Shear Behavior of Steel I-Beams Strengthened With CFRP Strips

K. M. El-Sayed, N. N. Khalil, I. M. El-Shennawy

Department of Civil Engineering, Benha Faculty of Engineering, Benha University, Egypt.

Abstract—*This paper studies the behavior of simply supported steel I-beams strengthened with carbon fiber reinforced polymers (CFRP) strips on the web as shear reinforcement. The experimental program contains seven simply supported steel beams. One of them was considered as a control beam and the other specimens were strengthened with different schemes; varying the position of CFRP strips to the web, its number of layers and its angle of orientation. The results show that applying CFRP strips on the web of the steel I-beams was an effective strengthening method for increasing the load bearing capacity and decreasing the deformations. Using two layers of diagonal CFRP strips on both sides of the web realized the highest increasing in the load capacity. Moreover, finite element analysis method has been utilized to analyze the tested specimens using ANSYS. A great convergence between the experimental results and the corresponding ones obtained from finite element simulation.*

Keywords— carbon fiber reinforced polymer, steel, specimen, strengthening.

I. INTRODUCTION

In recent years, strengthening of steel structures became a major concern of researchers in the civil engineering community [1 to 10]. There are many reasons to strengthen the steel structures such as design errors, construction errors, lack of proper maintenance, fatigue damage, and to increase the structure capability to carry excessive loads. In the past, the conventional methods for strengthening the steel structures were based on the use of steel plates attached to the existing systems by welding, bolting or adhesive bonding. The major disadvantages of using these traditional techniques were its heavy weight, difficult to fix, prone to corrosion and also, the sensitivity of the strengthened system to fatigue problems due to stress concentration produced by welding or drilling. In addition, these traditional techniques need technical labors and heavy equipments for installing the plates in their position.

The use of FRP for strengthening concrete structural elements demonstrates a great effect to enhance the strength of these elements. As successes of this technique, researchers have recently investigated the use of FRP for strengthening of steel elements as promising technique.Significant researches have been devoted to steel elements strengthened with CFRP as flexural reinforcement. CFRP reinforcement in flexural has proven to be an effective strengthening technique. Serviceability, elastic stiffness, yield load and the ultimate strength of steel flexural elements can be greatly enhanced by CFRP reinforcement. Recent developments and research activities in the use of high performance materials have been increasing lately.A series of traditional H shaped steel beams were strengthened and tested by PierluigiColombi et al.,(2004) [11] to study the static behavior of steel beams strengthened by CFRP strips in addition to control beam. The experimental program included testing of three (HEA140) steel beams strengthened by unidirectional CFRP (Sika® Carbodur® M614) strips. The used strengthening technique produced an improvement of the load-carrying capacity. The effect of CFRP strips on the plastic stiffness was also remarkable, while a significant increment of the elastic stiffness is attained when the strengthening is made with two layers. The use of two different epoxy adhesives had not led to a significant effect on the load-deflection curves nor the produced stresses in the strips.

S. Rizkalla et al.,(2007) [12] presented the results of an extensive experimental program that focused on understanding bond behavior of strengthening high modulus (HM) CFRP strips bonded to steel beams. The experimental program investigated the behavior of the strengthening system under fatigue and overloading conditions. The beams were loaded till failure in a four-point bending loads. These tests identified the bond stress distribution typically induced in beam applications. The tests indicated that two layers of the HM CFRP strips required twice the development length (the length from the end of the strip to the nearest load point) to achieve rupture of the fibers.

The using of carbon fiber reinforced polymer (CFRP) strips have been investigated commonly for flexural strengthening of steel beams but the effectiveness of using CFRP strips for strengthening of web as shear reinforcement is recently discussed by Narmashiri et al., (2010) [13]. The effectiveness of shear strengthening steel I-beams has been investigated by using different CFRP ratios (area of CFRP cross-section to cross sectional area of steel web) of 0.48 and 0.72. The requirements for applying CFRP on both or one side of web have been discussed. The ratio 0.48 is generated by using two strips of CFRP, and the ratio 0.72 is generated by using three strips of CFRP. The shear zone was surrounded by two stiffeners. The ratio of web height to shear span was 1.54 and web slenderness (web height to its thickness) was 19.7. The experimental work was consisted of five specimens. The first specimen was not strengthened. The second and third specimens were strengthened by using CFRP strips on both sides of the web using CFRP ratio of 0.72 and 0.48, respectively. The fourth and the fifth specimens were strengthened by using CFRP strips only on one side of the web with CFRP ratio of 0.72 and 0.48, respectively. The experimental results revealed that using CFRP strips on the web as shear reinforcement of steel I-beams was a successful method for increasing the load capacity and decreasing the steel beam deformations. Two failure modes were observed for the CFRP strips. The first failure mode was the longitudinal delamination of the CFRP strips which was more critical towards the point loads. The second failure mode was the debonding of the strips. It was also noted that, applying CFRP on the web decreased the vertical deflection of the beam, especially in the plastic region. The CFRP ratios of 0.72 and 0.48 on both sides of the web produced the same increment of load capacity.

This article aims to study the behavior of steel I-beams strengthened by using CFRP strips which attached to the web at the shear zones. Modes of failure, ultimate loads, strain on steel web and on CFRP strips, and deflection are observed and recorded to examine the shear behavior of the I-beam strengthened with CFRP.

II. EXPERIMENTAL PROGRAM

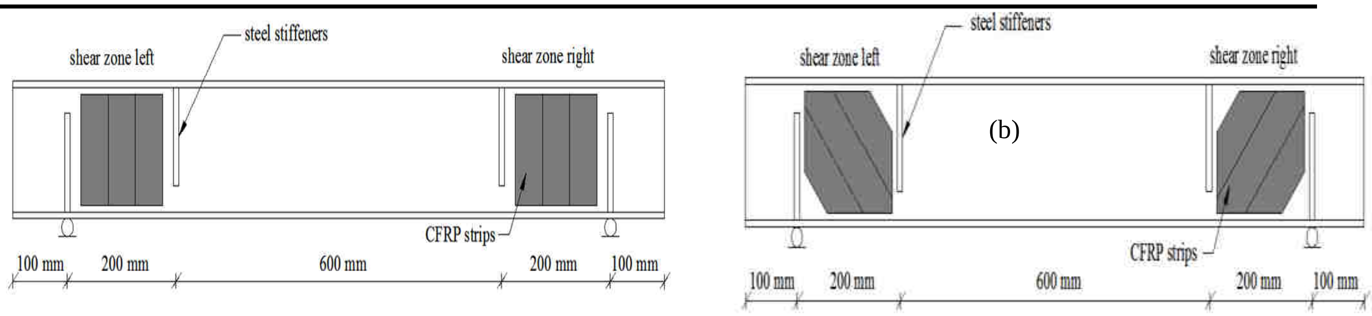
To examine the mentioned parameters, seven beams were experimentally tested; one of them was reference beam without CFRP strengthening. Three beams were strengthened by CFRP strips in diagonal orientation (45º), and three beams were strengthened by CFRP strips in vertical orientation. The strengthening was carried out with different number of layers (one & two layers) and different position with respect to web (on one side & on both sides).

Table (1) presents the study parameters corresponding to each tested specimen. The details of the tested specimens are shown in Figures 1 and 2.

Steel beams used in the experimental program have the universal steel section IPE 160. Its dimensions and mechanical properties are listed in Table (2). The used CFRP strips and epoxy resin are submitted from SIKA® CO., branch in Swiss under a commercial names Sika® Carbodur® plate S512 and Sikadur® 30, respectively. The nominal mechanical properties of the composite strips and resin provided by the supplier are reported in Tables (3) and (4), respectively.

Table 1: Experimental Program

Specimen	Position of CFRP on web	No. of layers	Orientation of CFRP
B0	-	-	-
B1-1-45	one side	one layer	45˚
B2-1-45	both sides	one layer	45˚
B2-2-45	both sides	two layers	45˚
B1-1-90	one side	one layer	90˚
B2-1-90	both sides	one layer	90˚
B2-2-90	both sides	two layers	90˚



(a) (b)

Fig.1: General details of the tested specimens with CFRP strips in vertical orientation (a), and CFRP strips in diagonal orientation (CFRP΄s angle = 45 º)

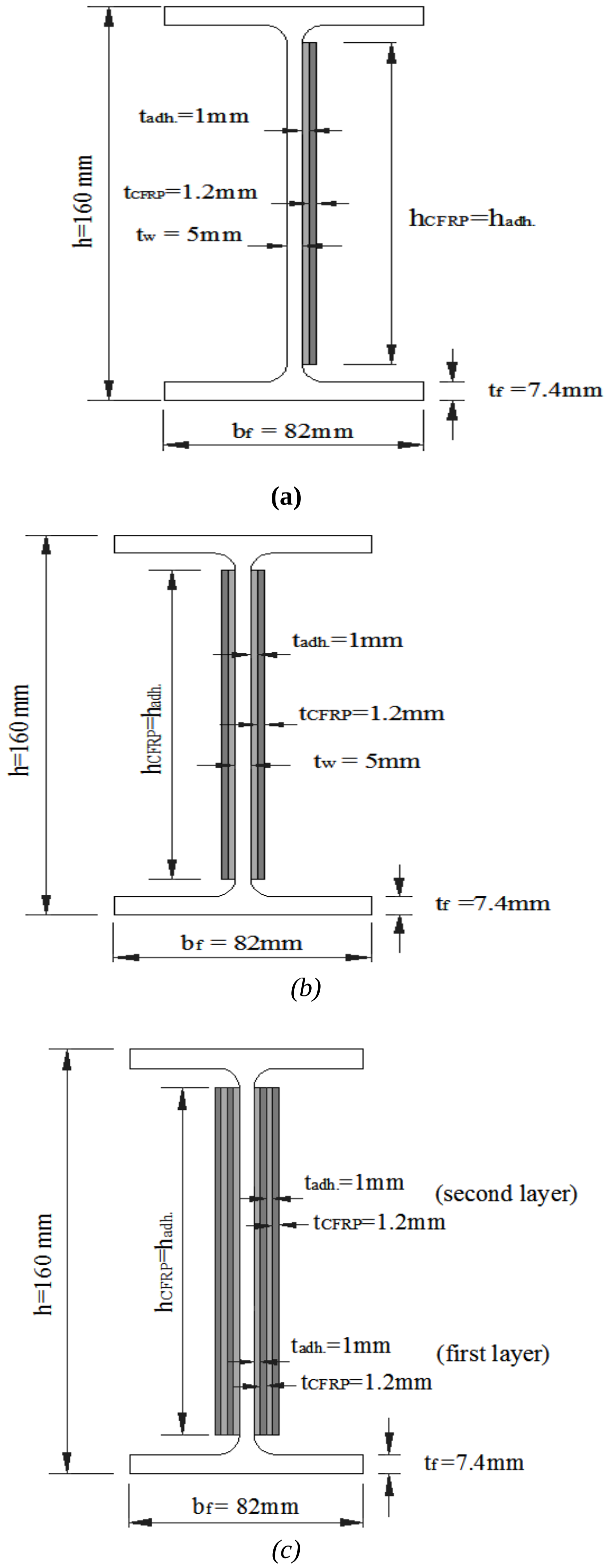


Fig. 2: Details of the sections strengthened with one layer of strip on one side of the web (a), strengthened with one layer of strip on both sides of the web (b), and strengthened with two layers of strip on both sides of the web (c).

Table 2: Dimensions and mechanical properties of used steel beam.

Steel I-beamdimensions (mm)			
Width (bf)	Height (h)	Flange thick. (tf)	Web thick. (tw)
82	160	7.4	5.0

Steel I-beam properties				
E-modulus(N/mm²)	Yield stress (Fy) (N/mm²)	Ultimate stress(Fu)(N/mm²)	Yield strain ($\mathcal{E}_y$) %	Ultimate strain ($\mathcal{E}_u$)%
209, 100	245	368	0.50	3.5

Table 3: Properties of CFRP strips.

Sika® Carbodur® plate (S512)			
E-modulus (N/mm²)			
Mean value	Min. value	5% Fractile Value	95% Fractile Value
165,000	>160,000	162,000	180,000

Tensile strength (N/mm²)				Strain	
Mean value	Min. value	5% Fractile Value	95% Fractile Value	Strain at break	Design strain
3100	>2800	3,000	3,600	>1.7%	< 0.85%

Table 4: Properties of epoxy resin.

Sikadur® -30			
Compressive strength (N/mm²)		Tensile strength (N/mm²)	
E-modulus	Strength at 7 days	E-modulus	Strength at 7 days
9,600	70-95	11,200	24-31
Shear strength (N/mm²)		Bond strength on steel (N/mm²)	
Strength at 7 days		Mean value	Min. value
14-19		>30	>21

To ensure a good quality bonding between the steel and the CFRP strips, shear zones surfaces was treated by an abrasive disk until the oxidation layer was totally removed, and then it is cleaned with Acetone.The CFRP strips were cut to the proper dimensions by a saw. The epoxy resin parts A and B were mixed together with a ratio 3:1 respectively for at least 3 minutes. This mix can only be used within its pot life, which is 70 minutes started from mixing the two parts together at room temperature. The CFRP strips were glued within 48 hours after the preparation of steel surface. The mixed resin was applied to the CFRP strips and the steel web at the specified regions (prepared surfaces), thenthe strips were installed and pressed to steel surface with a small pressure to force out the air bubbles and the excess epoxy. The strengthened specimens were tested after CFRP installation by at least 7 days.

III. TEST SET-UP

All strain gauges and LVDTs were arranged and fixed as shown in Figure 3.Three LVDTs were used to measure the beam vertical deflection and one was used to measure the horizontal displacement. All LVTDs were arranged and fixed independently. Strain gauges of 10mm length and with a resistance of 120 Ω were used to measure strains on steel web and CFRP at shear. Four strain gauges (1, 2, 3 & 4) were fixed to steel surface at shear zone to measure the steel strain in vertical direction. The aim of using more than one strain gauge was to avoid the fails in any used strain gauges and to ensure the recorded readings, so it was important to use many strain gauges at the same positions and make sure that all the strain gauges are working before testing. Also, four strain gauges (5, 6, 7 & 8) were fixed on CFRP surface to measure the CFRP strain in the fiber direction. A loading cell was mounted to monitor and control the applied loads during the test. Prepared specimens were carefully lifted and fastened to the frame test as shown in Figure 4.

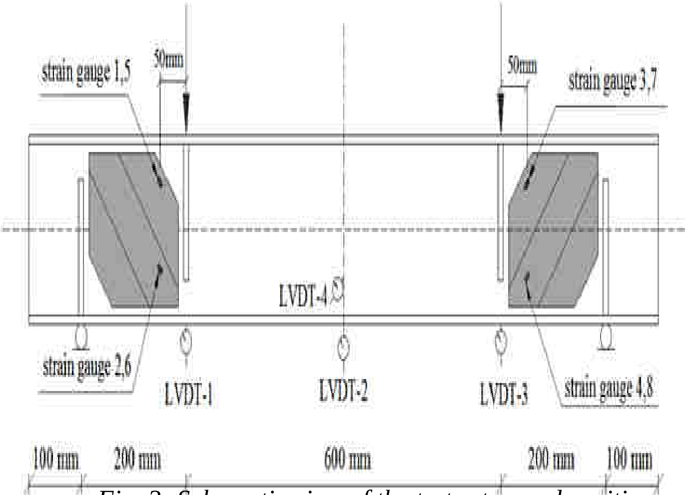


Fig. 3: Schematic view of the test setup and positions of strain gauges and LVDTs for specimens strengthened with CFRP strips in diagonal orientation (45°).

The tested beam was loaded in two points by using one hydraulic jack and a rigid steel beam which distributed the acting load equally. All initial readings of all instruments was reset to make it zero. The load was applied incrementally in small load intervals to get more accurate readings. All data of instruments devices were recorded automatically and saved in the format of well-known office software "excel". Also, the behavior of the tested specimen was recorded and photographed during the test. A schematic view for the Setup of the experimental test is shown in Figure 5.

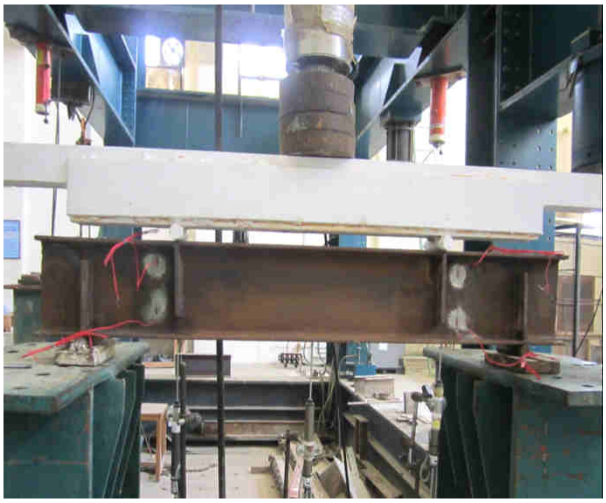


Fig. 4: Test setup for the control specimen (Bo).

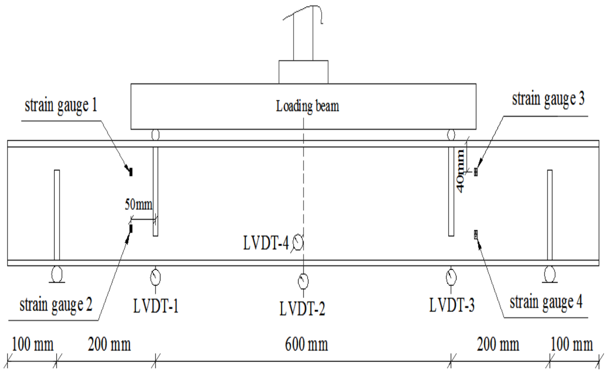


Fig. 5: Schematic view of testsetup forthe control specimen (Bo).

IV. FINITE ELEMENT SIMULATION

Nonlinear finite element method (NLFEM) is considered as another approach to study the shear behavior of the steel beams strengthened by the CFRP strips. In FE analysis, it is possible to have better control over the varied parameters compared with scaled tests and consequently it is easier to get results. The tested steel I-beams and steel stiffeners are modeled with a higher order 3-D, 10-node solid element (SOLID187), K. Narmashiri [13]. CFRP strips were simulated using eight-node (PLANE 82) element type, G. Odegard [14]. The interface of surfaces was defined between steel I-beam, adhesive and CFRP strips. Point-to-surface contact element (CONTAC48) was used to simulate the contact between CFRP strips strips and the steel beams at the shear zone region with a friction coefficient of 0.3, G.Odegard [14]. Steel I-beams were defined as nonlinear and isotropic material by using stress – strain curve that confirmed by testing coupons using tensile testing. The CFRP strips material was defined as elastic orthotropic linear material with linear properties due its unidirectional feature. Auto meshing with a global element size of 20mm was performed. This type of meshing is suitable for the element types used in this study to achieve high accuracy. Figure 6 shows the simulated specimen strengthened by diagonal CFRP strips on the web.

Non-linear static analysis was carried out in this study. The non-linear analysis method was based on the Trial and Error method. The load was applied to structure step by step. When the plastic strain in the first element got to the ultimate strain, then the incremental load step was stopped. The loading procedure for models was divided into a minimum of 40 load steps. Each load step had amaximum of 100 equilibrium iterations. The comparison between the experimental results and numerical ones of the investigated parameters shows a good agreement between them. Figure 7 illustrates the deformation shape of the simulated specimen.

V. RESULTS AND DISCUSSION

MODES OF FAILURE

In this study, the tested steel beams were subjected to two concentrated loads applied at one-fifth beam span. The cross section’s dimensions were chosen to ensure that all failure modes took place within the shear region. Two possible failure modes were occurred in the shear region of the tested beams due to yielding or instability. The first mode of failure was local buckling of the web at the critical region as shown in Figure 8. The second mode of failure was web crippling at the critical region near the fillet of the web as shown in Figure 9.

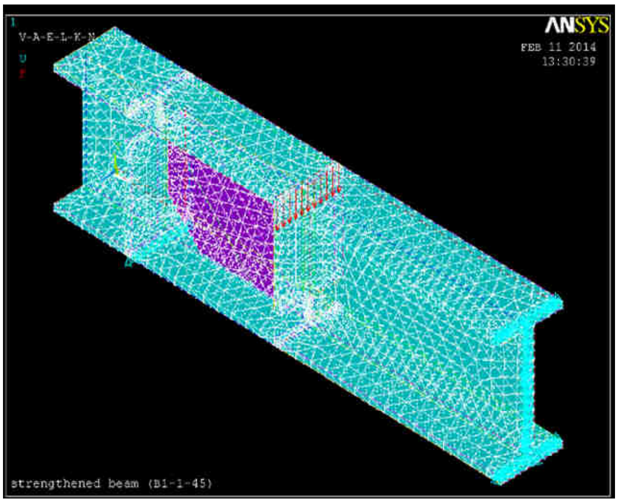


Figure 6: Simulated specimen strengthened by diagonal CFRP strips on the web.

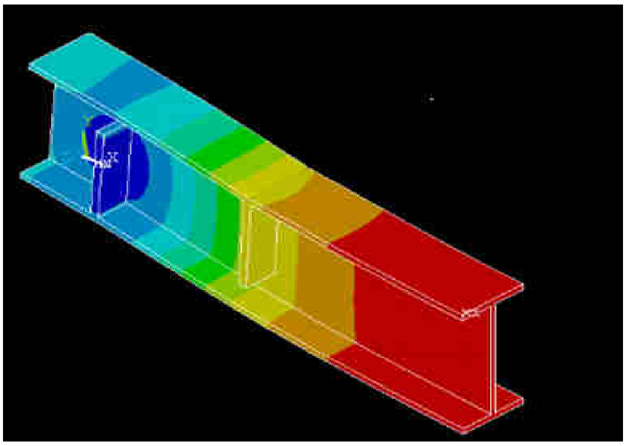


Figure 7: Deformed shape of simulated specimen.

Figure 8: Local buckling of the steel web.

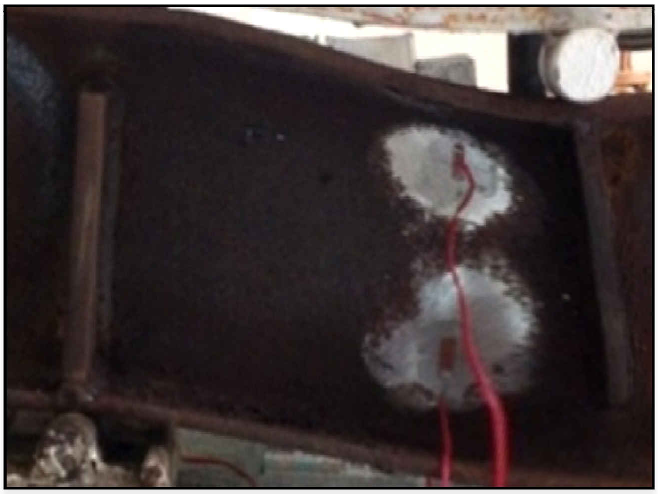


Figure 9: Failure due to web crippling.

The CFRP strips which were applied in this research were unidirectional. Delamination anddebonding of CFRP strips were observed during the failure process of specimens strengthened with vertical strips. The delamination of the CFRP strips was observed firstly at the critical area near the loading points, and then the debonding of the CFRP strips from the steel surface occurred. The debonding of the CFRP strips was only observed in the specimens strengthened with diagonal CFRP strips, this mode of failure occurred suddenly where both the adhesive and CFRP strips were debonded together without any delamination in the composite strips. Figures 10 (a), (b) and (c) shows the failure procedures ofspecimens strengthened with vertical strips, where the failure started with delamination of CFRP strips until its full debonding from the steel surface.

The ultimate load is considered as the most important criteria for the success of any strengthening scheme of structural elements. All the tested beams were loaded gradually till failure.It is observed that using three vertical CFRP strips on one side of the web had an increasing in ultimate load by 28.20% compared to non-strengthened beam. For the vertical strips on both sides, 43.40% increment in ultimate load can be obtained. For the case of two layers of vertical strips, the increase in ultimate load was 54.90%.

For diagonal strips, the ultimate load increased by 38.8% when three diagonal CFRP strips on one side of the web were used. For diagonal strips on both sides, the increment in ultimate load was 52.20%. The increase in ultimate load in the case of two layers of diagonal strips on the both sides of steel webs was 61.10%. The ultimate load for each of the tested specimens is given in Table 5. A comparison between the experimental and numerical results ultimate load of all the tested specimens is, also, shown in the same table. Finally, it can be concluded that applying CFRP strips on the web increased the ultimate load of beams considerably. Attaching of CFRP strips on both sides of the web increased the load capacity of the steel beam than on only one side of the web. Diagonal strips were more effective than the vertical strips. Specimen (B2-2-45) that strengthened using two layers of three diagonal strips on both sides of the web had revealed the highest increase in load bearing capacity.

(a)

(b)

(c)

Fig. 10: Failure procedures of CFRPstrips; delamination (a), initial debonding (b) and full debonding (c).

Table 5: Experimental and simulatedultimate loads for all the tested specimens.

Specimen	Experimental test		Numerical simulation		Error %
	Ultimate load (KN)	increasing percentage in ultimate load compared to control beam (B0)	Ultimate load (KN)	increasing percentage in ultimate load compared to control beam (B0)	
B0	438.44	-	440.00	-	+ 0.356
B1-1-90	561.88	+28.20	580.00	+31.82	+ 3.225
B2-1-90	628.56	+43.40	640.00	+45.45	+ 1.820
B2-2-90	679.22	+54.90	700.00	+59.09	+ 3.059
B1-1-45	608.54	+38.80	620.00	+40.91	+ 1.883
B2-1-45	667.11	+52.20	680.00	+54.55	+ 1.932
B2-2-45	706.45	+61.10	720.00	+63.64	+ 1.918

STRAIN ON THE STEEL BEAM

It was observed that attaching the vertical strips to the web on only one side of the web decreases the strain on the web by 62.86% while attaching the same vertical strips to the web on both sides decreases the strain by 78.40% compared to the control beam.

For the diagonal CFRP strips, it was concluded that attaching three diagonal strips to the web at shear zones on only one side of the web decreases the strain on the web by 69.72% while attaching the same diagonal strips on the both sides of the web decreases the strain by 84% compared to the control beam.For specimens (B2-2-90) and (B2-2-45), the steel strain obtained at the ultimate load of the control beam was still in the elastic region with a negative value; however the strain became positive in the plastic region when the beam failed.

Finally, applying CFRP strips on both sides of the web decreased the strain on the web than on only one side of the web. Also, the strain on the web decreased when two layers of CFRP strips were applied. Diagonal strips lead to decrease the strain on the web more than the vertical strips.Figures 11 and 12 illustrate strain on the web versus load relationships for experimented and simulated specimens, respectively. Figure 13 and 14 shows the shear strain distribution for simulated specimen after and before strengthening, respectively.

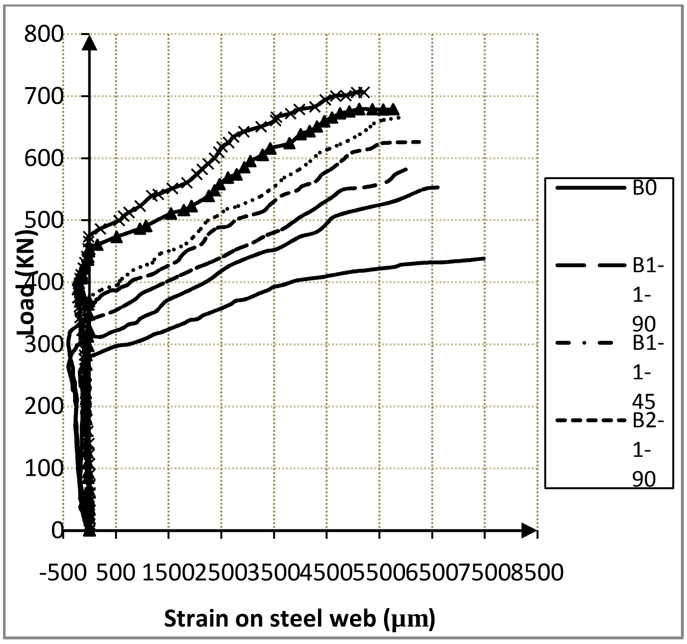


Fig. 11: Load – Strain on steel web relationship for experimented specimens.

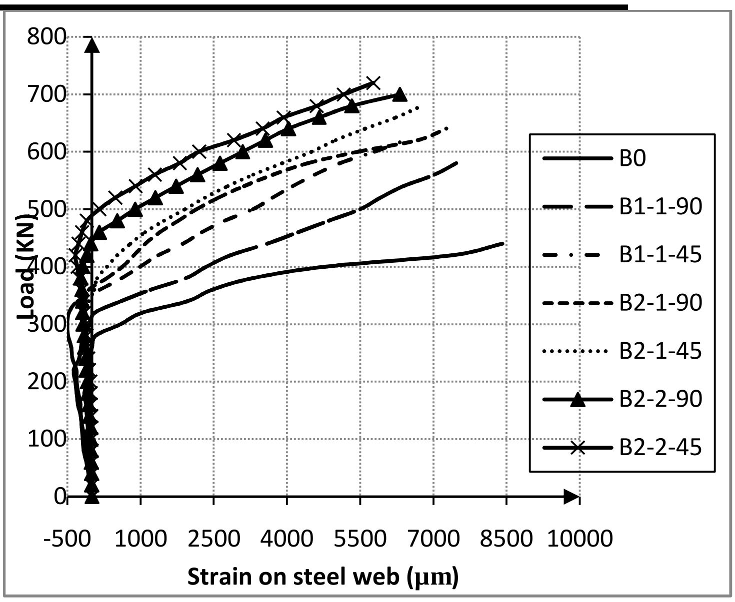


Fig. 12: Load – Strain on steel web relationship for

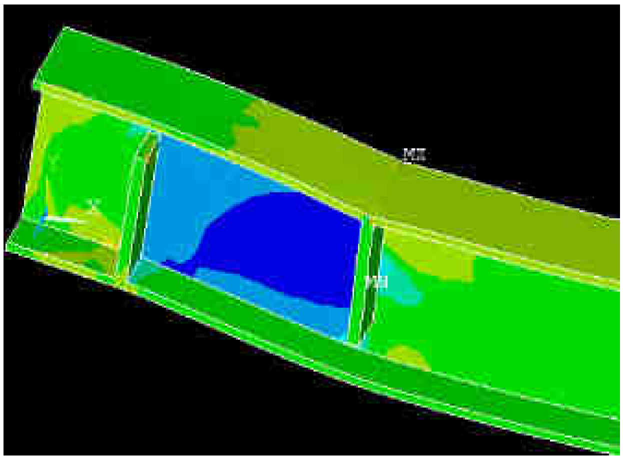
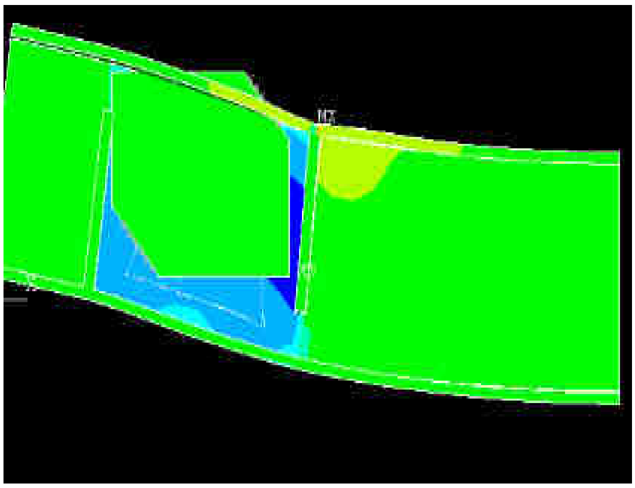


Fig. 13: Shear strain distribution before strengthening.



Fi.e 14: Shear strain distribution after strengthening (Debonding occurred)

.

STRAIN ON THE CFRP STRIPS

Only unidirectional CFRP strips were applied in this research. Delamination of CFRP strips at the critical area near the point load and the debonding between the CFRP strips and the steel surface were the two modes of failure observed in CFRP. For the specimens strengthened by the vertical strips the strain gauges were also pasted vertically in the same direction of fibers, while the specimens strengthened by using diagonal CFRP strips, the strain gauges were pasted in the same direction of strips (i.e. on an angle of 45^0).

It was concluded that using CFRP strips on both sides of the web instead of on one side only lead to decrease the strain on CFRP strips whether these strips were vertical or diagonal. It was also noted that the use of only one extra layer of vertical strips decreases the strain on CFRP strips by 27%, while the use of only one extra layer of diagonal strips decreases the strain on CFRP strips by 24%. Attaching of CFRP strips in diagonal orientation decreased the strain on CFRP more than in vertical one. Strain on CFRP versus load relationships for experimented and simulated specimens is shown in Figures 15 and 16, respectively.

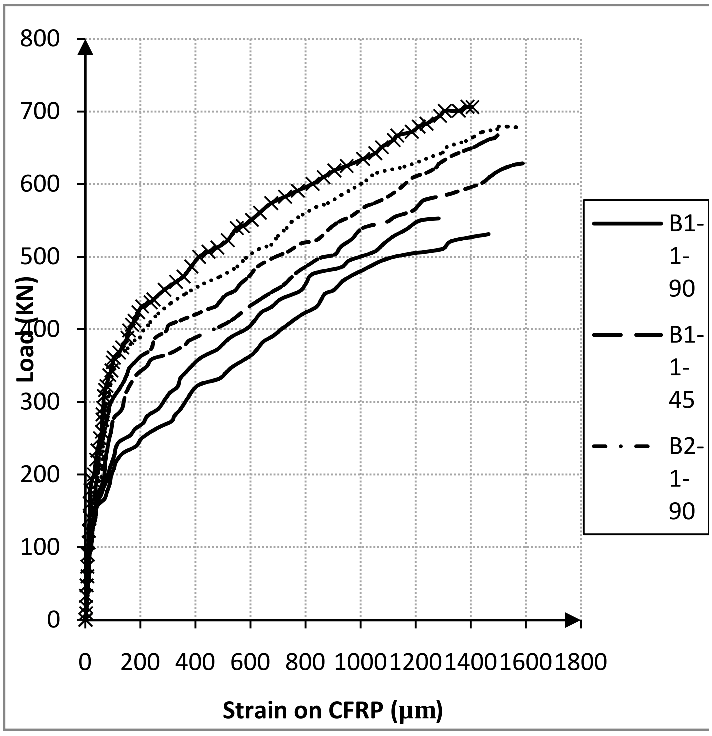


Figure 15: Load – Strain on CFRP strips relationship for experimented specimens.

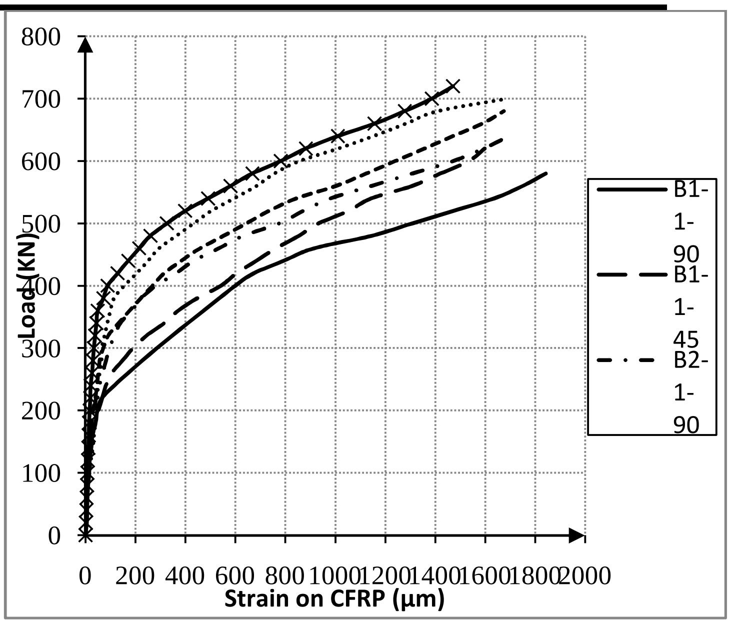


Figure 16: Load – Strain on CFRP strips relationship for simulated specimens.

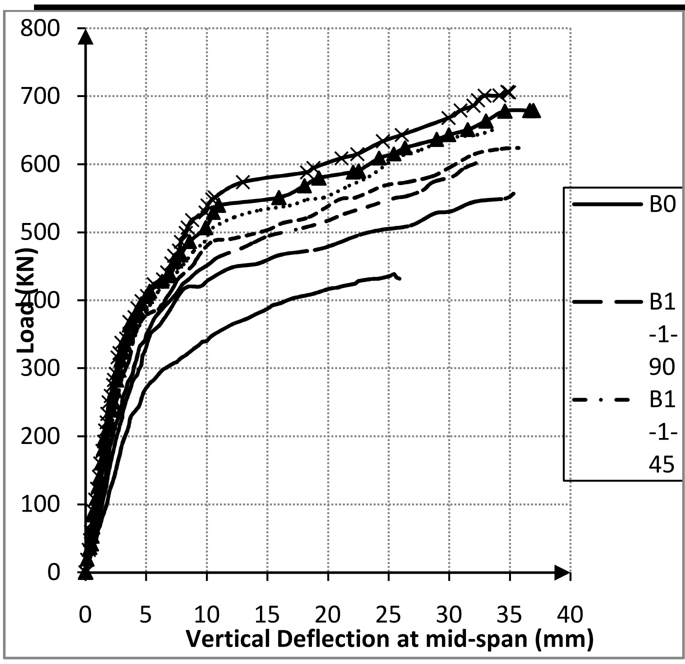
VERTICAL DEFLECTION

To measure the vertical deflection on the tested steel I-beams, three Linear Variable Deformation Transducers (LVDT-1, 2 and 3) were installed to the bottom flange of the steel beam at critical positions. LVDT-1 and LVDT-3 were installed to the bottom flange of the steel beam under the acting points of the two concentrated loads while LVDT-2 was installed at the mid-span of the beam to measure the vertical deflection of mid-span point. The aim of installing LVDTs at the point loads was to verify the readings but it was expected that the maximum vertical deflection was at mid-span.

It can be noticed that the vertical deflection at mid-span of the beam decreases by approximately 60.5% when CFRP strips on only one side of the web were used in comparison with control beam. When the vertical CFRP strips attached to both sides the vertical deflection was decreased by 70.5%. The vertical deflection decreases to 73.0% when two layers of vertical strips were applied on both sides of the web.

Using diagonal CFRP on one side of the web decreases the mid-span vertical deflection by approximately 67.15% and 71.74% for one layer and two layers of CFRP strips, respectively. Using two layers of diagonal CFRP on both sides of the web decreases the mid-span vertical deflection by approximately 75.3 % which corresponds to the least vertical deflection value.

Finally, it is noticed that using diagonal CFRP strips led to slightly decrease in the vertical deflection in comparison with vertical strips. Strain on CFRP versus load relationships for experimented and simulated specimens is shown in Figures 17 and 18, respectively.



Fig, 17: Load – Vertical deflection relationship for experimented specimens.

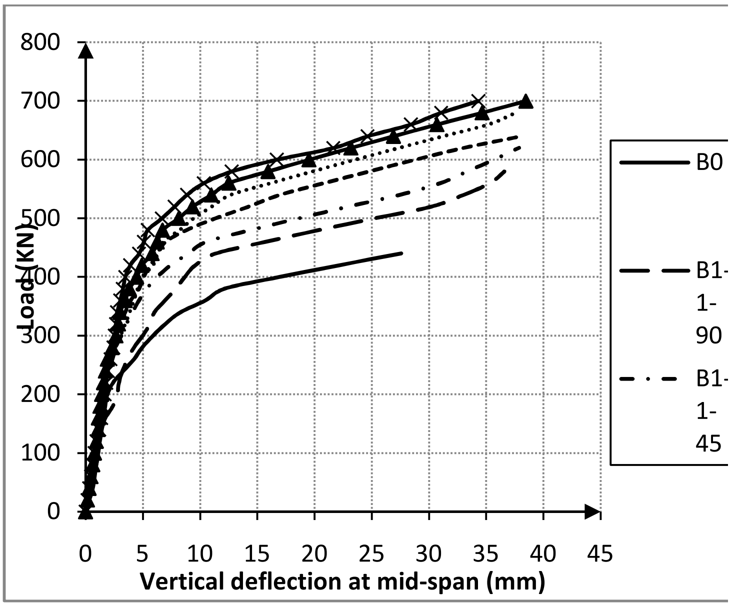


Fig. 18: Load – Vertical deflection relationship for simulated specimens.

VI. CONCLUSIONS

According to the obtained results, the following points can be concluded:

1. All the tested specimens were failed at shear region. Web crippling and web local buckling were the two failure modes observed in the unstrengthened steel I-beam (control). CFRP strips delamination and debonding between the CFRP strips and steel surface were the two failure modes observed for the tested steel I-beams strengthened with CFRP strips in shear zone.
2. Strengthening the web of the tested steel I-beams at shear zones by using CFRP strips of different schemes improved significantly the structural behavior of the I-beams under flexural loads.
3. Attaching CFRP strips on both sides of the web of the tested steel I-beams increases the ultimate load of the beam, and decreases the web strain and vertical deflection in comparison with using CFRP strips one side only.
4. The use of one extra layer of CFRP strips on both sides of steel I-beams web increases its ultimate load of the tested specimens.
5. Attaching the CFRP strips in diagonal orientation increases the ultimate load slightly more than attaching it in vertical orientation.
6. Increasing the number of CFRP layers from one layer to two layers produced a slight decreasing in web strain.
7. Strengthening the steel I-beams with two layers of CFRP in vertical or diagonal direction makes the specimen to behave in the elastic region till ultimate load.
8. A great convergence between the experimental results and the theoretical ones obtained from the finite element simulation.

VII. ACKNOWLEDGEMENT

I would like to record our appreciation for the Faculty of Engineering in Benha, Benha University, for rendering the necessary support to carry out this research.

ABBREVIATIONS

bf, width of flange; t_f, thickness of flange; ***h***, Height of section; t_w, thickness of web; t_{CFRP}, thickness of CFRP strip; t_{adh}, thickness of adhesive; h_{CFRP}, height of CFRP strips; h_{adh}, height of adhesive; ***a***, width of shear zone.

REFERENCES

[1] Nozaka K, Shield CK and Hajjar JF, "Effective bond length of carbon-fiber reinforced polymer strips bonded to fatigued steel bridge I-girders", Journal of Bridge Engineering, ASCE 2005; 10(2):195–205.

[2] Miller TC, Chajes MJ, Mertz DR and Hastings JN, "Strengthening of a steel bridge girder using CFRP plates", Journal of Bridge Engineering, ASCE 2001; 6(6):514–22.

[3] Ishikawa T, Okura L and Kita N, "Debonding shear stress in steel plates with a fiber sheet inserted under a CFRP plate", JSCE, Journal of Structural Engineering 2006; 52A:1317–26.

[4] Colombi P and Poggi C, "Strengthening of tensile steel members and bolted joints using adhesively

bonded CFRP plates", Construction and Building Materials 2006; 20(1–2):22–33.

[5] Al-Emrani M, Linghoff D and Kliger R, "Bonding strength and fracture mechanisms in composite steel–CFR elements", International symposium on bond behavior of FRP in structures, 2005; p. 433–41.

[6] Schnerch D, Stanford K, Summer E and Rizkalla S, "Strengthening steel structures and bridges with high modulus carbon fiber reinforced polymers: Resin selection and scaled monopole behavior", Transportation Research Record 2004; (1892):237.

[7] Fawzia S, Zhao XL, Al-Mahaidi R and Rizkalla SH, "Investigation into the bond between CFRP and steel tubes", The second international conference on FRP composites in civil engineering. 2004.

[8] Jiao H and Zhao XL, "CFRP strengthened butt-welded very high strength (VHS) circular steel tubes", Thin-Walled Structures 2004; 42(7):963–78.

[9] Xia SH and Teng JG, "Behavior of FRP-to-steel bonded joints", Chen JF, Teng JG, editors, Proceedings of the international symposium on bond behavior of FRP in structures, International Institute for FRP in Construction, Hong Kong; 2005.

[10] Hart-Smith L J, "Adhesive-bonded double-lap joints", National Aeronautics and Space Administration, CD-112235, Langley Research Center; 1973.

[11] Colombi P and Poggi C (2004), "An experimental, analytical and numerical study of the static behavior of steel beams reinforced by pultruded CFRP strips", Compos. Part B-Eng. 37:64-73.

[12] S. Rikalla, Mina Dawood and David Schnech, "Development of a carbon fiber reinforced polymer system for strengthening steel structures", 2nd Canadian Conference on Effective Design of Structures, McMaster University Hamilton, Ontario, Canada May 20 – 23, 2008.

[13] KambizNarmashiri, MohdZaminJumaat and N. H. RamliSulong, “Shear strengthening of steel I-beams by using CFRP strips”, Scientific Research and Essays Vol. 5(16), pp. 2155-2168, 18 August, 2010.

[14] G. Odegard and M. Kumosa, “Determination of shear strength of unidirectional composite materials with the Iosipescu and 10° off-axis shear tests, Composites Science and TechnologyVolume 60, Issue 16, December 2000, Pages 2917–2943.