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Performance of FRP-Steel Joints and FRP-Steel Beams Fastened by FRP Anchors

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Abstract **-** This paper reports on the experimental results of utilizing anti-corrosive FRP anchors in FRP-steel joints and FRP-steel beams for strengthening purposes. The FRP anchors were introduced in replacement of the steel bolts typically used in the mechanical fastening methods of strengthening steel structures. FPR laminates were fastened to steel plates in a double-lap arrangement using 10 mm and 13 mm diameter FRP anchors without a bonding agent. The tested joints showed good bearing between the anchors and the fastened FRP laminates. FRP-steel joints fastened by the 10 mm diameter anchors experienced early shear fracture, risking the joints' ductility. Better ultimate load capacity, bearing and ductility were attained by utilizing the 13 mm anchors compared to the 10 mm anchors. The fastening technique was then implemented on full-scale steel beams by fastening the FRP laminates to the beams' bottom flange using the 13 mm FRP anchors. The flexural performance of the beams under two point loads was reported in view of the load-deflection curves, observed failure modes and strain measurements. The strengthened beams showed good bearing between the anchors and the laminates before the fracture of the anchors occurred. The strengthened beams showed higher ultimate load capacity than the un-strengthened beams, opening the horizon for additional investigations on the utilization of FRP anchors in strengthening steel beams.

Keywords**:** FRP anchors, FRP laminates, fastened joints, bearing, strengthened steel beams.

1. Introduction

The continuous aging and deterioration of steel structures, along with the increased applied loads associated with the tremendous increase in the population, provoke the need to upgrade the structural performance of existing steel structures. Fiber-reinforced polymers (FRP) have been extensively used over the last decades to strengthen steel structures due to their high strength-to-weight ratio and corrosion resistivity. Bonding the FRP composites to the steel members using epoxy adhesives was the common practice in the strengthening application. However, research and practical applications reported undesirable brittle failure of the bonded FRP-steel system at the adhesive layer, as the bonded system is sensitive to the applied surface preparations and curing processes [1, 2]. Several investigations were conducted to analyze the behavior of the bonded FRP-steel joints and beams considering various types and layouts of FRP composites, epoxy adhesives, bond length and bond thickness [1], [3], [4]. Recently, researchers are proposing various end-anchoring techniques to avoid/delay the de-bonding failure that governs the behavior of the bonded technique [5–10]. Additionally, the bonded FRP composites were combined with shape-memory-alloys (SMA) in an attempt to enhance the performance of bonded FRP-steel elements [11, 12]. Despite the reported enhancement in the load capacity of the bonded FRP-steel beams, de-bonding controls the failure of the bonded FRP-steel system [6], [8].

Few studies investigated the adequacy of utilizing the FRP composites without a bonding agent (i.e., adhesives) for strengthening steel elements. The effects of various fastening parameters on the performance of mechanically fastened FRP-steel joints, including sheared-edge distance, rolled-edge distance, spacing between bolts, number of washers-per-bolt, tightening torque and bolt-hole size were investigated [13–16]. The promising results at the joint level provoked researchers to adopt the mechanical fastening technique at the beams' level. The structural performance of full-scale steel beams strengthened by fastening FRP composite at the tension flange using steel bolts was examined experimentally and numerically. The effects of the FRP length, FRP thickness, arrangement of bolts and spacing between bolts were examined

[17, 18]. The strengthened beams showed up to a 9.1% and 30.6% increase in the yield and ultimate loads, respectively, compared to the control beams [17]. Analytical solutions were also proposed to analyze the distribution of forces in the fastening steel bolts [19].

The former introduction proved the reliability of the mechanical fastening technique in enhancing the load capacity of the steel beams while providing ductile failure governed by bearing of the fastened steel bolts [17, 18]. This paper investigates the efficiency of the fastening technique while adopting non-corrosive FRP anchors to fasten the FRP laminates to the steel elements. The experimental performance of FRP-steel joints fastened by FRP anchors is reported in view of the observed failure modes and load-displacement relations. Moreover, the failure mechanisms of FRP-steel beams fastened by the FRP anchors are studied in addition to the beams' ultimate loads and strains' distribution along the FRP laminate.

2. Methodology

The experimental program involves two phases. The first phase investigates the performance of FRP-steel joints fastened by FRP anchors. Meanwhile, the second experimental phase examines the effectiveness of utilizing the FRP anchors in strengthening full-scale steel beams. The following subsections present the methodology of each experimental phase.

2.1. Phase I: FRP-Steel Joints

The first phase of the study investigates the failure modes of double-lap FRP-steel joints fastened using 10 mm and 13 mm diameter FRP anchors. The typical joint was composed of two steel plates (clamped and loaded) and two hybrid carbon-glass FRP laminates at the top and bottom of the steel plates in a double-lap arrangement. The FRP laminates had an average tensile strength of 852 MPa, a tensile modulus of 62.19 GPa and a width of 101.6 mm. Meanwhile, the fastened steel plates had average yield strength, ultimate strength and elastic modulus of 300 MPa, 460 MPa and 200 GPa, respectively. Non-corrosive FRP anchors were used to fasten the 3.175 mm thick FRP laminates to the 10 mm thick steel plates without a bonding agent. Each FRP anchor was composed of a 120 mm long fiberglass stud tightened using two hexagonal thermoplastic nuts with end-bearing washers, as shown in Fig.1. The 10 mm and 13 mm diameter anchors had shear strength of 90.6 MPa and 91.3 MPa, respectively, as reported by the manufacturer [20].

Fig. 1: Photo of the FRP anchor

The loaded side of the FRP-steel joint was composed of a single FRP anchor centered across the width of the FRP laminate with an anchor-hole clearance of 2 mm. The fastening FRP anchor was positioned at a distance of three times the hole diameter measured from the laminate edge in all specimens. The FRP-steel joints fastened by the 10 mm diameter FRP anchor were referred to as "Joint–10" specimens, while those fastened by the 13 mm diameter FRP anchors were denoted as "Joint–13" specimens. The FRP anchors were firmly tightened by applying the installation torques recommended by the manufacturer corresponding to 5.5 N.m and 11 N.m for Joint–10 and Joint–13 specimens, respectively. The FRP anchors were lightly lubricated to ease the movement of the nuts during the tightening process. Meanwhile, the clamped side of the joint was tightened using high-tensile M6x40 steel bolts with 375 MPa shear strength. Eight steel bolts were installed at the clamped side of each joint to force the interfacial slippage at the loaded side of the joints.

The longitudinal displacement of the joints was recorded while applying a tensile loading at a rate of 1 mm/min on the specimens. Two LVDTs were used to record the specimens' vertical displacement and to monitor the specimens' rotation during testing. Each configuration was tested twice to ensure the accuracy of the results. Figure 2 displays the test setup of the FRP-steel joints fastened by the FRP anchors.

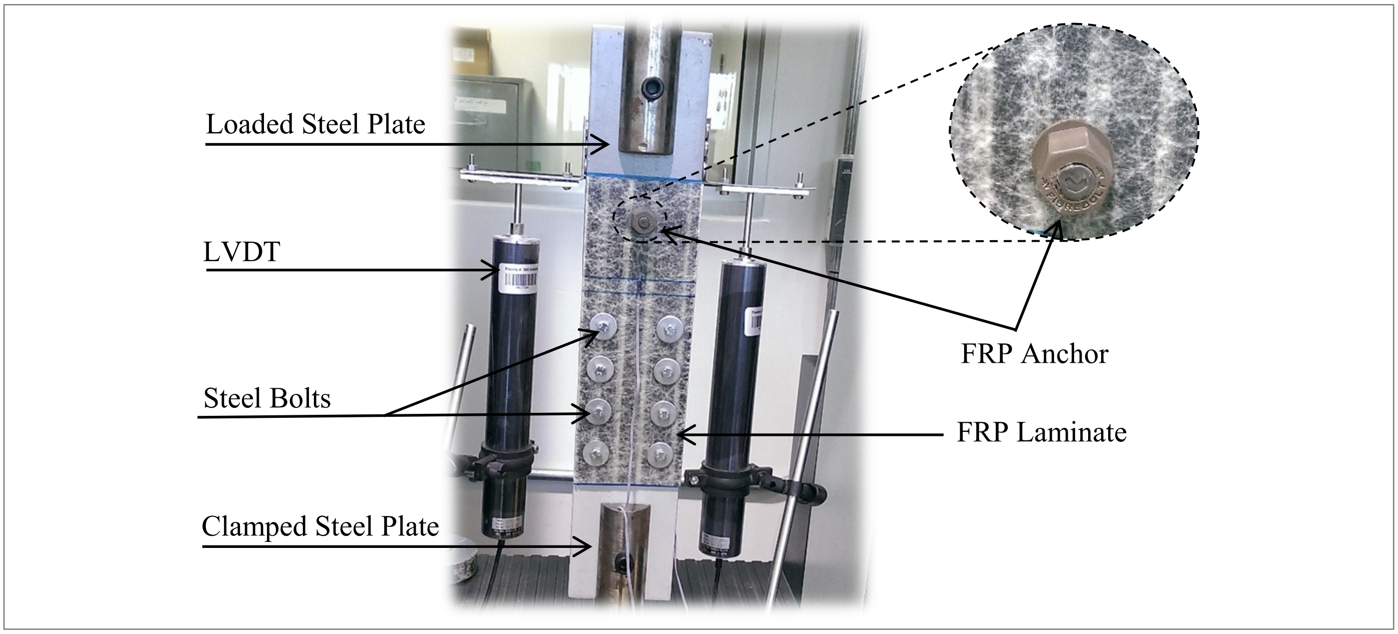


Fig. 2: Test setup of the tensile testing of the FRP-steel joints.

2.2. Phase II: FRP-Steel Beams

The second phase of the experimental program examines the application of the fastening technique adopted in Phase I on full-scale structural members. The effectiveness of using the FRP anchors to fasten the FRP laminates to UB203×102×23 steel beams for strengthening purposes was examined. The tested beams had a total length of 2000 mm, clear span of 1800 mm, flange width of 103.14 mm, flange thickness of 8.48 mm, web thickness of 5.78 mm and total depth of 203.75 mm. The mechanical properties of the steel beams showed a yield strength of 480 MPa, ultimate strength of 620 MPa and elastic modulus of 180 GPa. Two un-strengthened control beams were tested to provide a reference performance; additionally, two additional beams were strengthened by fastening a single FRP laminate at the beam's bottom flange using the 13 mm diameter FRP anchors described in Phase I. The fastened FRP laminate had a length of 1700 mm with a typical 14 mm anchor-hole spaced at 100 mm. The anchors were fastened without any bonding material and torqued to 11 N.m. All beams were tested under a two point loading scheme with a loading rate of 1.5 mm/min and instrumented with vertical and lateral LVDTs, as shown in Fig. 3. Electrical strain gauges were mounted along half the span of the FRP laminate to assess the stain distribution over the fastened FRP laminate.

3. Results and Discussions

3.1. Performance of FRP-steel Joints

Figure 4 presents the load-displacement curves of sample Joint–10 and Joint–13 specimens. The curves of both specimens showed an instantaneous increase in the load, attaining a value of around 2.5 kN due to the friction between the fastened FRP laminates and steel plates. Then, a load stabilization was recorded reaching a displacement of about 2.5 mm reflecting the relative slippage between the steel and FRP laminates. After that, the load-displacement plots showed a significant linear increase in the load until the peak load of the corresponding specimen was attained. This zone reflects the bearing action between the FRP anchors and the fastened FRP laminate as pictured in Fig. 5a. It is noteworthy that the slope of Joint–13 at the bearing zone was higher than that of Joint–10 due to the higher bearing strength and shear strength of the 13 mm diameter anchor compared to the 10 mm diameter anchor. The Joint–10 curve showed an ultimate load of 12 kN at 7 mm before the early failure of the specimen due to the sudden shear fracture of the 10 mm diameter anchor presented in Fig. 5b. Meanwhile, the ultimate load of Joint–13 was 23 kN with a better ductile behavior as reflected in the load stabilization from 8 mm to 13 mm in Fig. 4, where deformations at the anchor took place (see Fig. 5c). Nevertheless, the failure of Joint–13 was characterized by a shear fracture in the 13 mm diameter anchor at a displacement of 13 mm.

Fig. 3: Test setup of the flexural testing of the fastened FRP-steel beams.

Increasing the diameter of the FRP anchors from 10 mm to 13 mm significantly enhanced the ultimate load capacity of the fastened FRP-steel joints and improved their ductility (refer to Fig. 4) due to the higher bearing and shear strength of the 13 mm diameter anchor compared to the 10 mm diameter anchor.

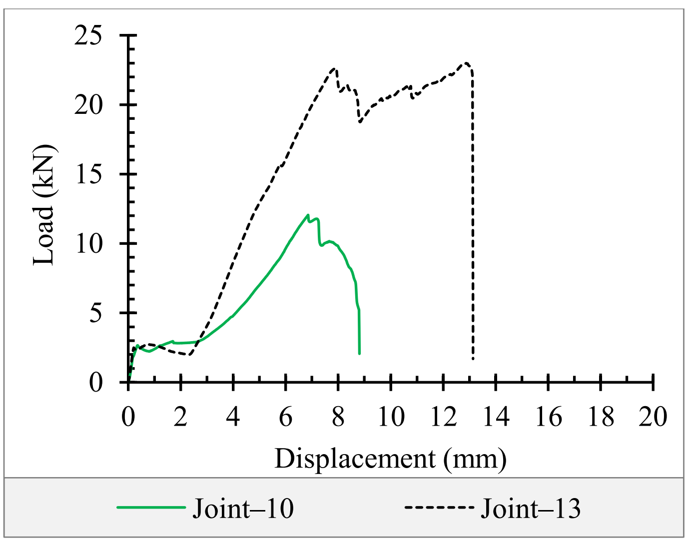
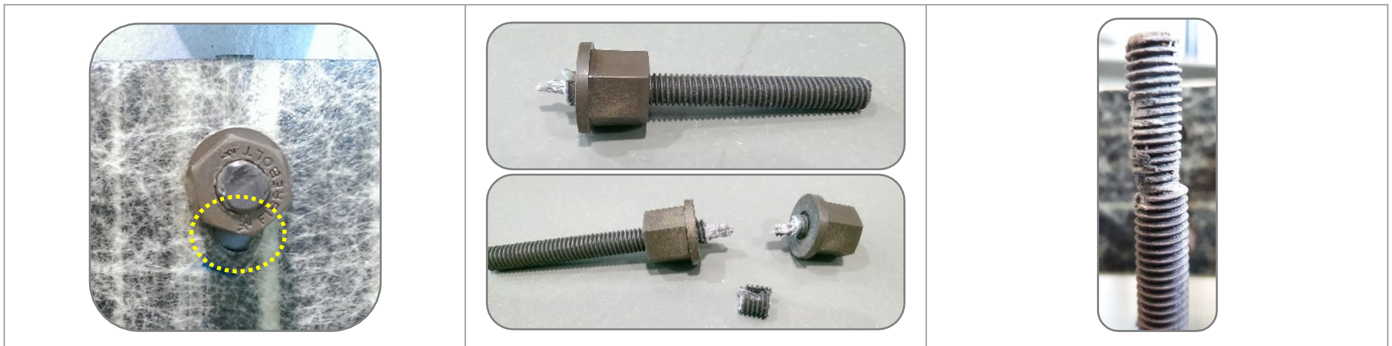


Fig. 4: Load-displacement curves of Joint–10 and Joint–13.

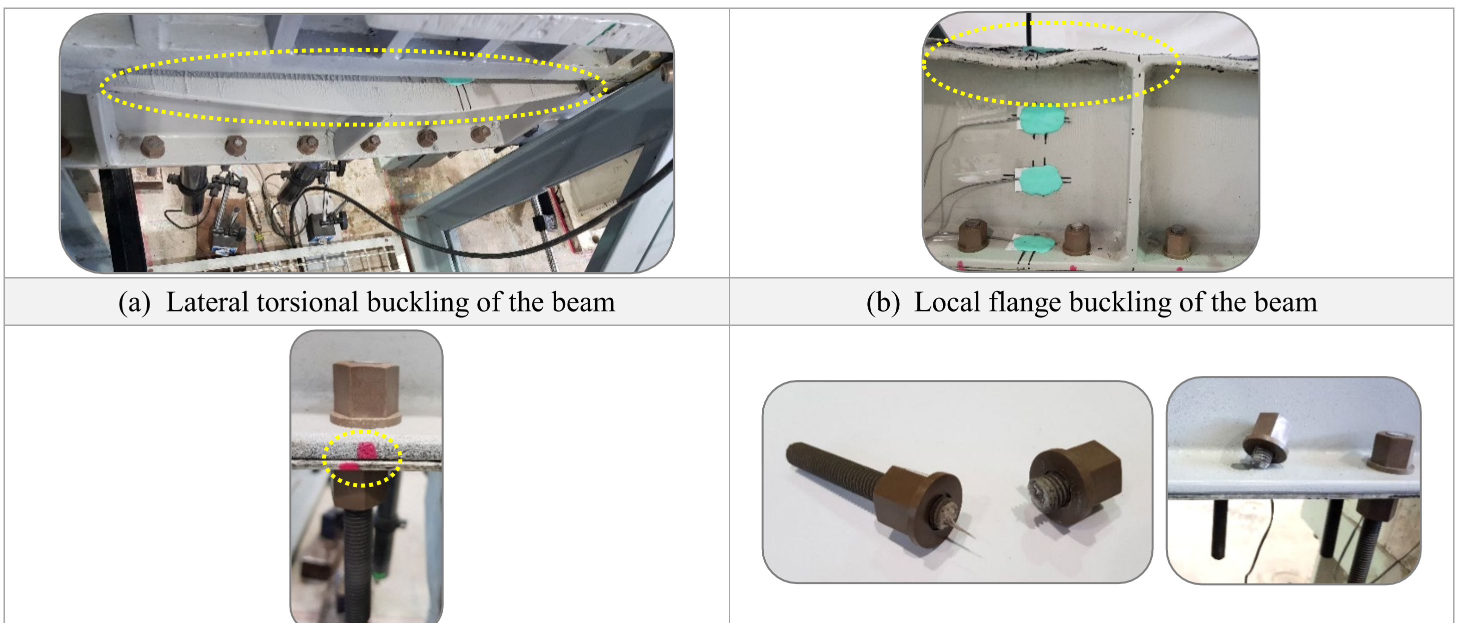


(a) Bearing between the FRP anchors and the FRP laminate | (b) Shear fracture of the FRP anchors | (c) Deformations of the FRP anchors

Fig. 5: Failure modes of the fastened FRP-steel joints.

3.2. Performance of FRP-steel Beams

Both replicates of the un-strengthened control beam experienced steel yielding before displaying lateral torsional buckling and local buckling at the top flange. The steel beams strengthened by the 1700 mm long FRP laminate utilizing FRP anchors spaced at 100 mm showed similar failure modes in addition to bearing between the anchors and the FRP laminate, as shown in Fig. 6. To visualize the bearing process, a marker was used to identify the initial alignments of the anchors with respect to the FRP laminate before testing. As bearing took place, the anchors were slightly displaced relative to the FRP laminate as reflected in the pictured misalignments of the marks (see Fig. 6c). Meanwhile, the failure of the strengthened beams was governed by the shear fracture of the anchors at high loads, as depicted in Fig. 6d.



(a) Lateral torsional buckling of the beam | (b) Local flange buckling of the beam

(c) Bearing of the FRP anchors | (d) Shear fracture of the FRP anchors

Fig. 6: Failure modes of the FRP-steel beams fastened by FRP anchors.

The flexural performance of representative beams is displayed in Fig. 7a. The un-strengthened beam showed a linear elastic behavior until steel yielding at a load of 285.0 kN. The slope of the load-defection plot was slightly reduced during the propagation of yielding through the beam section. The inelastic behavior of the un-strengthened beam started at a deflection of about 20 mm, where the minor application of loads caused a significant increase in the deflection reaching a value of 70 mm. The strengthened beam showed similar elastic behavior with a reduced yield load of 260.5 kN. The reduced yield capacity of the strengthened beam can be referred to the loss of the steel material at the locations of the drilled holes, in addition to the low applied torque (11 N.m) recommended by the manufacturer compared to the ultimate torque strength (24 N.m) of the anchor [20]. Nevertheless, the plastic segment of the load-deflection curve of the strengthened beam showed a positive slope attaining a peak load of 383.2 kN which presents a 5% enhancement in the ultimate load capacity of the beam compared to the un-strengthened beam. The yield and ultimate loads of both specimens are depicted in Fig. 7b. The minor improvement in the ultimate load of the strengthened beams along with the shear fracture of the fastening anchors reduce the practicality of utilizing the FRP anchors in the strengthening of steel beams. The shear fracture of the FRP anchors was reflected by a sudden drop in the load-deflection curve of the strengthened beam (see Fig. 7a).

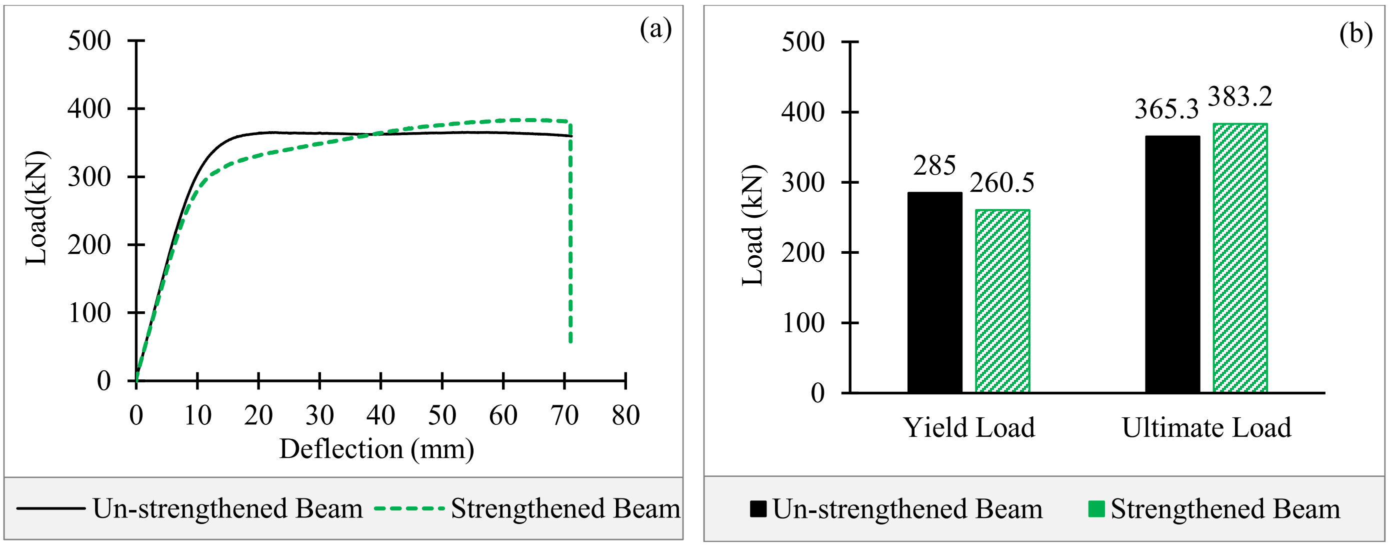


Fig. 7: Performance of fastened FRP-steel beams: (a) load-defection curves, (b) yield and ultimate loads.

Figure 8 shows the strain distribution along the span of the FRP laminate in a strengthened beam at a load of 300 kN. The highest strains were recorded between the loading points with a gradual strain reduction towards the edge of the FRP laminate. The overall distribution of strains along the fastened laminate follows a similar trend to the bending moment diagram of the beam. This observation agrees with the findings reported in [18] for beams fastened by steel bolts and those reported in [3], [21], [22] for bonded FRP-steel beams.

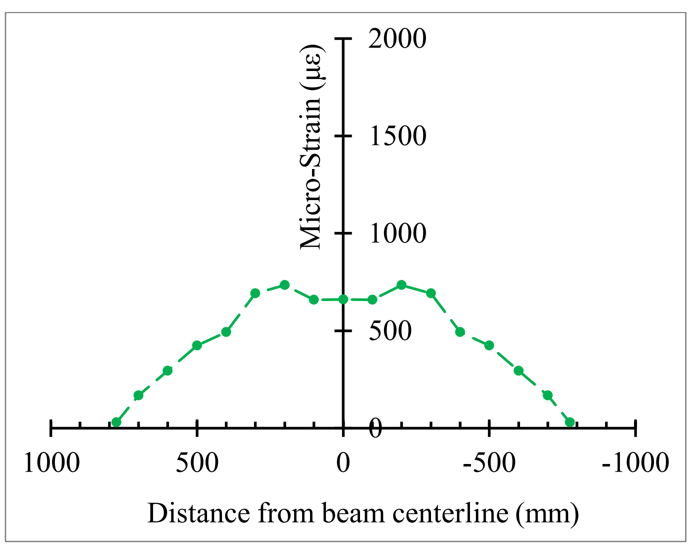


Fig. 8: Distribution of strains along the fastened FRP laminate at 300 kN.

4. Conclusion

The effectiveness of using anti-corrosive FRP anchors in the strengthening of steel members was investigated experimentally. The performance of double-lap FRP-steel joints subjected to tensile loading was examined. The FRP laminates were fastened to the steel plates using 10 mm and 13 mm diameter FRP anchors. The tested joints experienced a combination of failure modes, including friction and slippage between the fastened elements, bearing between the FRP anchors and the laminates and finally shear fracture of the anchors. Joints fastened by the 13 mm diameter anchor showed higher ultimate load and better bearing and ductility compared to those utilizing the 10 mm diameter anchor.

The reported bearing of the FRP anchors at the joints' level allowed for utilizing the 13 mm diameter anchor in strengthening full-scale steel beams. The flexural performance of steel beams strengthened by fastening FRP laminates and subjected to two-point loads was reported. The strengthened beams showed enhanced ultimate load capacity compared to the un-strengthened beam. The experimental findings showed promising results for the utilization of anti-corrosive material in the strengthening of steel structures. However, additional studies are required to delay the shear fracture of the FRP anchors to improve the ductility of the system.

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