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Behaviour of Damaged B.F.I. Beam Repaired by CFRP Strips under Static or Fatigue Loads Using Finite Element Simulation

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

This paper presents the numerical study to simulate the fatigue crack growth of artificially damaged steel Broad Flange I- beams section by single edge notched repaired with carbon fiber reinforced polymer CFRP strips. The study is carried out using ANSYS classic modeling approach is suggested to simulate the fatigue response of the beams, based on the cumulative damage theory and strain life method. Experimental test results were compared with FE results obtained. A parametric study was conducted using the validated model. The considered parameters were the number of CFRP strip layers used in the repair, the applied load range, initial crack length at time of strengthening and the thickness of CFRP strip. The numerical results indicated that the CFRP increased the critical crack length at which fracture occurred, and the strengthening was more effective at lower stress ranges. Moreover, the CFRP Strips can substantially delay failure and the results demonstrate the possibility of technique and highlight the importance of early intervention when repairing fatigue critical details. The ultimate load and ductility decreased substantially with increasing initial crack length at the time of installing the strengthening layer. Furthermore, increased capacity was achieved by increase the CFRP thickness and layers.

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1. INTRODUCTION

Rehabilitation of fatigue behavior of steel structures is of great concern in the structure engineering community. Many of steel structures prone to fatigue failure for example the cranes, bridges, offshore structures and slender towers, etc. which are subjected to cyclic loading [1]. The fatigue failure is due to progressive propagation of flaws in steel under cyclic loading. The application of carbon fiber reinforced polymer (CFRP) composites is proposed as an alternative to steel-plating repair methods. The advantages of CFRP materials include their non-corrosive characteristics, high stiffness- and strength-to-weight ratios, ease and rapidity of erection, and reduced long-term maintenance expenses [2]. The bonded strips have bridging effects on fatigue cracks which complicates the fatigue crack growth (FCG) analysis of FRP strip metallic elements. Numerical models have been proposed to predict the fatigue life and perform the FCG analysis. The models fall into two major methodologies: i) damage accumulation rules based on the material stress range vs. number of fatigue cycles to failure (S-N), or strain range-vs-number of fatigue cycles to failure (S-N), relationships; and ii) linear elastic fracture mechanics (LEFM) based cycle-by-cycle FCG analysis [3]. In recent times, researchers have explored FRP application for fatigue strength of steel elements. Performed an experimental and numerical study on flexural behavior of CFRP repaired steel beams [4]. Four different retrofitting materials high modulus CFRP, high strength CFRP, steel wire basalt FRP and welded steel plates [5] showed that high modulus CFRP plates exhibited the best fatigue behavior. FRP sheets / strips are effective in the strengthening of steel structural elements to extend fatigue life-time and reduce the crack spread [6,7,8], whether galvanic rust is prevented and sufficient bond is provided [9,10]. Based on the experimental study [11] the specimen with Sikadur30 as adhesive material was prone to de-bonding failure, therefor, Araldite 420 is suggested for strengthening schemes. Investigate the performance of combinations for two CFRP materials and five adhesive systems to enhance the fatigue behavior of steel structural sections, reported the greatest increase in fatigue strength resulting from the system combining the CFRP and adhesive having the lowest of modulus of elasticity [12].

2. SUMMARY OF TEST PROGRAM

As presented in our previous study [1], notched B.F.I. steel beams strengthened by CFRP strips were prepared for four-point bending test. The geometry of specimens is shown in Fig. 1. The B.F.I. steel beams had yield strength of 250 MPa, a tensile strength of 370 MPa and a young's modulus of 200 MPa, whereas the CFRP strips (Sika wrap-230C) had a tensile strength of 4,300 MPa, poison's ratio of 0.3 and young's modulus of 230 GPa in the FRP direction. In addition, Sikadur-30 adhesive for bonding. According to manufacturer's instruction, the adhesive has tensile strength of 30 MPa, shear strength of 18 MPa, shear modulus of 4.3 GPa, young's modulus of 11.2 GPa and tensile strain is 0.0035 [1]. Four point bending tests were conducted details of the experimental program and test results are shown in Table 1.

3. NUMERICAL MODEL

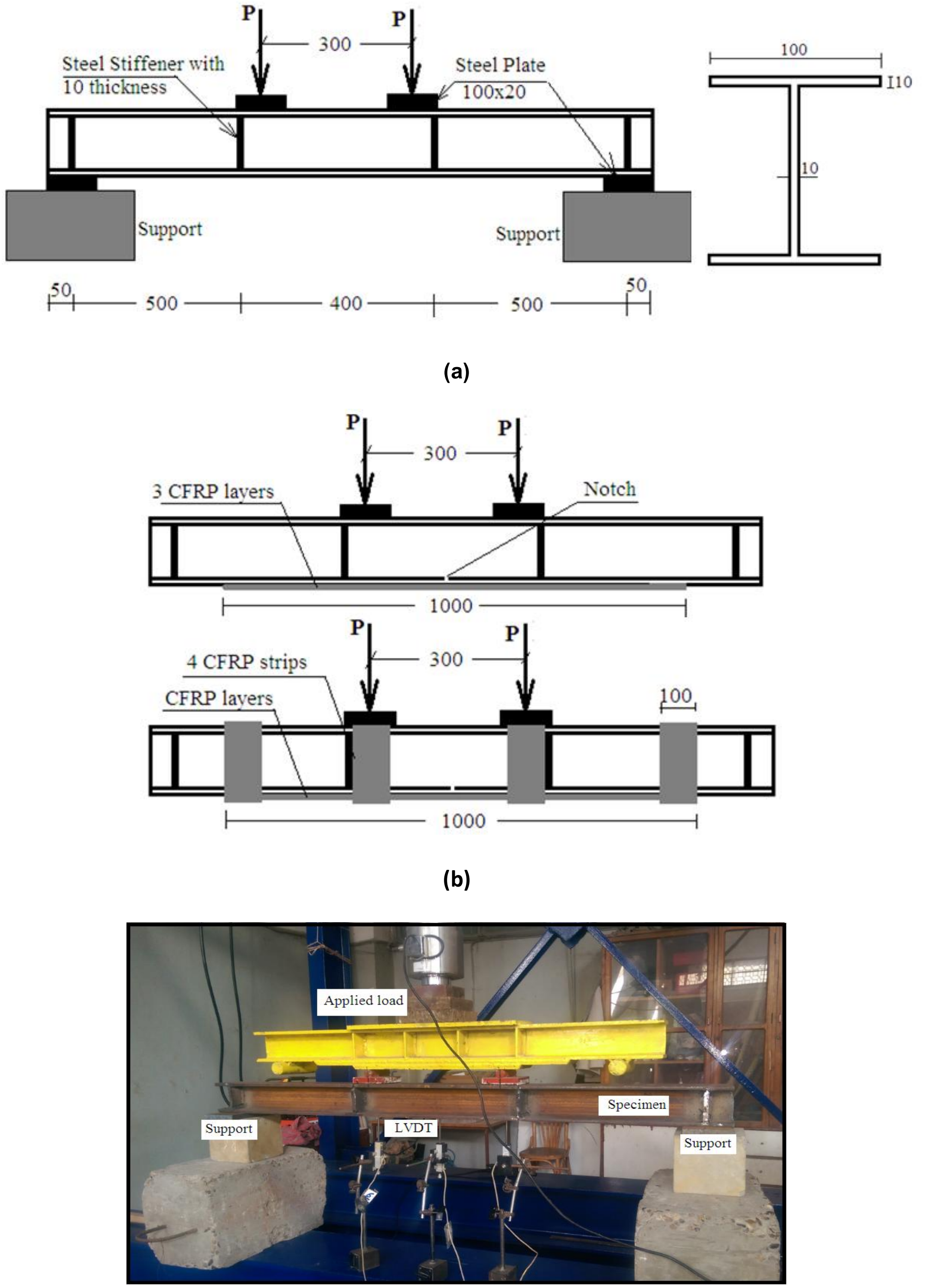
The flexural behaviors of the retrofitted and non-retrofitted beams under static and cyclic loads were obtained from FE analysis program ANSYS Version 14. According to our previous experimental study [1], a 3D nonlinear finite element model notched BF-I beam adhesive layer –CFRP strips was developed and verified by the experimental results. The following summarizes details of the modeling approaches.

3.1 Element Types

Steel beam was modeled with 3D solid element (solid 45). These 8 node elements with 3 translational D.O.F. per node. Two node 3D spar elements (link 8) were used to represent the CFRP strips. A perfectly elastic–plastic material stress-Strain relationship, having the properties given a blow, was used to model the steel. A linear stress–strain curve was established for CFRP. Both models are shown in Fig. 2-(I). Poisson’s ratios used were 0.3 for the steel and CFRP. Nonlinear interface element (COMBIN39) used to model the CFRP-steel interface. Have a bilinear bond-slip relationship established between steel and CFRP, as shown in Fig. 2-(II).

3.2 Meshing and Boundary Conditions

A constructed FE model is shown in Fig. 3. A relatively fine mesh having a maximum element



(a)

(b)

(c)

Fig. 1. Experimental test (a) Specimen geometry "dimension in millimeter, not to scale", (b) Details of the strengthened beams and notch details, (c) Test set-up details

Table 1. Details of the experimental program and test results

Specimen	Load type		Notched mm	No. of CFRP reinforcing layers		*Pu(kN)	No. of cycles	The max deflection mm
				Tension flange	web			
Control	CI	static	-	-	-	166.13	-	30.3
Control	CIR	fatigue	-	-	-	-	65	56.2
	CI1	static	4mm	-	-	65.3	-	9
Case 1	CIR1	fatigue	4mm	-	-	-	41	23.5
	CI2	static	4mm	3	-	80	-	34
Case 2	CIR2	fatigue	4mm	3	-	-	420	58
	CI3	static	4mm	3	4x2	118.3	-	38.6
Case 3	CIR3	fatigue	4mm	3	4x2	-	480	40
	CI repair	static	damaged	3	4x2	20	-	12
Case 4	CIR repair	fatigue	damaged	3	4x2	-	500	16

**Repeated load by 40% the value that produces a static failure*

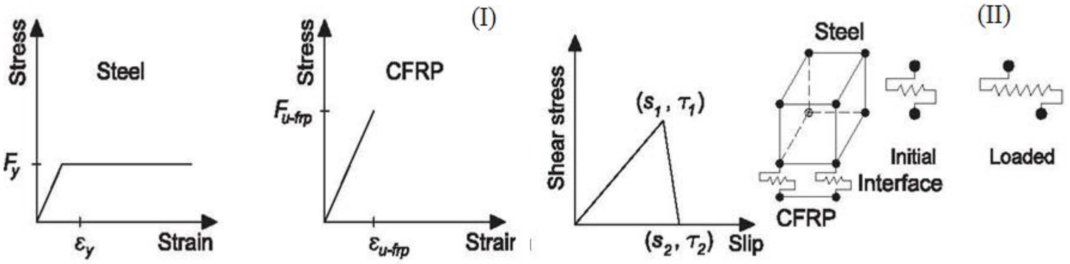


Fig. 2. Material modeling (I) Constitutive behavior of steel and CFRP [2], (II) Interface element model

length of 50 mm. The simply-supported beam condition was represented by restraining the nodes at supports.

3.3 Loading Model

An incremental load was applied for the model until failure occurred. The failure was modeled when either the steel section showed significant plasticity or rupture of the external layer was predicted for the repaired beams. The failure of the unidirectional CFRP was specified by the maximum stress failure criterion.

3.3.1 Static loading model

In the current analysis, load-control technique is selected. In this technique, total load is applied to a finite element model. The load is divided into a series of load increments (load steps) during the analysis. ANSYS program uses Newton-Raphson method for updating the model stiffness.

3.3.2 Fatigue loading model

The fatigue model of the test B.F.I beams was much more complicated than monotonic due to the need to change constituent properties with increased fatigue cycles. A typical stress range-fatigue life (S-N) relationship of structural steel used for this study is shown in Fig. 4 Category E in American institute of steel construction AISC [13]. The stress concentrating effect of the notch provided is essentially equivalent to a Category E detail. The initial endurance limit of the steel beams was 32 N/mm^2.

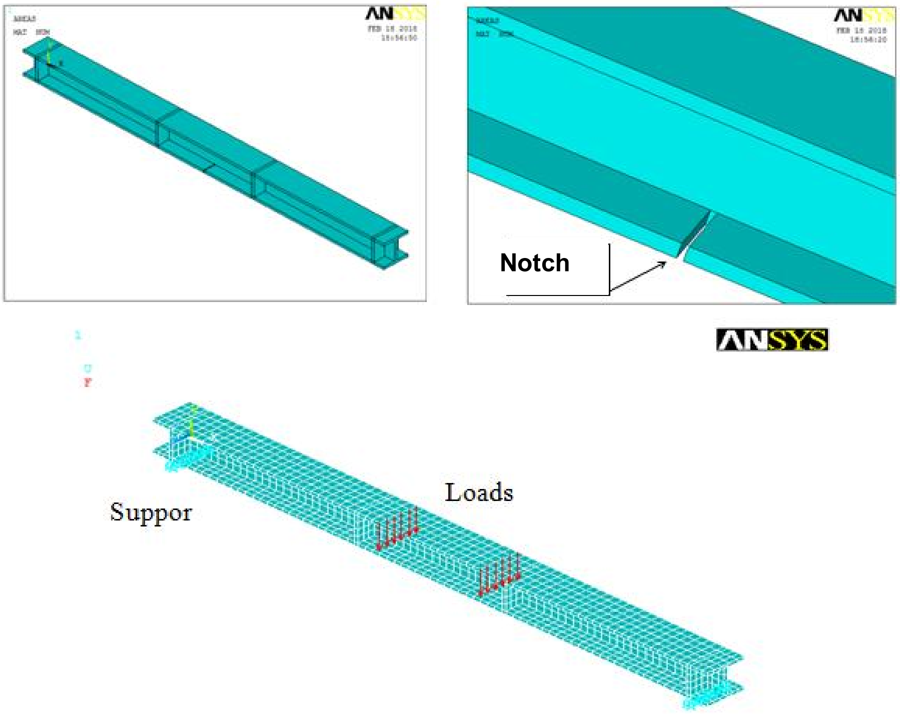


Fig. 3. The developed FE model

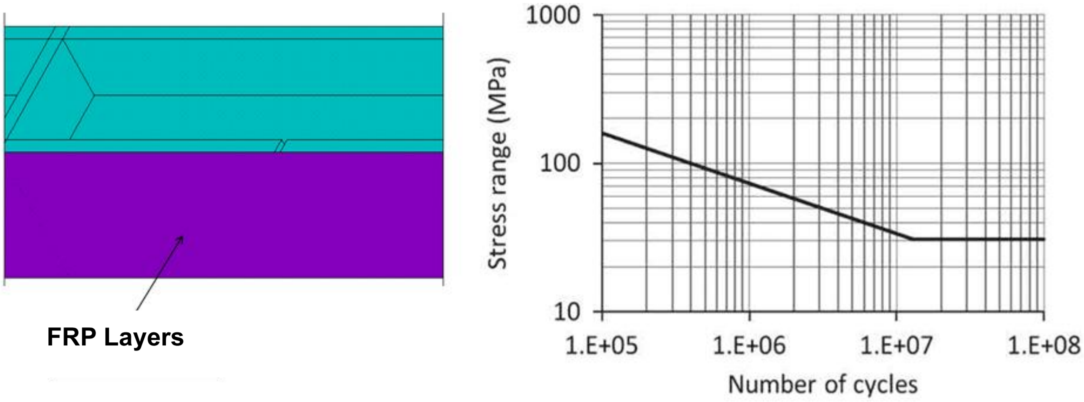


Fig. 4. S–N curve of steel beams

4. RESULTS AND DISCUSSION

This part provides a comparison of the experimental results [1] and FEA results of the beams under static and fatigue responses.

4.1 Static Behaviour

4.1.1 Load – deflection relationships

As shown in Fig. 5, the simulated model results agree with the experimental results for notched BFI beams and CFRP strengthened notched steel beams under static load. The results validated the reasonability of the parameters in the FE model and the accuracy of the simulation model for notched B.F.I beams strengthened by CFRP strips. The load – deflection curves of all tested / simulated B.F.I beams are shown in Fig. 5 (a) to (d), respectively. The experimental and FE model which indicated to the good ductility with strengthening by CFRP strips. All beams show plastic behavior of top flange and notched part of beam. The part near the notch could be in plastic state under low loading level. When load increases, the up flange of steel beam in compression zone could turn to the plastic state. Then the plastic behavior of the notched BFI beams becomes clear. The up flange of beam CI1 without strengthening turns to the plastic state soon after the yielding of steel near the notch. Then the notch propagation becomes the failure mode. While for CFRP strips strengthened notched steel beams, the up flange of beams becomes plastic state when load increased to more than 70 kN. Because the CFRP strips bonding can reduce the concentration at part near of notch, the steel yield at the notch could be hindering, as well as the upper flange steel yielding. When the CFRP strips strengthened steel B.F.I beam show obvious plastic behavior, the notch of the steel beam starts to propagate before the de-bonding initiated. After the de-bonding of CFRP strips, the notch crack propagation is accelerated and becomes failure finally. The ultimate load and ductility were improved after strengthening.

4.1.2 Ultimate capacity of notched (damaged) steel beams strengthened by CFRP strips

As shown in Table 2, the ultimate load and deflection from the FE model were compared with the test results of notched steel beams un-strengthened / strengthened by CFRP strips under static loads, and the deviation was calculated. The scattering of the test results was obvious, and the FE model results essentially agree, indicating that the finite element simulation is applicable for predicting the ultimate loads and maximum deflection.

4.1.3 Interfacial stress with different load levels

According to the FE model results, the longitudinal shear stress and normal stress distributions with bottom layer CFRP strip bond-line for different load levels when the load level about (15% Pu), the interfacial stress concentration initiated at positions close to the notch and CFRP strips ends. The maximum shear stress was near the notch and was much greater than that at CFRP ends. As load increased to about (25% Pu), the area of interfacial stress concentration near the notch increased, and normal stress reached the maximum along the CFRP strips bond-line. When the load reached (50% Pu), the maximum shear stress shifted to a position near from the mid span, indicating that the interfacial stress concentration moved from the notch towards the CFRP strip ends. In FEM after the interfacial stress exceeds the strength of the material, the element is invalid and stress becomes zero. Therefore, at load about (85% Pu) de-bonding load, the interfacial stress at mid span were zero, and maximum shear stress moved to near away from the mid span. Furthermore, when the load reached the ultimate load (100% Pu) the zero interfacial stress transferred to a position 100 mm from the mid span and complete de-bonding of the CFRP was observed after a slight decrease in load.

Table 2. Capacity comparisons of the experimental results and finite element model (static)

Steel beams	Ultimate load (kN)		Deviation	Deflection in mid span at ultimate load (mm)		Deviation	De-bounding load	
	Exp.	**FEA**		**Exp.**	**FEA**		**Exp.**	**FEA**
CI	166.13	156	6.4 %	20.2	18.3	10.3 %	-----	-----
CI-1	65.3	70	7.1 %	9	10	11.1 %	-----	59.5
CI-2	80	90	12.5 %	8.1	8.5	4.9 %	-----	73.5
CI-3	118.3	130	9.8 %	14	15	7.1 %	-----	110

Table 3. Fatigue life comparison of the experimental results and finite element model

Steel beams	First crack notched (mm)	Load rang (kN)	No. of CFRP layers		Fatigue life (N_f)		Deviation
			Tension flange	**Web (row*layer)**	**Exp.**	**FEA**	
CIR-1	4	0 - 60	------	-------	41	46	12.1 %
CIR-2	4	0 - 60	3	-------	420	433	3.1 %
CIR-3	4	0 - 60	3	4 * 2	480	500	4.1 %

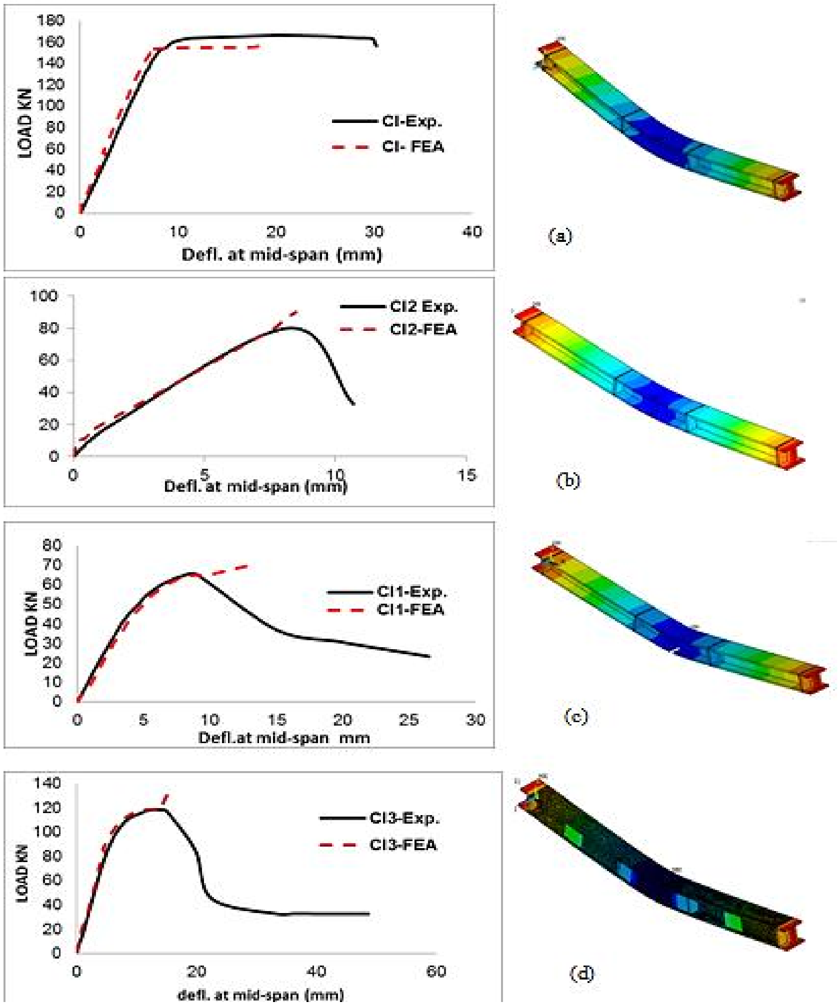


Fig. 5. Comparison of experimental and FEM load–deflection curves

4.2 Fatigue Behaviour of Repaired Beams

The fatigue results are detailed in Table 3, including the number of cycles. The proposed modeling approach showed a good agreement with experimental results for notched B.F.I beams and CFRP strengthened notched steel beams under fatigue effect. The fatigue behavior is significantly improved by using CFRP strips.

5. Parametric Study

In order to better understand the effect and guide the application of the CFRP strengthening system, a parametric study was conducted using the established FE model. The considered parameters were: i) number of CFRP layer NL; ii) CFRP thickness t_f; iii) the initial crack (notch) lo; and iv) applied load range for fatigue response, were systematically analyzed. Their influence on the capacity and interfacial stress of notched steel beams strengthened by CFRP strips was discussed for a better understanding of the strengthening of damaged steel structures. Table 4 summarizes the modeling matrix for parametric study.

5.1 Static Loading Parametric Analysis

5.1.1 Influence of the initial crack length at time of strengthening

To understand the influence of the notch length to the strengthening effect, three notches were modeled of lengths L_o= 4, 8 and 12 mm. The load-deflection at mid-span curve is presented in Fig. 6. The de-bonding and ultimate loads decreased with increasing notch length, as did the deflection in accordance with the ultimate load. When the notch length increased from 4 mm to 8 mm and 12 mm, the ultimate load decreased 20 and 36%, and the deflection decreased 9 and 15%, respectively. In addition, the interfacial stress developed with the load near the notch. The interfacial stress decreased after reaching the de-bonding load, which means adhesive layer softening initiated near the notch. Additionally, the deeper the notch was, the lower the load required for the initiation of adhesive layer degradation. After the adhesive layer was softened, for taller notches, the interfacial stress at the notch was lower and the decrease in stress was more rapid. As a result, the de-bonding load and ultimate load also decreased with increasing notch length. Thus, taller notches promoted cracking of the adhesive layer, which caused premature de-bonding failure by decreasing the bearing capacity and ductility.

5.1.2 CFRP number of layers

To enhance the understanding of the effect of the CFRP number of layers on the strengthening of notched steel beams, CFRP numbers of layers (2, 3 and 4) bottom layers were selected for the FEM analysis. As shown in Fig. 7. The largest number, the higher the observed ultimate load. However, as the ultimate load increases, the deflection decreases. When the CFRP numbers of layers increased from 0 to 2 to 3 and 4, the ultimate load increased 45, 85.7 and 100%, respectively. Therefore, the capacity of strengthened steel beams can be effectively improved by increasing the numbers of CFRP strips, but the sacrifice of ductility should be noted.

5.1.3 CFRP thickness

The CFRP thickness can affect the strength of strengthened steel beams. To enhance the understanding of the effect of the CFRP thickness on the strengthening of notched steel beams, three CFRP thicknesses (0.13 mm, 0.15 mm and 0.18 mm) were selected for the FEM analysis all beams rehabilitation with the same number of CFRP layers (three layers). As shown in Fig. 8. The thicker the CFRP strip is, the higher the observed ultimate load. However, as the ultimate load increases, the deflection decreases. When the CFRP thickness increased from 0.13 mm to 0.15 mm and 0.18 mm, the de-bonding load increased 13% and 27.3%, the ultimate load increased 11 and 24%, whereas the deflection decreased 6% and 12%, respectively. Therefore, the bearing capacity of strengthened steel beams can be effectively improved by increasing the CFRP strip thickness, but the sacrifice of ductility should be noted. When the shear and normal stresses reached their maximum values, the loads of the strengthened steel beams were 32.5 kN, 36 kN and 44 kN. Then, the shear and normal stresses decreased to zero (CFRP thickness 0.13mm, 0.15mm and 0.18mm) when the loads were 110 kN, 124.3 kN and 140 kN. Clearly. Using a thicker CFRP strip could also be an effective way to improve the de-bonding and ultimate loads. The results could be beneficial reference for the design of CFRP strengthened. However, as discussed in the above section, the conclusion may only be valid for strengthened deficient steel beams. For strengthened sound steel beams, plate-end de-bonding can occur, and the

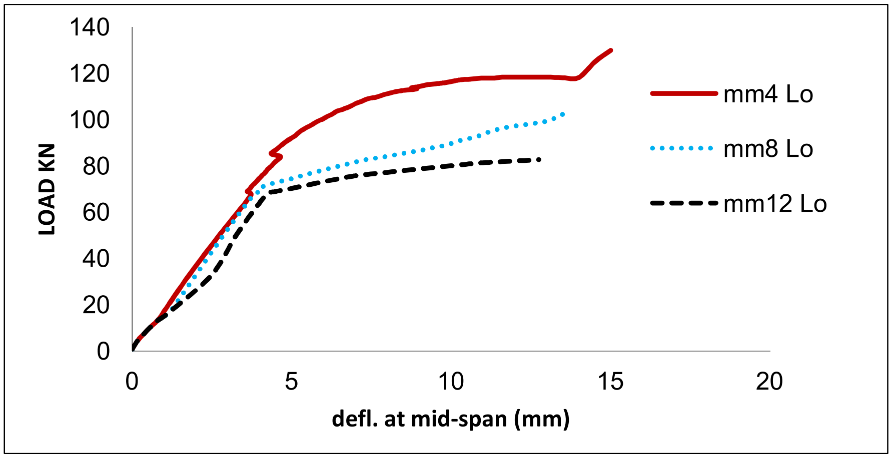


Fig. 6. Load–deflection curve strengthened beam with different notch length (L_o)

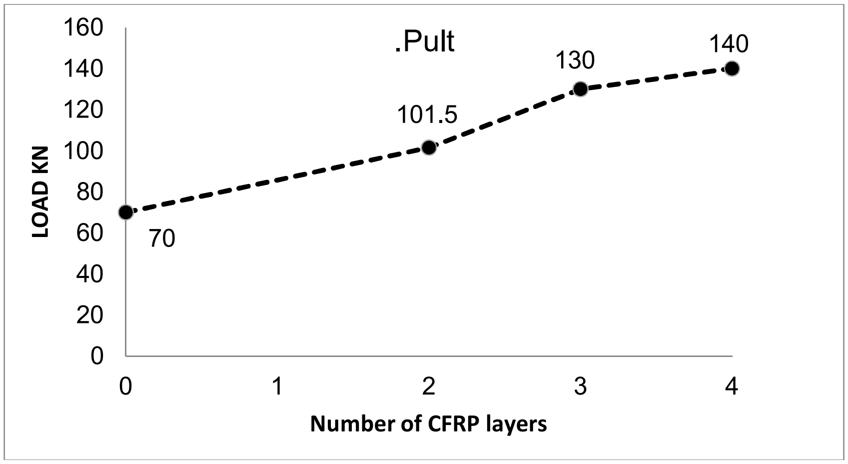


Fig. 7. Effect of number of CFRP layers on ultimate load

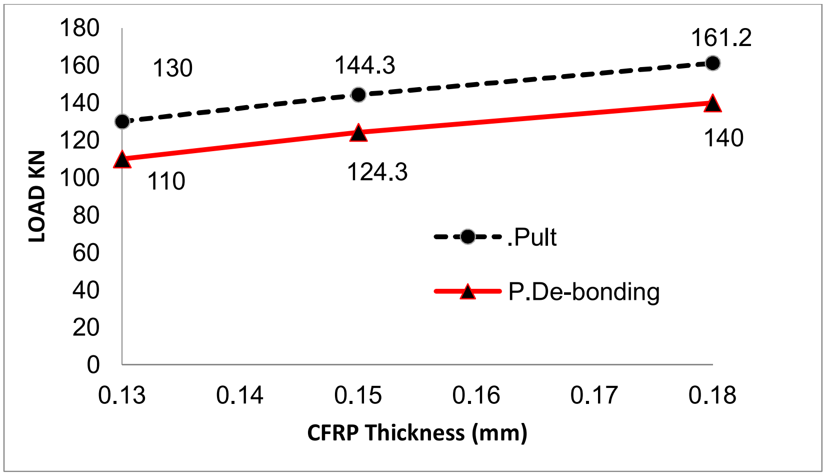


Fig. 8. Effect of CFRP thickness on ultimate and de-bonding loads

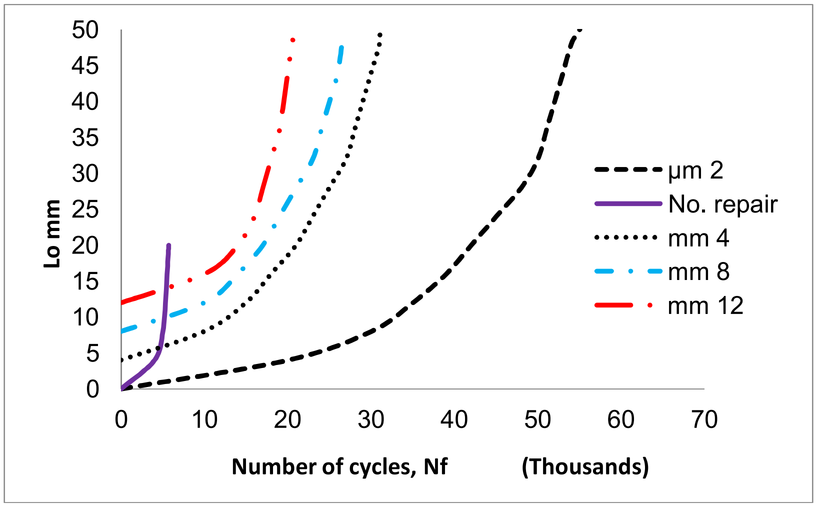


Fig. 9. Fatigue crack growth curves of beams strengthened at different notch (crack) length

Table 4. Parametric study matrix

Group	Load type	*Number of CFRP layer	CFRP wrap thickness mm	Notch length Lo mm	Applied load range kN
1	Static	0, 2, 3, 4	0.13	4.0	N/A
2		3	0.13, 0.15, 0.18	4.0	N/A
3		3	0.13	4, 8, 12	N/A
4	Fatigue	3	0.13	2µm, 4, 8, 12	0-22
5		0, 2, 3, 4	0.13	4.0	0-22
6		3	0.13	4.0	0-22, 0-13, 0-7

**All beams reinforced by four CFRP vertical strips fixed to every face of the web (10x8) cm as well as some samples of the experimental/FEM*

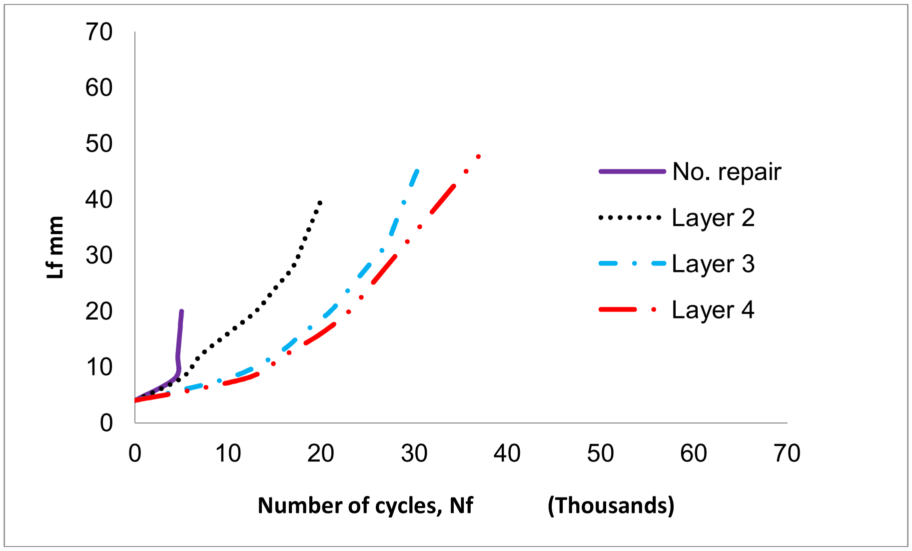


Fig. 10. Fatigue crack growth curves of different number of CFRP strips

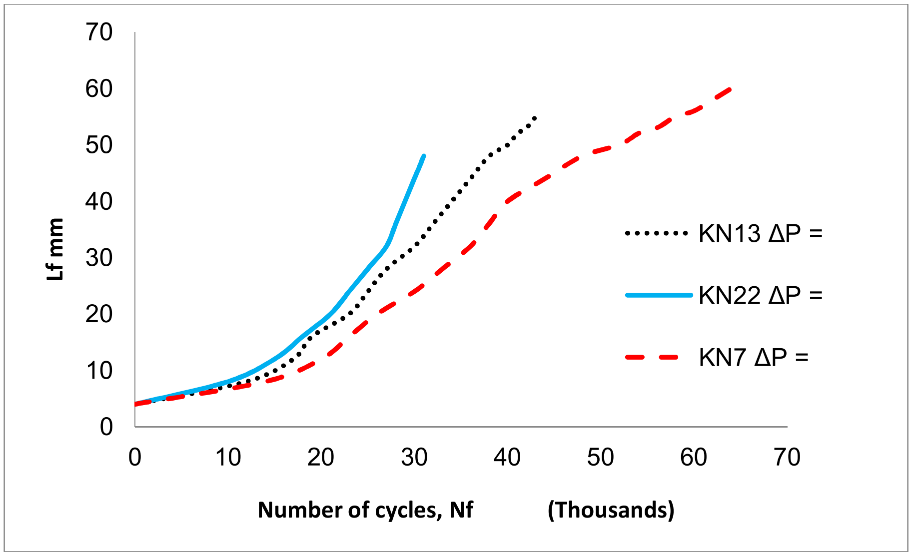


Fig. 11. Variation of the maximum load range effect on fatigue crack growth curves

increase of CFRP thickness has a negative effect on the de-bonding strength [14].

5.2 Fatigue Loading Parametric Analysis

5.2.1 Influence of the initial crack length at time of strengthening

The fatigue crack growth curves of the beam reinforced with the same number of CFRP layers (three layers) at crack length 2 μm, 4 mm, 8 mm and 12 mm were calculated Fig. 9 shows results for (0-22) kN load range. It is seen that if beam under fatigue response is reinforced before the generation of a visible crack, the fatigue life is improved by 10 times. If the fatigue detail is reinforced when crack length is appreciable, for example 12 mm the fatigue life improved by 3.6 times only. This indicates the significance of earlier strengthening of a fatigue detail. Nevertheless, the external CFRP strip is promising as a method of emergency repair.

5.2.2 Influence of the number of CFRP strips

The fatigue crack growth curves of the beam under load range from 0 to 22 kN are presented in Fig. 10. It is seen from the figure that increase the number of CFRP strips decreases the crack growth rate. The figure also shows that increasing the number of CFRP strips allows the crack to propagate further before fracture failure when the maximum stress intensity factor during crack growth reaches the fracture toughness. As it is indicated in the figure, the critical crack lengths are 20, 40, 48, 50 mm corresponding to 0, 2, 3 and 4 CFRP strips layers. This indicates slower propagation rate and longer propagation path due to the CFRP strips improves the fatigue behavior of the reinforced beams.

5.2.3 Influence of the load range

The load range was a governing factor for fatigue life of the repaired beams. When ΔP = 22 kN model was stopped at N= 31,000. Beams with ΔP = 13 kN and ΔP= 7 kN failed at N= 43,000 and N= 64,000 (were N is number of cycles), respectively. As shown in Fig. 11 the repaired beam subjected to a high load range, tends to show a large amount of brittle web fracture. When compared to those cases subjected to low load ranges that are associated with substantial fatigue crack growth prior to the brittle fracture. This indicates the strengthening was more effective at lower stress ranges.

6. SUMMARY AND CONCLUSIONS

The article presented a numerical study on the behavior of defected steel beams repaired with CFRP strips subjected to static and fatigue loads. The following observations can be made and conclusions drawn.

- The proposed modeling approach was validated by experimental results as effective model for simulating the behavior of notched B.F.I beams strengthened by CFRP strips. Compared with average ultimate loads from experimental and FEM results, the deviations are about 9%. The accuracy of the model is also demonstrated by load – deflection curves.
- The effects of the number of CFRP layers, CFRP thickness t_f, the initial crack (notch) L_o, and the applied load range were assessed through parametric analysis.
- When the CFRP numbers of layers increased from 0 to 2 to 3 and 4, the ultimate load in static modeling increased 45, 85.7 and 100%, respectively. And indicated slower propagation rate and longer propagation path due to the CFRP strips improves the fatigue behavior of the reinforced beams.
- The increasing of CFRP thickness from 0.13mm to 0.15mm and 0.18mm, the de-bonding load increased 13 and 27.3%, the ultimate load increased 11 and 24%, whereas the deflection decreased 6 and 12%, respectively.
- When the notch length varied from 4 to 12 mm, the ultimate load decreased 20 and 36%, and the deflection decreased 9% and 15%, respectively.
- Finally, the de-bonding and ultimate capacity of repaired beams decreased with the notch length substantially. Moreover, the bearing capacity increased with the number of strips and thickness of the CFRP strips, while the ductility decreased.
- The fatigue life (number of cycles, N) of repaired beams was significantly influenced by applied load range When ΔP= 22 kN model was stopped at N= 31,000. Beams with ΔP = 13 kN and ΔP = 7 kN failed at N= 43, 000 and N = 64,000, respectively.
- The fatigue life extension that can be achieved using the CFRP strips. The CFRP strips decreases the crack growth

rate while also allowing the crack to propagate further before failure.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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