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Performance of steel beams strengthened with prestressed CFRP laminate

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ABSTRACT: Prestressed Carbon Fibre Reinforced Polymer (CFRP) system is generally used for strengthening reinforced concrete beams where CFRP laminate can improve both the strength and serviceability behaviour of reinforced concrete beams via increasing the overall member stiffness. However, the applicability of this technique to strengthening steel structures is still lagging behind its application to concrete structures. In this study, the flexural behaviour of steel I-beams strengthened with prestressed CFRP laminate using a mechanical anchorage system is experimentally investigated. A total of nine steel beams subjected to flexural loading are tested in various conditions to evaluate the effectiveness of the proposed strengthening system. The experimental investigation confirmed that CFRP prestressing increases the ultimate load of the strengthened steel beams and moderately delays the premature debonding failure of the CFRP laminate. Even with low level of CFRP prestressing, significant enhancement in the ultimate load of the strengthened beam was recorded. Beams strengthened using non-prestressed CFRP laminate mainly failed due to premature debonding of the laminate with a slight increase in the failure load. Mechanical end anchorages maintain the CFRP laminate prestress after releasing the jacking force without encountering any debonding of the CFRP laminate till final failure of the strengthened steel beam. The results of the experimental programme and its outcomes are presented and discussed.

1 INTRODUCTION

The trend of using CFRP laminate (strips) in retrofitting and strengthening reinforced concrete structures is constantly growing in civil engineering applications as it was proven to be effective and reliable [e.g. 1–7]. This is not the case when it comes to steel structure [8–16]. One of the reasons for that is the premature debonding failure of the composite section of the steel and the CFRP laminate due to the adhesive layer failure which commonly used to bond the laminate to the steel forming the desired strengthened section.

Prestressing the CFRP laminate was introduced as an alternative to the typical method in order to increase the stiffness and overcome the debonding problem of reinforced concrete and laminate composite section. It was found that prestressing has a positive effect on delaying the debonding premature failure [17]. As such, it is thought to investigate the applicability of the same technique for steel beam strengthened with CFRP laminate.

There are several techniques that can be used to apply the prestressing force to the CFRP laminate bonded to a steel beam. One method is by applying a camber to the steel beam and after bonding the CFRP to the beam, the beam is released and, as such, the laminate are stressed. Another method for prestressing the laminate is by using a prestressing mechanical device. Neither of the two methods can be effective without a using a mechanical anchorage because of the debonding phenomena. Adding mechanical anchorage at both ends of the laminate can ensure more ductile behaviour while also increases the allowable level of pre-stressing that can be applied; it was found out that the use of a mechanical anchorage can result in a great improvement in serviceability and strength [17].

In this investigation, the effectiveness and feasibility of using a prestressed CFRP laminate with a mechanical anchorage system for strengthening steel beams is investigated. A total of nine steel beams strengthened with different configurations of prestressed CFRP laminate were tested under static loading which was monotonically increased to failure.

The main parameters considered in the experimental programme are the prestressing levels (7% and 12% of the tensile strength of the CFRP laminate were adopted), the yield strength of the steel beam and the presence of the mechanical anchorage at both ends of the CFRP laminate.

Many prestressing devices are currently promoted by the CFRP laminate manufacturers. However, a simple configuration for a jacking system is designed and adopted in this study in order to provide a practical and economical method that can be simply used on-site without requiring the targeted beam to be dissembled and transported to another location for retrofitting.

2 THE EXPERIMENTAL PROGRAM

2.1 *Description of the Beams*

The experimental program included a total of nine steel beams. The details of the experimental program are given in Table 1. All the beams have a cross-section of W6×20 and a total length of 2,900 mm. The steel beams have a yield strength of 390 MPa: Beams CB-1A and B4-45-AN have a yield strength of 350 MPa.

Beams CB1 and CB1A represent the control beams which did not have any CFRP strips. Beam CB2 was strengthened with bonded CFRP which was not prestressed. All other beams (Table 1) were strengthened with CFRP strips which were prestressed to different levels with/without end mechanical anchorage. The pretension levels in the CFRP strips were either 25 kN or 45 kN. The width of the CFRP laminate is 100 mm except for Beam B5-25-AN where the laminate width is 50 mm.

The last Beam B6-45-AN-NAD is similar to the beam strengthened with the 100 mm wide prestressed CFRP laminate with end anchorage but without adding any adhesive between the steel beam and the CFRP laminate (unbonded laminate). The thickness of the CFRP laminate adopted in the current investigation was 1.2 mm for all the beams.

To prevent the local buckling of the beams' web, vertical stiffeners were added to all beams above the supports and below the load application points. The beams were also laterally restrained to prevent lateral torsional flexure buckling of the beams' compression flange.

Table 1. Test Beam Details.

Beam	CFRP laminate	Anchorage system	Prestressing force
CB1	No	No	No
CB1A	No	No	No
CB2	100×1.2mm	No	No
B1-25-NA	100×1.2mm	No	25 kN
B2-45-NA	100×1.2mm	No	45 kN
B3-25-AN	100×1.2mm	Yes	25 kN
B4-45-AN	100×1.2mm	Yes	45 kN
B5-25-AN	50×1.2mm	Yes	25 kN
B6-45-AN-NAD	100×1.2mm	Yes	45 kN

2.2 *The Prestressing System*

The prestressing system adopted in the experimental program consists of mechanical anchorages and jacking assemblage with hydraulic jack which is schematically shown in Figure 1. The developed anchorage system and jacking assemblage were directly acting on the CFRP laminate against a permanent gripping assemblage mounted on the strengthened steel beam: Figure 2 shows the jacking assemblage of a typical strengthened beam.

The prestressing force was applied with the beams placed on the floor having its bottom flange facing upward. The system consisted of three gripping groups. Each group consists of two grip plates.

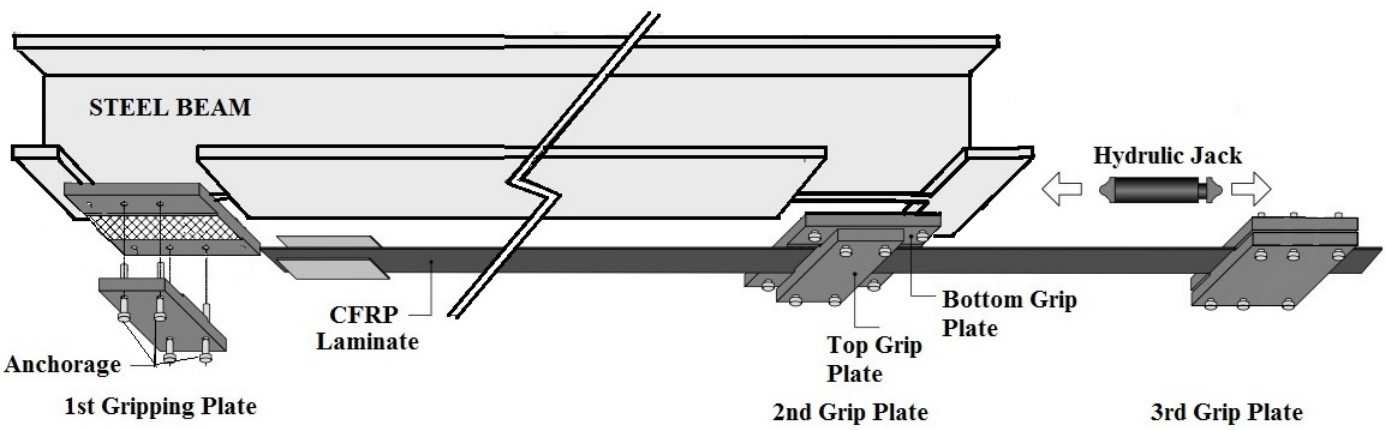

Figure 1. Prestressing system adopted for all beams strengthened with CFRP prestressed laminate.

The upper grip plate is bolted into position directly to the lower grip plate which is butt-welded to the beam lower flange. The beam lower flange was cut to accommodate the lower grip plate. Figure 3 shows a typical strengthened beam cross section at gripping locations. The first fixed group of plates is located at 600 mm from the end of the steel beam. The second group is located at 600 mm from the opposite side of the beam next to the jacking (third) group of plates. The jacking group was used to apply the tension force to the CFRP laminate and installed at the tip of the opposite end of the beam.

Figure 2. Torque tightening of grip bolts before applying pretension force (above) and prestressing jack adopted for prestressing of the CFRP Laminate (below).

For all three groups, the upper grip plates were fastened using 6M24 Grade 10.9 bolts. The process of prestressing the CFRP laminate started by applying the adhesive layer on the laminate. Then, the CFRP laminate was gripped by the bearing plates of the first group by tightening the grip anchor with a torque wrench and a torque multiplier. After that, the laminate was gripped from its other end by the third group with the same bolt tightening procedures, then the prestressing force was applied to the CFRP laminate. Two levels of prestressing force were adopted for each of the four prestressed beams. The target levels of prestress was selected relative to the ultimate tensile strength of the CFRP laminate, which were 7% and 12%. When the desired level of prestress in the laminate was achieved, the prestressing force was maintained in the laminate by using the second grip plates located in front of jacking assembly. The jacking system was then uninstalled and the beam was kept for 14 days to allow curing time for the adhesive and monitor any prestress losses.

Strain gauges were mounted on the beam middle cross section as shown in Figure 4. The prestressing strain in CFRP laminate slightly decreased after the 14 days curing time (i.e. after the removal of a jacking force). Later, the prestressing force converged to a constant value. In this prestressing system, the total loss of the prestressing strain in CFRP laminate measured was 1% of the initial prestressing strain.

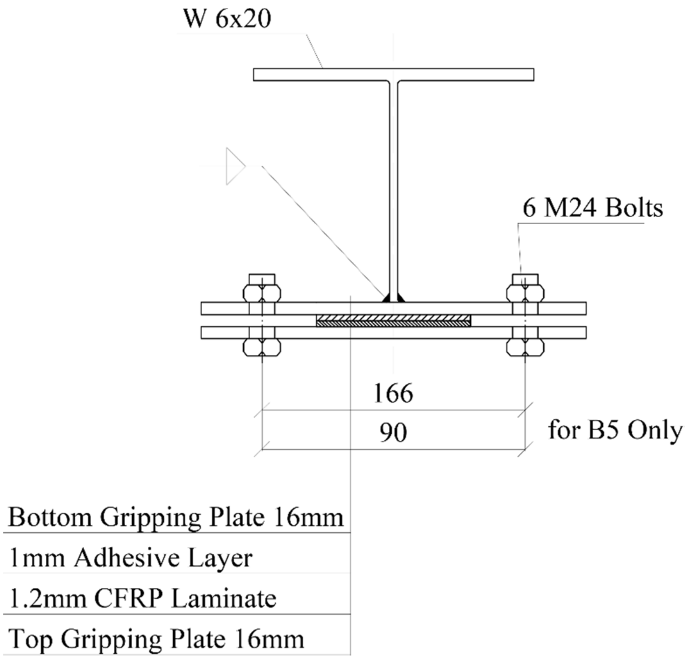

Figure 3. Strengthened steel beam's cross-section at the location of the gripping plates.

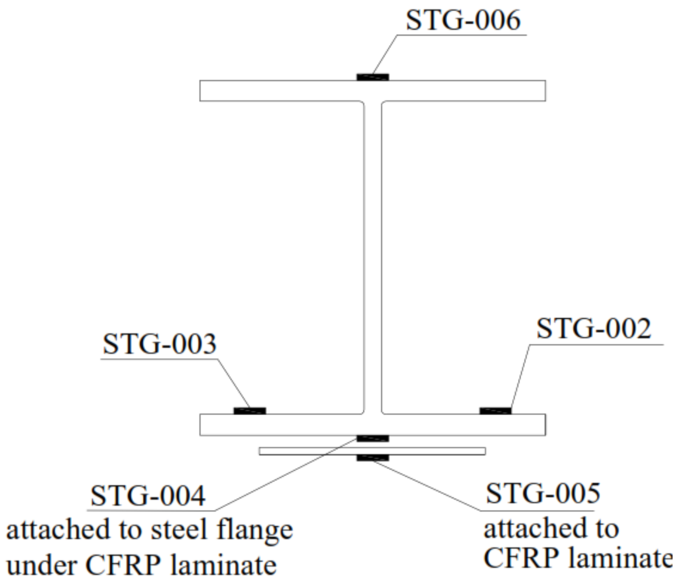

Figure 4. Arrangement of the strain gauges at the beam's midspan.

2.3 *Material Properties*

The mechanical properties of the steel beam and CFRP laminate are obtained from both material testing and manufacture data sheet. The measured material properties of the steel beam are shown in Table 2. According to the test results, the beams are designated into two categories: beams with a yield strength F_y of 390 MPa and beams with a yield strength F_y of 350 MPa.

The CFRP laminate used in this study is composed of pitch-based carbon fibres and epoxy resin of 1.2 mm thick, 50 mm or 100 mm wide plates. The fibre volume fraction of the strips was 68%. The mechanical properties of the CFRP laminate were determined from the manufacturer data sheet and presented in Table 3.

The average ultimate strength of CFRP laminate was 3,100 MPa. The average measured modulus of elasticity was 165 GPa. A two-component epoxy adhesive was used to bond the CFRP laminate to the surface of the steel beam. The average mechanical properties of the adhesive are shown in Table 4 as obtained from the manufacturer data sheet as well.

2.4 *Test Set-up*

The beams were simply supported and subjected to two points loading as shown in Figure 5. The load was applied gradually to the beam with a universal testing machine. In order to prevent the beam section from lateral torsional buckling, the beam is restrained at 4 points using angle bracing L50×5 as shown in Figure 6.

Table 2. Mechanical properties of the analysed beams.

Beam	Yield stress (MPa)	Tensile strength (MPa)
CB1	390	560
CB1A	350	520
CB2	390	560
B1-25-NA	390	560
B2-45-NA	390	560
B3-25-AN	390	560
B4-45-AN	350	520
B5-25-AN	390	560
B6-45-AN-NAD	390	560

Table 3. Properties of the CFRP laminate.

Mechanical properties	Value (MPa)
Tensile modulus	165,000
Tensile strength	3,100

Table 4. Properties of the epoxy adhesive.

Mechanical properties	Value (MPa)
Tensile strength	24.8
Compressive strength	61
Shear strength	24.8
Bond strength	18
Tensile modulus	4,400

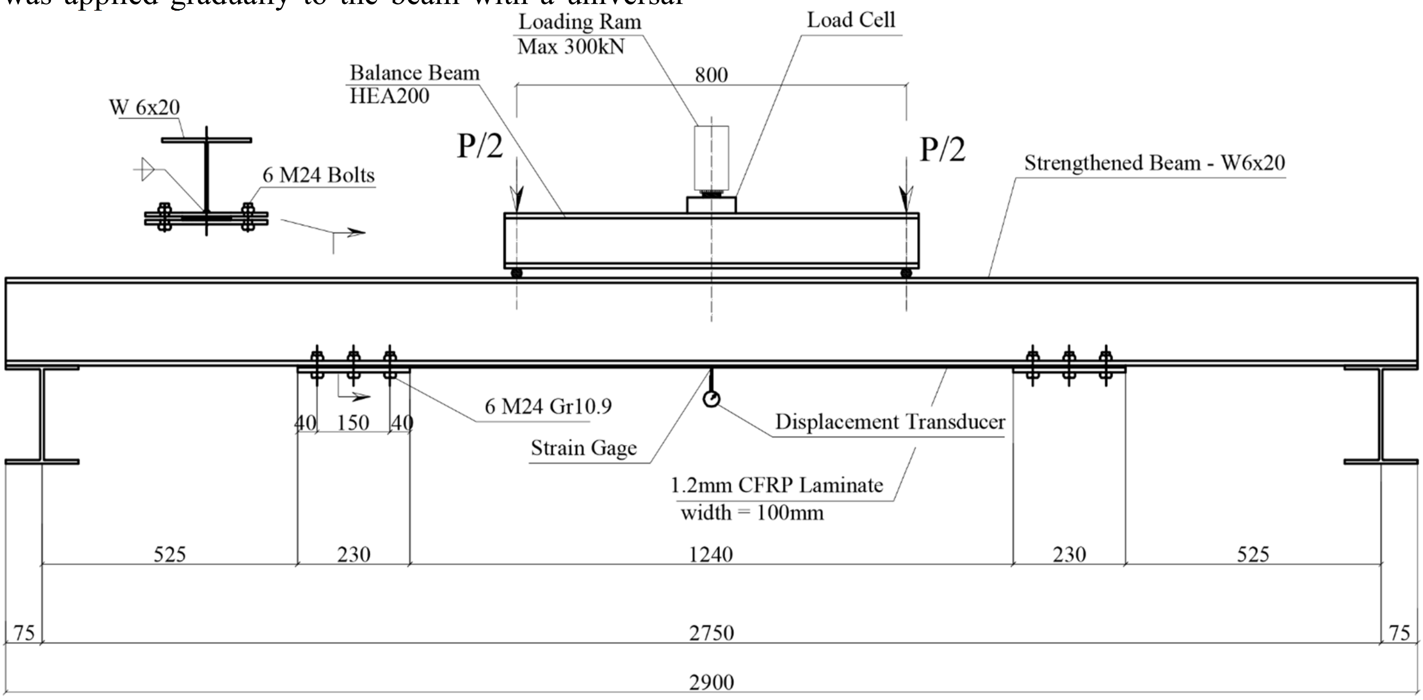

Figure 5. Test Setup for a typical strengthened steel beam with CFRP prestressed laminate.

2.5 *Instrumentation*

All beams were equipped to measure the applied load, mid-span vertical deflection, and the strains in the steel beam and in the CFRP laminate. Deflection at mid-span was measured using displacement transducer (LVDT). Electrical resistance strain gauges were mounted at mid-span of the beam on the top and bottom of the steel beam and on the CFRP laminate. A universal load cell was installed on top of the hydraulic jack used to apply the load during sample preparation and testing. All the signals from transducer, strain gauges, and load cell are automatically recorded by a data logger TDS-530.

Figure 6. Angles L50×5 used to brace the compression flange against lateral buckling.

2.6 *Prestressing the CFRP Laminate*

Sophisticated prestressing techniques for CFRP laminate compared to the one adopted in this study are available in the construction market. However, they are costly and difficult to apply. To simplify the prestressing technique, a simple grip plates with tightened bolts were introduced as previously discussed (Figures 1 and 2). After several trials, the adopted technique was found to be effective up to a certain limit of prestressing the CFRP laminate. Beyond this limit, the laminate breaks longitudinally along the strengthened beam length due to the uneven distribution of the gripping force that is caused by the praying action of the grip plates.

In order to increase the prestressing force of the system, 16 mm thick gripping plates were used with a 1.2 mm galvanized steel plate which is added on top of the CFRP laminate covering the contact area between the gripping plate and the laminate.

The distance between the M24 bolts in all beams was 166 mm except for Beam B5-25-AN: the 50 mm wide CFRP laminate adopted in this beam allowed narrowing the distance between the gripping bolts to only 90 mm. This reduction in width found to enhance the performance of the prestressing system because it reduced the praying force effect. The M24 bolts are tightened using a standard 750 mm wrench (Figure 2). In order to achieve the maximum torque tightening force, a torque multiplier was used. The achieved tightening torque for the bolts was 1.05 kN·m

2.7 *Beams Preparation*

The sample preparation differed for each beam. For Beams CB-1 and CB-1A, there was no preparation required except mounting strain gauges on the required location.

For Beam CB2 the preparation started by attaching strain gauges STG-004 and STG-006 (Figure 4) to the steel beam top and bottom flanges, respectively. The second stage of preparation was applying the epoxy mortar to the CFRP after cleaning bottom flange of the steel beam and roughening its surface using sand blasting to SA2½. To minimize the presence of air pockets inside the adhesive when the CFRP laminate was bonded to the steel surface, the epoxy was V-shaped along the CFRP laminate (Figure 7). The CFRP laminate was then bonded to the steel substrate. To ensure a constant thickness of the epoxy along the bonding length, a template with a gap of 2.2 mm was passed along the bonded length. All extra epoxy over the 1 mm thickness required was removed using this tool. After that, the CFRP laminate was placed in the required location. The strain gauge STG-005 was then attached to the laminate. As such, the beam was ready for testing after being left for 14 days for curing and monitoring any prestress losses. Then, strain gauges STG-002 and STG-003 were attached to the steel beam prior to testing.

Figure 7. Controlling the epoxy layer thickness of the adhesive and minimizing air voids.

For Beam B1-25-NA the preparation started by attaching strain gauges STG-004 and STG-006 to the steel beam top and bottom flanges, respectively. The second stage of preparation was applying the epoxy mortar to the bottom flange of the steel beam. After that, the CFRP laminate was bonded to the steel beam and strain gauge STG-005 was attached to the laminate.

The next step was attaching the gripping plates of anchorage (Group 1) and tightening the bolts. Next, the jacking group (Group 3) was fixed to the laminate and its bolts and tightened. The prestressing force was gradually applied to the laminate and all strain gauge readings were recorded against the applied load. When the prestressing force reached 25 kN, anchorage plates (Group 2) was fixed and tightened. The laminate was then mounted on the steel beam lower flange and prestressed to the required level. Then, the prestressing tool was released by untightening the jacking anchorage group. The strain gauge readings were recorded to evaluate the loss in the prestressing force. Before leaving the beam for curing, the laminate was pressed firmly against the steel section using a hard roller to ensure a good bond to the flange surface. After 14 days, strain gauge STG-002 and STG-003 were attached to the steel beam. Before starting the test, the mechanical anchorage of gripping groups (Groups 1 and 2) were released then the test load is applied.

Beam B2-45-NA was prepared following the same procedures of Beam B1-25-NA with the exception of applying a 45 kN prestressing force instead of 25 kN. Beams B3-25-AN, B4-45-AN and B5-25-AN were also prepared following the same procedures adopted for Beams B2-25-NA and B2-45-NA with the exception of leaving the mechanical anchorage attached to the ends of these beams (Groups 1 and 2) before and during testing. Beam B6-45-AN-NAD was prepared following the same procedures adopted for Beam B4-45-AN (i.e. 45 kN prestressing force with attached mechanical anchorage at both sides) except that no adhesive epoxy mortar was placed between the steel section and the CFRP laminate.

3 THE EXPERIMENTAL RESULTS

3.1 *Failure Modes*

Generally, prestressing the CFRP laminate reduced the deflection and delayed the premature debonding failure. Both the reduction of the deflection and the delay in debonding were proportional to the level of the laminate prestress.

Control Beams CB-1 and CB-1A failed in a typical flexural manner. Failure of the beam strengthened with non-prestressed CFRP laminate CB-2 started by the debonding of the laminate with a slight increase in the failure load.

The CFRP-prestressed beams without end anchorage (Beams B1-25-NA and B2-45-NA) failed by debonding of the CFRP laminate from the steel bottom flange which started immediately after releasing the grip anchor at both ends of the beam. The debonding started at the ends of the CFRP laminate which remained attached along the middle part of the beam. Final failure took place with total debonding of the laminate with a slight increase in the failure load.

The CFRP-prestressed Beams B3-25-AN and B5-25-AN with end anchorage and F_y =390 MPa also failed in a typical flexural manner. The CFRP laminate bonded to Beam B3-25-AN had a sudden rupture failure (Figure 8) compared to the non-strengthened control beam (Beam CB-1). Both these beams developed a full plastic hinge at failure after the CFRP rupture without encountering any premature debonding failure.

The same failure mode was recorded for the CFRP-prestressed beam (Beam B4-45-AN having F_y =350 MPa) with end anchorage, but the achieved strength enhancement was lower than the previous beams.

The behaviour of the CFRP-prestressed beam with end anchorage and no adhesive (Beam B6-45-AN-NAD) did not differ from that for beams with end anchorage and adhesive in terms of the flexural behaviour. However, the increase of the failure load was less than the beams strengthened using the adhesive layer. The strength increase was found to be 7% when it is compared to control non-strengthened beam (Beam CB-1). The CFRP laminate rupture occurred at the load of 186 kN; earlier than the corresponding beam with end anchorage and adhesive layer.

The results of the experimental investigation are summarized and tabulated in Table 5.

Figure 8. Typical CFRP rupture encountered in testing the beams.

3.2 *Strain Gauge readings*

There was no major strain loss recorded after tightening the second grip plates and releasing force in the prestressing tool. Figure 9 shows typical strain gauge readings (Gauges STG-004 and STG-005) during preparation of the beams. The difference in the strain behaviour of the two strain gauges is due to the fact that the adhesive layer was still in the hardening phase.

Table 5. Results of the experimental investigation performed on steel beams strengthened with CFRP laminate.

Beam	CFRP jacking strain (με)	Yield load P_y (kN)	CFRP debonding load		CFRP rupture load		CFRP failure
			P_{de} (kN)	Associated strain (με)	P_{fru} (kN)	Associated strain (με)	
CB1	–	172.7	N/A	N/A	N/A	N/A	N/A
CB1A	–	161.0	N/A	N/A	N/A	N/A	N/A
CB2	–	174.8	193.2	5290	No rupture	No rupture	Debonding
B1-25-NA	3092	N/A	64.8	15.16	No rupture	No rupture	Debonding
B2-45-NA	4021	N/A	76.33	16.48	No rupture	No rupture	Debonding
B3-25-AN	3140	194.66	204.5	3953	199.7	4435	Rupture
B4-45-AN	3984	166.3	182.7	5725	190.5	9601	Rupture
B5-25-AN	3103	195.2	No debonding	No debonding	No rupture	No rupture	N/A
B6-45-AN-NAD	4011	184.3	N/A	N/A	201.33	857	Rupture

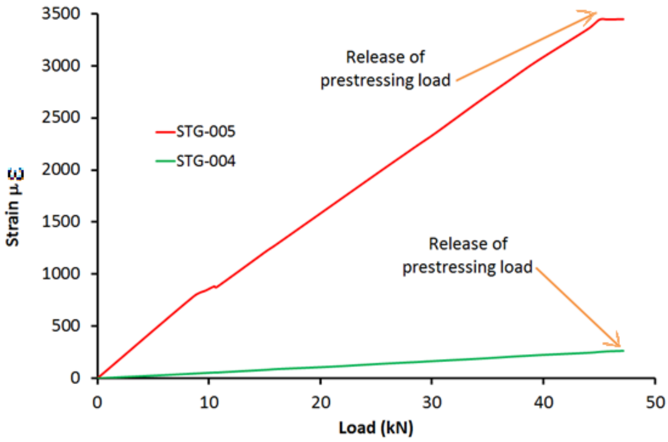

Figure 9. Typical load-strain relation during prestressing and up to releasing the prestressing.

Figure 10 shows the load–strain relationship for the same two strain gauges (Gauges STG-004 and STG-005) during testing. The graph shows identical strain behaviour up to the debonding load. Increasing the prestressing force changed the behaviour of the composite section. The strain–load relationship for Gauge STG-002 for Beams B3-25-AN and B4-45-AN is shown below in Figure 11. The strain for both sections is identical in the elastic phase. Increasing the prestressing force in the CFRP laminate noticeably reduced the strain.

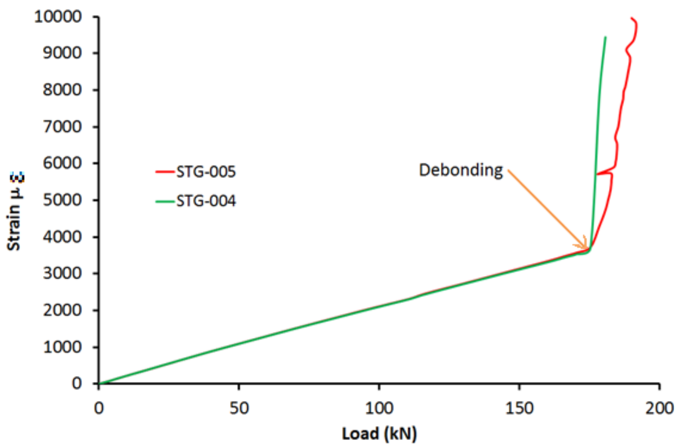

Figure 10. Load–strain relation for Beam B4-45-AN.

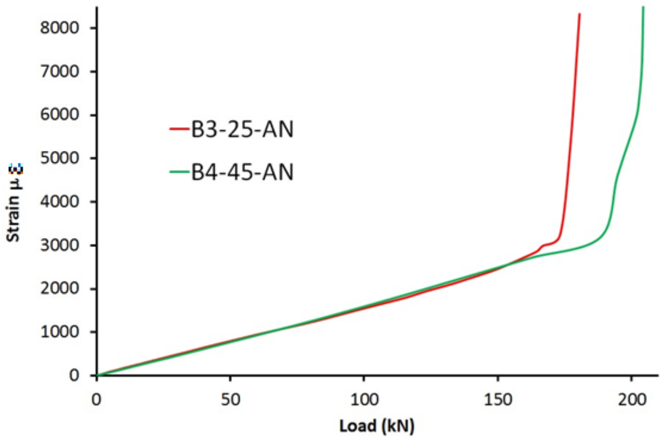

Figure 11. Load–strain relation for Beams B3-25-AN and B4-45-AN: strain gauge STG-002.

3.3 *Load-displacement relationship*

The load displacement relation for the tested beams is plotted in Figures 12 to 15. The Figures clearly indicate the yielding loads, the CFRP debonding load and the CFRP rupture load.

Figure 12 illustrates the load deflection response for Beam B5-25-AN versus the control Beam CB1. Both beams developed a full plastic hinge in a typical flexural manner. Beam B5-25-AN exhibited neither debonding nor CFRP rupture during the test. The measured yield load for Beam CB1 is 172.7 kN at corresponding deflection 20.46 mm, while the measured yield load for Beam B5-25-AN is 195.2 kN at corresponding deflection 26.28 mm. This indicated a 13% increase in the yield load capacity of the combined strengthened section. During the final stage of loading before failure, both beams exhibited a load drop caused by the high and sudden deflection at mid-span. The final failure load of Beam B5-25-AN is 207.8 kN at a corresponding deflection of 93.45 mm, while the failure load of Beam CB1 is 190.0 kN at a corresponding deflection of 82.63 mm.

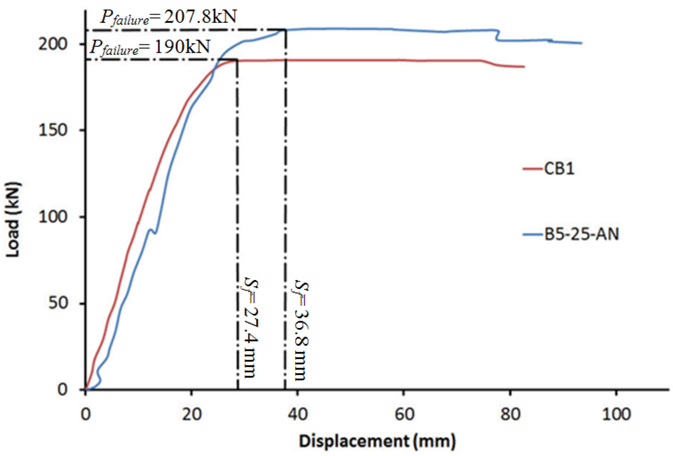

Figure 12. Load–displacement response for strengthened Beam B5-25-AN and unstrengthened Beam CB1.

Figure 13 illustrates the load deflection response for Beam B3-25-AN versus the control beams (Beams CB1 and CB2). The beams failed in a typical flexural manner. Beam CB2 attained its yield capacity with no premature failure observed. The recorded yield load for Beam CB2 was 174.8 kN at a corresponding deflection of 19.5 mm. This means that the CFRP strengthening with neither prestressing nor mechanical anchorage added only 1.2% to the yield strength of the combined section. After further loading, the beam exhibited a debonding failure associated with a sudden drop of the applied load. The recorded debonding load for Beam CB2 was 193.2 kN at corresponding deflection of 29.33 mm. After the debonding, the beam became unstrengthened and behaved similar to control beam (Beam CB1) until final failure. The recorded yield load for Beam B3-25-AN was 194.66 kN at corresponding deflection of 21.07 mm. This indicates a 13% increase in the yield load of the combined strengthened section when compared to control beam (Beam CB1). During the plastic stage, a partial debonding occurred at 204.5kN load associated with 35mm deflection. After that, the beam exhibited a load drop combined with a sudden deflection at the mid-span caused by the CFRP rapture at a load of 199.7 and a corresponding deflection of 37.05 mm. The beam exhibited a second and final rupture at load of 197.8 kN with a corresponding deflection of 57.53 mm before the section become unstrengthened and had the same behaviour of the control beam till final failure.

Figure 14 illustrates the load deflection response for Beam B4-45-AN versus the control beam CB1A. Both beams attained their yield capacity with no premature failure observed. The recorded yield load for Beam CB1A was 161.0 kN at a corresponding deflection of 22.0 mm while the recorded yield load for Beam B4-45-AN was 166.3 kN at corresponding deflection of 23.34 mm. This indicates only a 3.3% increase in the yield load capacity of the combined strengthened section; unlike what was expected based on other beams test results. This might be attributed to the imperfection during the beam's preparation or setup and testing. Both beams developed a full plastic hinge in a typical flexural manner. Beam B4-45-AN exhibited a partial CFRP debonding at a load of 182.7 kN and a corresponding deflection of 38.29 mm. The final failure load of the beam was 190.5 kN at a corresponding deflection of 76.73 mm which took place after the CFRP laminate rupture.

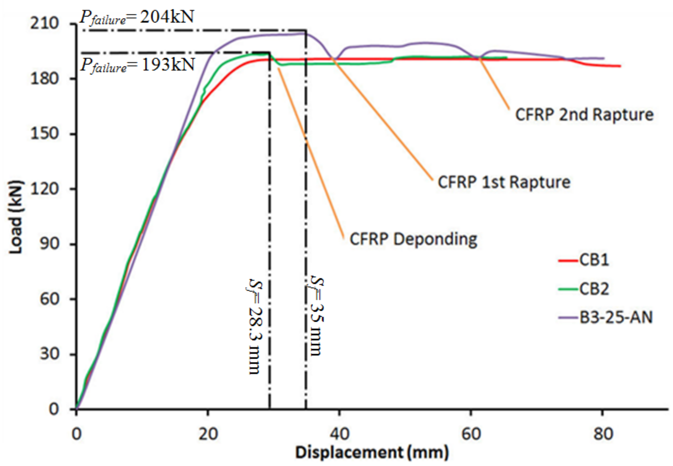

Figure 13. Load–displacement response for strengthened Beam B3-25-AN and unstrengthened Beams CB1 and CB2.

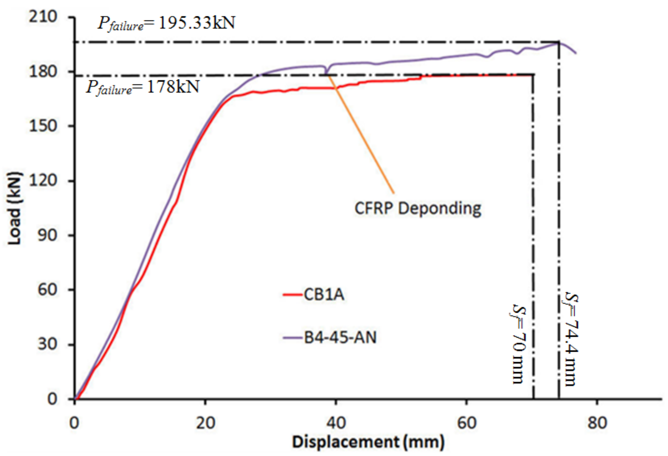

Figure 14. Load–displacement response for strengthened Beam B4-45-AN and unstrengthened beam CB1A.

A comparison between the behaviour of Beam B6-45-AN-NAD and Beam CB1 is illustrated in Figure 15 which reveals no difference in load deflection response from Beam B3-25-AN; the beam failed in a typical flexural manner and attained its yield capacity with no premature failure. The recorded yield load for Beam B6-45-AN-NAD was 184.3 kN at corresponding deflection of 24.71 mm. This indicates a 7% increase in the yield load which may be attributed to the lack of the adhesive layer which distributes the friction force between the two adherents. After further loading, the beam exhibited a rupture failure associated with a sudden drop of the applied load. The recorded rupture load for this beam was 201.33 kN at corresponding deflection 39.67 mm. The beam exhibited a second and final rupture at load at 202.33 kN with a corresponding deflection of 55.14 mm before the section become unstrengthened and had the same behaviour of the control beam till final failure.

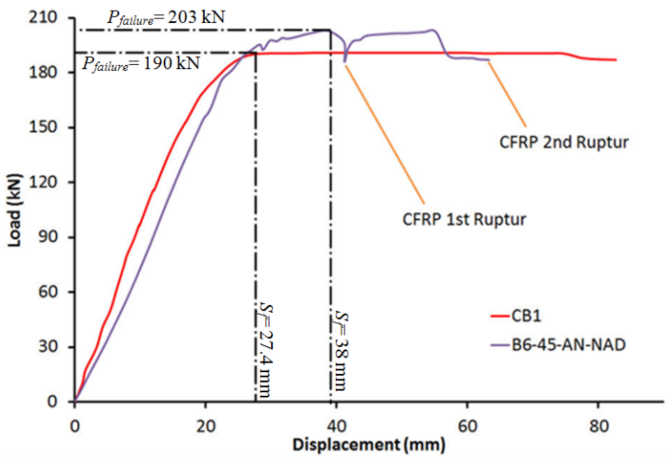

Figure 15. Load–displacement response for strengthened Beam B6-45-AN-NAD and unstrengthened beam CB1.

4 CONCLUSIONS

Tests were conducted on steel beams strengthened with CFRP laminate to investigate the flexural behaviour of these beams when bonded and unbonded prestressed CFRP laminate are adopted with/without mechanical end anchorage system. The effects of the CFRP laminate prestressing and the premature debonding failure were investigated.

It is concluded that the CFRP prestressing increases the ultimate load of the strengthened beam and moderately delays the premature debonding failure of the CFRP laminate. Beams strengthened using non-prestressed CFRP laminate mainly fail due to premature debonding of the CFRP laminate with a slight increase in the failure load.

It is also concluded that using mechanical end anchorage is essential to maintain the CFRP laminate prestress after releasing the jacking force. Epoxy mortar is not sufficient to maintain the laminate prestress by itself even at a low level of prestressing.

For low level of CFRP prestressing (7% to 12% of the ultimate CFRP strength), a significant enhancement in the ultimate load of the strengthened beam can be achieved. Furthermore, premature debonding failure can be avoided and the CFRP laminate are utilized up to their rupture strength.

The adhesive properties do not affect the ultimate load but they may have an effect on delaying the debonding of the laminate which is highly dependent on the efficiency of the anchorage system and the level of prestressing.

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