Testing of Steel Beams Externally reinforced using Anchored Hybrid FRP Composites

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ABSTRACT: Recent experimental and numerical research studies revealed the favorable ductile behavior of steel-FRP anchored lap connections. The current paper reports on the results of an experimental study that investigates the efficiency of using hybrid CFRP-FRP strips in strengthening steel beams. The study explores the performance of I-shaped steel beams externally reinforced with mechanically anchored hybrid FRP laminates. The program involves testing a total of seven full-scale beams in flexure based on a three-point loading setup. The response of steel sections is assessed based on load-midspan deflection measurements and strains developed at different locations along the beams. In addition, longitudinal strains induced in the FRP laminates are recorded. The influence of FRP laminates length and thickness on the behavior is also considered in the tests. Test measurements indicate ductile behavior of externally reinforced beams associated with increase in the load carrying capacity. The results imply that increasing the length of FRP laminates significantly improves the ultimate flexural capacity of the composite beam. Besides, it is shown that doubling the thickness of the FRP laminate enhances the flexural performance of the composite beam.

Keywords: steel, beams, fiber reinforced polymers (FRP), strengthening, externally anchored.

1 INTRODUCTION

The effective use of fiber reinforced polymers (FRP) in strengthening structural elements such as steel, concrete, masonry and timber has been reported during the past two decades. The remarkable interest in using these composite materials in Civil Engineering applications lies in the benefits they provide among other strengthening techniques. For instance, enlarging the section of the steel beam by welding additional elements such as steel plates requires special lifting equipment to handle the bulky strengthening steel elements during the erection process. Additionally, the dead weight of the enlarged section significantly increases which may result in a considerable reduction in its effectiveness. In some situations, welding may increase the fatigue problems resulted from the inappropriate application. On the contrary, the main advantages of FRP materials are their high strength-to-weight ratio, the ease of application to existing structures and their high resistance against chemical attacks. In general, FRP sheets can be attached to steel sections using adhesive (bonded) or using mechanical bolts (anchored).

Several research works related to the influence of strengthening steel members with bonded FRP composites have been carried out. An experimental study by Sen et al. (2001) explored the applicability of using CFRP laminates in retrofitting steel bridge members. It was concluded that the specimens retrofitted with CFRP laminates of higher thickness performed better in terms of stiffness gain. The increase in the elastic stiffness in the repaired beams came up to be relatively small for thin CFRP laminates and increased slightly for the thicker ones. Shaat, et al. (2003) reported that work carried out by Gillespie et al. (1996) on naturally corroded steel girders showed an increase in their ultimate capacity when retrofitted with CFRP strips of about 17% and 25% for severely and moderately deteriorated sections, respectively. Another study by Liu et al. (2001) on artificially notched steel girders revealed an increase of 60% and 45% in the inelastic load capacities for the specimens retrofitted with CFRP laminates that extend along the full and quarter length of the span, respectively. Tavakkolizadeh and Saadatmanesh (2003) confirmed the significant enhancement resulted from retrofitting steel beams with bonded FRP strips of different thicknesses. It was observed that using one, three and five layers of FRP sheets improved the ultimate carrying capacity of the strengthened beams by 44%, 51% and 76%, respectively. Lenwari et al. (2005) performed experimental and analytical studies on steel beams retrofitted with externally bonded CFRP plates. Their results revealed that as the length of the CFRP plate increased, the ultimate carrying capacity of the strengthened beam increased and the governing failure mode changed from debonding of short laminates to rupture at mid-span for the longer ones. In 2007, Dawood and Rizkalla investigated experimentally the influence of using high modulus bonded CFRP laminates on the behavior of steel beams. It was observed that using tapered joint configuration resulted in reducing the induced shear stresses at those ends and consequently increasing the ultimate flexural strength of the beam. The test results indicated also that using steel clamps at the laminates ends had an insignificant influence on improving the flexural strength of the beams.

Reported research work on bonded FRP to steel beams revealed that the response may be controlled by the unfavorable brittle debonding of FRP strips. Debonding may occur at the interface between the steel and the adhesive layer, in the adhesive layer itself, or by delamination of part of the FRP fibers. On the contrary, and to the best of the authors' knowledge, no research work has been yet reported on mechanically anchored FRP composites to steel beams. The current paper reports on the results of experimental investigation that is conducted as part of an ongoing research project that explores the potential success of reinforcing steel beams using externally anchored FRP composites in a trial to overcome the debonding problem of FRP strips in typical bonded steel-FRP systems.

2 EXPERIMENTAL PROGRAM

A total of eight UB 203x102x23 full-scale steel beams are tested to assess the efficiency of external reinforcement of steel beams using anchored FRP laminates. Tested beams are of 3,000 mm total length and have a clear span of 2,750 mm. In order to prevent local buckling failure mode, 12 mm thick stiffener plates are welded to the beam cross section in the loaded regions around the beam mid-span and near the supports. The FRP laminates used are hybrid GFRP-CFRP SAFSTRIP with typical cross section dimensions of 101.6mm x 3.2mm. Carbon tows, included in the laminates, are sandwiched between two layers of fiberglass mats and are bonded together by a highly corrosion resistant veinylester resin. Galvanized zinc coated bolts, nuts and washers are used to attach the FRP laminates to the bottom flange of the steel beams. M6x25 HILTI bolts with 6mm diameter are used. Bolts are made of high tensile steel of grade 8.8 with 375 MPa shear strength and 1.0 GPa bearing strength [BSI 5950-1:2000]. The mechanical properties of the steel beams are obtained by testing six standard coupons as per the ASTM standards [A370-03a]. Three coupon specimens are cut from the web while the other three are taken from the flanges. The average values measured are 335MPa, 429MPa and 1.9 x 10^5 MPa for yield stress, ultimate strength and modulus of elasticity, respectively. According to the conducted experimental program, three beams are used as control specimens. Meanwhile, four beams are reinforced with a single FRP layer with two of them having a length of 2200mm while the others have 1200mm length. Additionally, one beam is reinforced with two FRP layers having a length of 2200mm. The typical width of each laminate is 101.6mm which is slightly smaller than the width of the beam flange of 103.14mm. Bottom flanges of strengthened beams and FRP laminates are drilled at the specified bolts locations using 6 mm drill bits. Bolts are then used to attach the FRP laminate to the steel section. Two M6 1.6mm-thick zinc plated washers are placed to increase the bearing area at both sides of the connection. Bolts are then snug tightened after the full effort of a worker with an ordinary spud wrench as permitted by the ANSI/AISC 360-05 (2005). Table 1 summarizes the properties of the tested beams.

Table 1. Description of tested specimens

Beam Designation	Number of specimens	FRP Thickness (mm)	FRP Length (mm)	Bolts Longitudinal Spacing (mm)	Notes
CB	3	None	None	None	Control Beams
S2200	2	3.2	2200	100	Single Layer of FRP
S1200	2	3.2	1200	100	Single Layer of FRP
D2200	1	6.4	2200	50	Double Layers of FRP

3 TEST SETUP

All specimens are tested in three points loading while being braced with two pairs of lateral supports in order to prevent lateral torsional buckling during load application process as shown in Fig. 1. Lateral supports are placed close to the mid-span section where the bending moment and the associated compression in the flange are maximum. A gap of 1 mm between the lateral bracing system and the tips of the flanges is left and the surface of the each lateral bracing panel is greased in order to eliminate any potential friction with the steel beam in its deformed shape. Each specimen is instrumented with ten longitudinally-oriented 3mm strain gauges and one linear variable displacement transducer (LVDT) device. The strain gauges are mounted to the cross-section of the steel beam near to its mid-span and also to the surface of the FRP laminates along its length. Meanwhile, the LVDT is used to measure the vertical deflection at the beam mid-span section. Testing is terminated at a mid-span deflection value of 200 mm.

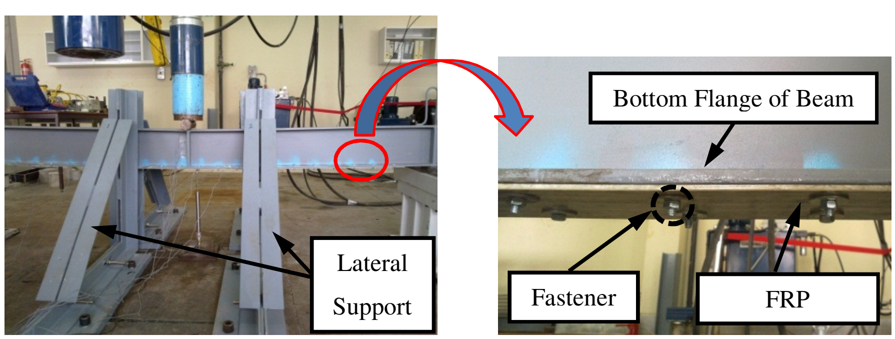


Figure 1. Loading and lateral supports of tested full-scale beams.

4 DISCUSSION OF EXPERIMENTAL RESULTS

The experimental behavior of the tested specimens with different configurations is presented based on the load-deflection relationships with a description of the failure modes controlling the response. Table 2 details the yield and ultimate loads of the tested specimens.

4.1 Specimens with single FRP laminate layer

Figure 2 shows the load-deflection curve for specimens S2200 (dashed line) and S1200 (solid line) compared to the control beam (dots). Experimental observations indicate that steel beams externally reinforced with a single FRP layer fail by bearing failure in the FRP laminate and rupture of some fibers. The onset of local buckling is noticed at a load value of 158 kN and 126.4 kN for the S2200 and S1200 beams, respectively. It can be noticed that application of anchored FRP laminates results in improvement in the yielding load value of about 1.8% for S1200 and 6.4% for S2200 over the yield load of the control beam CB. More significant improvement is realized in the ultimate load carrying capacity of externally reinforced beams. Such improvement is about 11.1% in the S1200 specimen while it reaches up to 19.4% in the S2200 specimen. Therefore, it is perceptible that the efficiency of the strengthening system exhibits better performance as the length of the laminate increases. In addition, Fig. 2 implies that increasing the length of the FRP laminates would remarkably reduce both the deflection and curvature of the mid-span section at a certain loading value.

Table 2. Summary of major experimental loads

Designation	P_y (kN)	P_u (kN)	$(P_y-P_{y\text{-}CB})/P_{y\text{-}CB}$ x100 (%)	$(P_y-P_{y\text{-}CB})/P_{y\text{-}CB}$ x100 (%)
CB	110	144	-	-
S2200	117	172	6.4%	19.4%
S1200	112	160	1.8%	11.1%
D2200	120	188	9.1%	30.6%

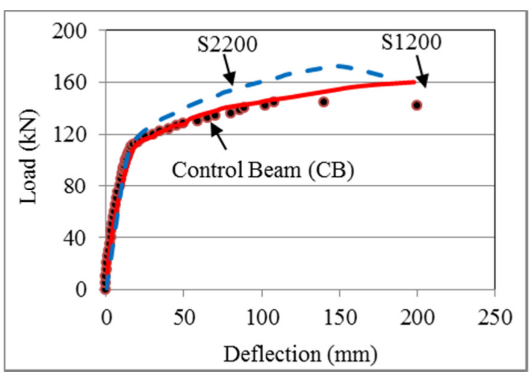


Figure 2. Effect of FRP length on load carrying capacity.

4.2 Specimens with double FRP laminate layers

The beam reinforced with double FRP layers is also examined experimentally. The laminates are connected to the steel beam's bottom flange using bolts that are spaced at 50 mm in the longitudinal direction in order to increase the number of bolts and, consequently, reduce the shear stress in each bolt to avoid premature bolts fracture. Similar to the response observed in beams reinforced with a single layer of FRP, failure of the D2200 specimen involves a combination of bearing in the FRP laminate and local buckling in the compressed part of the steel beam. The initiation of local buckling is located only at the mid-span region just to the right and to the left of the applied load where maximum compressive stresses are induced in the upper flange. Figure 3 shows the load-deflection curve for the D2200 specimen together with the CB and S2200 specimens. By examining these curves, it can be noticed that increasing the FRP thickness affects both the yield and the ultimate load carrying capacity of the beam. Attaching an FRP laminate with a thickness of 3.2 mm (i.e., case S2200) increases the yield load by 6.4% and the ultimate capacity by 19.4% with respect to the unstrengthened section (CB). Doubling the thickness of the strengthening laminate to 6.4 mm for specimen D2200 results in increase of 9.1% and 30.6% in the yield and ultimate capacities, respectively, relative to the results of the control beam (CB). These ratios, along with the load-deflection curves shown in Fig. 3, indicate that the change in the ultimate capacity of the section is due to both the increase in the yielding load of the section and the increase in the slope of the load-deflection curve in the inelastic region. Moreover, increasing the FRP laminate thickness leads to reducing both the deflection and the curvature of the mid-span section especially after yielding occurs.

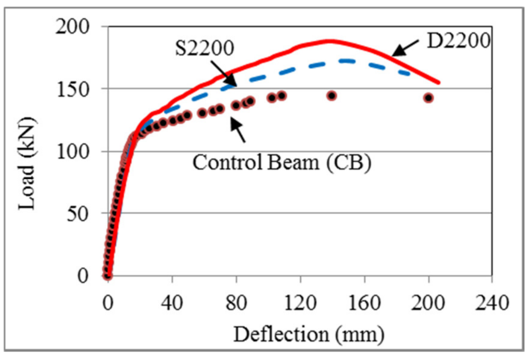


Figure 3. Effect of FRP thickness on load carrying capacity.

4.3 Strain measurements

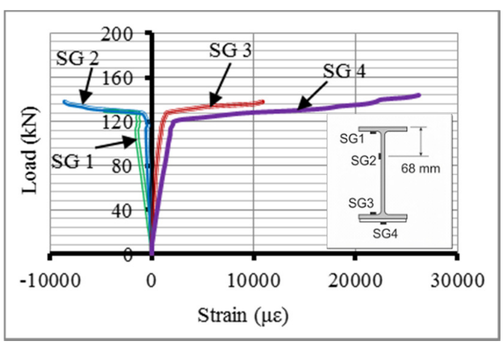
Ten strain gauges are mounted to each specimen at particular locations, as stated in details in section 3, to provide the necessary data to analyze the behavior of the externally reinforced system.

4.3.1 Strain distribution across the beam section

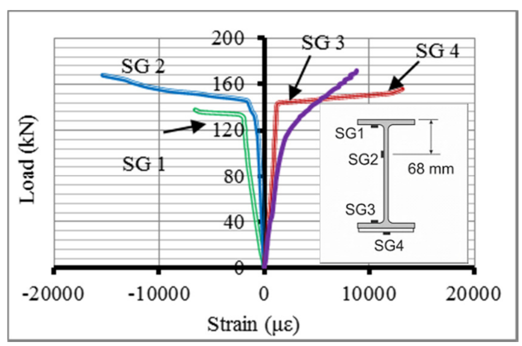
All strain measurements across the tested beams sections are recorded at a cross section located at a distance of 225 mm from mid-span. Figure 4(a) shows the strain distribution in the control beam (CB) where it can be noticed that initiation of yielding started at the extreme steel fibers (SG1 and SG4) and expands gradually towards the neutral axis. The strains measured at the compression flange are almost a mirrored image of the corresponding one measured at the tension flange. The slight difference in values are mainly due to unsymmetrical placement of the strain gauges SG1 and SG4.

Figure 4(b) illustrates the load-strain curves of specimen S2200. In order to investigate the behavior of the composite section, three strain gauges (SG1, SG2 and SG3) are installed in the steel beam while the fourth one (SG4) is mounted to the bottom surface of the FRP laminate. The attachment of the FRP laminate to the bottom flange results in shifting the neutral axis downward and consequently reducing the strain measurements at the lower flange (SG3) compared to the upper one (SG1). The trend of the load-strain curves for SG1, SG2 and SG3 exhibits a linear behavior up to yielding initiation beyond which the slope becomes almost flat. The load-strain curve of SG4 shows a linear behavior up to steel yielding after which the contribution of the FRP laminate in load carrying becomes more significant as indicated by the higher slope of SG4 in the inelastic region. The load-strain curve of SG1 installed at the compression side of the steel beam is not fully plotted until failure because at high loading values, local buckling is initiated which affects the strain gauges' readings causing fluctuation in their values and consequently meaningless measurements. Figure 4(c) presents the load-strain curves for specimen S1200. The graphs show a similar behavior to that of the S2200 specimen. It should be, however, noted that the tensile strains in the bottom flange of the S1200 specimen are higher than those induced in the tension flange of the S2200 specimen.

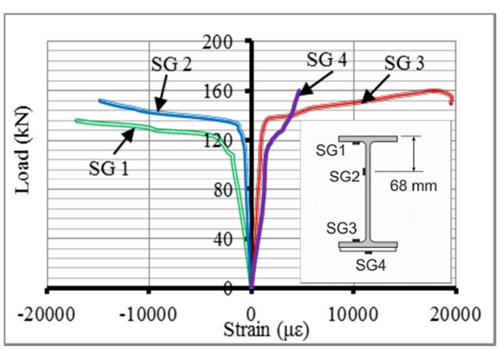
Figure 4(d) shows the load-strain curves at five locations on the composite cross-section of specimen D2200. Additional strain gauge (S5) is added to the bottom of the additional (bottom) FRP laminate. The figure reveals that increasing the thickness of the attached FRP laminate results in shifting the neutral axis downward and consequently delays the onset of yielding in the bottom steel flange as reflected by the load-strain curve for SG3. After yielding of the extreme steel fibers at the upper flange, both FRP laminates provide more significant contribution in resisting the additional applied load. The almost identical measurements of SG4 and SG5 implies that no relative slippage takes place between the two laminates.



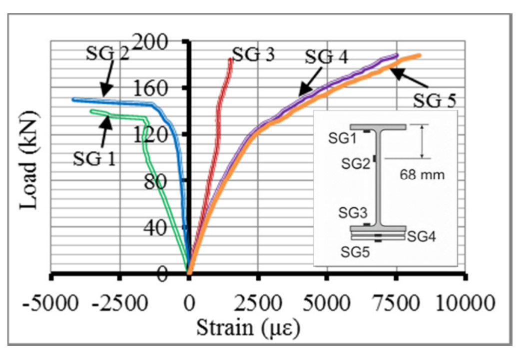
(a) Control Beam (CB)



(b) S2200 specimen



(c) S1200 specimen



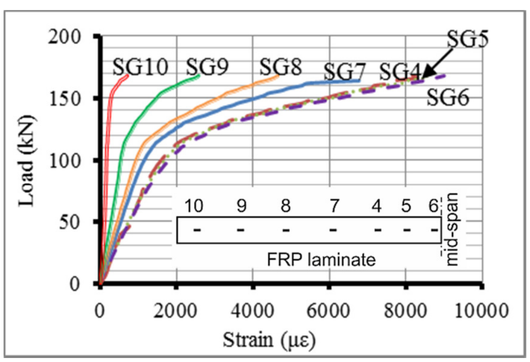
(d) D2200 specimen

Figure 4. Distribution of strains across sections of tested beams.

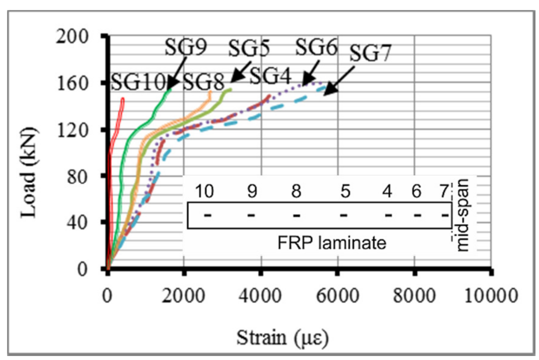
4.3.2 Distribution of FRP strains along the beam span

The longitudinal strain distribution along the FRP laminate is investigated using several strain gauges placed at the bottom side of the laminate. Figure 5(a) shows the strain distribution of S2200 specimen. The plots reveal that the FRP laminate contributes in resisting the applied load during the entire period of load application before and after yielding of the steel section. However, the main contribution of the FRP laminate occurs after yielding of the extreme steel fiber as indicated by the change in the slope at the yielding point of the section being considered. It is interesting to notice also the spread of yielding behavior along the span of the beam from the midspan (close to SG4) towards the supports (close to SG10). Another important observation is that at a certain loading value the strains developed in the FRP laminate at mid-span are higher than those induced at the tips of the laminate. This behavior is consistent with the bending moment distribution along the span of the beam.

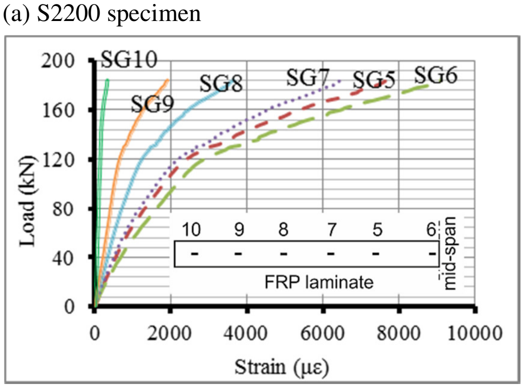
The strain distributions for specimens S1200 and D2200 are shown in Figs. 5(b) and 5(c), respectively. The strain distributions shown in these figures are similar to that of S2200 with two main exceptions. First, the higher levels of strains that can be achieved with longer FRP laminates; especially after yielding of steel. This increase in strains is associated with higher load carrying capacity for beams externally reinforced with longer FRP laminates. Secondly, it can be observed that for a specific length of FRP laminate, increasing its thickness results in enhancement in the load carrying capacity of the beam with less deflection. This can be concluded by examining the slope of the load-strain curves in the pre-yielding region of the specimens reinforced with double FRP layers compared to the corresponding ones strengthened with only one layer of FRP.



(a) S2200 specimen



(b) S1200 specimen



(c) D2200 specimen

Figure 5. Distribution of strains along length of FRP laminates.

5 CONCLUSIONS

This paper examines the performance of steel beams when externally reinforced with anchored FRP laminates of various lengths and thicknesses. The enhancement in the flexural capacity of the externally reinforced beams and the modes of failure governing their response are of particular concern. The experimental outcomes reveal that increasing the length of the FRP laminates from 1200 mm to 2200 mm leads to a slight to moderate improvement in the yield load and significant enhancement in the ultimate flexural capacity of the externally reinforced sections. This is indicated by a yield load increase of 1.8% to 6.4% and ultimate strength increase that ranges from 11.1% to 19.4% for the specimens that are externally reinforced with single layer of FRP laminates. Similarly, increasing the thickness of the FRP laminates results in a considerable increase in the yield load and the ultimate load carrying capacity of the composite section. This is shown by the gain of 9.1% in the yield load and the enhancement in the ultimate capacity that reaches up to 30.6% for the considered double layers specimen. The initiation of yielding in the steel beams under three-point loading starts at the mid-span section and then spreads towards the supports. At each section, yielding occurs at the extreme steel fibers and then expands gradually towards the neutral axis until full plastification of the section is reached. The attachment of FRP laminates to the tension flange causes the neutral axis to be shifted downward and consequently yielding of the extreme steel fibers at the upper flange takes place before their counterpart at the bottom flange. Additionally, the main contribution of the FRP laminates in resisting the applied load manifested after yielding of the steel fibers as the FRP modulus becomes relatively high relative to the post-yield modulus of steel.

6 ACKNOWLEDGMENTS

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