Experimental Study on Fatigue Cracked Steel Plates Under Mode (I) and Mixed-Modes (I/II) Repaired with CFRP and Stop Hole

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Abstract: This paper discusses the behavior of cracked steel plates in mixed cracking modes I/II, repaired using CFRP (Carbon Fiber Reinforced Polymer) materials and a stop hole under fatigue loading conditions. The study aims to evaluate the effectiveness of CFRP and stop holes as a repair method for enhancing the fatigue resistance of cracked steel structures. The experimental was tested under eccentric axial fatigue cyclic loading till failure in pure mode I and mixed mode (I/II) with a 45° angle. It was found that from test results, the fatigue life of steel plates strengthened with CFRP increased by 1.4 times when compared to un-strengthened steel plates. The fatigue life of steel plates strengthened with a stop hole increased by a factor of 1.45 compared to un-strengthened steel plates. The fatigue life of steel plates strengthened with CFRP and stop hole increased by a factor of 1.49 compared to un-strengthened steel plates.

Keywords: *Steel Plates, CFRP, Stop Hole, Cracks, Mixed Mode Fatigue.*

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I. INTRODUCTION

One of the most significant issues affecting a bridge's operating life and load-carrying capability is the occurrence of cracks in steel bridges, particularly those frequently subjected to fatigue loading from traffic. If the countries cannot control the spread of the bridge cracks, they may have to remove the bridge. Several bridges have employed various techniques to manage and fix cracks; these techniques include replacing or repairing damaged members or adding steel plates to bridge girders to extend the life and load-carrying capacity of the beams [1] [2]. However, these solutions are costly because of the need for periodic repair due to corrosion. The reinforcement of carbon fiber reinforced polymers (CFRP) is a viable alternative to standard fatigue crack repair methods, such as bolting, drilling, and welding [3]. It offers numerous benefits, including efficiency, time savings, cost effectiveness, minimal secondary damage, and ease of installation. The application of fatigue loads on stress-concentrated zones caused crack propagation in structures. The use of CFRP to strengthen steel and concrete structures has gained international recognition due to the characteristics of the CFRP composite [4]. The use of CFRP was limited in the aerospace field to explore the environment and build space shuttles as a result of its durability and load capacity, but it extended to other areas, including medical and construction. The most important advantages of CFRP are durability, non-corrosion, and lightweight. The main advantage of CFRP is the flexible response and strength of the carbon fiber matrix and the mechanical properties of the epoxy that was used. The CFRP repair technology effectively reduces crack propagation and increases the life duration of fractured structures [5]. Consequently, several researchers focused on experimentally investigating CFRP-reinforced cracked steel plates. Significant improvements in fatigue life of 1.18–3.08 times and 0.97–7.9 times were observed for single-sided and double-sided repair techniques, respectively [6], [7] [8]. According to reported results, a number of variables, such as CFRP thickness, initial fracture length, strengthening strategy, and local debonding size, affect repair effectiveness. Plates with central fractures under pure stress are the topic of the majority of these researches [9]. Typically, this is interpreted as cracks originating from rivet holes, a frequent method of construction for historic steel bridges.

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Nonetheless, it may be worthwhile to investigate additional causes that contribute to edge fractures. There are few studies that study the strengthening of cracked steel plates with different parameters and different specimens' shapes. Tao Chen et al [10] studied the fatigue crack propagation for a center-cracked steel plate under mixed mode (I/II) repaired with CFRP. The specimens were tested under fatigue loading until complete failure, and the results confirmed the great efficiency of strengthening the center-cracked steel plate. Lingzhen Li et al [11] studied the fatigue crack propagation for central inclined cracked steel plates having cracks with varying prestress levels and repair materials. Three types of carbon fiber reinforced polymer (CFRP) and two types of glue were used to repair. Reported results present that the material that fails the most frequently is the one with the lowest capacity for deformation. Also, prestressed proved to be more effective at extending fatigue life than CFRP's tensile stiffness.

Jiaxu Yao et al [12] studied the fatigue crack propagation for multi holes cracked steel plate. Steel plates with many holes exhibited a 33% lower fatigue life than those with a single initial crack. After CFP repair, a multi-hole steel plate's fatigue life improved by 334%, virtually equal that of a plate without holes. Similar research was carried out by Junhui Li et al., who studied notched steel beam specimens where a hot-rolled steel beam with an H-section had an initial notch cut through the bottom flange and web. The CFRP was patched and prestressed in the lower flange. The crack propagation was studied, and the high efficiency of prestressing was reported.

In this study, eight cracked steel plates were tested in a laboratory where specimens were tested under eccentric axial fatigue cycling loading till failure. The experiments include unrepaired and repaired specimens. CFRP strips were used for strengthening in four specimens, and a stop hole on the crack tip was used in some specimens for strengthening purposes. This study discusses the fatigue crack propagation in mode I and mixed mode I/II by changing the angle of specimens during the test to be 45°.

II. EXPERIMENTAL PROGRAM

The study was carried out at Cairo University's Faculty of Engineering, Mechanical Department Testing Lab. Eight specimens were created and put through tensile fatigue testing. In addition to strengthened specimens, which take into account various strengthening techniques, the specimens also represent control steel specimens. Every specimen was the same size and strengthened with the same CFRP. The following parts include specifics on the material, specimen size, strengthening techniques, and loading values.

➢ *Material*

Before manufacturing steel plate specimens, two steel coupons were extracted from the same plate from which the specimens were manufactured to ensure they would have the same mechanical properties. The two steel coupons ' cross-sectional dimensions were 50 * 8 mm with a length of 300 mm. They were tested according to ASTM E8/E8M [13] as presented in Fig. 1. Steel coupons were tested using a tension machine located in the Materials Testing Lab, Civil Department, Mansoura University. Table 1 presents the received results from the Material Testing Lab after the end of the test. The CFRP laminates (Sika Carbo Dur S 512) from SIKA EGYPT Company were used to repair the crack in steel plates due to their high tensile strength [14]. The laminates were externally bonded to the outer surface of plates using Sikadur-30 as an adhesive material for the repair purpose. The main advantage of CFRP is that it provides a cheap, easy installation solution and high carrying capacity [15]. Mechanical properties of adhesive material and CFRP laminates are shown in Table 2 and Table 3 from manufacturing data, respectively.

Fig 1 Tensile Testing Machine

Table 1 Steel Coupons Test Results

Sp. No.	Area (mm^2)	Initial Gage Length (mm)	Yield Load (KN)	Ultimate Load (KN)	Final Gage Length (mm)	Yield Stress (N/mm^2)	Tensile Strength (N/mm^2)	Elongation (%)
1	400	100	115	177.12	134	287.5	442.8	34.0
2	400	100	113.2	176.08	134.5	283	440.2	34.5

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Table 2 Mechanical Properties of Sikadur-30

Properties	Product Data Values
Density	1.65 kg/l ±0.1 kg/l (components A+B mixed) (at +23 °C)
Compressive Strength	70-80 N/mm^2
Modulus of Elasticity in Compression	9,600 N/mm^2 (at 23 °C)
Tensile Strength	24-27 N/mm^2
Modulus of Elasticity in Tension	11,200 N/mm^2 (+23 °C)
Shear Strength	14-17 N/mm^2

Table 3 Mechanical Properties of CFRP

Properties	Product Data Values
Laminate Tensile Strength	3100 N/mm^2
Density	1.60 g/cm^3
Modulus of Elasticity in Tension	170000 N/mm^2
Elongation at Break in Tension	1.80 %
Width	50 mm
Thickness	1.2 mm

Table 4 Dimensions of Specimen according to Standard

Dimension from (ASTM E647-13a) W =150		
Length of plate	1.2 W	180 mm
Width of plate	1.25 W	188 mm
Thickness of plate	W /20	8 mm
a_n	0.2 *W	30 mm
Hole diameter	0.25*W	37.5 mm
Max grip height	W/16	9.4 mm

➤ *Specimen Preparation*

To evaluate the propagation of crack and the efficiency of repairing techniques, eight steel specimens were fabricated from the same plate using laser cutting machine to be tested. Dimensions of these specimens were designed according to Standard Test Method for Measurement of Fatigue Crack Growth Rates (ASTM E647-13a) [16] as shown in Fig.2 and Table 4. There were many models for laboratory test specimens in the standard, the compact tension C (T) specimen were chosen due to the widely and successfully applied for measuring the fracture properties. In each specimen, a pre-crack was followed by an initial crack. A laser cutting equipment was used to accurately create an aperture that was 0.3 mm wide and 20 mm length [17]. The stop hole diameter is 10 mm in the end of initial cracks for specimens strengthened [18]. This study uses CFRP and stop holes as a different technique for improving the fatigue life and taking in consideration the effect of mixed modes between mode (I) and mode (II). So, eight cracked steel plate specimens were manufactured to compare the difference in results in fatigue life extension ratio of the two techniques and the mixed modes. The eight specimens were grouped as two unrepaired specimens as pure cracked steel plates (U), two repaired specimens with CFRP technique (R-CF), two repaired specimens with stop holes technique (R-ST) and two repaired specimens with stop holes technique and CFRP technique (R-CS).

Four specimens with different strengthening techniques were tested in mode (I), and the other four specimens were tested in mixed mode (I/II). The mixed mode (II) specimens were tested at 45 ° with the machine load cell to achieve a mix between mode (I) and mode (II) as presented in Table 5.

To install CFRP, wire brushing was used to clean and prepare the surface where the CFRP laminates will be attached after the eight specimens were fabricated as shown in Fig. 3. The two epoxy glue ingredients were then combined according to the manufacturer's recommended ratio and applied to the surface. The various strengthening schemes were taken into consideration when fixing CFRP laminates. To guarantee a full connection between CFRP and steel, a weight block was then positioned on top of the CFRP sheets to exert consistent pressure.

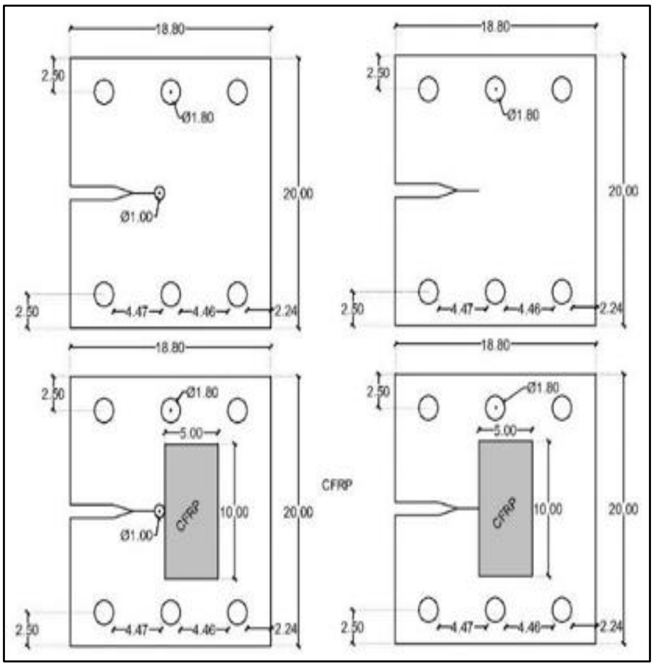

Fig 2 Configuration of Specimen’s Dimensions

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Table 5 Configuration of Specimen’s Dimensions

Specimens	Load application angle $\alpha/°$	crack mode	Repair Type
U-0	0°	I	-
R-ST-0	0°	I	Stop Hole
R-CF-0	0°	I	CFRP
R-CS-0	0°	I	Stop Hole+ CFRP
U-45	45°	I /II	-
R-ST-45	45°	I /II	Stop Hole
R-CF-45	45°	I /II	CFRP
R-CS-45	45°	I /II	Stop Hole+ CFRP

➢ *Test Set-Up*

Shimadzu Servo-Hydraulic Testing Machine model EN-10 (EHF-ED100KN-20L) in Mechanical Testing Lab., Mechanical Department, Cairo University was the fatigue testing machine used to perform the tests on the steel plate specimens. This machine has 100 KN capacity, variable frequencies from 10^{-5} to 500 HZ and can reach 10^{10} cycles in one fatigue test as presented in Fig. 4. The machine has the ability to produce sine, triangle and trapezoidal waves. The machine is composed of two main parts. The first part is the loading frame where the specimens were tested and the second part is the hydraulic Pump which pumps the oil to the loading frame as shown in. The upper and lower fixed U-grids in the loading frame can only achieve pure mode (I). As presented in Fig.5, two steel grips were fabricated to be attached to the fixed U-grids and the specimens to achieve mixed mode (I/II) with different angles, 30°,45°,60°,90°. Fig. 6 shows a steel plate with dimensions (75*25) cm and 2 cm thickness to be cut with a laser cutting machine to manufacture the two steel grips.

Fig 3 Preparing and Cutting CFRP Laminates

Fig 4 Shimadzu Servo-Hydraulic Testing Machine

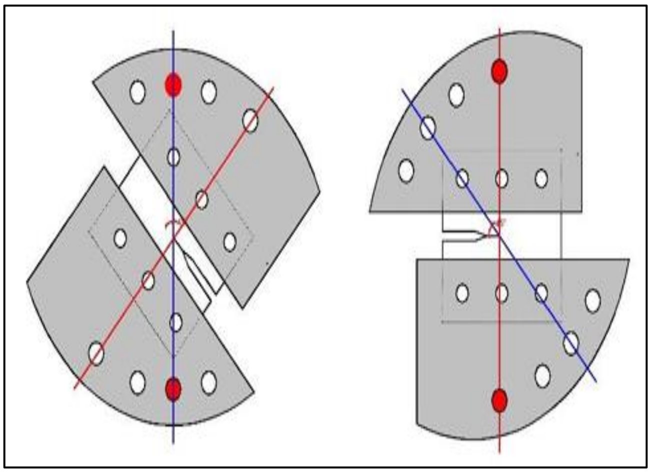

Fig 5 Configuration of Mode I and Mixed Mode I/II

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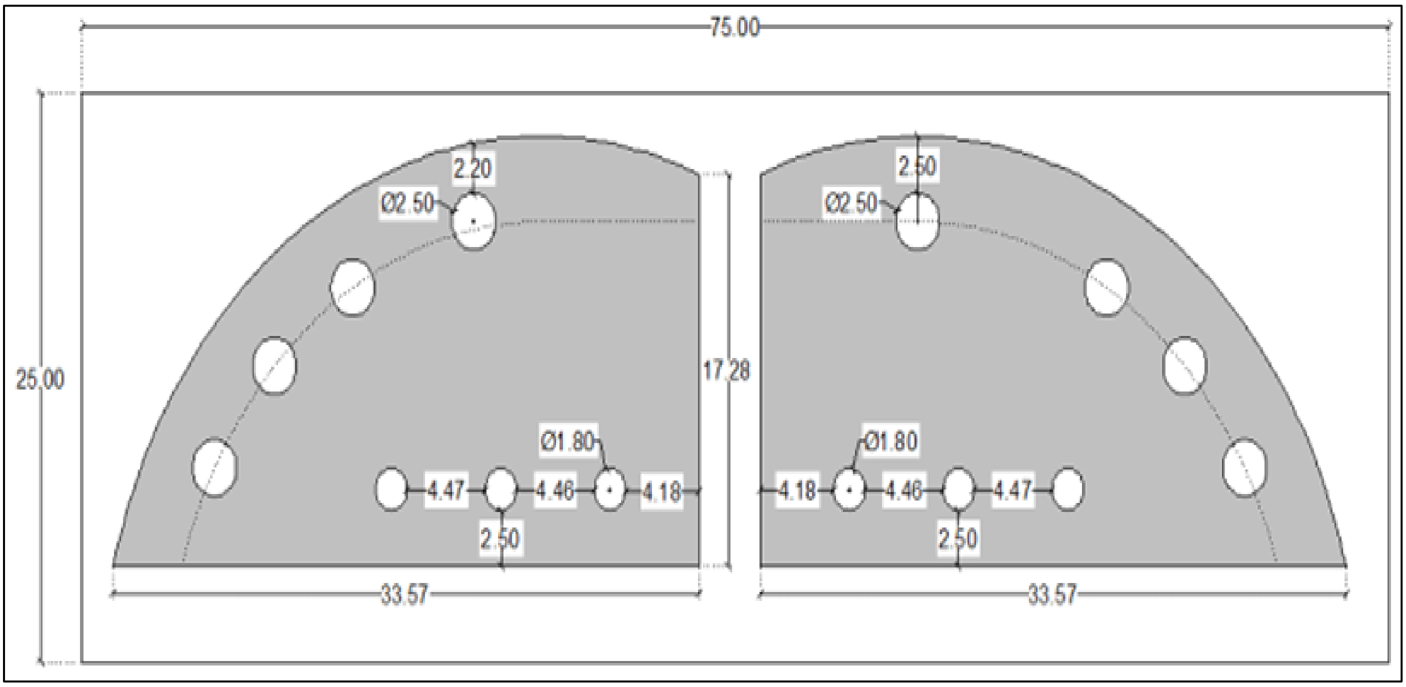

Fig 6 Manufactured Grips

➢ *Fatigue Test Loading Properties*

All specimens were subjected to cyclic tensile load with a maximum load of 40 KN and a minimum load of 4 KN to keep the stress ratio R (minimum load / maximum load) at 0.1 with a frequency of 10 HZ. This ratio was selected in accordance with the normal heavy dead load stress ratio in bridges. Fig. 7 describes the sinusoidal waveform used in the test, where the horizontal axis represents the number of cycles and the vertical axis represents the tensile load [19].

For measuring the fatigue crack propagation inside the specimens due to fatigue test, "Beach marking technique" was used [20]. This technique depends on the change in stress range from low stress range to high stress range. To apply this technique in the test, the maximum load was kept at 40 KN but the minimum load was increased to 22.5 KN, so the stress range changed from 0.1 to 0.55. Also, the frequency was changed to 20 HZ in the machine test. All these changes effect on stress intensity factor at crack tip and change the propagation of crack [21]. beach mark can be observed by naked eye on the cross section of propagated crack. The main function of this marks is reporting the relation between number of cycles and crack length [22].

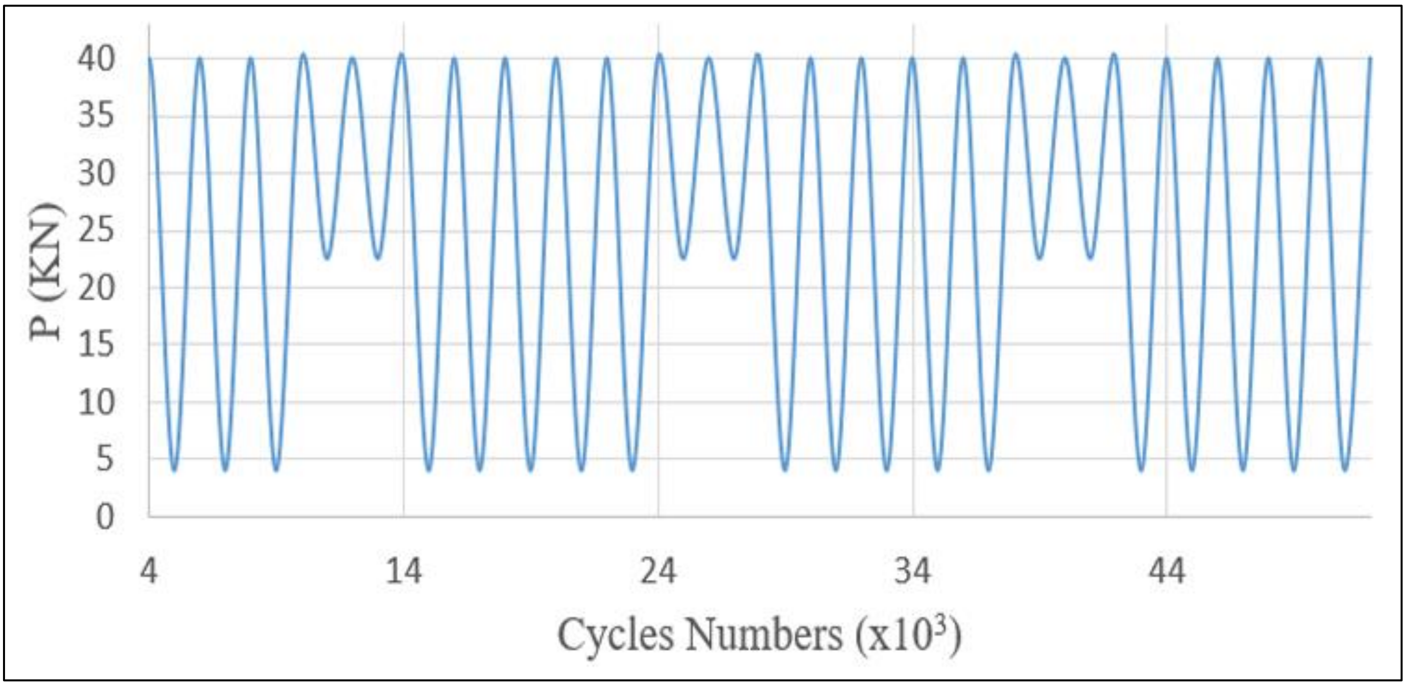

Fig 7 Test Loading History

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III. TEST RESULTS AND DISCUSSION

As the number of loading cycles increased, fatigue cracks propagated from the initial notch ends, producing records of beach marks as well as the number of cycles at failure. The test was set to end when the cracked steel plate completely failed, and each specimen was tested according to the same protocol and loading conditions as presented in Fig 8. The initial crack propagated horizontally as the number of cycles increased until the steel plate fractured. Table 6 lists a summary of test results including repairing type, number of cycles at failure and fatigue life extensions. It was found that cracks began spreading from the edge of the preexisting notch as the number of cycles increased. When the applied load direction was perpendicular to the fracture direction, straight cracks were seen. The fracture trajectories of repaired specimens were comparable to those of control specimens. It was observed that the various specimens had both smooth and rough surfaces. The fatigue crack propagation process, which causes the smooth surface, occurs steadily until the stress intensity factor (SIF) surpasses the base steel metal's fracture toughness. As the last fracture takes place, the surface becomes rough. Fig.9 and Fig. 10 present the crack propagation rate tests for mode I and mode I/II, respectively.

Table 6 Summary of Specimen Results

Specimens	Repair Type	Fatigue life cycles	Fatigue life extension ratio
U-0	-	62,000	-
R-ST-0	Stop Hole	90,000	1.45
R-CF-0	CFRP	85,000	1.4
R-CS-0	Stop Hole + CFRP	92,000	1.49
U-45	-	93,000	-
R-ST-45	Stop Hole	114,000	1.22
R-CF-45	CFRP	118,000	1.26
R-CS-45	Stop Hole + CFRP	135,000	1.44

The opening mode, or mode I, is the result of crack surfaces moving locally and straight apart. The sliding mode, also known as mode II, is the displacement of fracture surfaces over one another perpendicular to the crack edge. Crack surfaces moving in relation to one another parallel to the crack edge is a characteristic of mode III, often known as the ripping mode. Crack surfaces moving in relation to one another parallel to the crack edge is a characteristic of mode III, often known as the ripping mode.

In order to discuss the fatigue life extensions, a comparison between specimens will be performed. By comparing the number of cycles between unstrengthen, compared to un-strengthened steel plates. strengthen with CFRP or stop hole specimen in order to judge and discover the more suitable strengthening method for mode I and mixed modes I/II. As shown in Fig. 11 CFRP repairing and stop hole proved its efficiency in extending fatigue crack propagation life. The fatigue life of steel plates strengthened with CFRP increased by 1.4 when compared to un-strengthened steel plates.

Fig 8 Specimens after Finishing the Tests

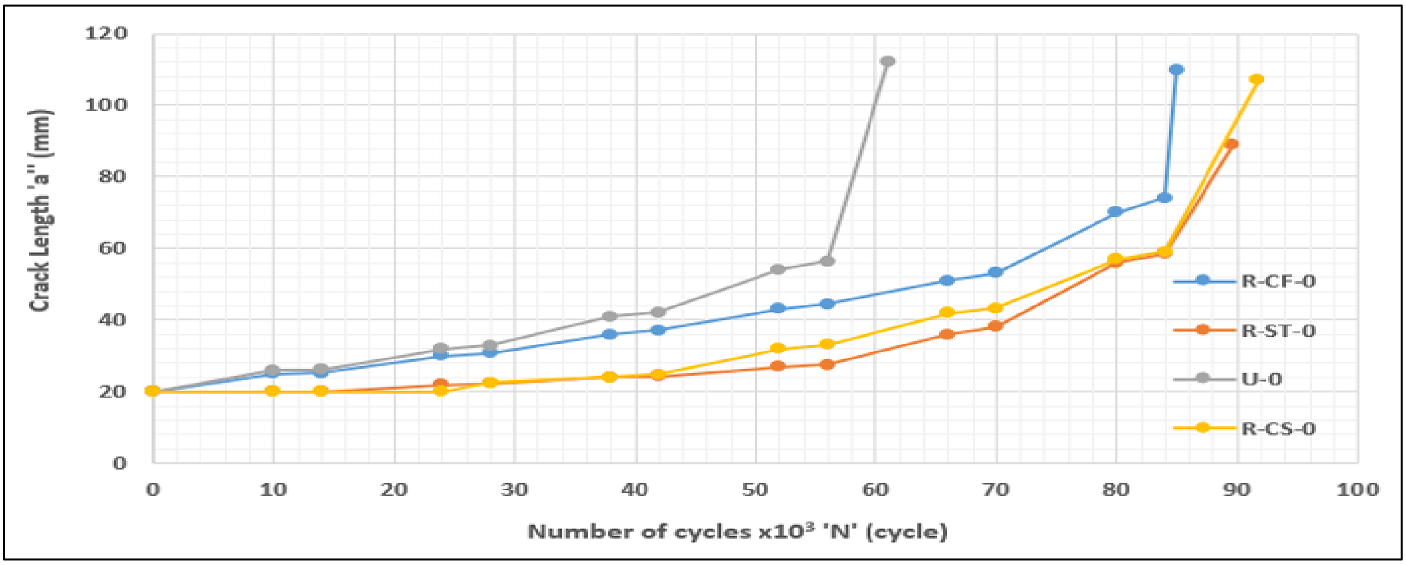

Fig 9 Fatigue Crack Propagation Rate Curves for Mode (I)

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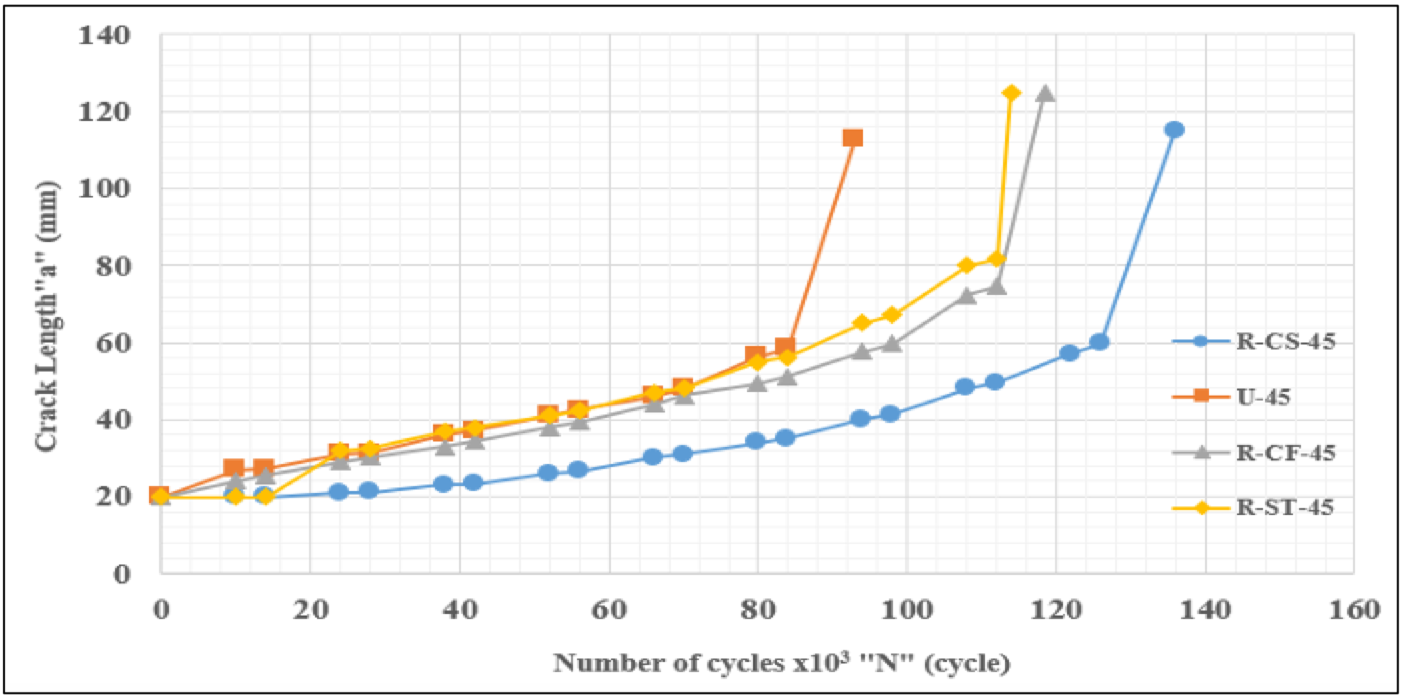

Fig 10 Fatigue Crack Propagation Rate Curves for Mode (I/II)

The fatigue life of steel plates strengthened with stop hole increased by a factor 1.45 when compared to un-strengthened steel plates. The fatigue life of steel plates strengthened with CFRP and stop hole increased by a factor 1.49 when compared to un-strengthened steel plates. As shown in Fig.12 for Mixed mode (I/II) (45°), CFRP repairing and stop hole proved its efficiency in extending fatigue crack propagation life. The fatigue life of steel plates strengthened with CFRP increased by a factor 1.26 when compared to un-strengthened steel plates. The fatigue life of steel plates strengthened with stop hole increased by a factor 1.22 when compared to un-strengthened steel plates. The fatigue life of steel plates strengthened with CFRP and stop hole increased by a factor 1.44 when compared to un-strengthened steel plates. The results mentioned above generally show that, depending on the chosen strengthening scheme, applied strengthening can decrease the rate of fracture formation and increase fatigue life. This improvement is ascribed to the adhesive CFRP patching's fracture-bridging effect and reorganization of stresses, which significantly lowers the crack propagation and increases fatigue life.

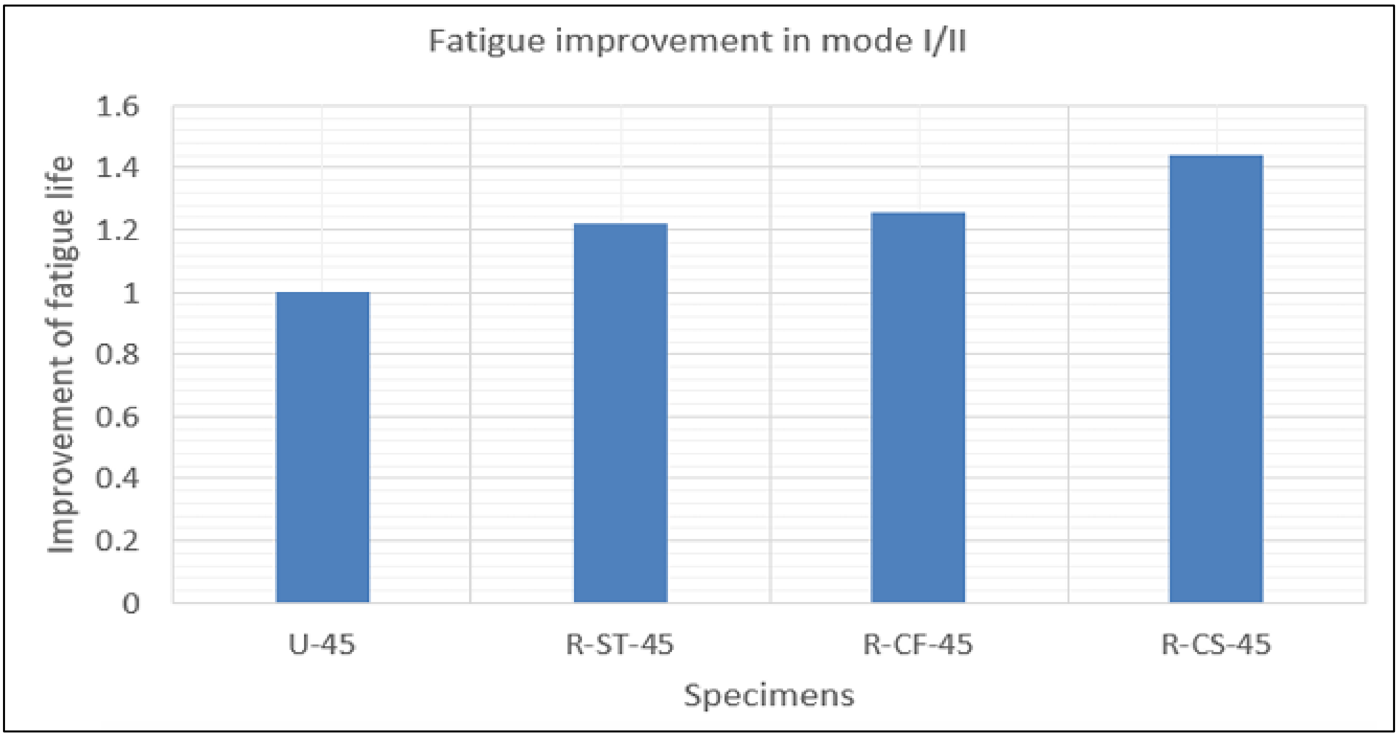

Fig 11 Improvement of Fatigue Life for Mode (I)

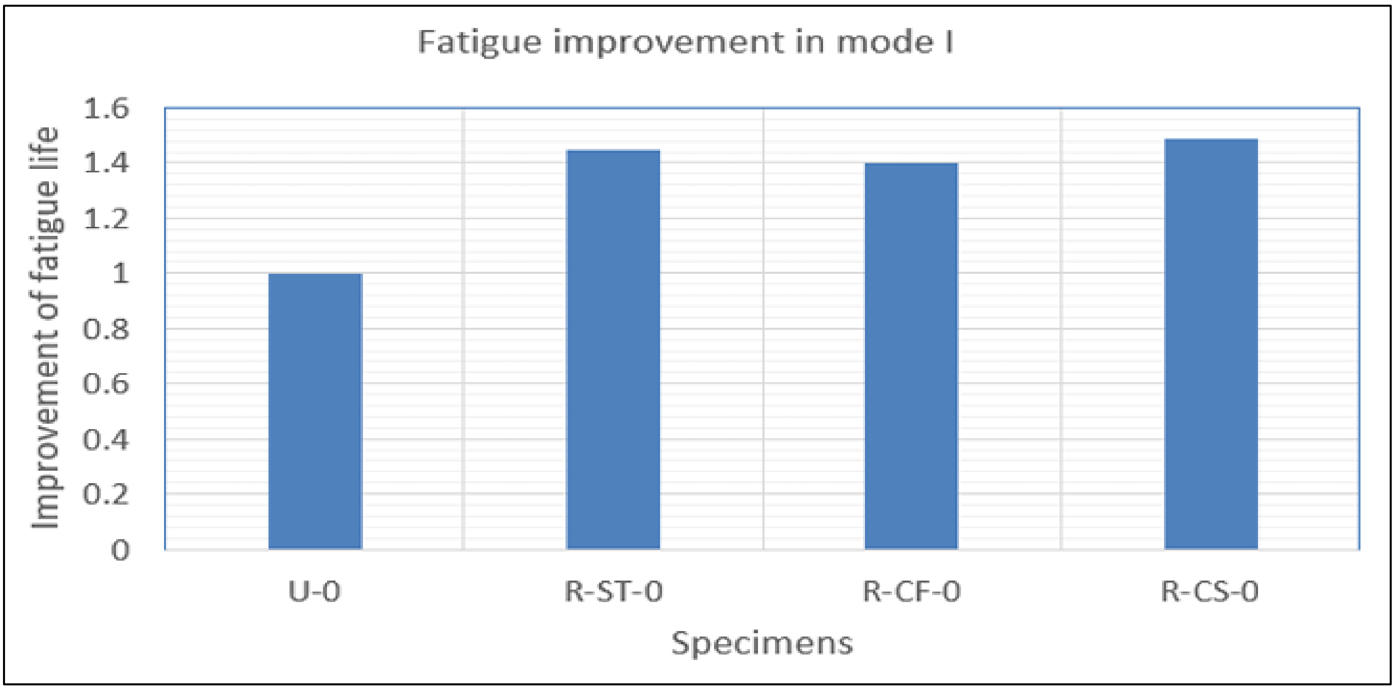

Fig 12 Improvement of Fatigue Life for Mode (I/II)

IV. CONCLUSIONS

The goals of this study were to present different repairing techniques of edge cracks steel plates and trying to find the safer and economy technique. The recent repairing methods were using CFRP laminates and drilling stop hole at the crack tip of the initial crack. The study include mode I and mixed modes I/II with angle 45° and the repairing methods were applied on all these cracks. The efficiency of repairing was estimated and the extension of life of cracked steel plates when comparing the strengthened plates with un-strengthened plates were presented. The following main conclusions can be reached:

- The repair using CFRP laminates and stop hole significantly lowers the rate of fatigue fracture growth and delays the rate of fatigue crack propagation.
- For cracked steel plates strengthened with CFRP laminates, the fatigue life increased by 1.4 and 1.26 for mode I and mixed mode I/II with angle 45°, respectively.
- For cracked steel plates strengthened with stop hole, the fatigue life increased by 1.45 and 1.22 for mode I and mixed mode I/II with angle 45°, respectively.
- For cracked steel plates strengthened with stop hole and CFRP, the fatigue life increased by 1.49 and 1.44 for mode I and mixed mode I/II with angle 45°, respectively.
- Stop hole is more economic than CFRP in strengthening process and achieve the same goals. The mixing between CFRP and Stop hole in strengthening cracked steel plates is not good idea and doesn't have any effect.
- The variation in angle of crack effect on the final number of cycles at failure, where the increase of angle of crack mean more resistance from the cracked plate and increase the number of cycles.
- For all the specimens strengthening with CFRP, the failure occurred by debonding between CFRP and cracked steel plates, not rupture in CFRP laminates.

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REFERENCES

[1]. Surjya Kumar Maiti, Applications fracture mechanics, India: Cambridge University Press, 2015.
[2]. A. Shukla, Practical fracture mechanics in design, U.S.A: Marcel Dekker, 2005.
[3]. C. T. Sun, Z.-H. Jin, Fracture mechanics, U.S.A: Elsevier Inc., 2012.
[4]. J. Dong, "Repairing of fatigue-damaged steel component," Journal of Physics, vol. 1629, no. 012049, 2020.
[5]. Jun Deng , Zhongyu Fei , Zhigang Wu , Junhui Li and Weizhe Huang, "Integrating SMA and CFRP for fatigue strengthening of edge-cracked," Journal of Constructional Steel Research, vol. 206, no. 107931, 2023.
[6]. Hans-Jürgen Christ, Fatigue of materials at very high numbers of loading cycles, Wiesbaden, Germany: Springer Spektrum, 2018.
[7]. U. Krupp, Fatigue crack propagation in metals and alloys, Germany: WILEY-VCH Verlag GmbH & Co. KGaA, 2007.
[8]. Yanlin Wang , Weigang Wang , Bohua Zhang and Yadong Bian, "Fracture resistance characteristics of mild steel under mixed mode I-II loading," Engineering Fracture Mechanics, vol. 258, no. 108044, 2021.
[9]. A.R. Torabi , H. Sadeghian and M.R. Ayatollahi, "Mixed mode I/II crack propagation in stainless steel

316L sheets," Engineering Fracture Mechanics, vol. 247, no. 107657, 2021.
[10]. Tao Chen,Cheng Huang , Liang Hu , Xiaobin Song, "Experimental study on mixed-mode fatigue behavior of center cracked steel," Thin-Walled Structures, vol. 135, pp. 486-493, 2019.
[11]. Lingzhen Li, Tao Chena, Ningxi Zhang and Yuya Hidekuma, "Test on fatigue repair of central inclined cracked steel plates using different," Composite Structures, vol. 216, pp. 350-359, 2019.
[12]. Jiaxu Yao,Tao Chen, Ruoyu Liu, and Lingzhen Li, "Fatigue behavior of steel plates with multi-holes repaired by CFRP," Composite Structures, vol. 242, no. 112163, 2020.
[13]. A. E. /. E8M-16a, Standard test methods for tension testing of metallic materials, West Conshohocken: www.astm.org, 2016.
[14]. SIKA, Writer, Sika CarboDur plates CFRP. [Performance]. SIKA, 2017.
[15]. SIKA, Writer, Product data sheet Sikadur-30LP. [Performance]. SIKA, 2019.
[16]. A. E647-24, Standard test method for measurement of fatigue crack growth rates, ASTM international, 2024.
[17]. M. Kuna, Finite elements in fracture mechanics, New York London: Springer Science, 2013.
[18]. Junhui Li , Miaochang Zhu and Jun Deng, "Flexural behaviour of notched steel beams strengthened with a prestressed," Engineering Structures, vol. 250, no. 113430, 2022.
[19]. Ravi Shankar Gupta, Haohui Xin and Milan Veljkovic, "Fatigue crack propagation simulation of orthotropic bridge deck based on extended finite element method," Procedia Structural Integrity, vol. 22, p. 283–290, 2019.
[20]. Maha M. Hassan, Mohamed A. Shafiq, Sherif A. Mourad, "Experimental study on cracked steel plates with different damage levels," International Journal of Fatigue, vol. 142, no. 105914, 2021.
[21]. Liang Fang , Zhong-Qiu Fu , Bo-Hai Ji and Shigenobu Kainuma, " Propagation mode and characteristics of fatigue cracks in steel," Advanced Steel Construction, vol. 18, pp. 544-551, 2022.
[22]. R. Baptista, V. Infante, "Fatigue crack propagation direction under different loading conditions using MTS and MSS criteria," Procedia Structural Integrity, vol. 37, p. 57–64, 2022.
[23]. Kenichi Masuda , Sotomi Ishihara and Noriyasu Oguma, "Effect of Specimen Thickness and Stress Intensity Factor Range," Materials, vol. 14, no. 664, 2021.