymers. Test plan have experimented eighteen short samples for detecting the effect of spacing between bolts, cutted-edge and formed-edge distance on load carrying capacities, assembling and installation capabilities. The outcomes indicate that the connections performance is highly affected by the magnitude of formed-edge distance and the most suitable distance is about six to seven times the bolt hole diameter. Besides the advantage of the technique of strengthening with fiber reinforced polymer, it produces disturbances in several circumstances during offering facilities leading to a shortage of structure composite resistance against applied loads. In some tests, during applying FRP strip for strengthening beams, fiber reinforced polymer laminate end is detached from the steel beam before it attains its ultimate moment capacity and de-bonding incident happens. This incident happens in beams during the increase in load intensity which means that the stresses between FRP strips layers are sticking , and besides below area of the steel beam raises have led to produce a distinguished tensile force and as a result de-bonding occurs. One solution to postpone de-bonding is to install an anchor on FRP strips. In this study, the influence of using an anchor in steel I-beam in reducing end stresses of FRP strips , and thus postponing de-bonding were investigated.

3. Rehabilitation of Steel Beams by using Carbon Fiber Reinforced Polymer

In bridges, beams and girders are usually suffering from creep consequences , but strengthening of tension flange (usually lower flange) is especially required because tension flange affords largest portion of corrosion, fundamentally because of wreckage cumulating [34]. Moreover, CFRP components have large tensile strength. The researches displayed in the paragraph below focus on the functional effectiveness beams and girders strengthened by CFRP.

A test of cyclic loading implemented for bridge girders naturally corroded that had been taken away from damaged bridges is displayed by Gillespie J. W. et al. [35]. The cyclic loading test includes applying one layer of CFRP to strengthen the bottom flanges (with whole length) of two girders which had been influenced by corrosion more upper flanges or webs. Outcomes of this research revealed that strengthening with CFRP has led to (10%) to (37%) improvement rate in the elastic stiffnesses of girders. Moreover, an enlargement of (17%) and (25%) had obtained in the ultimate strength of the two

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girders, and a (75%) reduction had occurred in the in-elastic strains in the bottom flange in comparison with unstrengthened girders at the same level of loading.

Synthetically nicked steel beams were tested by one concentrated (point) load bending test, the test was performed at Missouri Rolla University by Liu X. et al.[36]. 4-W12×14 having a length of (243.8) cm were utilized in this test. Two samples had been tested without CFRP adjustment but one of them had a (10.16)cm nick in the bottom (tension) flange to simulate the influence of corrosion. The other two samples were strengthened by CFRP laminates of (width = 10 cm, modulus of elasticity >200 GPa, and tensile strength at break >2300 N/mm^2) and utilized to cover the same nick, but one covers one quarter of the beam length and the other covers the whole length of bottom (tension) flange. Using CFRP led to an improvement in the plastic load capacity by (60%) for the full sample length and (45%) for the one quarter sample length.

Tavakkolizadeh & Saadatmanesh [37] have utilized two concentrated load bending test on two groups of S-5×10 steel beam (130)cm long which had been notched at mid-span to depth of (3.2 mm) for the 1st group and (6.4 mm) for the 2nd group. All beams had been strengthened by CFRP laminates with (0.13 mm) thickness and various lengths. The outcomes have revealed that the stiffness and ultimate strength of adjusted samples were close to their original values in the reference sample despite the CFRP patch length. The outcomes of the (6.4) mm notch group revealed a distinguished drop of ductility as compared with the (3.2)mm notch group.

Patnaik & Bauer [38] have utilized 4-I-section un-deteriorated beams. Two beams have strengthened by CFRP strips along the beam webs and subjected to shear failure test. The other two beams were strengthened by CFRP strips along the bottom (tension) flange and subjected to bending failure test . The first two shear strengthened beams, one have signaled (26%) improve in shear strength while the other have failed. The second two have recorded nearly (14%) improve in the flexural strength capacity.

Mertz & Gillespie [39] have investigated various reinforcing techniques for W8×10 members of (152) cm. length. Fig. (2) displays various retrofit mechanisms utilized for the samples. All experimented samples revealed remarkable improvement in stiffness and strength.

The improvement in ultimate strength of the adjusted steel girders conforming with various strengthening ratios of CFRP are illustrated in Fig. (3) [40,41,42]. This Figure reveals that the influence of using CFRP on improving the ultimate strength is obvious for small values of yield strength.

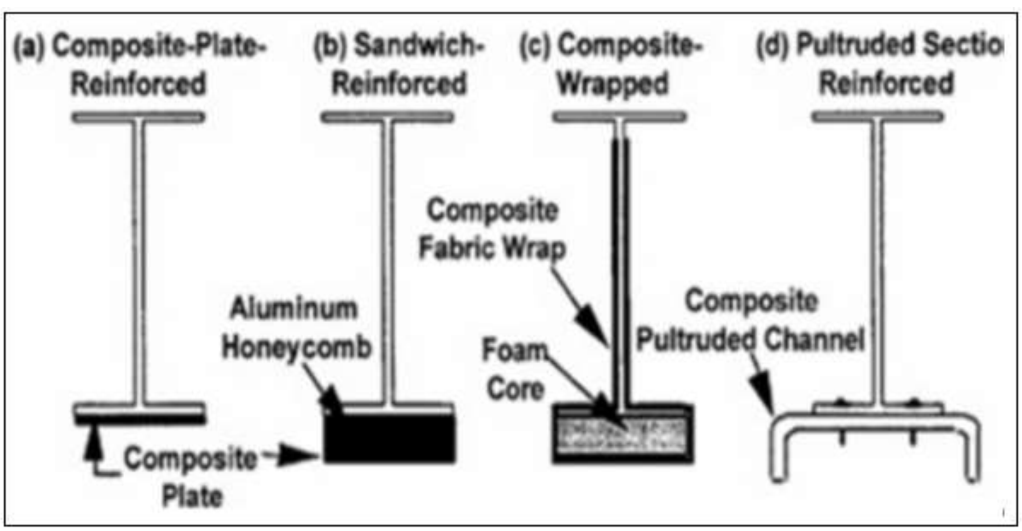

Figure 2: Various modification types [39]

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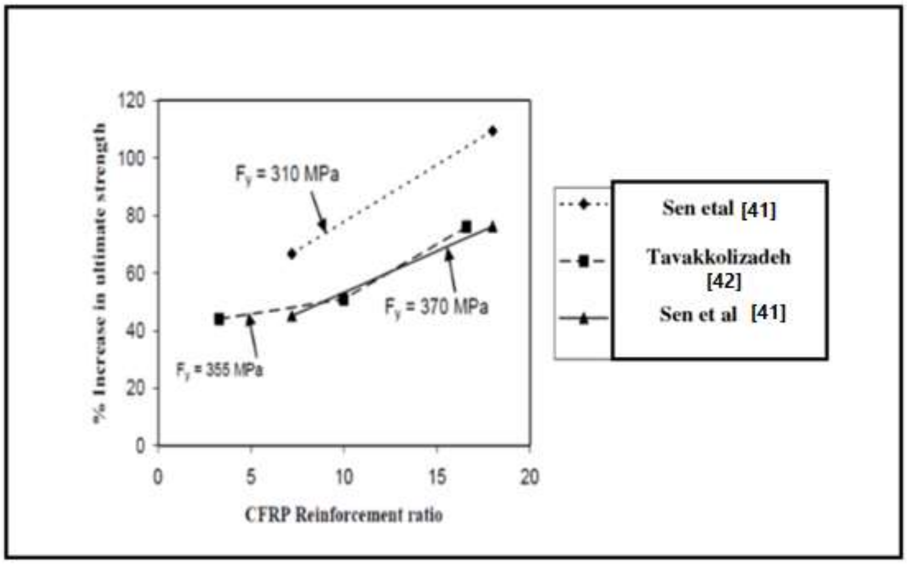

Figure 3: Influence of yield strength and the ratio of CFRP reinforcement on the ultimate strength of modified steel girders [40]

4. Finite Element Simulation of CFRP Steel Beams.

The finite element method (F.E.M.) is a reasonable tool for the analysis of structures utilizing computer software. Practically, the F.E. simulation is performed to support the theoretical or experimental results of fatigue strength. According to the surface crack widening energy release rate [43] utilizing G-integral [44] and an elementary material strength theory [45] and a theoretical approach was developed by Ghafoori & Motavalli [46] to speculate the stress intensity factors (S.I.F.) of a cracked steel I-beams. The repair of steel structures exposed to fatigue is usually anticipated to reduce the value of S.I.F. at the crack tip, and consequently, promote the post crack fatigue life [47]. Ghafoori et al. [12] suggested a numerical method using the data resulted from experimental tests (the crack lengths, the external flexural moments, and the conforming strains generated on the CFRP strips under cracked segments) and produce the S.I.F. They have utilized software named ABAQUS (version 6.8) to analyze the F.E. model of the steel beams to support the outcomes. (See Fig (4))

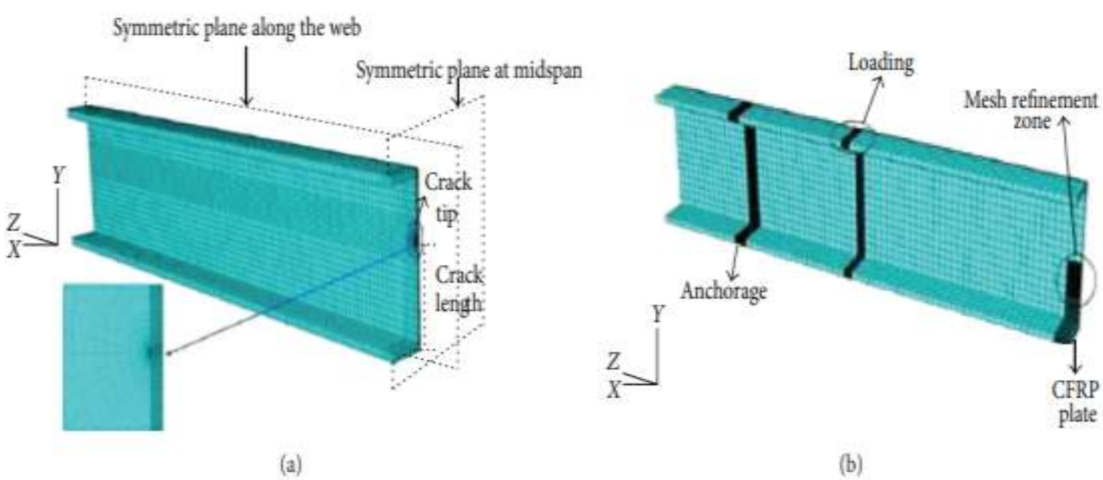

Figure 4: (a) A geometrical model using ABAQUS in the FE analysis and (b) the mesh refinement around the loading, anchorage, and crack zones [12].

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The method was modified to evaluate the adequate level of CFRP pre-stressing to hold the fatigue crack growth (FCG). Furthermore, the method had been utilized to investigate various in-active, semi-active , and active crack modes with a reinforced beams under loading. Numerous factors had been taken into consideration including commotion frequency, crack growth, and structural suppression on the life of the FCG [48]. Using the fracture concept, the model of fatigue crack propagation (FCP) was suggested by Xiulin & Hirt[49].

Wang & Nussbaumer [50] extended the previous work to the FCP of a metallic cracked element adjusted with adhesively binded composite patches. According to the crack propagation law of Paris-Erdogan [51], a model of linear elastic fracture mechanic (LEFM) was used to foretell the influence of peening treatment on the performance of fatigue of welded steel structure [52] and to verify the efficiency of the pre stressed CFRP strips [53].

Ghafoori et al. [11] developed a methodology for a deteriorated steel beam with a certain length of crack that is loaded by a specific cyclic loading according to the theory of fracture mechanics (F.M.) to evaluate the sufficient level of pre stressing by which the growth of crack is impounded. Certain strengthened steel beams had been experimented under different ranges of cyclic loading and the test outcomes revealed superior concord with the introduced fracture model. In F.M., according to the techniques of gradual damage modeling to foretell the life of fatigue, the crack propagation rate is correlated to the S.I.F. [48] or strain energy release rate [54,55,56,57]. A damage shift parameter was suggested by [56,57] to consider accelerative interaction influences in the situation of adhesively binded joints. Significant interaction influences had been investigated where the acceleration of crack growth was connected with the changings of mean load.

Yet, Lemaitre & Desmorat [58] had introduced models of continuum damage mechanic (C.D.M.) and developed for the generation of micro-cracks by [59,60]. The models of (C.D.M.) was utilized a law of damage progression for modeling both pre-cracking damage progression and crack propagation for variable and constant fatigue amplitude [61].

To foretell the fatigue strength of adhesively binded CFRP double lap joints, Wahab et al. [62] have made a comparison between both the D.M. techniques and F.M. They confirmed that the approach of modified C.D.M. is compared favorably with the method of F.M. for constant amplitude fatigue (C.A.F.). The fatigue life based on F.M. and D.M. foretelling of binded single lap joints (SLJs) under various types of variable amplitude fatigue (V.A.F.) loading was analyzed by Shenoy et al. [63] .

Kim & Harries [9] used a 3-dimensional non-linear finite element (F.E.) model for foretelling the fatigue strength of nicked steel beams utilizing ANSYS software. 3-D structural solid element (SOLID-45) was used to model the steel section; and a linear stress-strain relationship for the CFRP was modified. For modeling the behavior of the steel CFRP interface, a non-linear 2-nodes interface element (COMBIN-39) was used. For the element whose primary relative distance is zero , a bilinear bond slip relationship was made for them. The research has utilized the strain life technique and the conception of Henry’s damage theory [64] for the fatigue life foretelling of steel beams. The theoretical background of the strain life process is debated by Bannantine et al. [65]. The deflection behavior of strengthened and un-strengthened beams is displayed in Fig. 5(a). Moreover, a typical S-N curve resulted of strengthened steel beam is illustrated in Fig. 5(b) , which was compared with category (E) in the AISC by [66].

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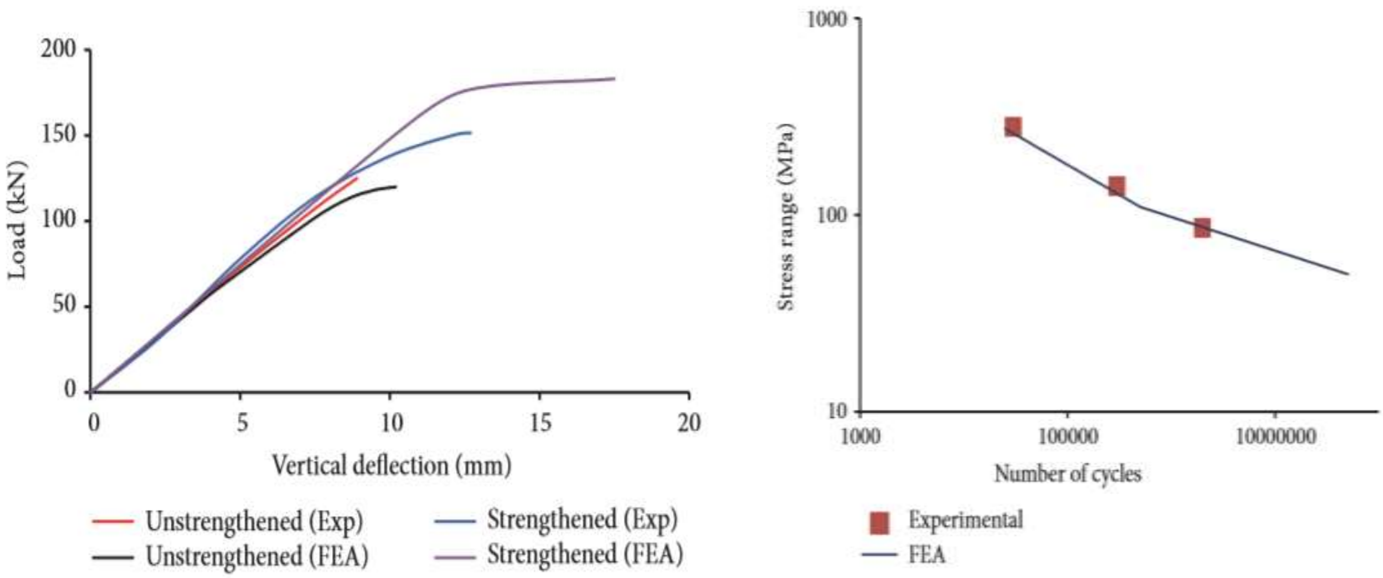

(a) Load deflection curve for numerical and experimental results (static) [67]

(b) σ-N curve for numerical and experimental studies [9]

Figure 5: Comparison between simulation and experimental results of steel beam.

Regardless of this, Youssef [68] introduced a model for foretelling the linear and non-linear performance of a repaired beam. The model was based on the differential equations solution governing the strengthened steel beam behavior, which involves simulation of the skin and shear behavior of the epoxy adhesive. A steel beam (W-shaped) strengthened by GFRP sheets was constantly tested to confirm the foretelling of the model, and superior concord was noticed between these outcomes.

To evaluate the decreasing in displacement of crack opening along with the enlargement of the postponed crack propagation of the reinforced nicked steel plates, Colombi [69] developed a proper plasticity based crack postponing model [70,71] as an extending of Newman's model [72,73]. The above mentioned literature have shown that the simulation in F.E.M could be a pivotal and useful tool in analyzing beams subjected to fatigue loading because it ultimately reduces the wastage in cost and time . The usefulness of the strengthening techniques is well assured by the adequate effectiveness of the simulation with experimental tests. So far, the features of strengthened steel beams subjected to fatigue loading without using nicks are still an important scope to be investigated. This concern could be treated by F.E. simulation in a proportionate way.

5. Conclusions.

This work reviewed a survey of the studies that dealt with strengthening, repair, rehabilitation and F.E. simulation of steel beams by utilizing CFRP. The survey had revealed that:

- The use of CFRP can enlarge the shear strength of an I-section steel beam when it is glued to the web, whereas gluing it to the tension flange could enlarge the flexural strength of the steel beam section.
- The use of a CFRP composite strip can not only postpone crack initiation, reduce the rate of crack propagation, increase yielding load and extend the fatigue life, but also decrease the stiffness deterioration and the remaining deflection.
- The preferable strengthening selection is found to be the pre-stressed CFRP.
- End anchorage prohibits de-bonding of the CRRP strips at the ends of the beam by decreasing the local interfacial skin and shear stresses.

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- Rehabilitation of steel structures by using CFRP assist beam section to retrieve the wasted capacity and afford further loads.
- The F.E. simulation is a good method to investigate the steel beams behavior reinforced with carbon fiber reinforced polymers.
- Outcomes of research revealed that strengthening with CFRP has led to (10%) to (37%) improvement rate in the elastic stiffnesses of girders . Moreover, an enlargement of (17%) and (25%) had obtained in the ultimate strength of the two girders, and a (75%) reduction had occurred in the in-elastic strains in the bottom flange in comparison with unstrengthened girders at the same level of loading.

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