

Anchorage Systems Used in FRP Strengthening of Concrete Members

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Abstract. In response to escalating demands to increase the strength of existing structures, new strengthening technologies have evolved, such as the use of fibre composite materials (FRPs) as externally bonded reinforcement. In spite of their potential benefits, the use of externally bonded FRP systems is hampered by the occurrence of premature debonding. Improvement in the efficiency of FRP systems is an area of ongoing research that is still in its infancy. However, promising results have been achieved by the use of anchorage systems, such as bidirectional fibre patch anchors applied to the ends of the FRP to improve the FRP-to-concrete bond performance. Although previous experimental studies on patch anchors have demonstrated significant enhancements in the strength of FRP-to-concrete joints when tested using a near end supported direct shear test, the performance of patch anchors when applied to large-scale beams remains to be investigated. The present paper presents an experimental study where large scale post-tensioned T-beams were strengthened in shear using FRP and later modified by the inclusion of bidirectional fibre patch anchors. The results suggest that the addition of bidirectional fibre patch anchors significantly enhance the maximum laminate strains attained prior to beam failure, in addition to increasing the peak failure load. The research highlights the importance of the influence of potential beam failure mechanisms on the bond performance of FRP patch anchors due to the possibility of shear failure within the FRP anchorage zone, and shows that such failure does not typically occur in direct shear tests.

Keywords: Shear · Strengthening · Anchorage · CFRP · Post-tensioned beams

1 Introduction

The number of existing concrete structures which are insufficient in shear strength is increasing. There are different reasons for this rising number, including freezing and thawing, reinforcement corrosion, deficiencies in the design codes, deterioration of buildings and burdening existing structures with extra loading. When such problems occur, extra measures need to be taken, which include demolishing the structure or strengthening it. For a more economical solution, strengthening of the structure with cost-effective method is considered the best option (Hoult and Lees 2009). Considering the catastrophic type of failure of structures due to shear since it occurs without

warning, more experimental and analytical research is needed in this area. However, most of the research to date has focused on flexural strengthening of concrete structures (You et al. 2011). Different techniques and materials have been used to strengthen existing structures against shear forces. Steel plates, steel brackets, and steel strips with anchorage have been used for the strengthening of reinforced concrete beams (Adhikary and Mutsuyoshi 2006). The outstanding properties of the fibre reinforced polymer (FRP) material make it useful in strengthening reinforced concrete (RC) beams in shear (Koutas and Triantafillou 2013). Debonding of the FRP is the most common failure type of RC structures that are strengthened with FRP (Kalfat et al. 2013). Therefore, anchoring the FRP is a measure taken to improve the performance of the FRP system. The proposal of new and easy to install anchorage systems for the FRP is necessary to enhance its role in retrofitting of structures. Pre-stressing or post-tensioning of concrete is common in construction, specifically in bridge girders. Retrofitting of such structures is needed, especially for bridges with overloaded traffic. Most of the research which has been conducted on this area has not focused on shear strengthening of these structures (Ary and Kang 2012); therefore, more research on the strengthening of post-tensioned beams is needed. This paper reports the results of tests on the performance and shear strength of post-tensioned beams strengthened with CFRP composites, and a new and easy to install anchorage system is proposed.

The aims and objectives of the research are to study the performance of large scale post-tensioned (PT) beams and their shear strength, and to investigate the effect of strengthening using carbon fibre reinforced polymer (CFRP) on the shear capacity of PT beams. A further aim is to study the performance of the proposed anchorage system in enhancing the efficiency of CFRP in the shear strengthening of large-scale PT beams, since this anchorage system has been tested on small prisms, but has never been tested on full-scale beams.

2 Experimental Program

2.1 Specimen Details

Three full-scale post-tensioned T-beams were designed with a span length of 5000 mm, and a depth of about 1050 mm, and 625 mm and 175 mm flange width and depth respectively. The web width was about 225 mm and depth 875 mm. As for the longitudinal reinforcement eight 32 mm diameter bars and one 32 mm post-tensioned bar were used as shown in Fig. 1(b). In order for these beams to fail in shear, the spacing between the stirrups of 475 mm was made to be less than the minimum shear reinforcement. $\text{Ø}10$ mm bar was used for the stirrups, and the duct of the post-tensioned bar had a diameter of 38 mm as shown in Fig. 1(a). The first specimen was left without strengthening as a control beam. The second specimen was strengthened using CFRP laminates, with twelve strips at each side of the beam divided into two groups of six strips in the shear areas of the beam as shown in Fig. 2 with a spacing of 300 mm. Finally, the third beam was strengthened using CFRP laminates with epoxy as the adhesive. The laminate was anchored using two plies of bi-directional CFRP sheets with $\pm 45^\circ$ fabric as shown in Fig. 3.

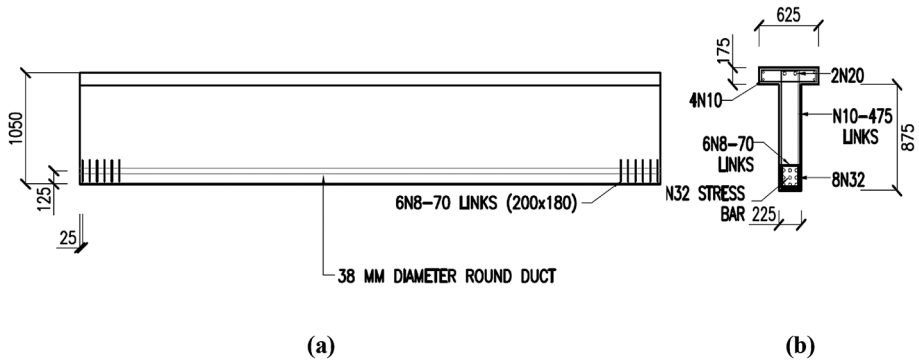


Fig. 1. Cross section details of the beam, and the post-tensioning duct.

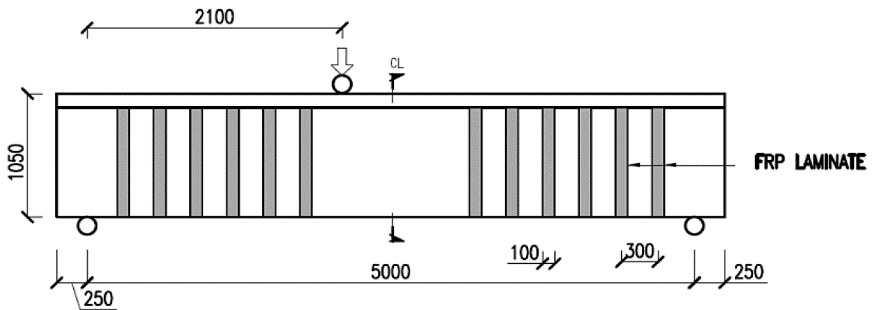


Fig. 2. Strengthened beam.

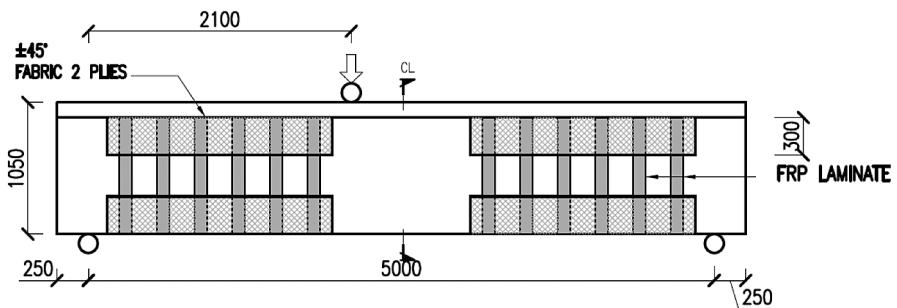


Fig. 3. Strengthened beam with anchors.

3 Patch Anchor Description

The patch anchors proposed by Kalfat and Al-Mahaidi (2014) showed promising results; therefore, in this investigation these patch anchors were used to anchor the CFRP laminate. This anchoring method includes using bi-directional CFRP sheets with $\pm 45^\circ$ fabric as the anchorage system, and these sheets are applied at both ends of the

laminate. The application included applying a first layer of CFRP bi-directional sheets which had been saturated with the adhesive, of which the sheet width was 600 mm and the depth 300 mm with a thickness of 0.86 mm as shown in Fig. 4(a). Three sheets were used along the width to achieve a coverage of 1800 mm. Later CFRP laminate strip was installed with a width of 100 mm, a length of 860 mm and a thickness of 1.4 mm. This was followed by another layer of the sheet as shown in Figs. 4(b and c), Fig. 4(d) shows the bi-directional CFRP sheets with ± 45 fabric. The beams were left to cure for 7 days. The Martial properties are included in Tables 1 and 2.

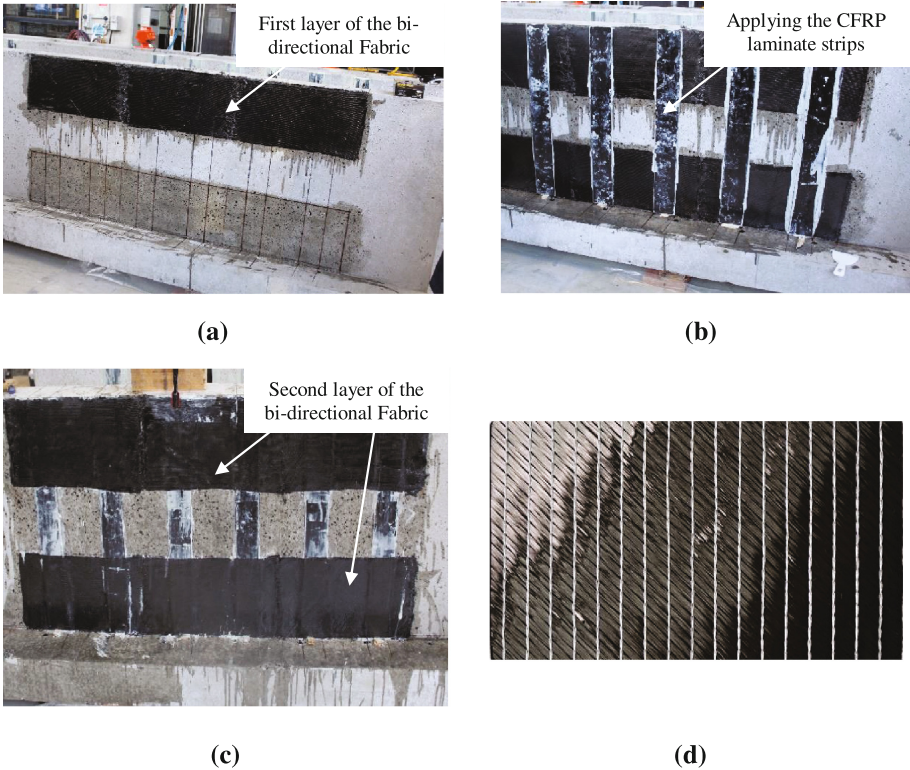


Fig. 4. Patch anchor application process.

Table 1. Concrete material properties.

Properties	Value
Compressive strength	60 MPa
Modulus of elasticity	39117 MPa

Table 2. CFRP laminate and sheet material properties (provided by manufacturer).

Properties	CFRP laminate (MPa)	CFRP sheet (MPa)
Tensile strength	3300	3790
Modulus of elasticity	210000	230000

4 Test Set-Up

In order to extract more data from the tested beams, each beam was tested twice, by testing one side at a time. Therefore, extra reinforcement was needed in the shear area of the non-tested side, in order to force the failure on the second side. Eighteen 20 mm high tensile strength all thread bars were installed in the holes, these holes were drilled in both sides of the flange at a distance of 300 mm c/c. Steel bearing plates 30 mm thick were applied on the top and bottom of the beam, as shown in Figs. 5(a), (b) and (c). This process was followed by applying a stressing force of 100 kN on each bar using a hydraulic jack. All beams were tested under three-point bending moment loading. The beams were tested using a 5000 kN Universal testing machine in the Smart Structures Laboratory at Swinburne University of Technology.

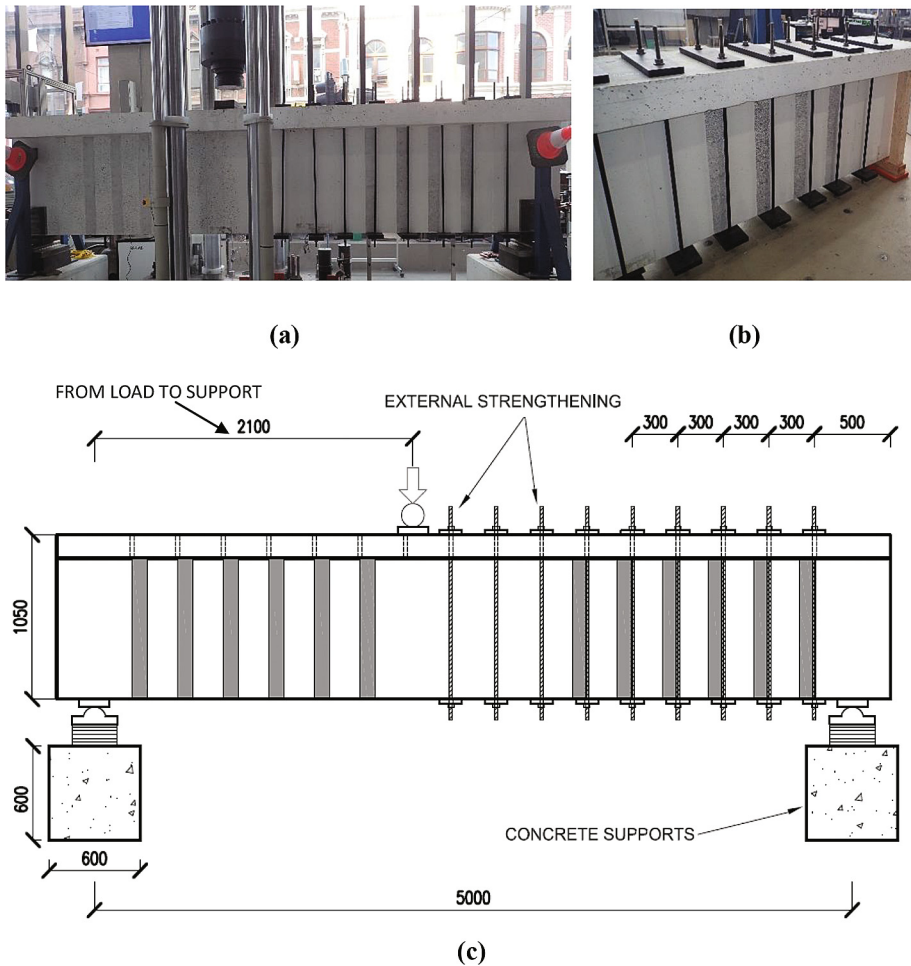


Fig. 5. External shear-reinforcement.

The specimens were instrumented with strain gauges and LVDT's, and photogrammetry was also used to observe the strain in the carbon fibre and the concrete.

5 Results and Discussion

5.1 Load-Deflection

Figure 6 shows the load-displacement diagrams for the tested beams, and Table 3 shows the maximum loads for all beams. The use of the externally bonded CFRP increased the failure load by 32.7% compared to the control beam and by 63.9% when using the patch anchors.

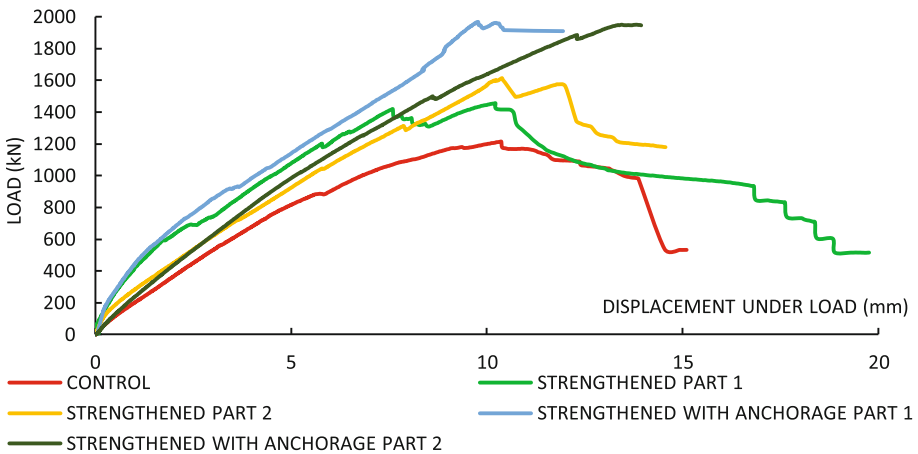


Fig. 6. Load-displacement diagram for the all beams.

Table 3. Maximum load for the tested beams

Beam	Symbol	Maximum load value (Percentage increase over control beam)
Control beam	C	1216 kN
Strengthened beam test 1	ST1	1454 kN (19.6%)
Strengthened beam test 2	ST2	1614 kN (32.7%)
Strengthened beam with anchors test 1	STA1	1967 kN (63.9%), (35.3%)
Strengthened beam with anchors test 2	STA2	1948 kN (60.2%), (20.7%)

5.2 Failure Modes

The control beam C failed in shear due to a critical diagonal crack in the shear spans at the load of 1216 kN. The first and second tests of the strengthened beam failed by end debonding of the carbon fibre with the propagation of the shear crack at loads of 1454 kN and 1614 kN respectively. In addition, the failure mode for the anchored beam was due to the propagation of the shear crack which led to debonding of the patch anchor and breakage of the CFRP laminate as shown in Figs. 7(a), (b), (c) and (d).

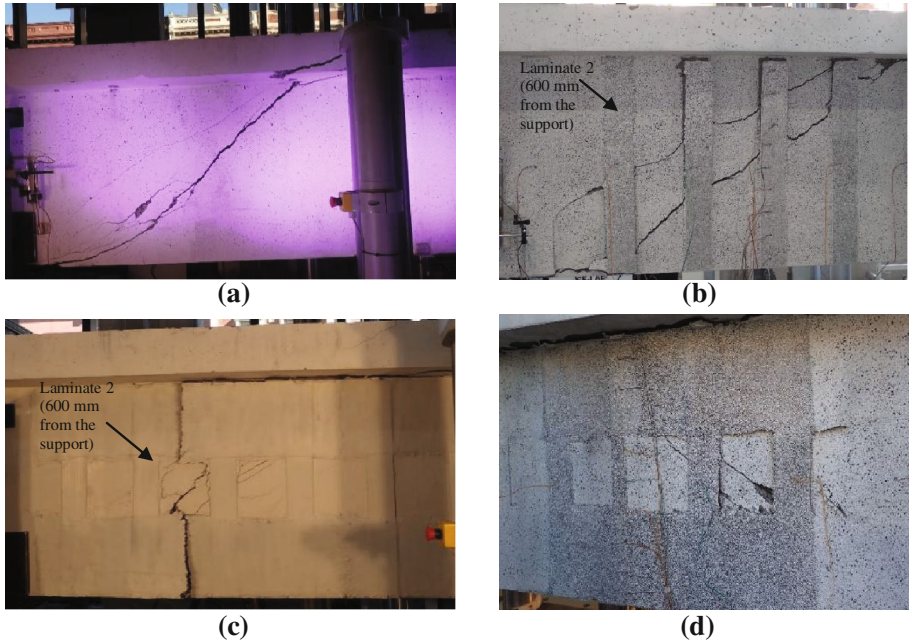


Fig. 7. Cracks at failure for the (a) Control, (b) Strengthened and (c, d) Strengthened with anchorage beams.

5.3 Strain in the Concrete and Main Reinforcement

Figures 8(a) and (b) show the strain in the main reinforcement which did not yield, indicating that there was adequate longitudinal reinforcement in the beams for them to not fail in flexure. The strain in the concrete did not reach 0.003; therefore, the failure was not due to crushing of concrete. All of the strain gauge readings indicated that the failure mode was due to shear.

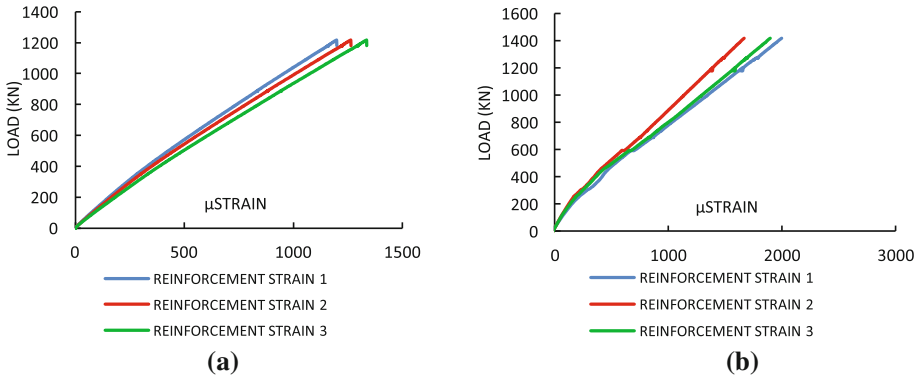


Fig. 8. Strain in the longitudinal reinforcement (bars in the bottom) for (a) Control beam, (b) Strengthened beam.

5.4 CFRP Strain

To investigate the influence of the patch anchors on the CFRP strain and their contribution to the ultimate shear resistance, the CFRP strains of the strengthened beams were measured. The plots of the strain along one of the laminates at certain loads are presented in Figs. 9(a) and (b). These plots show the highest strain in the CFRP along

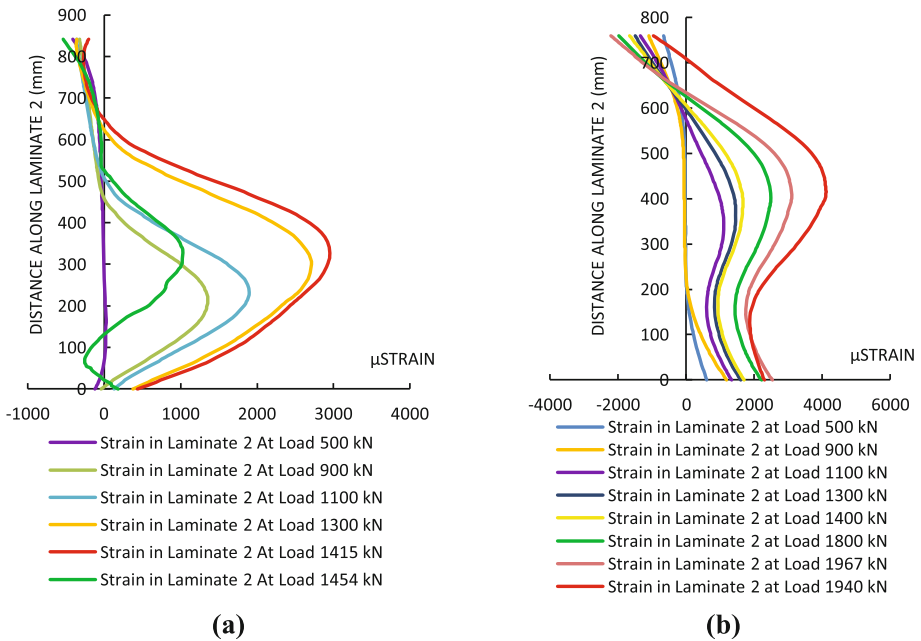


Fig. 9. Strain along CFRP laminate 2 in (a) Strengthened beam (b) Beam strengthened with anchorage at certain loads.

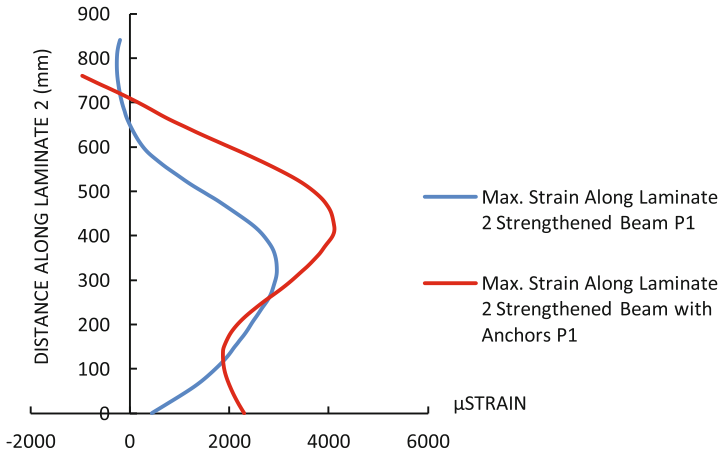


Fig. 10. Comparison of the maximum strain along laminate 2 between strengthened and strengthened with anchorage beams.

the shear span, and at which load the laminate de-bonded. It should be noted that the use of the patch anchors increased the strain in the CFRP from 3000 micro-strain (obtained from the CFRP in the strengthened beam without anchorage) to 4000 micro-strain (obtained from the anchored beam). Figure 10 presents a comparison of the strain between the CFRP laminates in the strengthened beam and strengthened beam with anchors.

6 Conclusion

In the present paper, an experimental study was conducted to investigate the effectiveness of a new anchoring technique for post-tensioned large-scale T-beams strengthened in shear using CFRP laminate strips. This technique involves sandwiching the CFRP laminate strip with two CFRP sheets with $\pm 45^\circ$ fabric at both ends in the web area of the beam. Based on the results, the following conclusions can be drawn:

- The use of carbon fibre laminate as an external strengthening enhances the shear capacity of the beams; in addition, patch anchors are an effective anchorage technique, since they considerably enhance the shear capacity of CFRP shear-strengthened beams.
- The use of patch anchors improves the contribution of the CFRP laminate as shown by the increased strain in the laminate.
- There is a delay in premature debonding failure due to the use of patch anchors. Therefore, the patch anchors are a promising anchorage method.

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