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Full Length Research Paper

Shear strengthening of steel I-beams by using CFRP strips

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Normally, carbon fiber reinforced polymer (CFRP) strips have been used for flexural strengthening of steel beams, but in this research, application of CFRP strips as shear reinforcements was innovated. In this novel method, investigation on the requirement of applying CFRP on one or both sides of the web, and using different values of CFRP area on the web were the two main objectives. In this research, five specimens were selected. The first specimen (B1) was not strengthened. The second and third beams (B2 and B3) were upgraded on both sides of web with the CFRP ratios of 0.72 and 0.48, respectively. The fourth and fifth specimens (B4 and B5) were strengthened on one side of web with the CFRP ratios of 0.72 and 0.48, respectively. Both numerical simulation and experimental test were used in this research. The results show that by using CFRP strips on web, could appropriately increased the load bearing capacity up to 51%. Also, the CFRP ratios of 0.72 and 0.48 for both sides of web have produced the same load capacity. Using less CFRP in the shear zone with the same load capacity of the steel I-beams was one of the significant achievements of this research.

Key words: Carbon fiber reinforced polymer, I-beam, shear, steel, strengthening.

INTRODUCTION

Studies on enhancing structures have significantly increased recently. Different methods exist for strengthening various structures. Using Fiber Reinforced Polymer (FRP) is more popular than other materials for strengthening structures because of their high tension strength, low weight, and more resistance against corrosion. Normally, two type of FRP has been produced: (a) Glass Fiber Reinforced Polymer (GFRP) and (b) Carbon Fiber Reinforced Polymer (CFRP). Applying CFRP had been recognized as more appropriate than GFRP for enhancing different structures because of its higher strength.

Strengthening steel structures by using CFRP materials have been increasing lately. For instance, Sen et al., (2001) (2001) used FRP strips for strengthening steel bridges.

Deng et al. (2004) researched on stress analysis of steel I-beam reinforced by CFRP. The effects of bond length for CFRP strips of strengthened I-beams were investigated by Nozaka et al. (2005). Colombi (2006) researched on delaminating of strengthened steel I-beams. Colombi and Poggi (2006) carried out some analytical and numerical experiments on strengthening steel I-beams. Strengthening steel beams using CFRP and GFRP was studied by Photiou et al. (2006). Besides, an analytical approach for linear and non linear analyses of steel beams was shown by Youssef (2006). Al-Saidy et al. (2007) researched on strengthening steel-concrete composite by using CFRP strips. Bonding behavior of reinforced steel I-beams was researched by Deng and Lee (2007a). Also, they (Deng and Lee, 2007b) studied the fatigue performance of steel beams. A parametric research on upgrading steel beams was done by Al-Saidy et al. (2008) and Fam et al. (2009). Pellegrino et al. (2008) used an analytical approach for strengthening steel I-beams. Rizkalla et al. (2008) used high modulus (HM) CFRP for strengthening steel structures and bridges. They (Rizkalla et al., 2008) developed the use of

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CFRP strips for strengthening steel beams including selection of an appropriate adhesive for bonding HM-CFRP materials to steel and the performance of large-scale steel–concrete composite beams were tested to examine the behavior of using different strengthening schemes. An analytical method for investigating the strengthening of steel beams was examined by Bocciarelli (2009). He (Bocciarelli, 2009) presented a simple approach to evaluate the response of statically determined steel beams reinforced by CFRP plates in the elastic-plastic regime. The effect of CFRP end cutting shape for flexural strengthening steel beams was researched by Linghoff et al., (2009).

Applying CFRP strips for strengthening six specimens was researched by Patnaik et al. (2008). They enhanced two specimens for flexural and two specimens for shear. Two non strengthened beams also were tested as the control beams. The beams had the ratio of a/d=1270/330=3.85, where a is the width of shear zone or the distance of the first point load to the closest support, and d is the height of the web. Using this amount of a/d caused that beams behaved more flexural. They chose the same ratio of a/d for both flexural and shear strengthening cases. Three failure mode shapes in shear behavior were observed (Salmon et al., 2009): Local web buckling, web crippling, and sideway web buckling. The ratio of d/t_w in the Patnaik's beams was 103.13, where t_w is the web's thickness. They stated in their manuscript: "The slenderness ratio for the web of the shear failure beams in this study was large enough to cause buckling of the elastic web." They chose the slender web, which allow them to report only web crippling. Moreover, for measuring the shear failure of the beams, they applied some strain gauges on the beams, but they did not tabulate the results of measuring strain in some tables or graphs to better investigate the effects of CFRP shear strengthening steel I-beams. Besides, they did not explain the effects of CFRP shear strengthening on the horizontal and vertical deflection. They pasted CFRP strips on the full length of shear zones and on the both sides of web. They described the effects of using CFRP on load bearing appropriately. Using CFRP strips, they increased the load capacity of the specimens up to 26%.

Harries et al. (2009) researched on web, strengthening the flanged steel sections using CFRP strips. The non strengthened control and four retrofitted scenarios specimens were examined using either HSCFRP strips or ultra-high modulus (UHM) GFRP strips. For each material, two cases were considered. The FRP strips were applied to each side of the sections. Their tests were experimented for the short length specimens. It indicates that they loaded the specimens directly under the compressive load. In this case, the specimens behaved only in shear.

They used the slenderness ratio of d/t_w=29.8. They pasted only one strip on each side of web (one or two layers), and they did not compare the effects of different percentage of CFRP. As indicated, using the mentioned value of CFRP could increase the load capacity up to 9%. Also, they used cyclic loading that help to examine the effects of CFRP strengthening under this kind of loading.

Fernando et al. (2009) examined end load bearing of the sixteen rectangular steel tubes that were strengthened by using CFRP with different adhesives. They also used Finite element modeling for better examination the effects of CFRP strengthening on tube end bearing. They found that four different failure modes were observed in the tests: (1) Adhesion failure; (2) Cohesion failure; (3) Combined adhesion and cohesion failure; (4) Interlaminar failure of CFRP plates.

Zhao and Mahaidi (2009) researched on web strengthening light steel beams using CFRP subjected to the end load bearing. They used three types of strengthening methods; applying CFRP plates on the outer side or inner side or both sides of the web. As the light steel sections had high web slenderness, they were able to study only the web crippling of the specimens. As mentioned: "It was found that the CFRP strengthening significantly increases the web-buckling capacity especially for those with large web depth-to-thickness ratio." They did not investigate other web slenderness to understand the effects of web slenderness to CFRP strengthening the web.

Zhao et al. (2006) studied the end load bearing of the cold formed rectangular hollow sections that were strengthened by using CFRP wraps. They found that by using CFRP wrap, the load capacity can increase appropriately.

In this paper the following objectives have been studied:

(1) To investigate the effectiveness of shear strengthening steel I-beams by using different CFRP ratios on the shear zone.
(2) To investigate the requirement for applying CFRP on both or one side of web.

In order to examine the mentioned objectives, different parameters such as failure modes, load bearing, shear strain on web, strain on CFRP strip, lateral-torsional-buckling, and vertical deflection have been investigated. In the present research, the ratio of a/d was considered 1.54, so, the most behavior of the specimens was in the shear state. Also, web slenderness is d/t_w=19.7, so, all shear failure mode shapes also can occur. Besides, two different CFRP ratio ACFRP/ASZ of 0.48 and 0.72 in this research have been used in which A_{CFRP} is the sectional area of the used CFRP on the shear zone, and A_{SZ} is the sectional area of the shear zone. Using semi covering and one side pasting CFRP strips on the shear zone, helps in the usage of CFRP strips economically. The full length testing was used, which helps to investigate the effects of combination of shear and flexure behavior, which

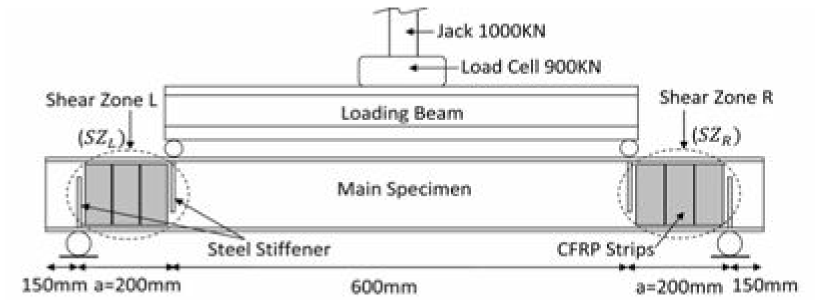

Figure 1a. General specifications of the specimens.

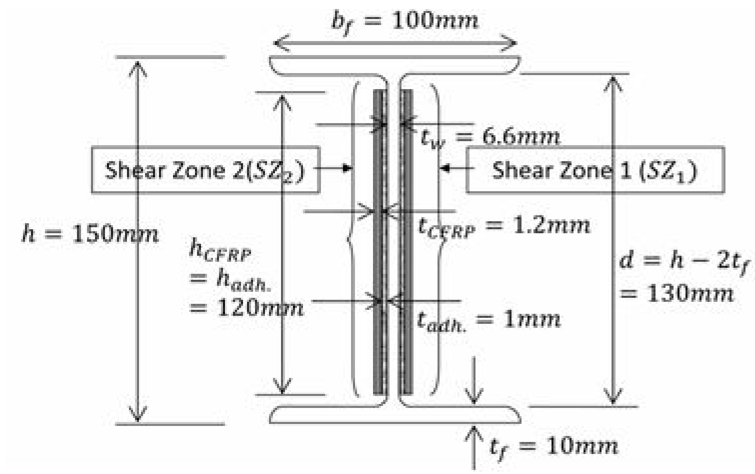

Figure 1b. Section's specifications.

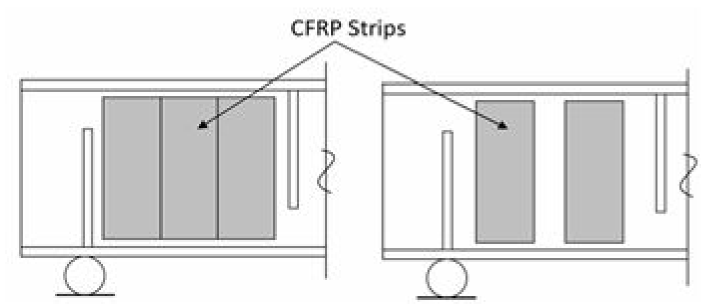

Figure 1c. Strengthening the web by using two or three CFRP strips.

is too closer to the reality of the beams' behavior.

The results are indicated in tables, graphs, and figures in order to investigate the effectiveness of using CFRP strips on web as shear reinforcements.

MATERIALS AND METHODS

Specifications of the specimens

To examine different effects of shear strengthening steel I-beams by using CFRP strips, five specimens were chosen. General specification of the beams and section are indicated in Figures 1a, b, and c. Also, more detail specifications of the specimens are indicated in Table 1. The first specimen (B1) was not strengthened. The shear zone of the second beam (B2) was enhanced by using three CFRP strips on both sides of the web. Application of two or three strips on the shear zone was chosen based on the widths of shear zone (a = 200 mm) and CFRP strips (each 50 mm). These amounts of CFRP strips (two or three strips) generated the CFRP ratios of 0.48 and 0.72, respectively. The shear zone is a region which was surrounded by two stiffeners and two flanges near the supports as indicated in Figures 1a, 1b, and 1c. The third specimen

Table 1. Specifications of the specimens.

Specimen	CFRP's ratio A_{CFRP}/A_{SZ} in the shear zone			
	SZ_{R1}*	SZ_{R2}*	SZ_{L1}*	SZ_{L2}*
B1	0	0	0	0
B2	0.72	0.72	0.72	0.72
B3	0.48	0.48	0.48	0.48
B4	0.72	0	0	0.72
B5	0.48	0	0	0.48

*sz_{ij} : (i = R: shear zone at right and L= shear zone at left) and (j =1: shear zone at region 1 and 2: shear zone at region 2) (Figure 1b).

Table 2. Steel I-beam's dimensions and properties.

Mild steel A36-ASTM								
Steel I-beams' dimensions (mm)				E-Modulus (N/mm^2)	Stress (N/mm^2)		Strain	
Width	High	Flange's Thick.	Web Thick.	Mean value	Yielding (F_y)	Ultimate (F_u)	Yielding (ε_y) %	Ultimate (ε_u) %
100	150	10	6.6	200000	250	370	0.50	3.5

Table 3. CFRP strip's dimensions and properties.

CFRP Strip: Sika® CarboDur® S512/80												
Dimensions (mm)			E-Modulus (N/mm^2)				Tensile Strength (N/mm^2)				Strain	
Width	Thick	Length	Mean value	Min. value	5% fracture value	95% fracture value	Mean value	Min. value	5% fracture value	95% fracture value	Strain at break	Design strain
50	1.2	1500	165000	>160000	162000	180000	3100	>2800	3000	3600	>1.7%	<0.85%

Table 4. Adhesive's dimensions and properties.

Adhesive: Sikadur® -30									
Dimensions (mm)			Compressive strength (N/mm^2)		Tensile strength (N/mm^2)		Shear strength (N/mm^2)	Bond strength on steel (N/mm^2)	
Width	Thick	Length	E-Modulus	Strength 7 days	E-Modulus	Strength 7 days	Strength 7 days	Mean value	Min. value
50	1.0	1500	9600	70 - 95	11200	24 - 31	14-19	30	> 21

(B3) was strengthened by using two CFRP strips on the both sides of the shear zone. Figure 1c shows the application of three or two CFRP strips. The shear zone of the fourth beam was enhanced by using three CFRP strips only on one side of the web. The fifth specimen was strengthened in the shear zone by using two CFRP strips only on one side of the web. More detailed specifications of the specimens are mentioned as follows: The beams span is 1000 mm, h=150mm where h is total height of the section, b_f=100mm Where b_f is the flange's width, t_f=100mm where t_f is the flange's thickness, d=130mm, where d is the height of web, and t_w=6.6mm, where t_w is the web's thickness. The material properties of steel beam are shown in Table 2. The CFRP strips had the following specifications: (made by SIKA® Co., branch in Malaysia) pultruded Sika® Carbo Plate type S512/80, 50 mm in width, t_{CFRP}=1.2mm where t_{CFRP} is the thickness of CFRP strips, and h_{CFRP}=120mm, where h_{CFRP} is the height of the CFRP strips. The module of elasticity is 165 Gpa, the tensile strength is 3 Gpa, and the strain at break is 1.7% (SIKA® product information, 2008). The material properties of CFRP are indicated in Table 3. The CFRP strips were glued to the webs of the steel I-beams by using 1 mm in thickness of the adhesive SIKA®DUR30. The material properties of adhesive are given in Table 4.

Setup of test

The following processes were carried out for the experimental tests. Firstly, the CFRP strips were cut to 120 mm in length pieces.

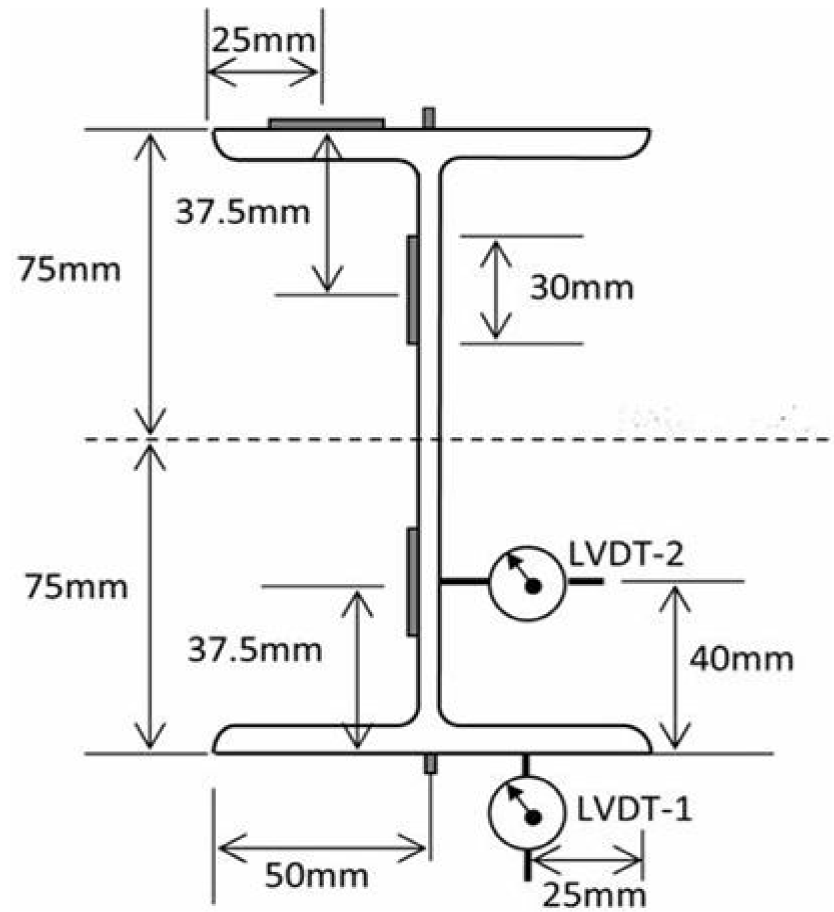

Figure 2a. Locations of the strain gauges and LVDTs in the cross section direction.

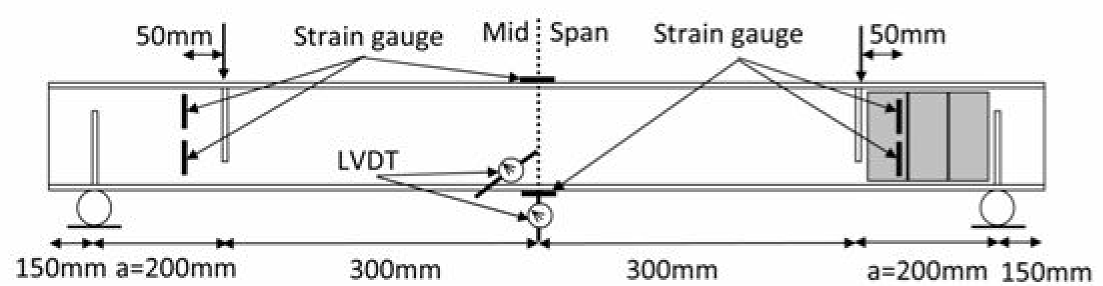

Figure 2b. Locations of the strain gauges and LVDTs in the longitudinal direction.

Secondly, the shear zones were sandblasted according to Sa 2.5 (Swedish standard, SIKA® product information, 2008). The maximum duration after sandblasting and before gluing CFRP strips at the temperature of +30˚C must be less than 48 h (SIKA® product information, 2008). After that, strain gauges (TML® 30mm) were installed on different regions of the steel beams. Figures 2a and b indicate the places of installing the strain gauges. For each strengthened specimen, seven strain gauges were installed. To measure strain in the critical regions, the strain gauges were used.

Strain gauge can measure the strain in the self longitudinal direction. To measure the normal strain, the strain gauges were pasted on flanges in the longitudinal (beam axis) direction. To measure shear strain, the strain gauges were installed on web parallel to the web direction. The locations of strain gauges were I-beams, so, the following items will be investigated: Load capacity, shear strain on steel at the shear zones, strain on CFRP strips, transverse strain on top flange, horizontal deflection, and vertical deflection. One strain gauge was installed on the outer side of the top flange at mid span in the centroid and longitudinal direction to measure compression strain. Another strain gauge was installed on of bottom flange to measure tension strain. Two strain gauges were installed on web at the shear zone in which one of them was located above the neutral axis, and another one was placed below the neutral axis for measuring the shear strain on steel. Another two strain gauges were installed on CFRP to measure strain on CFRP strips in which one of them was placed above, and another one was located below the neutral axis. Then, the strain gauges which were located below the adhesive and CFRP strips were coated by silicon. Afterward, CFRP strips were pasted on the shear zones by using adhesive with the average thickness of 1 mm. After that, two strain gauges were installed on the CFRP strips. One week after gluing the CFRP strips, the adhesive had appropriately been hardened, and the tests were carried out.

For tests setup, firstly, beams were placed on the rollers supports. Secondly, a loading beam with the supports' distance of 600 mm was located over the main beam. Then, a load cell with a maximum capacity of 900 kN was placed at the mid span of the loading beam. After that, two Linear Variable Deformation Transducers (LVDTs) were installed at the mid span for measuring the vertical and horizontal deflections. Then, strain gauges and LVDTs were connected to the Data Logger to measure strain and deflection on the mentioned region of the beams. The load was applied with a hydraulic jack with the maximum capacity of 1000 kN. Figure 3 indicates the experimental setup which was based on the four-points bending test.

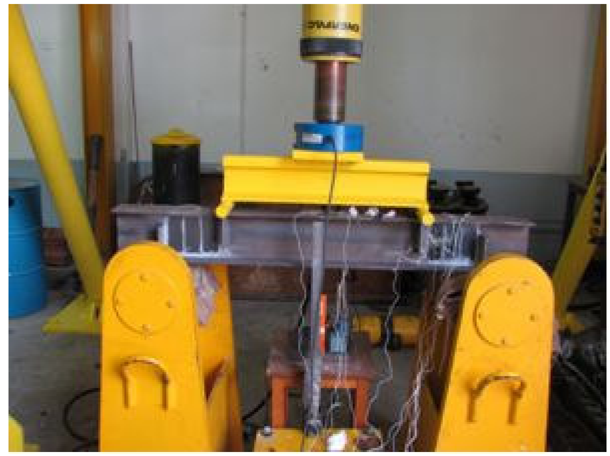

Figure 3. Setup of the experimental test.

Numerical simulation

To evaluate the experimental test, the full three dimensional (3D) simulation using ANSYS software was performed. The steel I-sections, steel stiffeners, steel plates, steel bolts, CFRP strips, and adhesive were simulated by using the 3D solid triangle elements (Ten nodes 187). The interface of common surfaces was defined between steel I-beam, adhesive and CFRP strips. Debonding occurred when the plastic strains were more than the ultimate strain on adhesive. Non-linear static analysis was carried out to verify the debonding behaviour. The non linear analysis method was based on the Trial and Error method. In this case, 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 linear and nonlinear properties of materials were defined. The CFRP strips' material properties were defined as linear and orthotropic, because CFRP materials have linear properties and are unidirectional. The other materials were defined as non linear and isotropic properties. For meshing, combination of auto meshing and map meshing were used. In the critical region, the elements were meshed smaller than the other regions. Figure 4a shows the simulated model of the shear strengthened specimen by using two CFRP strips on the web, and Figure 4b illustrates the normal stress on the specimen. In this paper, the validation of experimental test results was carried out by using computer simulation in light of load capacity. Comparison between the result of experimental and numerical studies on the other parameters such as strain and deflection on different regions, also shows a good agreement between the experimental and simulation results, which are not presented.

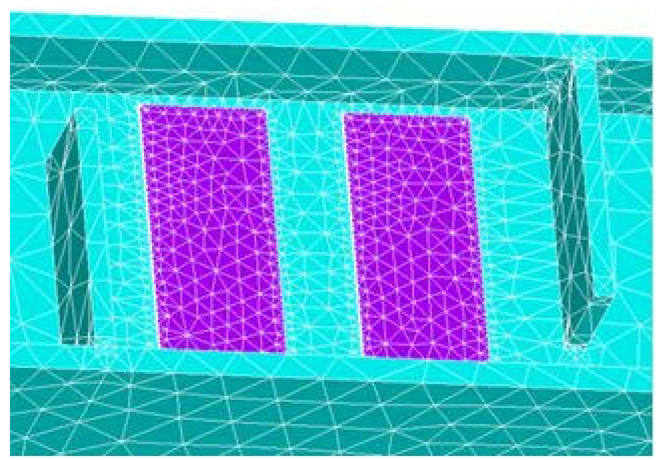

Figure 4a. Simulated specimen.

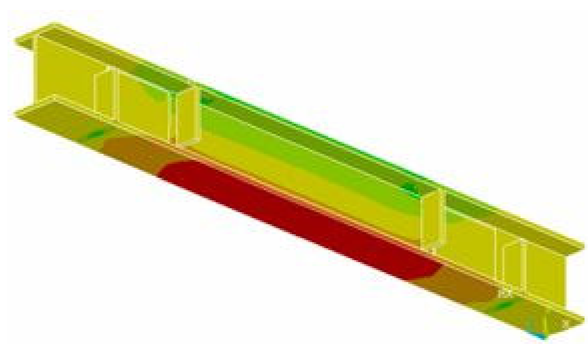

Figure 4b. Distribution of normal strain.

RESULTS AND DISCUSSION

Load capacity

Normally, one of the most important criteria for a strengthened structure is the increment of load bearing capacity of the upgraded structural elements compared to the non strengthened elements. Table 5 shows the load capacity for the different specimens. It illustrates that by using three CFRP strips on both sides, increased the load capacity up to 51.67% compared to the non strengthened

Table 5. Load capacity of the specimens.

Specimen's name	Experimental test			Maximum load bearing P (kN) in the numerical simulation
	Maximum load bearing P (kN)	Load bearing increasing percentage in comparison by the non-strengthened specimen (B1)	Load bearing decreasing percentage in comparison by the full-strengthened specimen (B2)	
B1	393.3	-	-	384.5
B2	596.5	+51.67	-	585.3
B3	595.5	+51.41	-0.50	584.1
B4	564.3	+43.48	-15.85	557.3
B5	532.5	+35.39	-31.51	527.8

beam. For the two strips on both sides, 51.4% increment can be obtained. This means that using three or two strips had the same effects on the load bearing capacity of the specimens. Hence, two strips are recommended because, less CFRP was applied. For the strengthened specimen which have three CFRP strips on one side, the load capacity increased up to 43.48%, and for the upgraded beam with two CFRP strips on one side, the load capacity increased up to 35.39%. Table 5 also showed that applying CFRP on both sides is more effective than one side. Also, comparison between the results of experimental and numerical studies on load bearing capacity of the specimens as Table 2 indicates, appropriately, a conformity of them.

Finally, it can be concluded that applying CFRP strips on the web as shear reinforcement increased the load capacity of beams considerably. Also, CFRP ratios of 0.72 and 0.48 on both sides of the web had the same effect on the load capacity.

Figure 5a. Local yielding of web at the critical region.

Shear strain on the beam's web

When concentrated loads are applied to a beam, then there are two following possible behaviors: (a) Yielding and (b) Instability. According to these behaviors, three shear failure mode shapes may occur: (1) Local web yielding, (2) Web crippling, and (3) Sideway web crippling (Salmon et al., 2009).

Figure 5a illustrates crippling of the beam at the critical region near the fillet of the web. Since the top flange is not restrained, it has caused the compression (top) flange to rotated, laterally. Figure 5b shows the web crippling, which occurred on the shear zone. Figure 6a indicates a shear zone before loading. In this figure both diagonals (D_o) were the same. Under shear force, the web is subjected to shear buckling, where the diagonal D_o changed to the compressive diagonal D_c and the tensile diagonal D_t. The relation of these diagonals can be represented as:

Figure 5b. Web crippling.

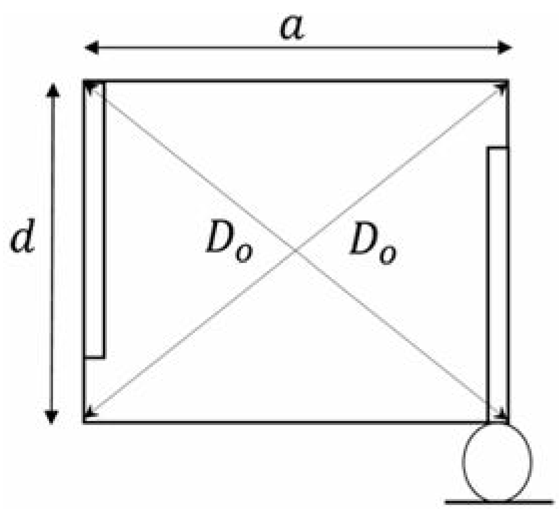

Figure 6a. Shear zone before loading.

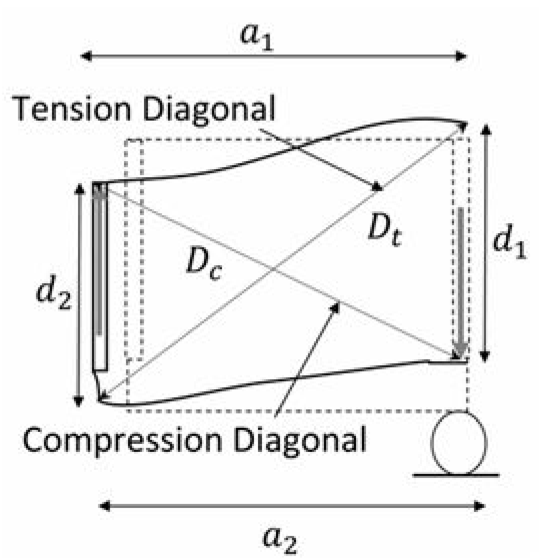

Figure 6b. Shear zone after loading.

$$D_t > D_0 > D_c \quad (1)$$

In this paper, the section's dimensions were chosen to ensure that all three shear failures took place. Figures 7a and b shows the shear strain distribution on the shear zone before and after strengthening. When the web was not strengthened, the compressive diagonal in the shear zone increased considerably (Figure7a). Also, when CFRP strips in discretely shape were applied on the web, then high strain intensity between the CFRP strips was observed (Figure 7b). It is recommended when discretely CFRP on web is used, then stress and strain intensity on web must be considered well because it can have an effect on web's stability especially for thin webs.

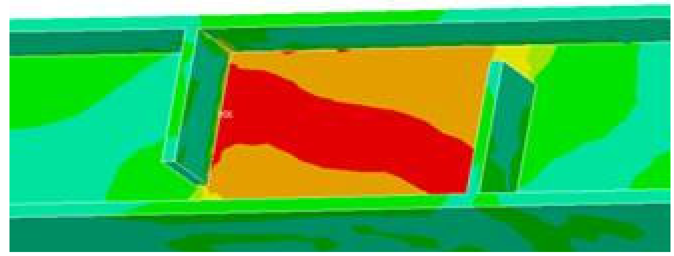

Figure 7a. Shear strain distribution on web before strengthening.

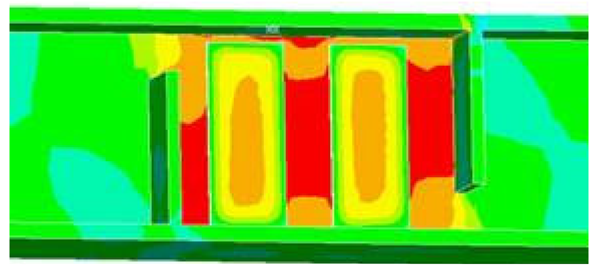

Figure 7b. Shear strain distribution on web after strengthening.

To measure the shear strain on the web, two strain gauges were installed. For the specimens that were strengthened with two CFRP strips, the strain gauges were installed on web between the CFRP strips. Figure 8 illustrates shear strain on web versus load. It shows in the elastic region, all specimens had the same strain, but in the plastic region, the beam of B3 had more strain on web than other specimens because in the discretely CFRP case, high strain intensity occurred between the strips.

Finally, applying more CFRP on shear zone decreased shear strain on web appropriately. Also, using CFRP in the discrete arrangement has caused strain intensity to develop on web (Figures 5a, b, 6a, 7a, b and 8).

Strain on the CFRP strip

The CFRP strips which were applied in this research were unidirectional. A large amount of shear stress was distributed on web in the vertical direction, and so, CFRP strips were pasted along the same direction. In the shear zones, normal stress also occurred due to bending moment. The value of normal stress which was generated with bending moment in these areas was less than the mid span. The maximum bending moment occurred at the mid span, and it was steady until the point loads.

Toward the roller support, it decreased linearly to zero. The sequences of CFRP failure are illustrated in Figures 9a - c. The first failure mode shape of the CFRP strips was longitudinal delaminating. In this failure mode, cracks

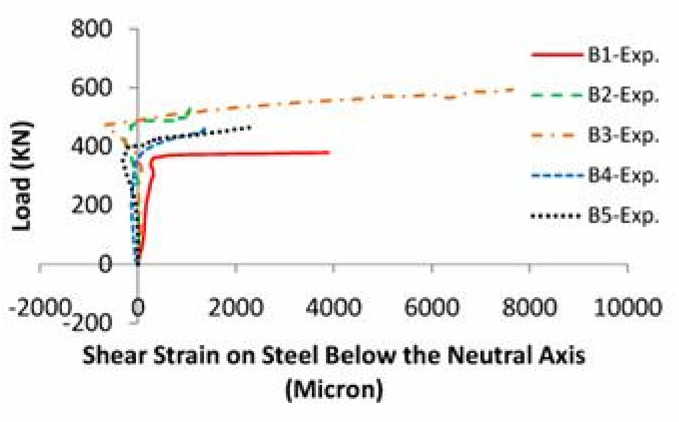

Figure 8. Shear strain on web below the neutral axis.

were developed on the CFRP strips in the longitudinal direction to delaminate the CFRP strips. The numbers of cracks were significant towards the point load.

It can be concluded that combination of shear force and bending moment has produced this sort of failure mode. Figure 10 indicates three debonded CFRP strips. The completely delaminated CFRP was the closest strip to the point loads. The second CFRP failure mode shape was debonding. Debonding of CFRP in the compressive and tensile region was completely different (Figure 11). In The compressive region, adhesive remained on the web, but CFRP strip was debonded. In the tensile region, adhesive and CFRP debonded together. Compressive debonding occurred earlier than tensile debonding. It shows that CFRP strengthening in the tension region was better than the compressive region.

To measure the longitudinal strain on the CFRP strips, strain gauge was installed on the CFRP strips. Figure 12 shows the strain on the CFRP above the neutral axis versus load. As it illustrates in the elastic region, strain on the CFRP was the same for all specimens, but in the plastic region, strain on CFRP for the beams of B2 and B4 was less than other specimens.

Overall, two failure mode shapes were observed for the CFRP strips used in strengthening the web. The first failure mode shapes was longitudinal delaminating at the critical area near the point load. The second failure mode shape was debonding in the compressive and tension region, where debonding in the compressive region was more critical than tension region. Also, using CFRP ratio of 0.72 had the least strain on the CFRP.

Lateral-Torsional-Buckling

One of the most critical behaviors of the unrestrained steel I-Beam is lateral-torsional-buckling. When the beam is not restrained laterally, the compressed flange will

Figure 9a. Procedures of CFRP failing.

Figure 9b. Procedures of CFRP failing.

Figure 9c. Procedures of CFRP failing.

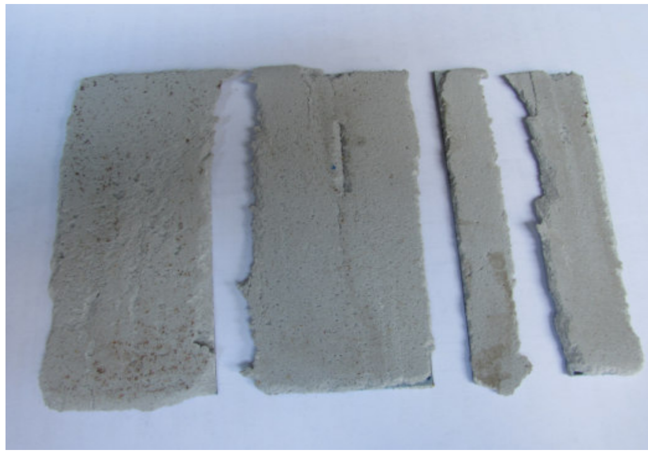

Figure 10. Debonded CFRP strips

Figure 11. CFRP debonding on the tension and compression area.

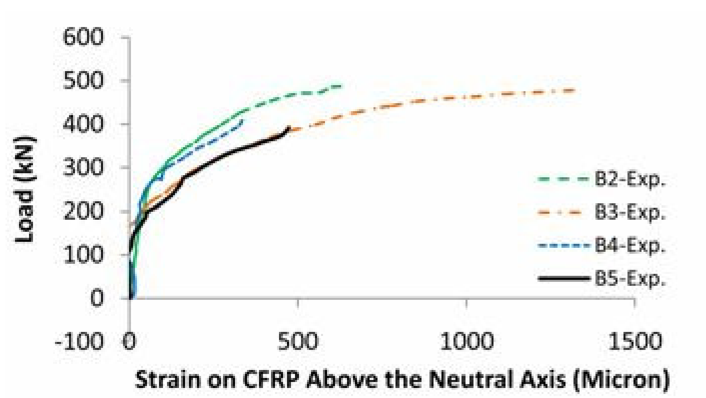

Figure 12. Strain on CFRP above the neutral axis.

deflect laterally and twist. This will reduce the capacity of the beam, and buckling resistance will govern. Figures 13a shows the deformed specimen in both vertical and horizontal directions. This behavior is confirmed by finite element model, shown in Figure 13b. Investigation on the effects of CFRP shear strengthening on lateral-torsional-buckling can be determined based on: (a) Transverse (shear or perpendicular) strain and (b) Lateral deflection. A strain gauge was installed on the outer side of the top flange of each specimen in the perpendicular direction of the beam's length to measure the transverse strain due to the torsional-lateral-buckling effect. Figure 14 illustrates in the elastic region, transverse strain for all specimens were approximately the same, but in the plastic region the enhanced specimens had less transverse strain. Transverse strain for the beams of B2 and B3 were less than others. In order to investigate lateral deflection, a LVDT was also installed on the web at the mid span (Figure 2). Figure 15 indicates that in the elastic region, the lateral deflections of the strengthened and non strengthened specimens were the same, but in the plastic region, lateral deflections of the enhanced beams especially B2 and B3 were smaller. It can be concluded that by using both sides strengthening of the web, will decrease lateral deflection significantly.

Finally, applying CFRP on the web decreased the transverse strain and lateral deflection appropriately, especially in the plastic region. Also, strengthening on both sides of the web has resulted in a lesser deformation. Using CFRP ratios of 0.72 and 0.48 had the same effect on the lateral deformation (Figure 13a, b, 14, and 15).

Figure 13a. Lateral-torsional-buckling (experiment).

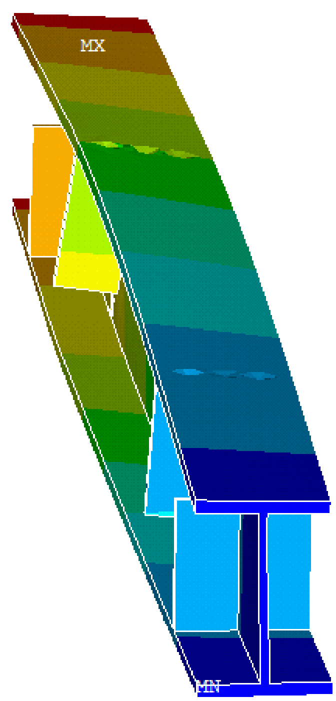

Figure 13b. Lateral-torsional-buckling (Simulation).

Vertical deflection

One of the most important objectives for CFRP strengthening of the structures is to reduce the vertical deflection of the beams. When the vertical load was applied to the I-beam, it deformed in both vertical and horizontal directions, but vertical deformation is more than horizontal deflection (Figure 16).

To measure the vertical deflection at the mid span, a LVDT was installed on the outer side of the bottom flange (Figure 2) Figure 17 shows in the elastic region that the vertical deflections of all beams were the same, but in the plastic region, the strengthened specimens had less vertical deflection in comparison with the non strengthened beam. Also, the vertical deflections of the specimens of B2 and B3 were less than the other strengthened beams. It means both side strengthening of the web decreased the vertical deflection, appropriately.

Finally, applying CFRP on the web decreased the vertical deformation especially in the plastic region. Also, both sides web strengthened specimens had the least occurred vertical deflections.

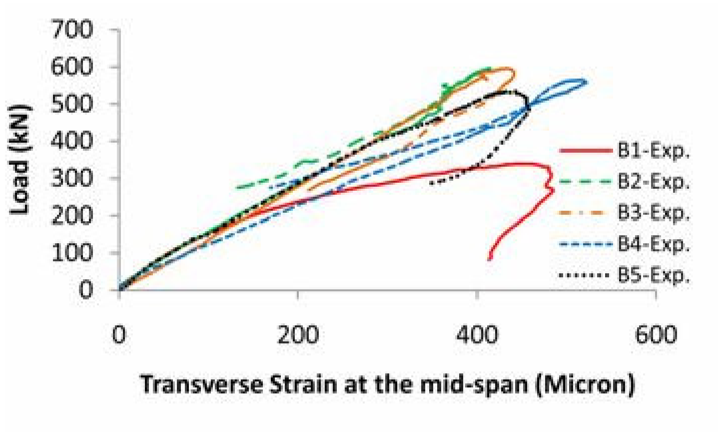

Figure 14. Transverse strain on the compression flanges.

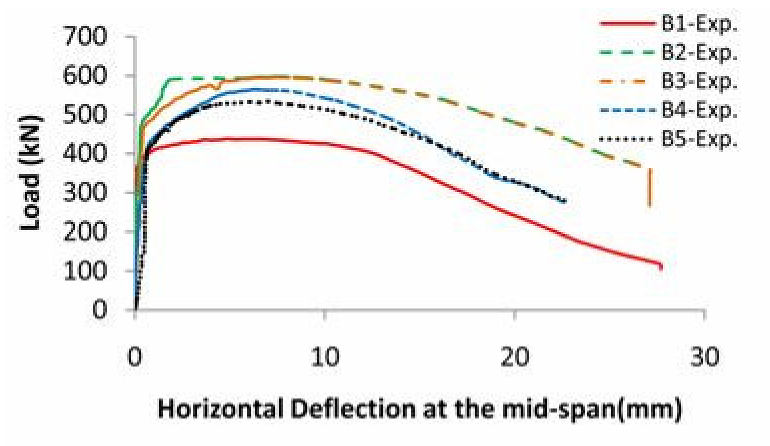

Figure 15. Horizontal deflections.

Figure 16. Vertical deflection of the specimen.

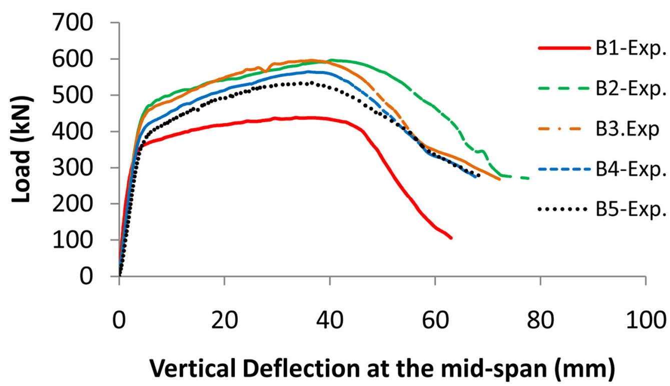

Figure 17. Vertical deflection.

Conclusions

According to the mentioned results and discussions, the following points can be concluded:

1. Applying CFRP strips on the web as shear reinforcement of steel I-beams was a successful method for increasing the load capacity and decreasing the deformations.
2. The CFRP ratios of 0.72 and 0.48 on both sides of the web produced the same increment of load capacity.
3. Using suitable amount of CFRP ratio on the shear zone decreased the shear strain on the web, appropriately.
4. Applying discretely CFRP in the shear zone, caused strain intensity on the web.
5. Two failure modes were observed for the CFRP strips which were used in strengthening the web. The first failure mode was the longitudinal delaminating of the CFRP strips which was more critical towards the point loads. The second failure mode was the debonding of the strips.
6. Different behaviors were observed for CFRP strips in the compressive and tensile regions.
7. Debonding in the compressive region was more critical than in the tensile region.
8. Using CFRP on the web decreased transverse strain and lateral deflection, appropriately, especially in the plastic region.
9. Both sides strengthening of the web, caused less deformation, where CFRP ratios of 0.72 and 0.48 had the same effects on the lateral deformation.
10. Applying CFRP on the web decreased vertical deflection of the beam, appropriately, especially in the plastic region.
11. Both sides web strengthened specimens had the least vertical deflections.

Finally, this research indicates the effectiveness of applying CFRP strips on web to improve shear behavior of steel I-beams.

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Abbreviations: ***P*****,** Total vertical load; b_f, width of flange; t_f, thickness of flange; ***h*****,** Height of section; ***d*****,** effective height of section (height of shear zone = h - 2t_f); 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 before loading (distance of first point load to the closest support); a_1,a_2, Widths of shear zone after loading; d_1,d_2, heights of shear zone after loading; D_0, diagonal of the shear zone before loading; D_c, Compression diagonal of the shear zone after loading; D_t, tension diagonal of the shear zone after loading; ***sz*****,** shear zone; sz_{ij}, Shear zone (*i*:R(right) or L(left)support –*j*:1 or 2 (side of section); A_{CFRP}, sectional area of CFRP in the shear zone; A_{sz}, sectional area of shear zone; A_{CFRP}/A_{SZ}, CFRP ratio.

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