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Enhancing the End Anchorage of Strengthened Steel I-Beams UsingCFRP Laminates

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Abstract-Strengthening of steel structural elements using carbon fiber reinforced polymer (CFRP) laminates has been applied widely in the last few years. One of the main problems of using CFRP for flexural strengthening of steel beams is the debonding at the ends of CFRP laminate. This research work presentsan experimental study and detailed analysis of the effectiveness of three different mechanical techniques of end-anchoring. Five steel I-beams were tested in flexure using three-point load test. The first beam was not strengthened and was used as a control beam. The second beam was strengthened by CFRP laminateswithout any end-anchorage. The other three beams were strengthened by CFRP laminateswith three different mechanical end-anchorages techniques using steel plates and bolts (with three different configurations).Test results revealed that applying steel plates and bolts to anchor the ends of CFRP laminate is an effective technique. Using end anchorage significantlyimproved the load carrying capacity of the strengthenedsteel I-beam, decreased the deformation and strain of the whole beam including vertical deflection, lateral deflection, and tensile strain on the CFRP laminates. In addition, applying end anchorage suppressed the end debonding failure and changed the failure mode from sudden failure to pre-warning failure.

Index Terms- CFRPlaminates, Deflection, Flexural strengthening, Interfacial stress analysis, Mechanical end anchorages, SteelI-beam, Tensile strain.

1 Introduction

FRP laminates have been widely used in structural repair and strengthening techniques for buildings and bridges in the recent years. The superior properties of CFRP laminates such as high young's modulus, high tensile strength, high strength to weight ratio, high stiffness to weight ratio and good durability have made them a good alternative to the traditional repair and strengthening materials.

Many studies have recently been conducted on the strengthening of steel/composite beams by the bonding of FRP laminates to the tension flange of a simply supported beam [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12].These studies have demonstrated that significant strength gains and, in some cases, significant stiffness gains can be obtained using adhesively bonded FRP laminates. However, flexural strengthening of steel beams by using FRP usually suffers problem in the form of debonding at the end of the FRP laminate. This is normally attributed to the very high stress and strain intensity that occurs at the end of the laminates [11], [13], [20],[21].

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Some researchers have demonstrated techniques to overcome this problem (debonding at the end of the CFRP laminates) for steel structures by using a tapered CFRP end cutting shape [11], [14], [15], [16], [17], [18], [19], [20].Using a longer CFRP laminate reduces the bending moment at the ends and hence the magnitude of the stress level [22], but this is not economic because of the high cost of CFRP laminates. Applying mechanical end anchorage at the end of the CFRP laminates by using a three-piece clamping system for steel-concrete composite bridges increased the resistance against peeling and debonding [13]. The application of steel plates and bolts as a CFRP end anchorage for steel I-beams improved the load carrying capacity and decreased the strain and deformation of the whole beam [21].

Galal et al. [23] proposed a ductile anchorage system to overcome the problem of CFRP laminate debonding for repairing damaged steel beams with different percentages of artificial deterioration using different CFRP systems. The anchorage system proposed by the investigators demonstrated that it would increase both strength and ductility of the repaired beams and could delay debonding or peeling of the CFRP sheets from the steel substrate.

Karam et al. [24] investigated the flexural performance of pre-damaged steel-concrete composite beams repaired using externally-bonded CFRP laminates with and without mechanical anchors. The used mechanical anchorage was applied by using steel coupons and two rows of bolts with 6 mm diameter spaced laterally at 75 mm which were drilled on the tensile flange and were spaced along the longitudinal direction with intervals of 135 mm. The mechanical anchorage was installed at specified locations along the soffit of bottom steel flange after the application

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of the CFRP. The application of mechanical anchors in the repair regime improved the strength gain from 15% to 19% and from 46% to 63% for the beams with 45% and 100%damage states, respectively, relative to the strength of the corresponding damaged un-strengthened beam.

The main objective of this research is to study experimentally the effectiveness of different mechanical techniques by using steel plates and bolts to improve the end anchorage of CFRP laminates used for strengthening steel I-beams in flexure.

2 Experimental Program

To investigate the effectiveness of different mechanical techniques of CFRP end-anchoring by using steel plates and boltsfor strengthening steel I-beams, five small-scale specimens were tested in flexure and three different configurations of end anchorages were suggested. The first beam, specimen (CL), was non-strengthened and used as a control specimen. The second beam, specimen ST, was strengthened without applying any end anchorage which used as a reference to the strengthened specimens with endanchorages. The other three beams, specimens STA, STB and STC, were strengthened with three different end anchorages A, B and C respectively. Details of the three anchorage systems configurations will be explained later. The load bearing capacity, vertical deflection, lateral deformation, strain on CFRP laminate, strain on steel bottom flange and modes of failure were measured for all five beams.

2.1 Test Specimens

In this study, steel I-beams with grade 37 according to Egyptian code of practice were used. All beams were 1.20 m long. Beam section was built up section with dimensions as illustratedin Fig. 1. To suppress premature web crushing and flange buckling, two 6 mm thick steel stiffeners were welded to each beam at the mid span and two supports, one either side of the web.

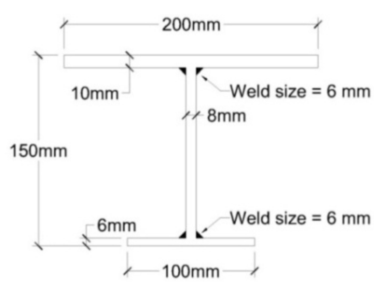

Fig. 1. Dimensions of steel I-beam cross section

The used CFRP laminates wereSika® CarboDur® S512/80 with50 mm in width and 1.20 mm in thickness, they were cut to a length of 500 mm for strengthening beams. They have a mean modulus of elasticity of 165 GPa, a mean tensile strength of 3.10 GPaand an ultimate strain of 1.70 % according to manufacturer's data sheet.The CFRP laminates were installed on the beam flange by using special adhesive. The adhesive must be strong enough to resist the high stress generated during loading. The type of the adhesive used in this study was Sikadur® 30. It hasa modulus of elasticity of 9.60 GPa in compression and 11.20 GPa in tension, a tensile strength of (24 to 31) MPa after 7 days, a shear strength of (14 to19) MPa after 7 days and a mean bond strength on steel of 30 MPa. The thickness of adhesive layer was uniform at 1 mm.

Two different steel plates (a) and (b) were used to anchor the CFRP laminate with the bottom flange of the steel beam at the end of the CFRP laminate. The length and the thickness of the steel plates were the same, but their widths were varied because of the different spacing. Anchor plate type (a) was used for end anchorage types (A and B) and anchor plate type (b) was used for end anchorage type (C). The steel grade of the used steel anchor plates and steel I-beams was the same. The dimensions of the different steel anchor plates are illustrated in Fig. 2.

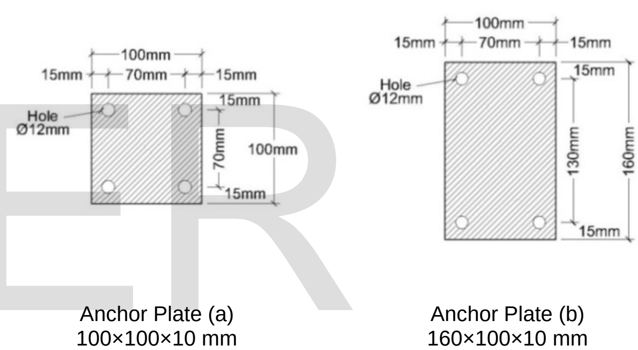

Fig. 2.Dimensions of the steel anchor plates

To connect the steel anchor plate to the bottom flange of the steel I-beam at each end of the CFRP laminate, four bolts were used. Two different bolts were used because of the different configurations of the suggested end anchorages, one of themwith diameter 10 mm and length 60 mm (Bolt A), and the other with diameter 12 mm and length 200 mm(Bolt B). Bolt (A) was used for end anchorage types (A and B) and Bolt (B) was used for end anchorage type (C).

Three different anchorage systems were applied on the specimens in this study by using steel anchor plates and bolts. The specifications and dimensions of the different anchorage systems A, B and C are illustrated in Fig. 3, Fig. 4 and Fig. 5 respectively.The Specimens code and detailed description of the three anchorage systems are as follows:

STA End anchorage system was applied by using steel anchor plate of dimensions (100x100x10 mm) which was installed at the end of CFRP laminate along the soffit of bottom steel flange through four bolts of diameter 10 mm. These four bolts were attached to the bottom flange via four holes of diameter 12 mm made in the bottom flange using a driller. Details of this anchorage system are shown in Fig. 3.

STB The same pervious steel anchor plate was used to apply the anchorage system for specimen STB, but the installation method was different. The anchor plate was attached to the bottom flange by using four bolts of diameter 10 mm. The four bolts were fixed at the outer face of the bottom flange by welding after cutting their heads. This anchorage system may be the most appropriate solution in case that the inner face of the bottom flange is inaccessible. Details of this anchorage system are shown in Fig. 4.

STC The end anchorage system used for specimen STC was applied by making an external frame installed at the end of CFRP laminate without drilling holes or welding in the bottom flange. The anchorage system consists of steel anchor plate of dimensions (160x100x10 mm) attached to the bottom flange via four bolts of diameter 12 mm which fixed at the top flange through four holes made by driller. Details of this anchorage system are shown in Fig. 5.

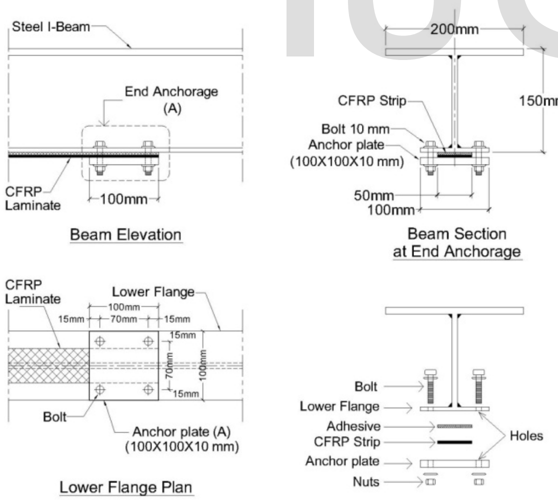

Fig. 3.Configuration of anchorage system type (A) – Beam STA

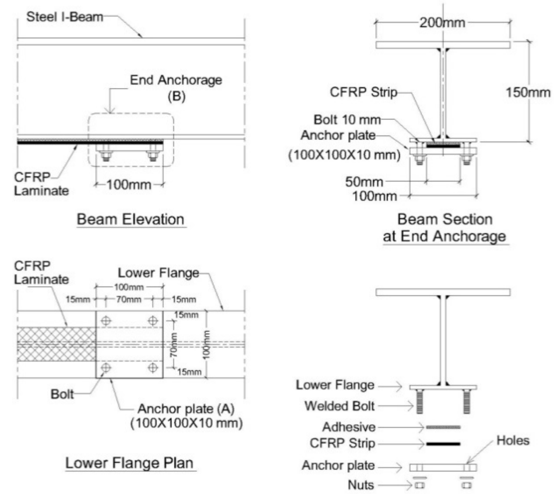

Fig. 4.Configuration of anchorage system type (B) – Beam STB

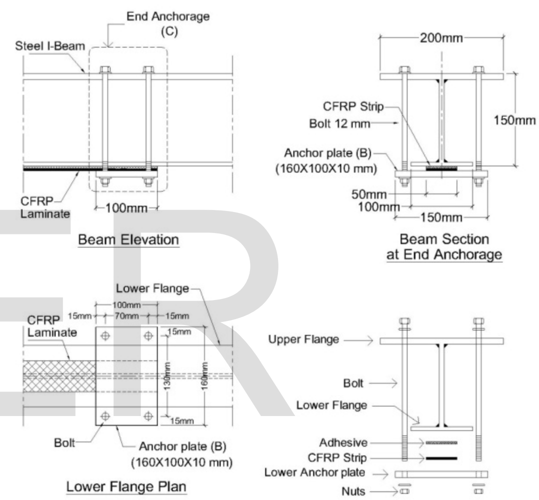

Fig. 5.Configuration of anchorage system type (C) – Beam STC

Preparation of test specimens

The following procedures were carried out for the preparation of test specimens; First,The surfaces of the anchor steel plates and the bottom flange of the steel I-beams were prepared to eliminate burrs or bevels and to make the surface rough and clean in the region that connected with CFRP laminates and also the surface of the CFRP laminates were prepared to be rough by using sandy sheet.

Second,the adhesive material was mixed according to the producing companymanufacturer data sheet instructions. Then, the surface of steel and CFRP laminates were cleaned by solvent. Then, the CFRP laminates were glued to the bottom flange of the specimens to achieve the required overlap area and thickness. The method of applying the adhesive was to lay more adhesive material along the center than the outer edges, which allowed the air trapped between the CFRP laminate and the bottom flange

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to escape when they were pushed together. Subsequently, both ends of the CFRP laminates were covered by adhesive in the region that connected with the anchor plates. Then, the surfaces of the steel anchor plates were covered with adhesive to be pasted at the end of the CFRP laminates. Subsequently, the steel anchor plates were placed at the ends of the CFRP laminates. Steel blocks were placed on the top of CFRP laminate during curing to ensure the correct positioning of the strip on the steel I-beam. After that, the excess adhesive along the longitudinal sides of the laminate and that covered the holes was cleaned.

After the adhesive wascured for 48 h, the bolts of the end anchorages were tightened and the steel blocks were replaced with wooden plates and steel clamps to make uniform pressure on the CFRP laminate during the remaining period of curing. The specimens were allowed to cure at room temperature for at least 7 days before testing. Directly before testing, the strain gauges were installed on the specimens.

2.2 Testset-up and instrumentation

The specimens were tested in a hydraulic testing machine with a maximum capacity of 200 ton, subjected to a three-point load bending set up. The clear span was kept constant at 1.00 m. The specimens were supported on two saddle supports through a support beam, which rested on the testing machine. Four lateral supports were used to resist the lateral torsional buckling of the steel I-beams; these lateral supports were connected to the support beam. The schematic of the three-point loadbending setup and the support beam is shown in Fig. 6.

Mechanical dial gauges and electrical strain gauges were installed on the specimens in order to measure deflections and strains. Fig. 7shows the locations and directions of the used dial and strain gauges for all specimens. One strain gauge (SG1) was installed on the CFRP laminate at the mid span in the longitudinal direction to measure the tensile strain in the CFRP laminate. In addition, two strain gauges (SG2 and SG3) with equal spacing were installed along the length of the CFRP laminate up to the start of the anchor steel plate to measure the strain distribution along the length of the CFRP laminate. Another strain gauge (SG4) was installed on the outer side of the beam's bottom flange to measure the tensile strain on the steel at the mid span. One dial gauge (DG1) was installed horizontally on the upper flange at the mid span to measure the lateral deformation, and another dial gauge (DG2) was installed vertically on the beam's bottom flange at the mid span to measure the vertical deflection. After placing the support beam and the specimen on the testing machine, the load was applied at the middle of the specimen using the hydraulic jack via a load cell of 85 ton capacity.

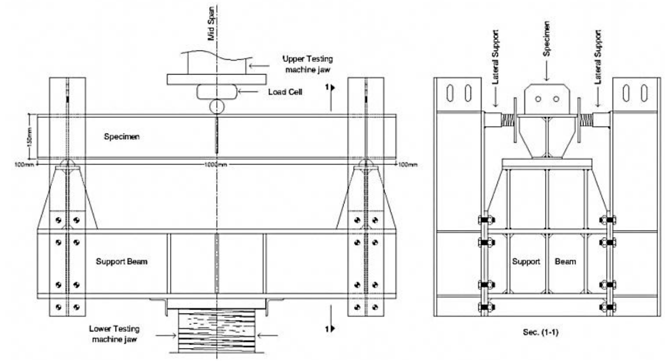

Fig. 6.The schematic of the three-point load setup and the support beam

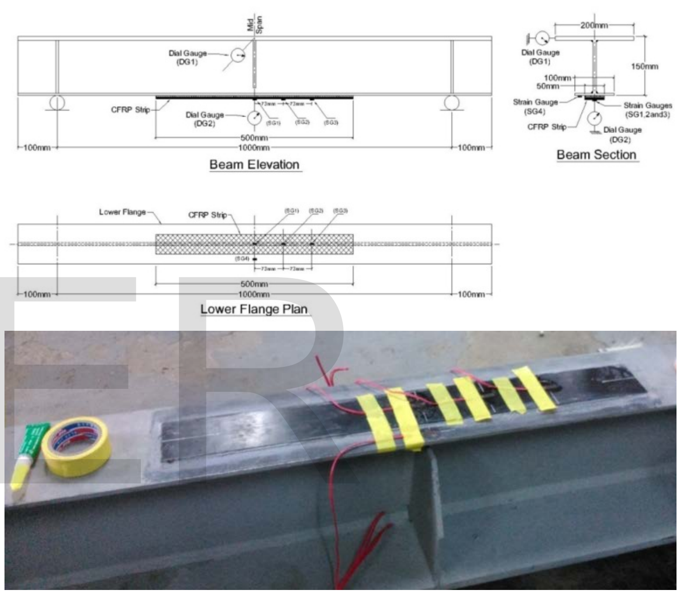

Fig. 7. The locations and directions of the used dial and strain gauges

3 Test Results and Discussions

3.1 Load carrying capacity

One of the most important parameters required from the strengthening process is the increase percentage in the ultimate load of strengthened specimens compared with non-strengthened ones.

Table 1demonstrates the ultimate load for the tested specimens. By applying anchorage at the CFRP ends, the ultimate load of the steel I-beams could increase by about 24.19%. This means that applying end-anchorage on steel I-beam strengthened by CFRP laminates lead to an appropriate increase in the ultimate load.

Also this table shows that the maximum load increase was obtained from applying end-anchorage type C, and the load increments were obtained by using end-anchorage

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types A and B are the same. This means that using end-anchorage system without drilling and welding the bottom flange of the upgraded beam is the best.

TABLE 1
SPECIFICATIONS AND LOAD CARRYING CAPACITIES OF THE SPECIMENS

Specimen	Code	CFRP end-anchorage system	Ultimate Load		
			Load (ton)	Load increase compared with B1 (%)	Load increase compared with B2 (%)
B1	CL	N/A	31	0	---
B2	ST	N/A	34	9.68	0
B3	STA	Type A	36	16.13	5.88
B4	STB	Type B	36	16.13	5.88
B5	STC	Type C	38.5	24.19	13.24

3.2Failure mode shapes

For the control beam (CL), the failure mode was bending failure due to steel yielding as presented in Fig. 8. For the strengthened beam without end anchorage (ST), the failure modes were debonding and delamination which can be clearly seen in Fig. 9. The failure of this beam was sudden failure and was due to the stress concentration at the ends of the CFRP laminates.

Fig. 8.Failure mode of control beam(CL)

Fig. 9.Failure mode of strengthened beam without end anchorage(ST)

By applying the mechanical end anchorage, the failure of CFRP strengthened steel I-beams has initiated by debonding at the mid span and then pull out of the CFRP laminate ends took place. Fig. 10,Fig. 11 and Fig. 12 show the end debonding and pulling out failure of the anchored strengthened beams STA, STB and STC respectively. It can be seenthat applying end anchorage by using steel plates and bolts suppressed the effect of the delamination and debonding at the ends of the CFRP laminate.

The effect of the three end anchorages types (A, B, and C) used in this research on the failure mode was the same. For the end anchorage type B, a crack was observed in the bottom flange of the steel beam in the anchorage zone as shown in Fig. 13. This is may be due to the effect of welding that madewas usedto fix the bolts in the bottom flange of the steel beam.

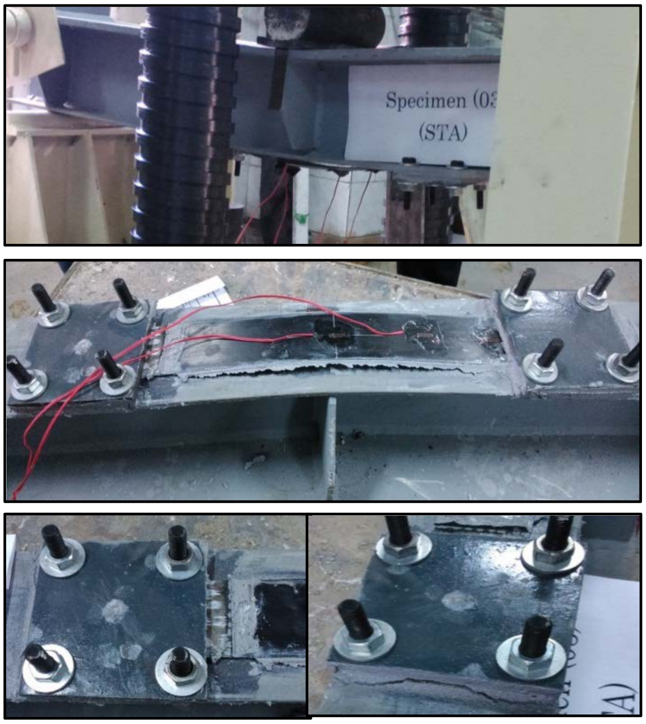

Fig. 10.Failure mode of STA beam

Fig. 11.Failure mode of STB beam

Fig. 12.Failure mode of STC beam

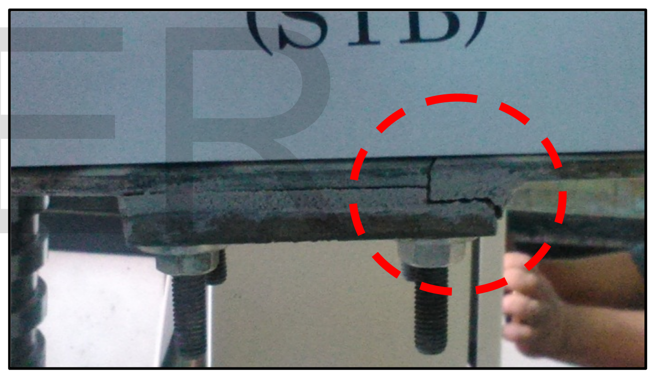

Fig. 13.Bottom flange crack in the anchorage zone (STB)

3.3 Vertical deflection

One of the most important parameters in the flexural strengthening is to decrease the value of vertical deflection for the strengthened beams compared with the non-strengthened ones.

Fig. 14 demonstrates that vertical deflections of the strengthened beams were less than the non-strengthened one. In addition, the application of end anchorage decreased the vertical deflection considerably. The best result achieved by the specimen STC which strengthened with end anchorage type C. There were no significant differences in the deflections of the strengthened beams with end anchorage type A and type B.

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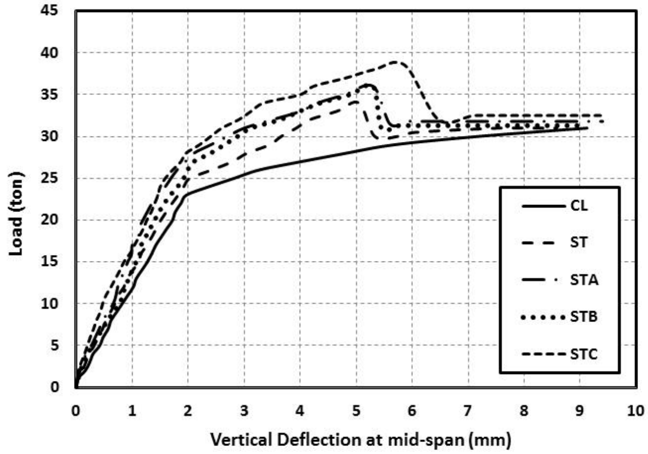

Fig.14.Vertical deflection at the mid span

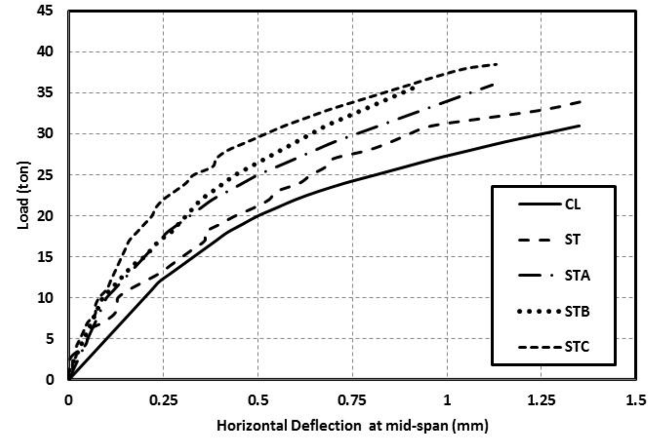

Fig. 16.Lateral deformation at the mid span

3.4Lateral deformation

In this research, the lateral deformation of the compression flange of the steel I-beams was prevented at each support as shown in Fig. 15. Due to this prevention, no lateral-torsional-buckling occurred and the values of lateral deformations for the tested beams were low. Fig. 16 demonstrates that the lateral deformation of the strengthened beams was lower than that of the non-strengthened ones. Moreover, Fig. 16 demonstrates that the lateral deformation of the anchored beams was less compared with non-anchored beams and the best result achieved by the specimen (STC).

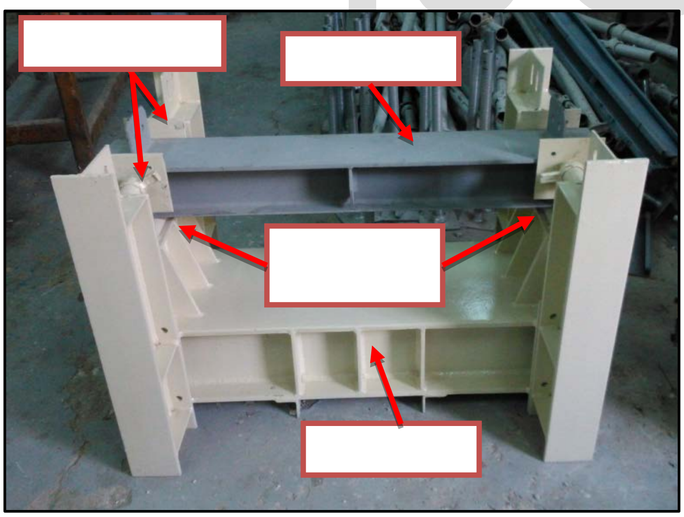

Fig. 15.Lateral supports of the tested specimen

3.5 Strain on the CFRP laminate

Tensile strain on the CFRP laminate at the mid of span, 75mm from the mid-span, and 150mm from the mid-span were chosen to study the effectiveness of using CFRP mechanical end anchorage on the strain distribution along the CFRP laminate . The tensile strain on the CFRP at the mid-span, 75 mm from the mid-span, and 150 mm from the mid-span versus the loadare shown in Fig. 17, Fig. 18, and Fig. 19 respectively. It can be seenthat by applying end anchorage, the strain on the CFRP decreased compared to the non-anchored specimens.

The strain distribution on the CFRP laminates for the different beams at the load values 24ton, 25ton, and 34ton is shown in Fig. 20, Fig. 21, and Fig. 22 respectively. These show that applying end anchorage decreased the strain along the length of CFRP laminate.

It has been also found that the end anchorage increased the utilization effectiveness of CFRP laminate, where the ultimate strain of the CFRP laminate at the mid span for the anchored strengthened beam is higher than that of the non-anchored strengthened one. For instance, by using end anchorage type (C), the ultimate strain of the CFRP laminate reached 93.10 % from the maximum strain of the CFRP laminate obtained from tests while the ultimate strain of CFRP laminate reached 77.62 % from the maximum strain in case of using end anchorage type (A). Fig. 23 and Table 2 show the ultimate strains of the CFRP laminate at the mid span for the strengthened beams and their percentage from the maximum strain of the CFRP laminate.

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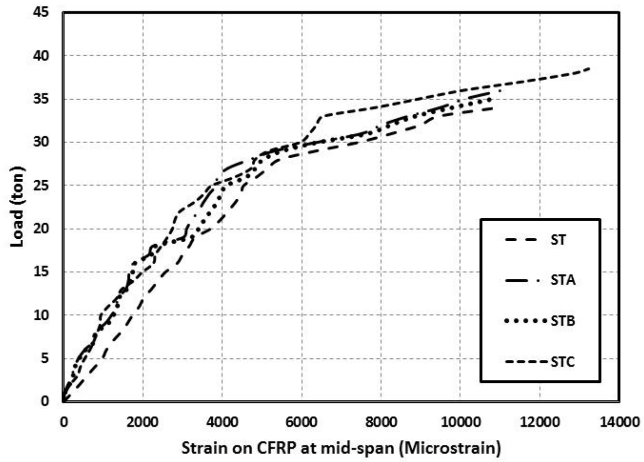

Fig. 17.Tensile strain on CFRP laminates at the mid span

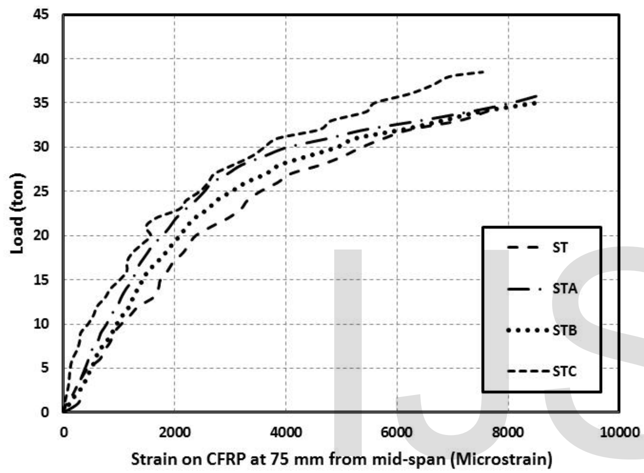

Fig. 18.Tensile strain on CFRP laminates at 75mm from the mid span

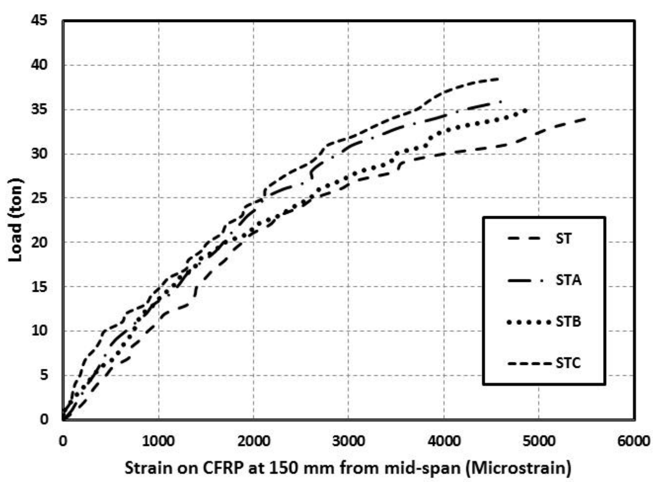

Fig. 19.Tensile strain on CFRP laminates at 150mm from the mid span

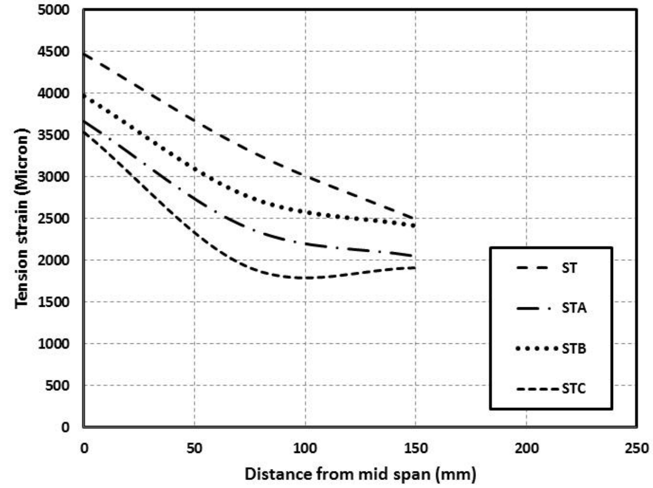

Fig. 20.Tensile strain through the CFRP laminates length at load 24ton

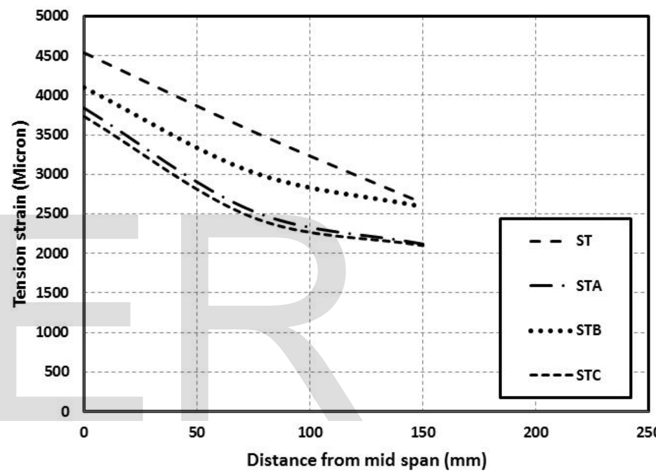

Fig. 21.Tensile strain through the CFRP laminates length at load 25ton

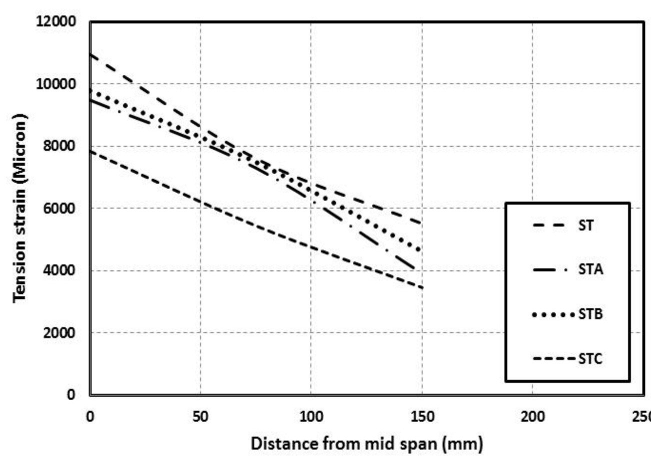

Fig. 22.Tensile strain through the CFRP laminates length at load 34ton

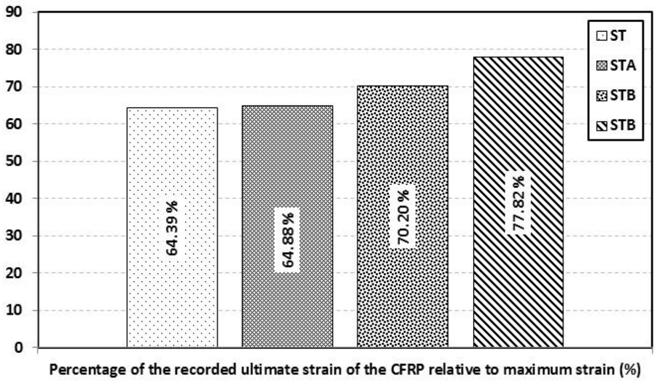

Fig. 23.Comparison between the strengthened beams regarding the percentage of the ultimate CFRP strain relative the maximum strain

TABLE 2
ULTIMATE STRAINS OF CFRP LAMINATE FOR STRENGTHENED BEAMS

Beam	CFRP end anchorage system	Ultimate strain of CFRP at mid span (micro strain)	Maximum strain of CFRP (micros train)	Percentage (%) of the CFRP maximum strain
ST	N/A	10946	17000	64.39
STA	Type A	11030		64.88
STB	Type B	11934		70.20
STC	Type C	13230		77.82

3.6 Strain on the steel bottom flange

The variation of tensile strain with the load for the bottom flange at the mid of span is shown in Fig. 24. Also this figure demonstrates that applying end anchorage system reduced the strain on the steel bottom flange. The effectiveness of the end anchorage on decreasing the tensile strain in the bottom flange was so obvious in the specimen STC.

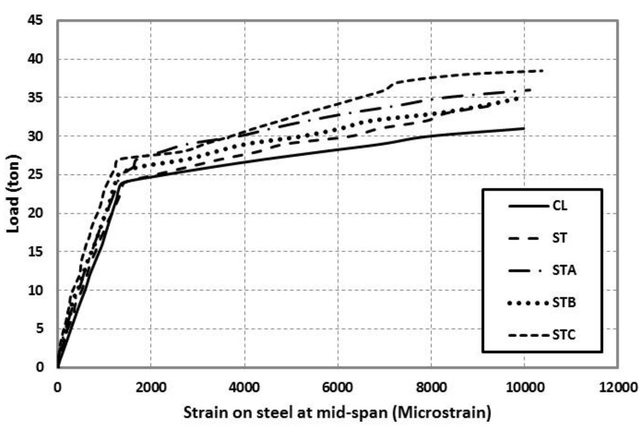

Fig. 24.Tensile strain on beam bottom flange at the mid-span

3.7 Interfacial stresses at CFRP laminate end

End debonding failure occurs when the interfacial principle stresses at the CFRP plate end reaches the material ultimatestrength. The results of the theoretical analysis performed by Deng and Lee [23] and Deng et al. [24] have been used to calculate the maximum principle stresses at the CFRP plate end for strengthened steel I-beams.

At the CFRP plate end, interfacial stresses are induced by the applied shear force and bending moment on the beam at the CFRP plate end. These interfacial stresses are shear stresses and normal stresses. The maximum shear stress τ_{max} and maximum normal stress σ_{max} at the end of the CFRP plate can be calculated as follows:

$$\tau_{max} = \sqrt{\frac{G}{t_a b\lambda}}(\alpha_b - \alpha_p)\Delta T + g\sqrt{\frac{G}{t_a b\lambda}}\, M(0) + \frac{g}{b\lambda}\, V(0) \quad (1)$$

$$\sigma_{max} = -\beta t_p \tau_{max} - \frac{E_a}{2\beta^3 t_a}\frac{1}{E_b I_b}\left(V(0) + \beta M(0)\right) + \frac{t_p G}{2t_a}\left((\alpha_b - \alpha p\Delta T + gM0\right) \quad (2)$$

Where

$$g = \frac{t_b/2}{E_b I_b}$$

$$\beta = \sqrt[4]{\frac{E_a b}{4t_a E_p I_p}}$$

$$\lambda = \frac{\left(\frac{t_b}{2} + \frac{t_p}{2}\right) t_b/2}{E_b I_b} + \frac{1}{E_b A_b} + \frac{1}{E_p A_p}$$

V(0) and M(0) are the applied shear force and bending moment on the beam at the end of CFRP laminate, respectively, (b) is the laminate width, (G)is the adhesive shear modulus, (α) is the thermal expansion coefficient, (ΔT) is the change intemperature, and (t, A, E and I)are the thickness, the area, modulus of elasticity and the second moment of area, respectively. The subscripts (a, b and p) denotethe adhesive, the steel beam and the CFRP laminate, respectively.

By combining the maximum shear and normal stresses, the maximum principle stress σ1max can be written as:

$$\sigma_{1max} = \frac{|\sigma_{max}|}{2} + \sqrt{\left(\frac{\sigma_{max}}{2}\right)^2 + \tau_{max}^2} \quad (3)$$

The interfacial stresses for strengthened beams are calculated in accordance with (1), (2) and (3) by using the properties of strengthened beams.Table 3 shows the values of the calculated interfacial stresses at the CFRP laminate end for the ultimate load levels of the four strengthened beams. This table shows that the non-anchored strengthened beam (ST) failed at load level equal to 34 tondue toend debonding when the principle stress at the CFRP laminate end reaches the material ultimatestrength, whereas the mean value of bond strength on steel for the used adhesive material equals to 30 MPa according to data sheet. This indicates that equations (1, 2 and 3) could be employed to predict accurately the load capacity of the non-anchored strengthened beams. The anchored strengthened beams (STA, STB and STC) reached ultimate load levels higher than that of ST beam which means that using these anchorages suppress the end debonding failure and increase the load carrying capacity by increasing the adhesive material strength. Also this table shows that the anchorage type C is more significant than the other types.

TABLE 3
CALCULATED INTERFACIAL STRESSES

Beam	CFRP end anchorage system	Ultimate load (ton)	Calculated max. interfacial shear stress (MPa)	Calculated max. interfacial normal stress (MPa)	Calculated max. interfacial principle stress (MPa)
ST	N/A	34	23.16	11.59	29.67
STA	Type A	36	24.51	12.27	31.40
STB	Type B	36	24.51	12.27	31.40
STC	Type C	38.5	26.2	13.1	33.56

4 CONCLUSIONS

Based on the results of the experimental work and theoretical analysis carried out in this research, the following conclusions can be drawn as follows:

1- Applying steel bolts and plates as a mechanical end anchorage for CFRP strengthened steel I-beams was found to be an effective technique. End anchorage type (C) was better than types (A) and (B), and the effect of the two types (A) and (B) is almost the same. Using end anchorage type (C) improved the ultimate load of the steel I-beam by 24.19 % compared with the non-strengthened beam (control beam), and by 13.24 % compared with the non-anchored strengthened beam. Using end anchorage type (A) and (B) improved the ultimate load of the steel I-beam by 16.13 % compared with the non-strengthened beam (control beam), and by 5.88 % compared with the strengthened beam without end anchorage.

2- The Failure modes of the CFRP for the non-anchored beams are different from those for the anchored beams. The modes of failure for the non-anchored beam were delamination and end debonding. On the other hand, the modes of failure for the anchored beams were intermediate debonding followed by pulling out of CFRP ends. This means that using mechanical end anchorage can suppress the end debonding effects and change the sudden failure to pre-warning failure.

3- Using end anchorage decreased vertical deflection, lateral deformation, and tensile strain on the CFRP laminates for the strengthened steel beams.

4- Using end anchorage increased the utilization effectiveness of CFRP laminate, where the ultimate strain of CFRP laminate reached 77.82 % from the maximum strain by using end anchorage type (C) while reached 64.39% from the maximum strain in case of no end anchorage used.

5- Based on the analytical study, it was found that equations (1, 2 and 3) which used for calculating the interfacial stresses at the CFRP laminate ends could be employed to predict accurately the load capacity of the non-anchored strengthened steel beams.

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