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# IMPROVING SHEAR RESISTANCE OF THE STEEL I-BEAMS USING LOCALLY AVAILABLE CFRP BY DIFFERENT TECHNIQUES

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**ملخص البحث**

لقد استخدمت تقنية تدعيم العناصر الإنشائية المصنوعة من الصلب باستخدام شرائح من البوليمرات المسلحة بالألياف الكربونية على نطاق واسع في السنوات القليلة الماضية ، ولذلك كان هدف هذا البحث الرئيسي هو تقييم كفاءة استخدام شرائح البوليمرات المسلحة بالألياف الكربونية ومواد اللصق الخاصة بها في تدعيم كمرات من الصلب التي على شكل حرف (I) في تحسين مقاومة قوى القص ، حيث تم اختبار عدد ستة كمرات من الصلب التي على شكل حرف (I) باستخدام أربع نقاط تحميل ، فكانت الكمرة الأولى بدون أي تدعيم لتستخدم ككمرة مرجعية ، وتم تدعيم الكمرة الثانية والثالثة في القص باستخدام شرائح من البوليمرات المسلحة بالألياف الكربونية في اتجاهين مختلفين بدون استخدام أي وسيلة لتثبيت نهايات تلك الشرائح ، وقد تم تدعيم الكمرة الرابعة والخامسة في القص باستخدام شرائح من البوليمرات المسلحة بالألياف الكربونية أيضا بالضبط مثل الكمرات الثانية والثالثة ولكن مع إضافة نهايات تثبيت ميكانيكية بواسطة ألواح من الصلب ومسامير لتثبيت تلك الشرائح ، وقد تم تدعيم الكمرة السادسة والأخيرة في القص بالطريقة التقليدية المعتادة في تدعيم المنشآت المعدنية ذلك بلحام ألواح من الصلب ، وقد أظهرت نتائج البرنامج العملي أن لصق شرائح البوليمرات المسلحة بالألياف الكربونية يحسن من جساءة ومقاومة القص للكمرات المختبرة ، بالإضافة إلى أن استخدام طريقتين مختلفتين لنهايات التثبيت الميكانيكية بواسطة ألواح من الصلب ومسامير لتثبيت نهايات الشرائح قد حقق تحسن واضح وملموس في قيمة الحمل التي تحملتها الكمرات المختبرة ، وقد خفضت تقنيات التدعيم المختلفة المستخدمة جميعها التشكلات والانفعالات لمعظم الكمرات المختبرة خاصةً في حدود المرونة .

## ABSTRACT

The strengthening of steel structural elements using CFRP laminates has been applied widely in the last few years. The main goal of this research work is to evaluate the efficiency of the locally available CFRP laminates and bonding materials in the shear strengthening of I-section steel beams. Six steel I-beams were investigated using four-point loading testing. The first beam was used as a control beam without any strengthening. The second and third beams were strengthened in shear by CFRP laminates in two different directions without any end-anchorage. The fourth and fifth beams were strengthened in shear exactly like the second and third beams but with two different techniques of mechanical end-anchorages (steel plates and bolts). The sixth and last beam was strengthened in shear by the traditional welded steel plate. Stiffness and strength of all the six beams were determined experimentally. Results of the experimental program showed that applying the CFRP laminates improves shear strength of the tested beams. Furthermore, using the two different techniques of end anchorage had significantly improved the load carrying capacity and reduced deformations and strains of the whole tested beams especially in the elastic zone.

**Keywords:** CFRP laminates, Steel I-beam, Shear strengthening, Mechanical end anchorages, Shear strain, CFRP strain, Shear resistance.

## 1. Introduction

Strengthening technique by using steel sections has a good achievement to increase strength and stiffness of steel structural elements. However, this method is labor and cost intensive coupled with the needed onsite welding and drilling operations. Regardless of the huge time consumed in the strengthening operations and the consequent traffic disruption in highway road at strengthened steel bridges operations or disrupts the movement production in factories. Moreover, many problems are accompanied with this technique such as the heavy weight of steel plates with a large thickness, carrying and lifting difficulty during construction, a lot of machines and equipment, additional to occurring of rust and corrosion in iron metal, and finally fatigue problems due to stress concentration and weld effect. Obviously, there is a need to find durable strengthening materials and rapid strengthening techniques. Fiber reinforced polymers (FRP) are latest available alternatives materials. FRP become an attractive material in the strengthening field of steel buildings because of its stunning mechanical and physical properties [1]. Many studies have recently been conducted on the strengthening of steel elements by the bonding of a CFRP laminate to the steel surface. However, strengthening of steel elements by FRP subjected to compression had tested in many studies. These studies have shown that significant strength gains and, in some cases, significant stiffness gains can be achieved using adhesively bonded FRP laminates [2-6]. Another group of studies has been studied strengthening of steel web by CFRP subjected to end bearing. It was found that consolidation by CFRP dramatically increases the web crippling capacity exclusively for those with large web slenderness ratio, and test results proved that there increase in the web-buckling capacity especially by bonding CFRP laminates on both side of the web and for specimens with high depth-to-thickness [7-10]. The shear strength of steel beams is controlled by the capacity of the web plate. The collapse of the web because of yielding of the material or elastic buckling that depends on the ratio of the slenderness of the web. The elastic buckling of slender web plates is directly related to the level of the major compression stresses induced within the high shear zones of the beam. Strengthening of steel web by using (CFRP) materials has the chance to decrease the stress level in the steel web, and subsequently growth the shear carrying capacity of the steel web. In order to evaluate the efficiency of the (CFRP) materials for improving the shear strength of steel I-beams, their performance in resisting the major compression stresses and their ability to undergo large deformations associated with buckling should be specified [2]. Some researchers have demonstrated techniques for the strengthening of steel webs by CFRP subjected to shear. Patnaik et al. (2008) published results of an analytical and experimental program focused on shear consolidation of steel built-up I-beams. Three beams were designed to fail in shear. Two were strengthened by bonded (CFRP) to the webs, while, one was kept as an unstrengthened control specimen. Test results of shear strengthening confirmed the effectiveness of shear strengthening application by growing the shear resistance ability of steel beam up to 26%. The collapse load of the control beam caused elastic buckling; however, inelastic buckling was the collapse mode of the strengthened beam. Failure of all the three beams occurred gradually, similar to ductile failure [11]. Okeil et al. [12-14] improved the lateral stiffness of buckling-prone steel by bonding pultruded GFRP sections. Steel I-beams were designed to fail in shear buckling and were tested to explore the feasibility of the proposed technique. Thinly walled steel plates were bonded by GFRP T-shaped in a direction that contributes to the lateral stiffness of steel web plate more than the in-plane strength as is the popular practice in the most (FRP) strengthening cases. The strengthened specimen experienced shear buckling in 56% higher load compared with control un-strengthened specimen. However, the popular (FRP) strengthening techniques, the performance of the strengthened specimen was more brittle compared with control specimen. Collapse modes of the control (reference) specimens were because of web shear buckling. The strengthened specimens were right until the beams collapse by debonding of the GFRP

stiffener followed direct web buckling. Debonding occurred due to the beginning of epoxy failure followed by cracking noises. Most of the epoxy cracks were not visible as they were under the (GFRP) stiffener with only a few cracks that could be seen at the edges. The study on using T-shaped GFRP stiffeners for shear consolidation of the steel I-beams was continued by Babaizadeh (2012) in parametric and analytical studies. Results of FE analysis showed that strengthening steel beams with different flange width can result in the growth of shear capacity up to 66% for square shear zones and up to 36% for the rectangular shear zone. Furthermore, results designated that GFRP stiffeners are more effective than steel stiffener in terms of improving the shear resistance ability of the strengthened steel beam. However, the failures of the (CFRP) stiffened beams are less ductile compared with unstiffened or steel stiffened beams [15]. To examine the success of (CFRP) as strengthening system, application of CFRP laminates as shear reinforcement was examined by Narmashiri et al. (2010). Strengthening specimens were developed by applying CFRP on one or both side of the steel web, and using different values of CFRP area on the web. Five steel I-section beams were tested as illustrative in Figure (2.17). Two beams were strengthened on both sides of the web with the CFRP ratios of 0.72 and 0.48. Two beams were strengthened on one side of web with the CFRP ratios of 0.72 and 0.48. Last beam was kept as un-strengthened control to be used for comparison. Results clearly showed that externally bonded CFRP could increase the shear resistance ability of the steel strengthened I-beam up to 51%. Furthermore, both CFRP ratios for both sides of web almost had similar level of growth in shear capacity. Two failure modes including longitudinal delaminating of the CFRP strips and CFRP debonding of strips were observed experimentally [16].
The main objective of this research is to study the effectiveness of applying CFRP on the web of steel I-beam to improve shear resistance by using different techniques for strengthening steel I-beams in the shear. Modes of failure, ultimate loads, the 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.

## 2. Experimental Program

## 2.1 Material Characterization

### 2.1.1 Steel I-beam

In this study, steel I-beams from grade 37 were used. Beam section was built up section with dimensions as shown in Figure (1).

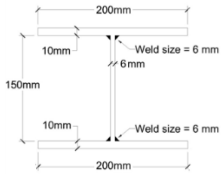



Figure (1): Dimensions of steel I-beam

### 2.1.2 CFRP Strips

CFRP strips were cut according to the shape and dimensions of the needy as shown in Figure (2). The dimensions and properties of the used CFRP strips are shown in Table (1).

Table (1): Dimensions and properties of CFRP strips

<table>
<tr><th rowspan="2">CFRP Strip</th><th colspan="2">Dimensions (mm)</th><th colspan="2">E-Modulus (N/mm$^2$)</th><th rowspan="2">Fiber Volume (%)</th><th colspan="2">Tensile Strength (N/mm$^2$)</th><th rowspan="2">Ult. Strain (%)</th></tr>
<tr><th>Width</th><th>Thick.</th><th>Mean</th><th>Min.</th><th>Mean</th><th>Min.</th></tr>
<tr><td></td><td>50</td><td>1.2</td><td>165000</td><td>>160000</td><td>68</td><td>3100</td><td>>2800</td><td>> 1.70</td></tr>
</table>

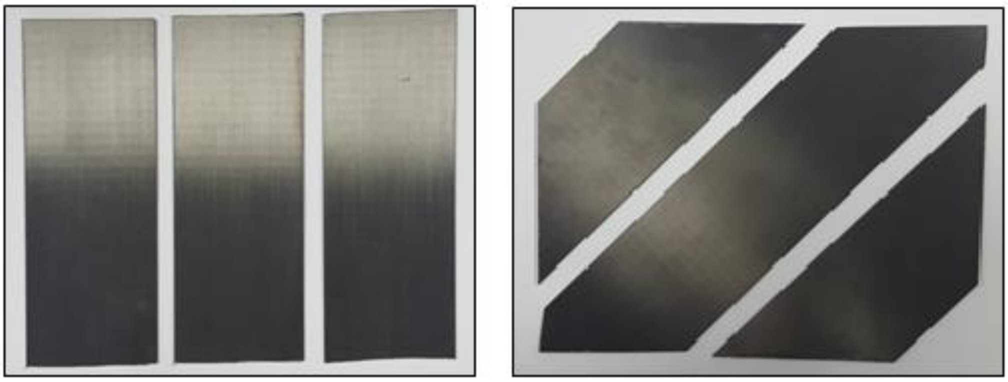


Figure (2): Vertical CFRP strips and Diagonal CFRP strips

### 2.1.3 Adhesive material

The CFRP laminates were installed on the beam web by using their special adhesive. The adhesive material must be prepared by mechanically mixed until the both of components have fully dispersed and the mix is uniform in color as shown in Figure (3). The properties of the used adhesive material are shown in Table (2).

Table (2): properties of adhesive material

| Adhesive | E-Modulus ($N/mm^2$) | | Tensile Strength ($N/mm^2$) – 7 days | Shear Strength ($N/mm^2$) – 7days | Bond Strength ($N/mm^2$) |
|---|---|---|---|---|---|
| | Compressive | Tensile | | | |
| | 9600 | 11200 | 24 - 31 | 14 - 19 | On steel > 21 |

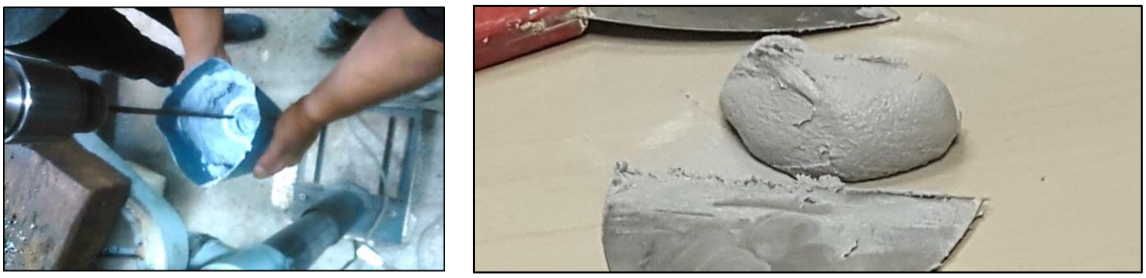
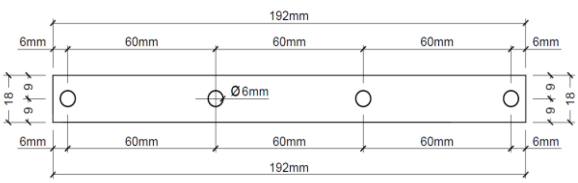


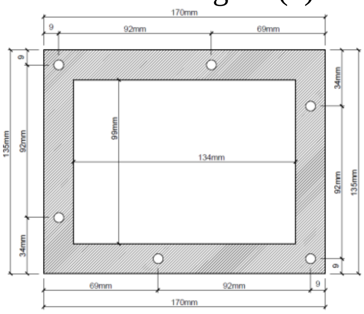
Figure (3): The adhesive material after the mixing process

### 2.1.4 Steel Anchor Plates

Steel anchor plates were used in specimens, It manufactured from grade St.37 with min requirements ( $F_y = 2.4\ t/cm^2$ & $F_t = 3.6\ t/cm^2$ ). Two different steel plates (A and B) were used to anchor the CFRP strip with the web of steel I-beam at the CFRP strip ends. The properties of the anchor plates were the same as the web of the used steel I-beams. The dimensions of the different steel anchor plates are illustrated in Figure (4).




Anchor Plate (A)



Anchor Plate (B)

Figure (4): Specifications and dimensions of the steel anchor plates

### 2.1.5 Bolts

Bolts were used to connect the steel anchor plate to the web of steel beams at the CFRP laminate ends. The bolts were high strength bolts grade 10.9 with diameter 6 mm and length 40 mm as shown in Figure (5).

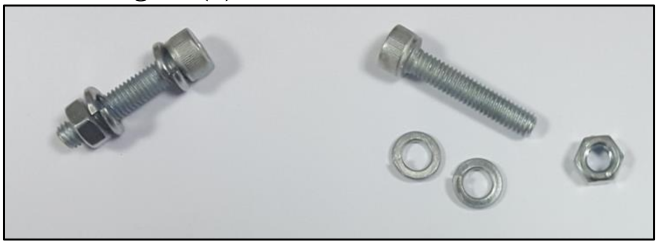


Figure (5): Shape of the used bolts

### 2.1.6 Steel Strengthening Plates

Steel strengthening plates were used to strengthen the web of steel I-beam by the traditional method. It manufactured by dimensions 180x135mm with 3mm thickness and from grade St.37 with minimum requirements (Fy= 2.4 t/cm2 & Ft= 3.6 t/cm2). Steel strengthening plates were cut according to the shape and dimensions of the needy as illustrated in Figure (6).

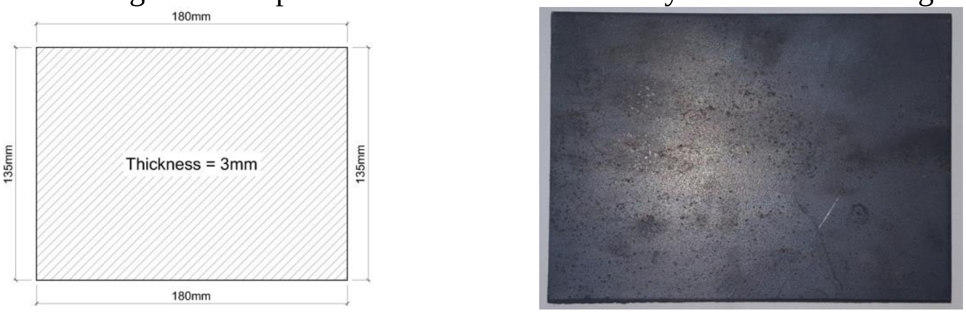



Figure (6): The dimensions and the shape of the steel strengthening plates

### 2.2 Test Specimens

To investigate the applying CFRP on the web of steel I-beam to improve shear resistance by using different techniques for strengthening steel I-beams in the shear. Six steel I-beams were tested in flexure using a four-point load arrangement to study the effect of shear forces on their webs. Two different end anchorages were suggested. The specifications of the specimens are shown in Table (3) and as illustrated in Figure (7).

Table (3): Specifications of test specimens

| **Specim** | **Code** | **Specimen Description** |
|---|---|---|
| (01) | **CL** | Control without strengthening |
| (02) | **SCLV** | Strengthened by vertical CFRP strips without end |
| (03) | **SCLD** | Strengthened by 45˚ Diagonal CFRP strips without |
| (04) | **SCLV** | Strengthened by vertical CFRP strips with end |
| (05) | **SCLD** | Strengthened by 45˚ Diagonal CFRP strips with end |
| (06) | **SSPW** | Strengthened by traditional steel plate |

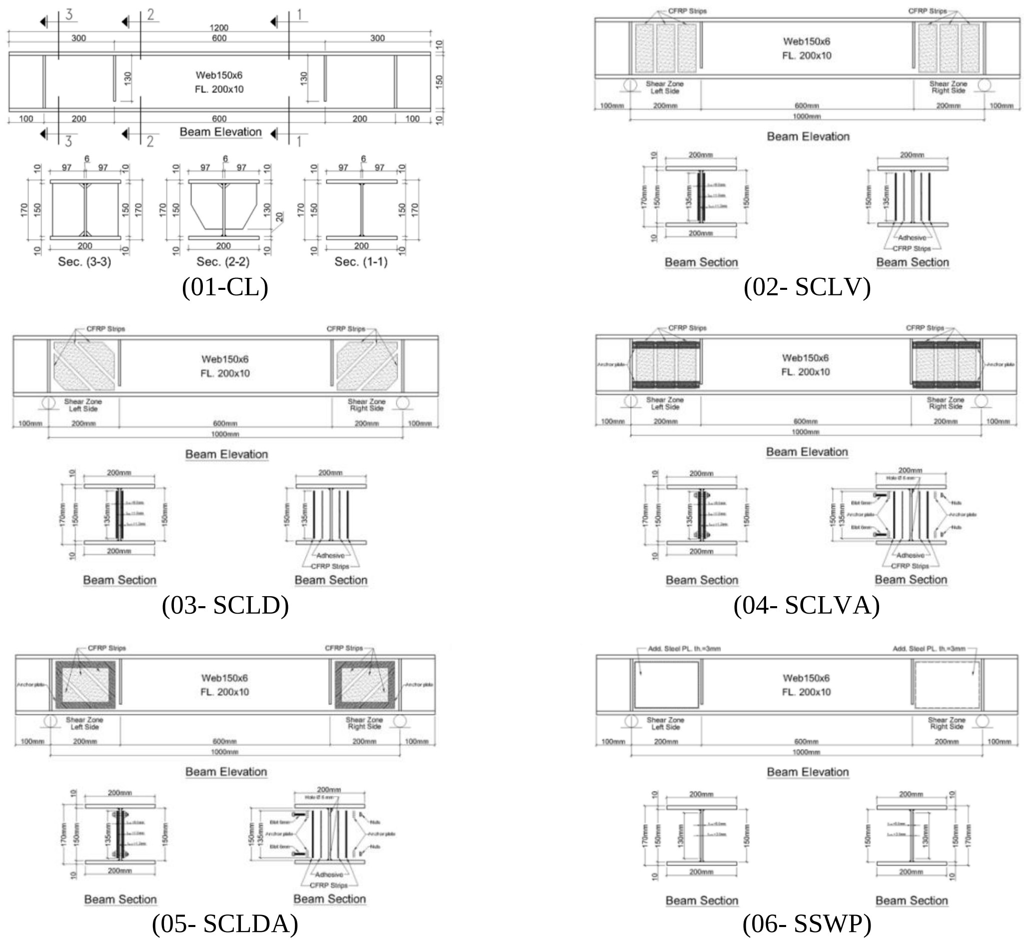



Figure (7): Specifications and dimensions of the test specimens

## 2.3 Preparation of Test Specimens

All test specimens were manufactured in the factory specialized in the construction of steel structure. And the preparation process of the all test specimens were done with the help of the technical staff and labors of the laboratory. The first beam wasn't strengthened and it was used as the control beam. It just had drawn net grids in the left shear zone and right shear zone. The following procedures were performed to prepare the two specimens (02-SCLV) and (03-SCLD): Firstly, eliminate burrs or bevels and to make the surface rough and clean by Sandblasting. Secondly, the surfaces of the CFRP strips were also prepared to be rough by using sandpaper. Thirdly, surface of steel and CFRP strips were cleaned using solvent. Fourthly, adhesive material was mixed according to the manufacturer data sheet instructions as mentioned in-phase (I). Fifthly, Then CFRP strips were attached to the web to achieve with the required thickness of adhesive material. Lastly, the specimens were cured for at least 7 days at room temperature prior the testing. After that, the second two specimens (04-SCLVA) and (05-SCLDA) were prepared by the following procedures: Firstly, eliminate burrs or bevels and to make the surface rough and clean by Sandblasting, then drill the holes for bolts of the end anchorages plates in the web of specimens. Secondly, the surfaces of the CFRP strips were also prepared to be rough by using sandpaper. Thirdly, surface of steel and CFRP strips were cleaned using solvent to make it sure from that it was clean from any oil and greases. Fourthly, adhesive material was mixed according to the manufacturer data sheet instructions as mentioned in-phase (I). Fifthly, Then CFRP strips were attached to the web to achieve with the required thickness of adhesive material. Sixthly, the ends of the CFRP strips were glued by adhesive in regions that connected with the anchor plates, and the surfaces of anchor plates were glued also by adhesive. Then, the anchor plates were positioned at the CFRP laminates ends. Seventhly, after the adhesive had been cured for 12 hour, the bolts of the end anchorages were tightened. Lastly, the specimen was cured for at least 7 days at room temperature prior the testing. And the strain gauges were installed on the specimens directly prior the testing. Two different strengthening systems were used to anchor the CFRP strip with the web of steel I-beam at the CFRP strip ends in the test specimens (04-SCLVA) and (05-SCLDA) as illustrated in Figure (8). For the last specimen, the following procedures were performed to prepare the specimen (06-SSWP): Firstly, eliminate burrs or bevels and to make the surface of steel web or strengthening steel plates rough and clean from any paints by sandblasting. Secondly, strengthening steel plates were cut with the dimension that was needed. Thirdly, surface of steel web and strengthening steel plates were cleaned using solvent to make it sure from that it was clean from any oil and greases. Fourthly, and strengthening steel plates were attached to the web of test specimen in the left and right shear zone reciprocally. Then strengthening steel plates were welded to the steel web by 3 mm thickness of weld.

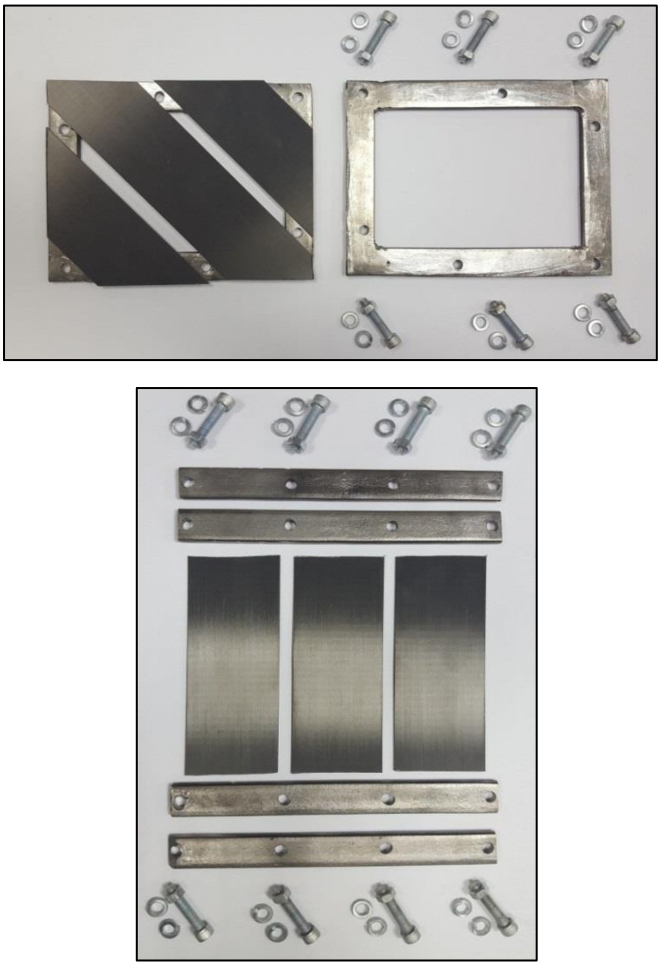


Figure (8): Strengthening system for the test specimens (04-SCLVA) & (05-SCLDA)

## 2.4 Mechanism of the test setup

The hydraulic compression testing machine with capacity 100 ton was used to test the specimens. That testing machine used to apply the load on the test specimen and measure this load with the required accuracy. It consists of fixed jaw, movable jaw, hydraulic system, load cell and other parts like: (springs - pointers - ... etc.). And the load was applied through the relative movement between the fixed jaw and movable jaw. Mechanical dial gauges with 30mm gauge length were installed on the specimens in order to measure Ver. & Hor. deformations. It depends on the magnification of the measured deformation by using gears. Electrical strain gauges with 10mm gauge length were installed on the specimens in order to measure shear and flexure strains. Deformation of the test specimens because of the applied load will be transferred to the electrical strain gauge due to the bond. The flexure test was performed using a four-point load arrangement. Because of that, it appeared the needed for the support beam to convert the axial load of the hydraulic compression testing machine to the four-point load arrangement. That support beam consisted of saddle supports, main support beam and four lateral support beams. The specimens were supported on the two saddle supports of the support beam with clear span 1.0m which rested on the testing machine as illustrated in Figure (9). After that, four lateral supports were used to resist the lateral torsional buckling may occur to the specimens due to test load effect.

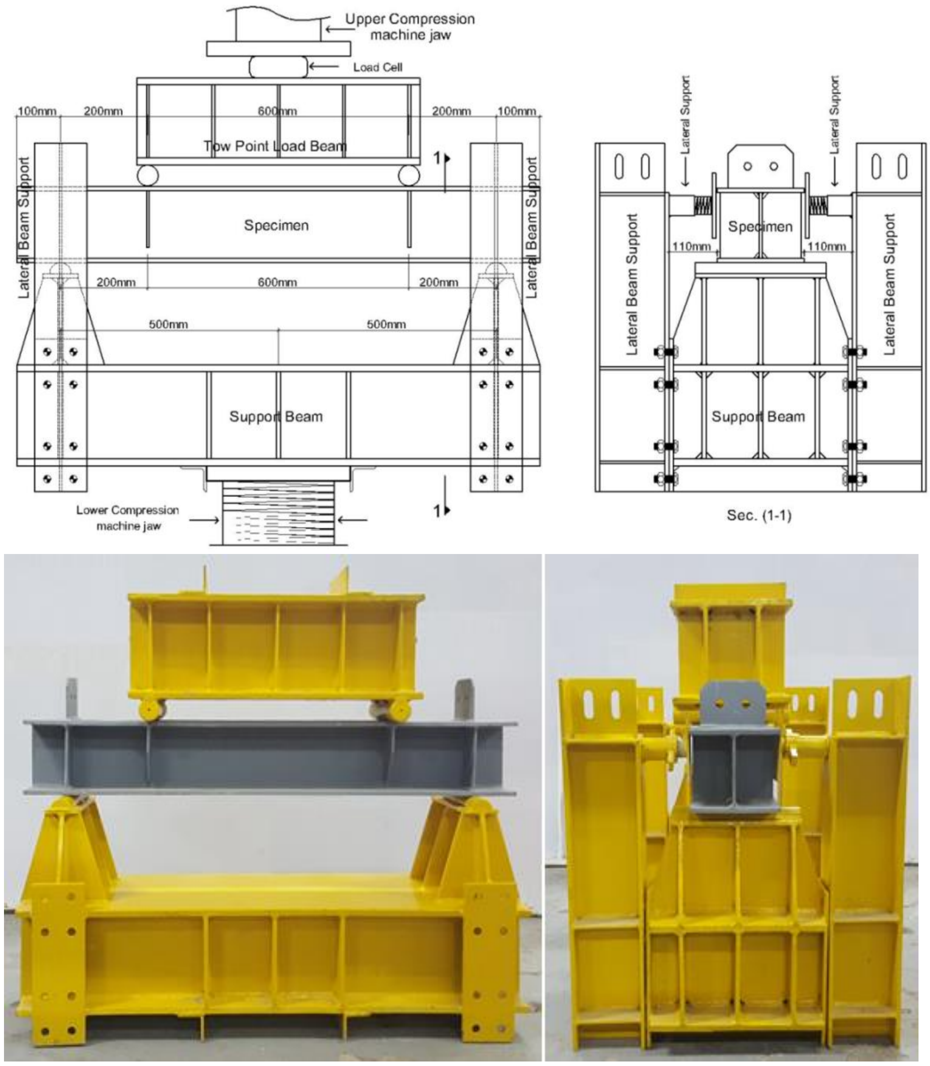



Figure (9): The schematic of the Four-point bending test and the support beam

## 2.5 Measurements on the test specimens

After placing the support beam on the testing machine, the test specimen was put on the saddle supports of the support beam. Then the two-point load beam was placed in the middle of the test specimen. Thereafter the two-point load beam was subjected to load by using the hydraulic jack of the compression testing machine via a load cell of 85 ton capacity. There are many measurements on the test specimens. Mechanical dial gauges and electrical strain gauges were installed on the specimens in order to measure deformation and strain. Figure (10) show the locations and directions of the used dial gauges and strain gauges for all specimens. Dial gauge (DG1) was installed vertically under the bottom flange of the test specimens at the mid-span to measure the maximum vertical deflection. Two dial gauges (DG2 and DG3) were installed vertically under the bottom flange at the left shear zone and the right shear zone of the beam test to measure the vertical deflection. Dial gauge (DG4) was installed horizontally at the mid-span to measure the horizontal deformation. The strain gauge (SG1) was installed to measure the strain on the bottom flange at the mid of span. Two strain gauges (SG2 and SG3) were installed to measure the strain on the steel web at the left shear zone and the right shear zone. Other two strain gauges (SG4 and SG5) were installed to measure the strain on FRP at mid-length of CFRP strips in the left shear zone and the right shear zone.

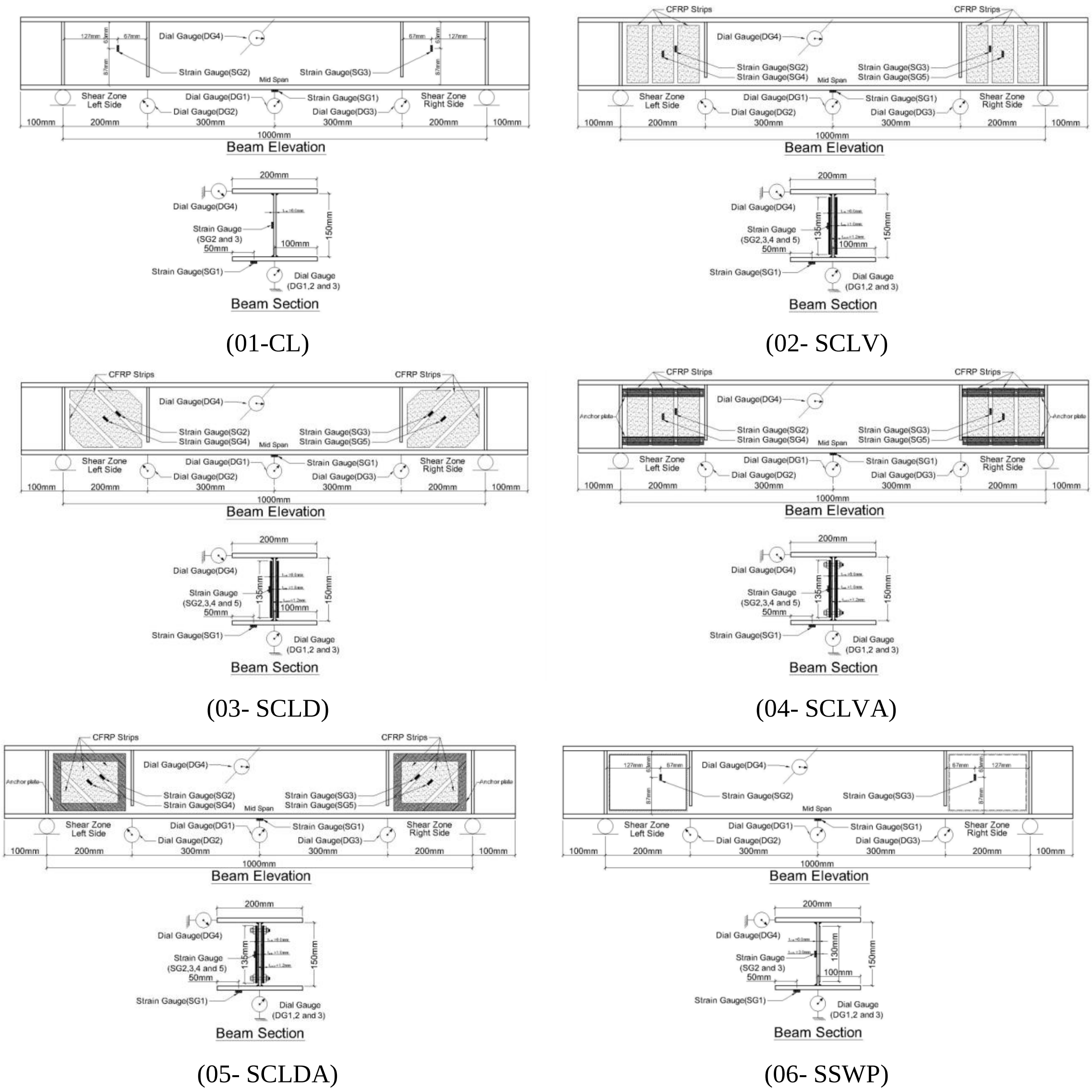



Figure (10): The locations and directions of the used dial gauges and strain gauges

## 3. Test Results and Discussions

### 3.1 Modes of failure

Modes of failure were different from specimen to other. For the control beam (01-CL), the failure mode was a shear failure due to steel yielding and shear buckling of the beam web. And it would be clearer when seen the grid that drawn on the steel web in the shear zone as displayed in Figure (11). For the strengthened specimen by vertical CFRP strips without end anchorage (02- SCLV), the failure mode was shear buckling for the steel web and by debonding for CFRP in the left shear zone and by delamination for CFRP in the right shear zone as displayed in Figure (12). Moreover, for the strengthened specimen by 45˚ diagonal CFRP strips without end anchorage (03- SCLD), the failure mode was shear buckling for the steel web and by debonding for CFRP in the both of shear zones as displayed in Figure (13). The failure of both specimens (02- SCLV) and (03- SCLD) were a sudden failure without apparent indication of the failure. The modes of failure for the CFRP laminate before and after anchoring were not the same. Through applying the mechanical end-anchorage with steel plates the behavior of the strengthening beams was changed. For the strengthened specimen by vertical CFRP strips with end anchorage (04-SCLVA), the failure mode was shear buckling for the steel web and by delamination for CFRP in the both of shear zone without any pulling out for the CFRP from the end-anchorage steel plates as displayed in Figure (14). Which mean the end-anchorage steel plates system that used in the specimen (04-SCLVA) was affected system due to prevented the CFRP from the pulling out. Moreover, for the strengthened specimen by 45˚ diagonal CFRP strips with end anchorage (05- SCLDA), the failure mode was shear buckling for the steel web with debonding and pulling out for CFRP in the both of shear zones from the steel web and end-anchorage steel plates as displayed in Figure (15). And the failure of the specimens (04-SCLVA) and (05-SCLDA) were not sudden failure with apparent ductile indication before the failure. For the last specimen that strengthened by traditional welded steel plate's method (06-SSWP), the failure mode was shear buckling for the steel web with a collapse in the strengthened steel plates beside the area of weld in the left shear zone as displayed in Figure (16). This is may be due to the effect of the welding on the steel. The failure of the specimen (06-SSWP) was a sudden failure without apparent indication of the failure due to the collapse in the welding area.

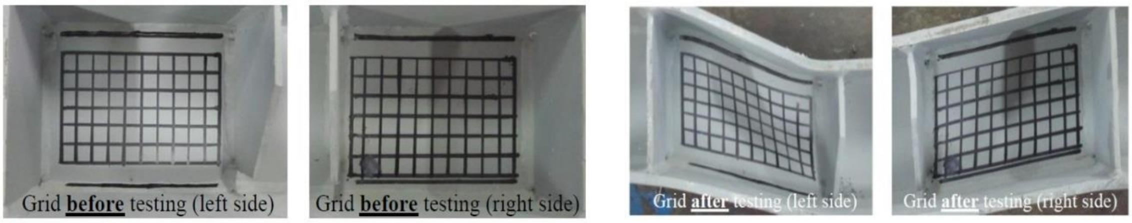



Figure (11): The grids in the left and right shear zone before and after testing for (01-CL)


Figure (12): Debonding in the left shear zone and delamination the right shear zone for specimen (02-SCLV)

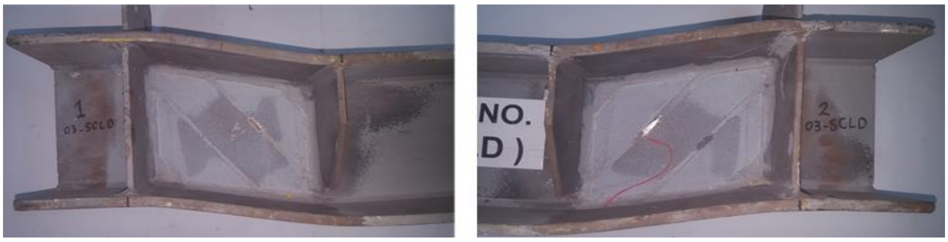


Figure (13): Debonding in the left and right shear zone by shear failure in the material of epoxy  for specimen (03-SCLD)

Figure (14): Delamination for CFRP in the both of shear zone without any pulling out for the CFRP from the end-anchorage steel plates for specimen (04-SCLVA)

Figure (15): Debonding and pulling out for CFRP in the both of shear zones from the steel web and end-anchorage steel plates for specimen (05-SCLDA)

Figure (16): Shear buckling for the steel web with collapse in the strengthened steel plates beside the area of weld in the left shear zone for specimen (06-SSWP)

## 3.2 Vertical Deflection

The vertical displacement has a great indication to make a comparison between test specimens that were tested. Perhaps even the most important parameter in the shear and flexural strengthening is to reduce the values of vertical displacement for the strengthened beams compared with the non-strengthened ones. The vertical displacements of the strengthened beams were less than the non-strengthened one. Furthermore, the application of end anchorage decreased the vertical displacements considerably. The effect of the end-anchorage system (type A) on the strengthened specimen by vertical CFRP strips and the comparison in the load-vertical displacements carve at the mid-span with the non-strengthened ones by CFRP in the specimens (01-CL) & (06-SSWP) is displayed in Figure (17). Also, the effect of the end-anchorage system (type B) on the strengthened specimen by 45˚ diagonal CFRP strips and the comparison in the load-vertical displacements carve at the mid-span with the non-strengthened ones by CFRP in the specimens (01-CL) & (06-SSWP) is displayed in Figure (18). The greatest result of the reducing vertical displacements achieved by the specimen (05-SCLDA) which strengthened by 45˚ diagonal CFRP strips with using end anchorage system type B, where vertical displacement at proportional limit reduced by 86.6%.

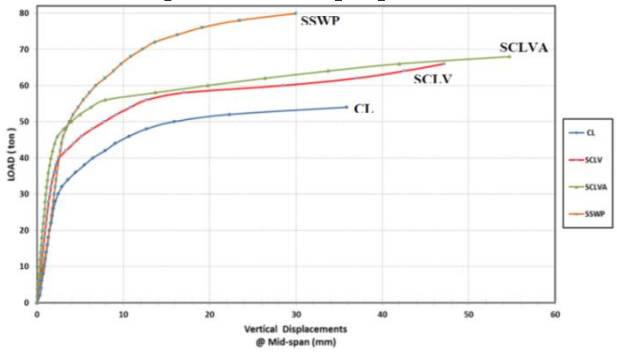



Figure (17): Load-Vertical displacements carve at the mid span for the specimens (01-CL), (02-SCLV), (04-SCLVA) and (06-SSWP)

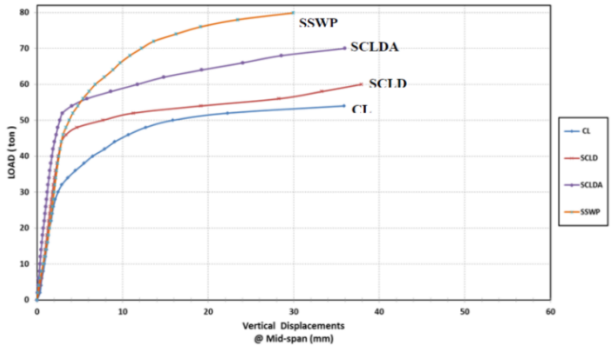



Figure (18): Load-Vertical displacements carve at the mid span for the specimens (01-CL), (03-SCLD), (05-SCLDA) and (06-SSWP)

## 3.3 Load Carrying Capacity

The increased percentage of the ultimate plastic load and the maximum elastic load of strengthened specimens is the most significant parameters necessary for the strengthening method, naturally compared with the non-strengthened beam (control beam).

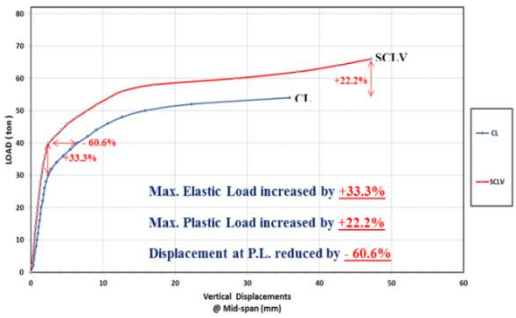
It appears clear in Table (4) the maximum elastic load for the tested specimens. By applying the CFRP on the steel web of specimens, the maximum elastic load of the steel I-beams could increase by about 33.33% in the vertical direction and by about 46.47% in the diagonal direction. When applying anchorage at the CFRP ends, the maximum elastic load of the steel I-beams could increase by about 53.33% in case of used CFRP end-anchorage system type A and by about 73.33% in case of used CFRP end-anchorage system type B. In addition to using of traditional strengthening method by welding steel plates on the web of specimen increase the maximum elastic load by about 53.33% in this experimental study. This means that applying of the CFRP strips on the web of I-beams lead to a great increase in the elastic load bearing capacity, that means great increase in the global shear strength for I-beams as illustrated in Figure (19).

Also, Table (4) shows that the maximum elastic load was increased with applying end-anchorage system type A by about 15.00% from the same specimen without end-anchorage. And the maximum elastic load was increased by applying end-anchorage system type B by about 18.18% from the same specimen without end-anchorage. This means that using end-anchorage system has somewhat acceptable.

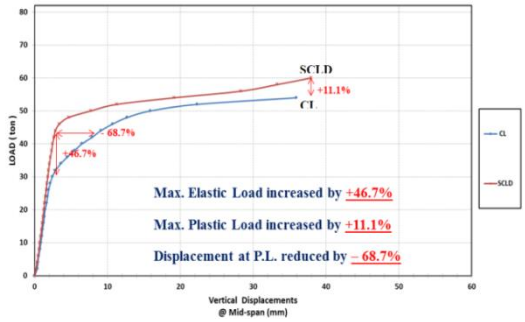
In the Table (5) demonstrates the ultimate (Plastic) load for the tested specimens. By applying the CFRP on the steel web of specimens, the ultimate (plastic) load of the steel I-beams could increase by about 22.22% in the vertical direction and by about 11.11% in the diagonal direction. When applying anchorage at the CFRP ends, the ultimate (Plastic) load of the steel I-beams could increase by about 25.92% in case of used CFRP end-anchorage system type A and by about 29.62% in case of used CFRP end-anchorage system type B. In addition to using of traditional strengthening method by welding steel plates on the web of specimen increase the ultimate (Plastic) load by about 48.15% in this experimental study. This means that applying of the CFRP strips on the web of I-beams lead to a good increase in the ultimate (Plastic) load bearing capacity as illustrated in Figure (19).

As well, Table (5) shows that the ultimate (Plastic) load was increased with applying end-anchorage system type A by about 3.03% from the same specimen without end-anchorage. And the ultimate (Plastic) load was increased with applying end-anchorage system type B by about 11.67% from the same specimen without end-anchorage. This means that using end-anchorage system had small acceptable values in the ultimate (Plastic) load bearing capacity from the specimen without end-anchorage.

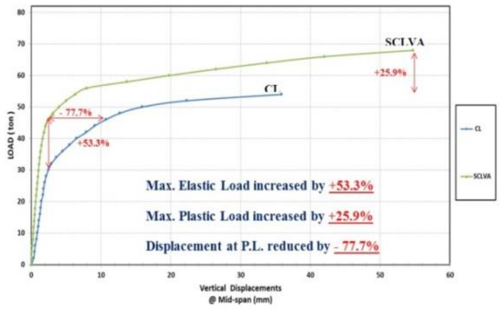
All previous results and percentages are clearly displayed in the graphs from Figure (19-a) to Figure (19-e), it shows the comparison in the load-vertical displacements carve at the mid-span between each test specimens that were tested with the control specimen (01-CL).



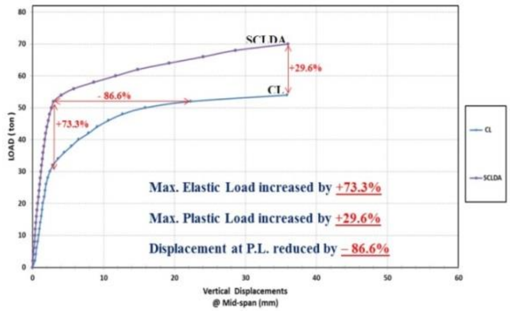

**a)** (02- SCLV) compare with (01-CL)



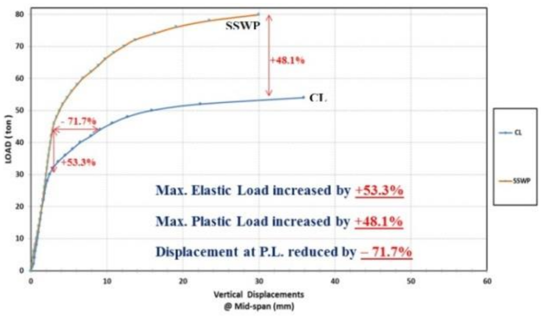

**b)** (03- SCLD) compare with (01-CL)




**c)** (04- SCLVA) compare with (01-CL)




**d)** (05- SCLDA) compare with (01-CL)




**e)** (06- SSWP) compare with (01-CL)

Figure (19): Load-Vertical displacements carve at the mid span for each specimens compared with control specimen (01-CL)

Table (4): Maximum elastic load carrying capacities of the specimens

| Specimen | CFRP end-anchorage system | Elastic Load | | |
|---|---|---|---|---|
| | | Load (ton) | Load increase compared with control beam (%) | Load increase compared with non-anchorage beam (%) |
| **01-CL** | N/A | 30 | 0 | - |
| **02-SCLV** | N/A | 40 | 33.33 | 0 |
| **03-SCLD** | N/A | 44 | 46.47 | 0 |
| **04-SCLVA** | Type A | 46 | 53.33 | 15.00 |
| **05-SCLDA** | Type B | 52 | 73.33 | 18.18 |
| **06-SSPW** | N/A | 46 | 53.33 | - |

Table (5): Ultimate plastic load carrying capacities of the specimens

| Specimen | CFRP end-anchorage system | Ultimate (Plastic) Load | | |
|---|---|---|---|---|
| | | Load (ton) | Load increase compared with control beam (%) | Load increase compared with non-anchorage beam (%) |
| **01-CL** | N/A | 54 | 0 | - |
| **02-SCLV** | N/A | 66 | 22.22 | 0 |
| **03-SCLD** | N/A | 60 | 11.11 | 0 |
| **04-SCLVA** | Type A | 68 | 25.92 | 3.03 |
| **05-SCLDA** | Type B | 70 | 29.62 | 11.67 |
| **06-SSPW** | N/A | 80 | 48.15 | - |

## 3.4 Lateral deformation

The lateral deformation of the steel I-beams was stopped at each lateral support beams as shown in Figure (20). Due to this prevention, no lateral torsional buckling happened and the values of lateral deformations for the test specimens were very low. Figure (21) shows that the lateral deformation of the strengthened beams was lower than that of the non-strengthened ones. Furthermore, the lateral deformation of the specimens that using end-anchorage to fixation the ends of CFRP strips was less compared with non-anchored one, expect the strengthened specimen (02-SCLV) by vertical CFRP strips has the best-achieved result.

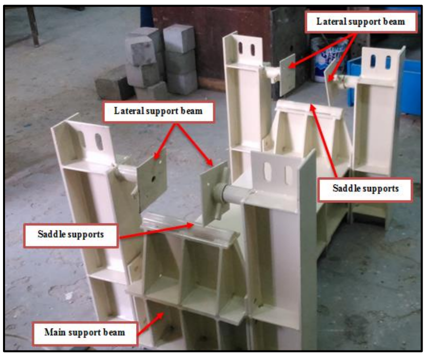



Figure (20): Lateral supports

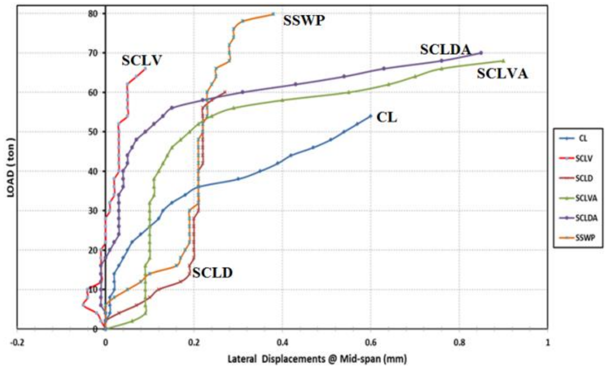
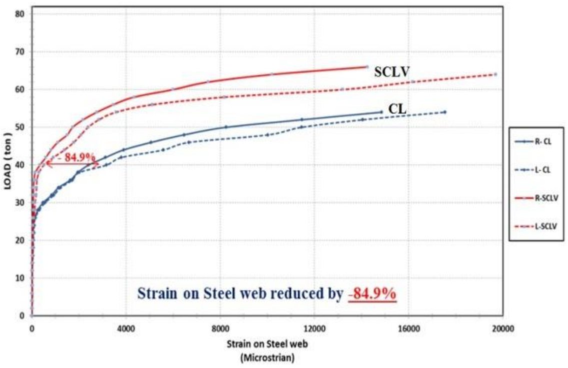



Figure (21): Lateral deformation at the mid span

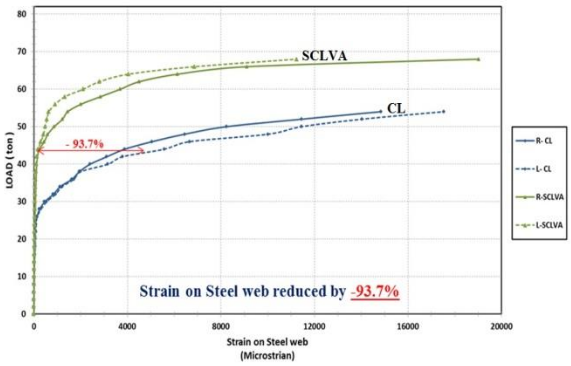
## 3.5 Strain on steel web in the shear zones

The total applied load affected on the values of shear strain on steel web in the shear zones. To measure the shear strain on the steel web in the shear zones the strain gauges were installed on the steel web in the distance between the CFRP strips that pasted.

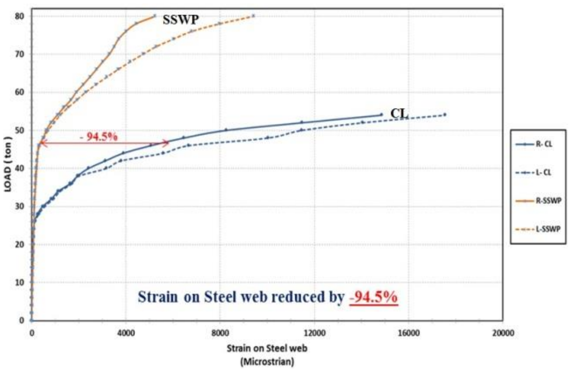
It was founded that pasting the vertical strips on the steel web of specimens on both sides reduced the strain by 84.90% compared to the control beam as illustrated in Figure (22-a). Besides that, the using of end-anchorage with vertical strips pasting to the steel web on both sides reduced the strain by 93.70% compared to the control beam as illustrated in Figure (22-b). For the strengthened specimen by 45˚ diagonal CFRP strips pasting to the steel web on both sides reduced the strain by 76.40% compared to the control beam as illustrated in Figure (23-a). Also, when used the end-anchorage with 45˚ diagonal CFRP strips to the web on both sides reduced the strain by 78.70% compared to the control beam as illustrated in Figure (23-b). Also, it was observed the reduction of the shear strain gotten by strengthening the specimen by 3mm thickness of steel plate on shear zone, can get almost the same reduction in the shear strain by using vertical strips pasting on the steel web with used end-anchorage system type A to fix the ends of CFRP strips by 94.5% as illustrated in Figure (22-c).
As discussed above, the strengthening system contributed to the load carrying capacity by highly reducing the shear strains at each load level which is resulted to an increase in shear capacity. However, it is clear that increasing the restricted of the steel web by the strengthening system lead to increase the shear capacity of the strengthened specimens.
Finally, applying CFRP strips on shear zones decreased shear strain on web appropriately. And applying CFRP strips with using end-anchorage on the steel web decreased the shear strain on the web than applying CFRP strips on the web without end-anchorage as illustrated in Figure (22-d) and Figure (23-c).



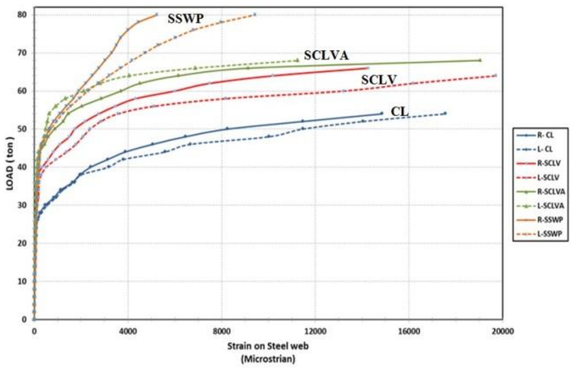

**a)** (02- SCLV) compare with (01-CL)




**b)** (04- SCLVA) compare with (01-CL)

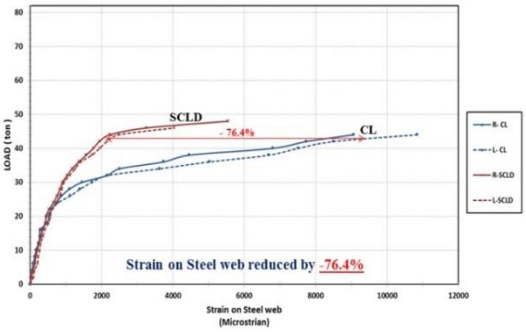



**c)** (06- SSWP) compare with (01-CL)

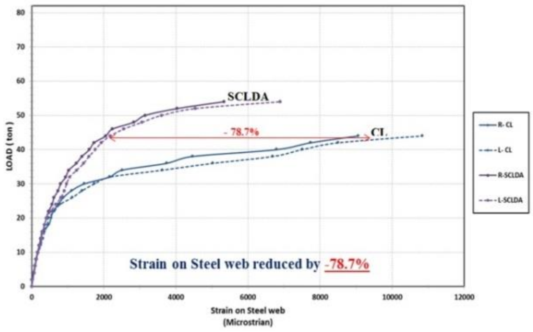



**d)** (01-CL), (02-SCLV), (04-SCLVA) and (06-SSWP)

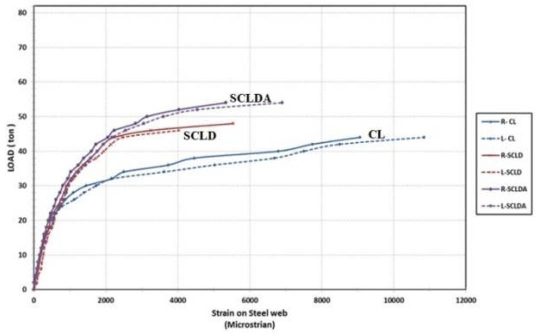
Figure (22): Load-Strain carve for the steel web at left and right shear zone for each specimens compared with control specimen (01-CL)




**a)** (03- SCLD) compare with (01-CL)




**b)** (05- SCLDA) compare with (01-CL)




**c)** (01-CL), (03-SCLD) and (05-SCLDA)

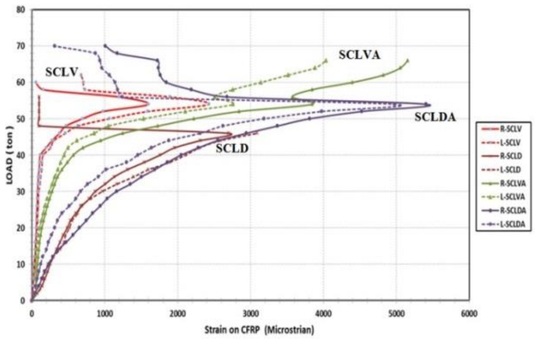
Figure (23): Load-Strain carve for the steel web at left and right shear zone for each specimens compared with control specimen (01-CL)

## 3.6 Strain on the CFRP Strip

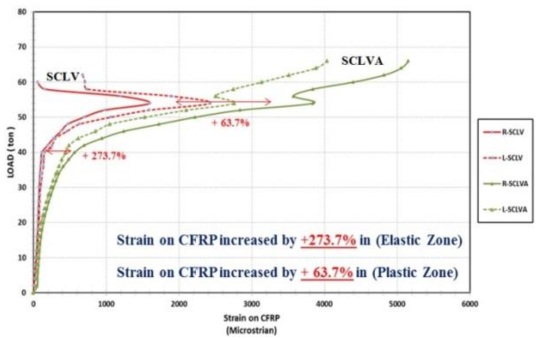
The CFRP strips which were pasted on the web of test specimens in this study were unidirectional laminates. And the tensile strain that was generated on the CFRP strips because of CFRP strips restriction for steel web deformation or tendency to buckling. The tensile strain on the CFRP strips at the mid of span was measure to study the effectiveness of using CFRP strips on the web of steel I-beams and the effectiveness of using mechanical end anchorage to fix CFRP strips as illustrated in Figure (24-a).

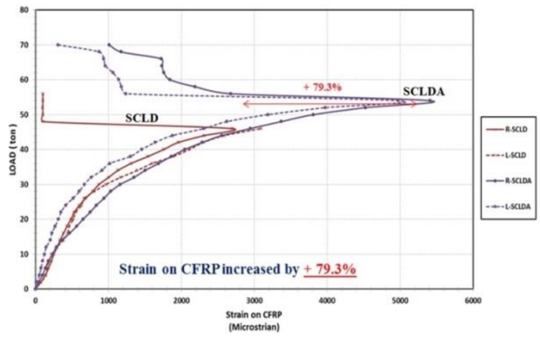
The first failure mode was longitudinal delaminating then debonding from steel web for CFRP in the both of shear zone in the specimen (02-SCLV). In this failure mode, cracks were formed on the CFRP strips in a longitudinal way then debonding occurred to the parts of CFRP strips that delaminated at the first. The second failure mode was debonding for CFRP in the both of shear zones in the specimen (03-SCLD). The third failure mode was delamination for CFRP in the both of shear zone without any pulling out of the CFRP from the end-anchorage steel plates in the specimen (04-SCLVA). Which mean the end-anchorage steel plates system that used in the specimen (04-SCLVA) was affected system due to prevented the CFRP from the pulling out. Moreover, the fourth failure mode was debonding and pulling out for CFRP in the both of shear zones from the steel web and end-anchorage steel plates in the specimen (05-SCLDA).

From the results that gotten, the pasting CFRP strips on the steel web has prevented the web of steel I-beams from distortion at low load values and delay the yielding point for the material of the web by a significant value that due to CFRP strips restriction. Moreover, results of CFRP strains show that applying end anchorage on the ends of CFRP strips increased the strain in CFRP strips. The strain increasing of the CFRP strips in specimens (04-SCLVA) was +63.70% compared with the strain of CFRP strips in the specimen (02-SCLV) as illustrated in Figure (24-b). And the strain increasing of the CFRP strips in specimens (05-SCLDA) was +79.30% compared with the strain of CFRP strips in the specimen (02-SCLD) as illustrated in Figure (24-c).




**a)** (02- SCLV), (03- SCLD), (04- SCLVA) and (05- SCLDA)




**b)** (02- SCLV) compare with (04- SCLVA)

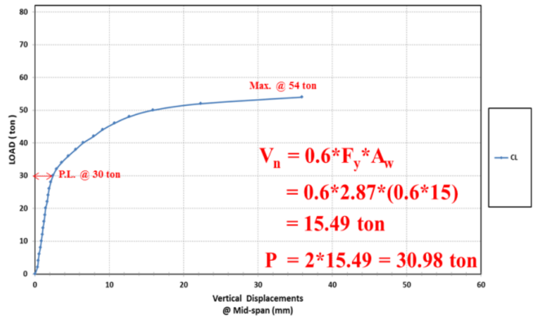
**c)** (03- SCLD) compare with (05- SCLDA)

Figure (24): Tensile strain on CFRP strips at the mid span of strips

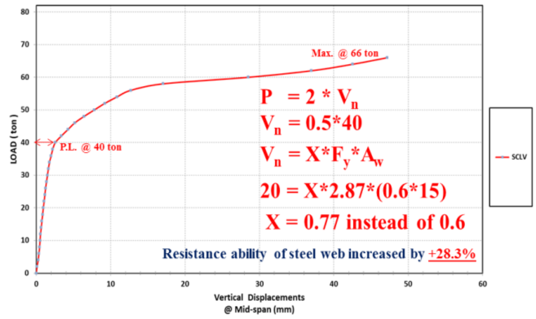
## 3.7 Shear resistance ability of steel I-beams web

Shear resistance ability of steel I-beams web has a constant value for any beam that able to calculate it. Especially for the beams without strengthening in the web or for the beams that strengthened by traditional method for the strengthening of steel beams. But the results of tests were shown that, strengthening the steel web by using CFRP strips enhance the behavior of the steel web and shear resistance ability of steel I-beams web. The value of shear resistance ability of steel I-beams depend on dimensions of steel web and material properties of steel web, shear resistance ability of steel I-beams usually equal 60% from yielding stress of steel as shown in Figure (25-a) & Figure (25-f).

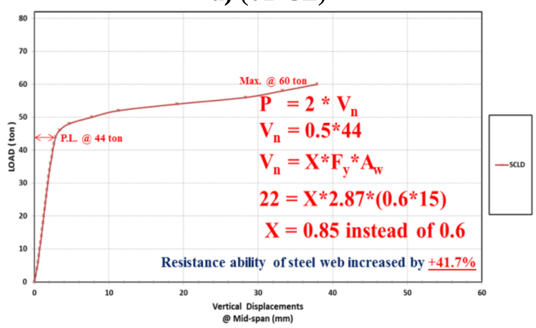
Moreover, it was founded that pasting the vertical strips to the steel web of the specimen on both sides increased the shear resistance ability of steel I-beams by +28.30% compared to the control beam as illustrated in Figure (25-b). Besides that, the using of end-anchorage with vertical strips pasting to the steel web on both sides increased the shear resistance ability by +41.70% compared to the control beam as illustrated in Figure (25-c). For the strengthened specimen by 45˚ diagonal CFRP strips pasting to the steel web on both sides increased the shear resistance ability by +48.30% compared to the control beam as illustrated in Figure (25-d). Also, when used the end-anchorage with 45˚ diagonal CFRP strips to the web on both sides increased the shear resistance ability by +65.00% compared to the control beam as illustrated in Figure (25-e).



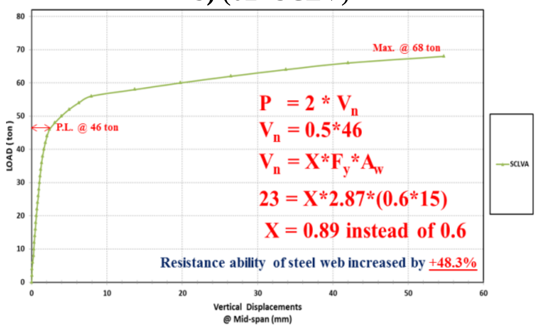

**a)** (01-CL)



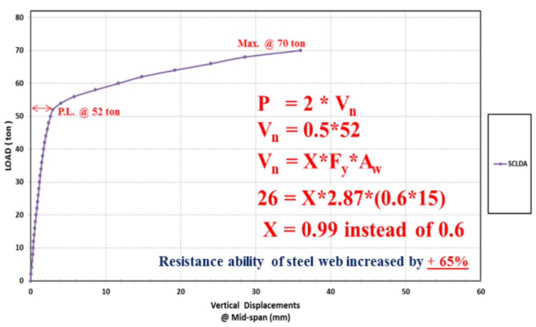

**b)** (02- SCLV)



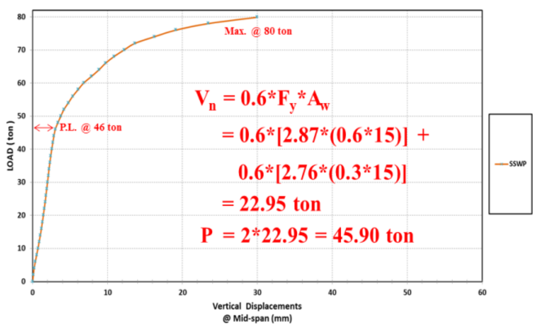

**c)** (03- SCLD)




**d)** (04- SCLVA)




**e)** (05- SCLDA)




**f)** (06- SSWP)

Figure (25): Shear resistance ability of steel web for test specimens

## 3.8 Strain on the Steel Bottom Flange

The difference of tensile strain with the load for the bottom flange at the mid of span is shown in Figure (26), and it shows that applying CFRP strips and end anchorage system reduced the strain on the steel bottom flange. Also, that little variation in the tensile strain on the bottom flange versus the load at the mid-span led to increasing the global stiffness of steel beam due to the various strengthening system.

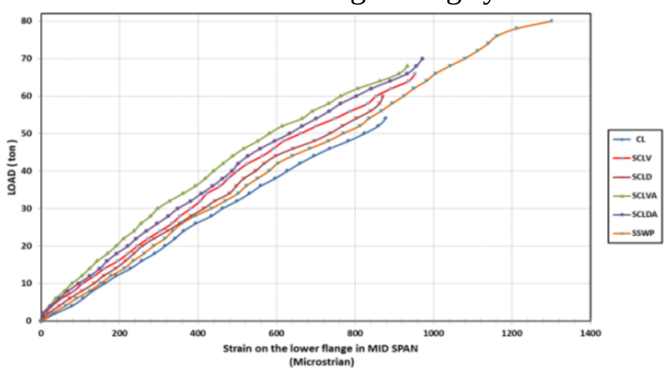



Figure (26): Tensile strain on beam bottom flange at the mid-span.

## 4. Conclusions

Based on the results of the experimental work executed in this research, the following conclusions can be drawn as follows:

1- Pasting CFRP strips without anchorage on the steel I-beams web in vertical and 45˚ diagonal orientation increased the maximum elastic load by about +33.3% and +46.7% respectively, moreover it increased the ultimate plastic load by about +22.2% and +11.1% respectively, furthermore decreased the strain on steel I-beams web by -84.9% and -76.4% respectively, and decreased the vertical displacement at proportional limit by -60.6% and -68.7% respectively in comparison with the control beam.

2- Using mechanical end anchorage to fix the ends of CFRP strips on the web of the tested steel I-beams in vertical and 45˚ diagonal orientation increased the maximum elastic load by +53.3% and +73.3% respectively, furthermore it increased the ultimate plastic load by +25.9% and +29.6% respectively, moreover decreased the strain on steel I-beams web by -93.7% and -78.7% respectively, and decreased the vertical displacement at proportional limit by -77.7% and -86.6% respectively compared with the control beam.

3- Applying steel plates and bolts as a mechanical end anchorage for the ends of CFRP strips to strengthen steel I-beams was found to be an effective technique. end anchorages that used to fix the ends of CFRP strips on the web of the tested steel I-beams in vertical and 45˚ diagonal orientation increased the maximum elastic load by about +15.0% and +18.18% respectively, moreover it increased the ultimate plastic load by about +3.03% and +11.67% respectively compared with the strengthened beam by CFRP strips without end anchorage.

4- Attaching the CFRP strips with end-anchorage in 45˚ diagonal orientation increased the strain of CFRP strips more than attaching it without end-anchorage by about +79.3%, but attaching the CFRP strips in the vertical orientation with end-anchorage increased the strain of CFRP strips more than attaching it without end-anchorage by about +63.7%.

5- Strengthening the web of the tested steel I-beams at shear zones by using CFRP strips in vertical orientation with end-anchorage achieved a close results to strengthening the specimen by traditional method with steel plate in most properties of structural behavior such increasing in the maximum elastic load which was +53.3% for each, reduction of the shear strain on steel I-beams web which was -93.7% & -94.5% respectively and reduction of the vertical displacement at proportional limit which was -77.7% & -71.7% respectively.

6- The shear resistance ability of steel web in the steel I-beams became 77.0% and 85% for specimens strengthened by using CFRP strips without end-anchorage in vertical and 45˚ diagonal orientation respectively, also it became 89.0% and 99% for specimens strengthened by using CFRP strips with end-anchorage in vertical and 45˚ diagonal orientation respectively instead of 60% in the control beam or in the beam that was strengthened by steel plates (traditional method).

7- The failure mode in the beam that was strengthened by steel plates (traditional method) was sudden failure without apparent indication before the failure due to the collapse in the area beside welding due to the effect of weld, also the failure modes of strengthening specimens by CFRP strips without end-anchorage were sudden failure with a little indication of the failure before the failure due to delamination and end debonding for CFRP strips , but the failure modes of strengthening specimens by CFRP strips with end-anchorage weren't sudden failure they apparent ductile indication before the failure due to the effect of end-anchorage in change the sudden failure to pre-warning failure.

8- Using CFRP strips in the strengthening of steel I-beams web improved the shear resistance of steel web with a decrease in the vertical displacements, lateral deformation, and shear strain on the web of the strengthened steel I-beams.

9- Using end-anchorage on the CFRP strips increased the utilization efficiency of CFRP strips and changes the failure modes from the sudden failure to pre-warning failure.

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