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The Influence of FRP Spike and Patch Anchors on the Bond Performance of FRP-to-Concrete Joints

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ABSTRACT: It has been demonstrated that the governing failure mode of concrete structures strengthened with fiber reinforced polymer composites (FRP) is by premature debonding of the FRP material from the concrete substrate. Research has shown that one means by which the FRP-to-concrete bond performance may be improved is to provide anchorage measures that resist the interfacial shear and peeling stresses that are generated along the FRP bond line. FRP spike anchors and bidirectional fiber patch anchors are a proven means to enhance the bond performance of FRP materials when bonded to concrete. Although the above mentioned anchorage systems have shown significant promise when investigated independently, the present research aims to combine their unique properties into a hybrid anchorage system. In this study, FRP spike anchors were used to anchor bidirectional fiber patches and used to restrain FRP laminates tested in direct shear resulting in a superior anchorage strength which was demonstrated through experimental testing.

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1 INTRODUCTION

Alongside the demand for structural rehabilitation and strengthening of bridge infrastructure, new materials such as advanced fiber reinforced polymer composites (FRP's) have become a popular means to increase the flexural, shear and torsional resistance of existing reinforced concrete (RC) structures when applied as externally bonded reinforcement. FRP's have replaced steel as a preferred strengthening material due to their high tensile strength, light weight, ease of installation, corrosion resistance and durability. FRP's are typically applied to structural members using epoxy resin and the lack of mechanical fastening has resulted in lower installation costs compared to other strengthening solutions such as steel. Even though advanced composites have a high tensile strength, in shear and torsional retrofit applications, this strength may be little utilised due to the ineffective bond between the composite and the concrete. Compiling results from numerous tests it was seen that FRP de-bonded on average at a strain level of about 50% of the materials tensile capacity (Bonacci and Maalej 2001). However is has been found that for heavy shear and torsional strengthening applications this utilisation level can be as low as 10-25% (Kalfat and Al-Mahaidi 2010). The inherent drawback has lead to recent research into CFRP-to-concrete bond strength improvement and the introduction of efficient anchorage systems.

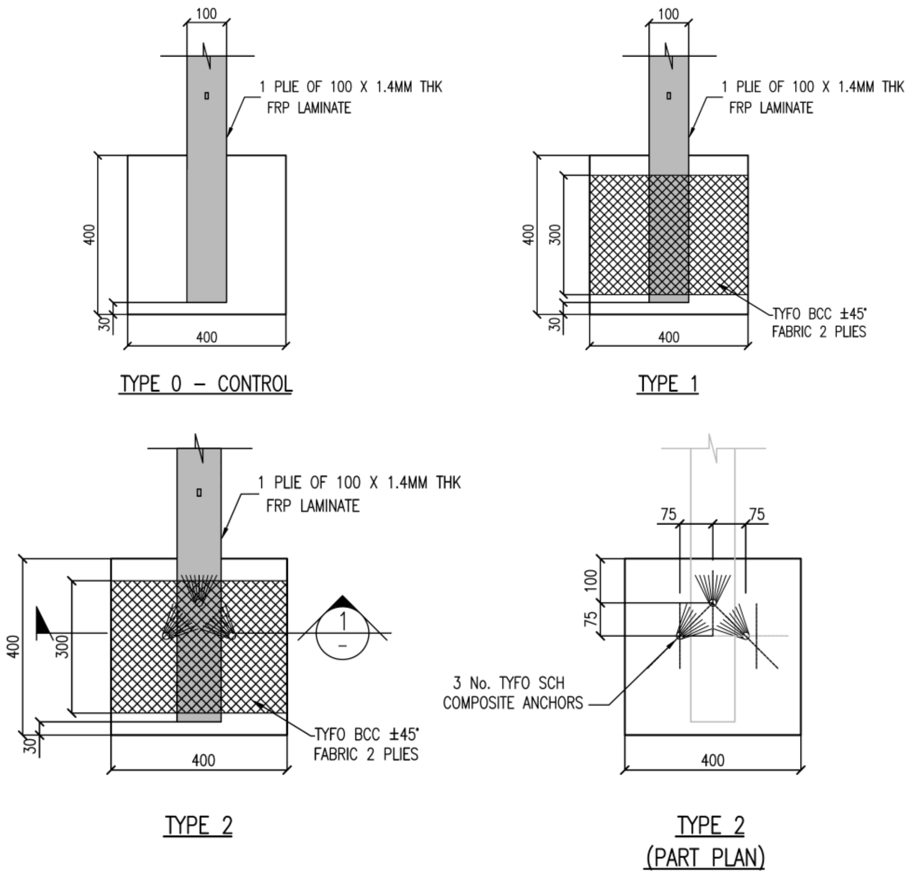
It has now been proven through extensive research that when sufficiently anchored, the CFRP material strain at failure can approach its ultimate strain at rupture. Hence the use of anchorages means that a given strengthening capacity can be achieved requiring less material than would be possible without the use of anchors (Orton, Jirsa et al. 2008). Although these benefits have now been widely acknowledged in design guidelines such as the ACI 440.2R-08, there remains a lack of design guidelines to enable the practical use of such anchors. In addition, current forms of anchorage have been developed primarily with flexural strengthening applications in mind. Examples of these are: U-straps, mechanical fastening and clamping devices. Of the many anchorage systems investigated for shear strengthened members, ±45° bidirectional fiber patch anchors have shown the most promise (Kalfat, Al-Mahaidi et al. 2013) and were able to increase laminate utilisation levels by up to 30-35.5%. The predominant failure mode of patch anchors has been documented as: patch anchor debond where the bidirectional fiber patch together with the FRP laminate debonded from the concrete as a rigid element. All the studies on patch anchors to date have focused on anchoring a single layer of FRP laminate with 2 layers of ±45° bidirectional fiber sheets. In the present paper, we will present a new study which improves the patch anchor concept by anchoring the bidirectional fiber patch anchor to the concrete with several FRP spike anchors. The enhanced anchorage system will be used to anchor FRP laminates in an attempt to achieve a higher FRP force at a lower level of strain prior to failure.

2 EXPERIMENTAL PROGRAM

2.1 Specimen design and preparation

The experimental program devised was designed in a manner analogous to previous studies on FRP-to-concrete patch anchored joints. Each specimen consisted of 400x400x250 mm reinforced concrete blocks, reinforced with 3 x 8mm diameter closed links in each direction with 20mm cover. Three groups of specimens were designed consisting of 2 specimens in each group. The first group consisted of control specimens consisting of 100mm wide x 1.4mm thick FRP laminates bonded to the concrete with epoxy resin (without anchorage) over a 370mm bond length. The second group anchored the FRP laminates with a 300mm long x 400mm wide patch anchor consisting of 2 layers of ±45° bidirectional fiber sheets. Lastly, the third group introduced 3 x spike anchors to anchor the bidirectional fiber sheets (used in the second group) to the concrete. The spike anchors used (Tyfo Fibr Anchor) were commercially available from Fyfe and placed strategically based on the results of numerical simulations (Kalfat and Al-Mahaidi 2015) which indicated that the stresses were concentrated beneath the FRP laminate and over a patch anchor width 50mm either side of the edges of the FRP laminates. The use of a narrower laminate width, increased the likelihood of laminate slippage from between the 2 layers of bidirectional fiber sheet due to the loss of contact area. In order to compensate for this, a higher strength of saturating adhesive was used after several types of adhesive were independently tested. Prior to application of the FRP, the concrete was sandblasted to achieve a surface roughness of 1.5mm and later cleaned to remove dust and debris. If spike anchors were required to be installed, a masonry drill bit was used to drill 18mm diameter holes into the concrete to a depth of 100mm at the required locations (refer figure 1b). The holes were cleaned thoroughly using a special steel brush and compressed air to blow out dust from hole and remove remaining dust from surface of specimen. The next steep involved the mixing of a 2 part epoxy saturating resin and thoroughly impregnating each spike anchor using brush and trowel. The first layer of ±45° bidirectional fiber sheet was impregnated with resin and applied to the concrete surface using a wet lay-up approach. Holes were then created within the ±45°

bidirectional fiber matrix, aligning with the predrilled holes in the concrete using a 3 mm steel rod ensuring that no fibers were cut. The holes were filled with saturating resin and the dowel end of the spike anchor was inserted into the hole while a fan was created at the other end and bonded to the top of the first layer of bidirectional fiber sheet. A 2mm thick layer of FRP laminate adhesive was applied over a 400 mm bond length of the FRP laminate and the FRP laminate was applied to the concrete. 50 mm adhesive tappers were constructed at the laminate edges to provide a smooth transition for the second layer of bidirectional fabric over the FRP laminate in the transverse direction. Finally, the second layer of ±45° bidirectional fiber sheet was saturated and applied over the top of the FRP laminate, effectively sandwiching the laminate in between two layers of bidirectional sheet. A summary of the specimen properties are depicted in figure 1.



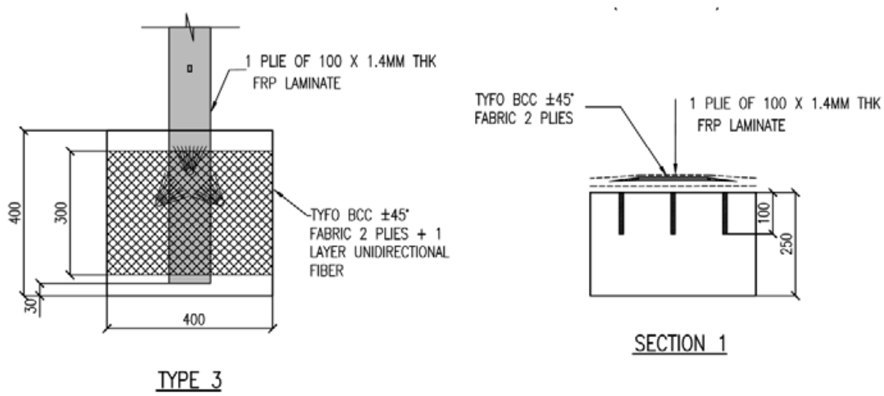


Figure 1 - **S**pecimen summary

2.2 Experimental Setup

All specimens were tested in direct shear using a near end supported (NES) single shear pull test configuration. A custom made steel rig was constructed (refer figure 2) which consisted of 30mm thick top and bottom steel plates with 4 x M20 high tensile threaded rods securing the concrete specimen. The rig was fastened to an MTS 1MN universal testing machine using M24 high tensile bolts, which secured the test rig into place. Special aluminium 100x100x2mm plates were sandblasted to create a roughened surface and placed between the FRP and the jaws of the testing machine. However, prior testing it was imperative that the specimen was carefully levelled and aligned to eliminate any vertical and horizontal misalignments and to ensure concentric loading. A front clamping plate was placed at the bottom of the concrete specimen to ensure that no backward rotation of the specimen occurred during loading.

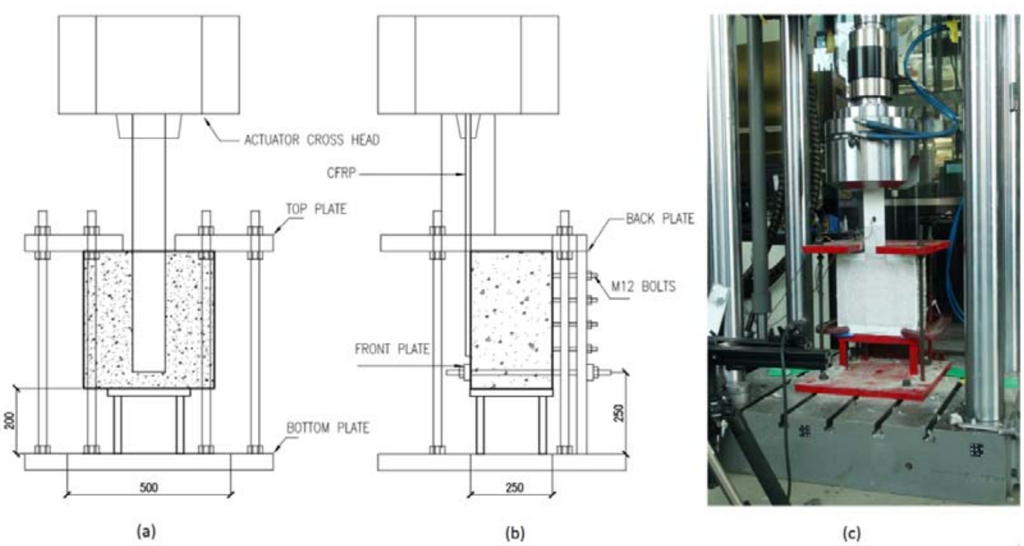


Figure 2 - Specimen testing rig details (a) configuration of test rig (front view); (b) configuration of test rig (side view); (c) Photo of specimen inside testing rig

2.3 Instrumentation and loading procedure

All specimens were instrumented with 2 strain gauges at the front and back of the laminate in the same location, 150mm above the uppermost concrete face on the unbonded portion of the FRP laminate. The purpose of the strain gauges was to record the maximum strain and monitor any bending in the FRP laminate during testing indicating the presence of tilting. All specimens were loaded using displacement control at a rate of 0.5mm/min until failure. A second data acquisition technique was implemented on all specimens using an optical full field measurement method, otherwise known as digital image correlation (DIC) photogrammetry. The technique involved painting the surface of the specimens white and creating a random high contrast speckle pattern using a black permanent marker. The data was acquired using a pair of high resolution CCD cameras to acquire images of the test area at one second intervals from commencement of the test until failure. The images were later analysed using an image correlation algorithm (Vic3d) in order to provide full field strain and displacement measurements in 3D. The data acquisition technique has been used extensively by the authors and verified with strain gauging on countless occasions. As a result, only a minimum amount of strain gauges were instrumented on each specimen.

2.4 Quality Control Tests

2.4.1 Material properties

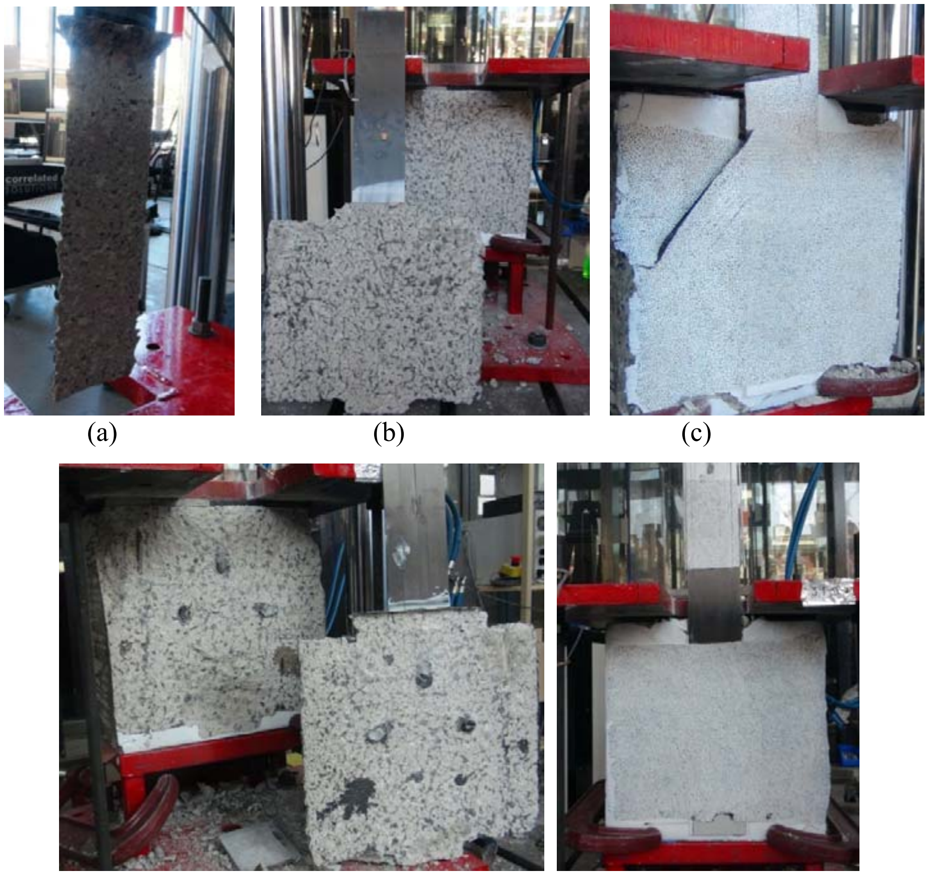
The concrete material was delivered, pre-mixed from a local supplier. A total of 7 concrete cylinders were cast and tested in accordance with (AS 1012.9 1999) to verify the concrete compressive strength properties. The concrete cylinders were crushed after 300 days curing at room temperature and the average compressive strength of the concrete was 28.7 MPa. The cylinders were crushed approximately 3 days after testing. In order to verify the correctness of surface preparation, concrete tensile strength and mixing of adhesives, pull off testing was carried out according to (I.S. EN 1542 1999). Eight adhesion tests were performed which all failure by fracture of the concrete a few mm below the adhesive layer. The average tensile strength of the substrate as determined from the pull-off test results was 3.0 MPa. The laminate adhesive and saturating resin were supplied by the manufacturer Fyfe. The tensile strength of the adhesives were verified using tensile coupon samples which were prepared and tested in accordance with ASTM-D638-10. Based on the average of 5 samples, the tensile strength of the laminate adhesive (Tyfo-TC 1 Epoxy) was 21.8 MPa, while the strength of the saturant (Tyfo S Epoxy) was 63.1 MPa. The tensile strength and elastic modulus of the FRP laminates were verified using three laminate coupon tests in accordance with (ASTM: D 3039 2000). Each test coupon had an overall length of 200 mm and average width of 50 mm. A single strain gauge was installed at the centre of the specimen and the strain reading was used to find the modulus of the FRP. The results indicated a mean elastic modulus of approximately 170 GPa which verified the manufacturers value. A summary of the FRP properties are presented in table 1.

Table 1 - FRP Properties data

Properties	Bidirectional FRP (±45°)	FRP Laminate	Units
Tensile Strength	3.79	2.79	GPa
Tensile Modulus	230	170	GPa
Ult. Elongation	2.1	1.8	%
Thickness	0.55	1.4	mm
Width		100	mm

2.5 Failure Modes

An examination of the various failure modes of each specimen has identified several mechanisms. Both control specimens (Type 0) failed by a clean form of concrete cover separation failure approximately 3-5mm within the concrete cover zone at a load level of 52.0-55.2 kN. No interfacial debonding was observed between the FRP and the adhesive and the failure plane is depicted in figure 3a. The type 1 specimens, which were anchored with bi-directional fiber patch anchors only, failed similarly by concrete cover separation failure, while engaging the full area that the patch anchor was bonded to the concrete. The failure mode demonstrates the effectiveness of the patch anchor in distributing the bond stresses that were typically localised to the width of the FRP laminate to a larger area of concrete resulting in load level of 159.4-177.7 kN being reached prior to failure. Two mechanisms of failure were observed in the specimens anchored with spike anchors in addition to the bidirectional fabric patchs (Type 2). The first failure mode is shown in figure 3c was partial interlaminar separation failure, where debonding partially occurred between the two layers of bidirectional fabric and between the first layer of bidirctional fabric (bonded to the concrete) and the FRP laminate at 276.2 kN. The partial interlaminar separation failure occurred simultaneously with concrete cover separation failure, which occurred at a deeper level within the concrete cover zone (10-15mm). The second specimens which were anchored using the same means, failed by pure concrete cover separation failure at a load level of 286.8 kN, resulting in rupture of all three FRP spike anchors and separation of the entire laminate/patch anchor structure from the concrete as a singular rigid element. This occurred at a load level that was over 5 times higher than the unanchored control specimens and 1.6 times higher than specimens anchored with patch anchors only. The addition of 1 layer of unidirectional fabric to the two layers of bidirectional fabric anchored to the concrete with FRP spike anchors (Type 3) did not show any benefits in terms of the maximum load reached prior to failure (251.7-287.7 kN). The first specimen anchored in this manner, failed by slippage of the FRP laminate from between the two layers of bidirectional fiber sheets, as indicative in figure 3e. No other specimen failed in this manner and it was thought that the failure mode may have been due to imperfections in the interlaminar bond as a result of the addition of the unidirectional fiber. The second specimen failed by patch anchor debond at a similar load to specimen type 2. As a result, the addition of the unidirectional fabric was unsuccessful in providing any further improvement to the anchorage configuration used in type 2, which relied on the bidirectional fabric and spike anchors only.



(a) (b) (c) (d) (e)

Figure 3 - Summary of failure modes (a) Type 0 Control specimen – Concrete cover separation failure; (b) Type 1 - Patch anchor debond; (c) Laminate slippage Partial inter laminar/concrete separation failure; (d) Type 2 – Patch anchor debond + spike anchor rupture; (e) Laminate slippage;

2.6 Overview

In tables which follow reference is made to V3D (Photogrammetry) and SG (strain gauge). These refer to the two data acquisition techniques used in the experimental program.

Table 2 summarises the failure loads and maximum FRP elongations reached in all specimens tested. The experimental data was indicative that specimens anchored with bidirectional patch anchors (type 1) achieved laminate strain levels of 5451-6205 με prior to failure, thereby increasing the fiber utilisation levels to 30-35.5%. This was improved even further by the addition of FRP spike anchors (type 2) to anchor the bidirectional fabric sheets to the concrete, resulting in laminate strains of 9209-9787 με prior to failure and a utilisation level of 51-54.4%. A wider scatter of results was achieved as a result of the addition of unidirectional fabric (type 3) as a result of the premature failure mode of laminate slippage observed in specimen 3.1 and produced a slightly lower level of laminate strain prior to failure (8276-8492 με). However, specimen 3.2 which failed by patch anchor debond reached similar strain levels to the type 2 specimens (9347-9995 με).

Table 1 - Results summary

Specimen	**Exp Failure Load (kN)**	**Max Laminate strain (με) (SG)**	**Max Laminate strain (με) (V3D)**
0.1	55.2	2097	2138
0.2	52.0	2201	2334
1.1	177.7	6180	6205
1.2	159.4	5451	5646
2.1	276.2	9209	9533
2.2	286.8	9429	9787
3.1	251.7	8276	8492
3.2	287.7	9347	9995

3 CONCLUSION

The paper has presented the results of an experimental program designed to investigate the combined properties of bidirectional fiber patch anchors, anchored to the concrete with FRP spike anchors. The hybrid anchorage system was used to enhance the bond properties of FRP laminates bonded to concrete. FRP-to-concrete joints were constructed and tested in direct shear which yielded significant enhancements in terms of the maximum force required to cause debonding and the maximum FRP laminate elongation reached prior to failure. Specimens anchored with bidirectional fiber patch anchors alone yield strength enhancements of 2-3 times that of the control specimen and the addition of spike anchors resulted in a strength enhancement of over 5 times. The strains in the bidirectional fabric were in the order of 2500-3000 με.

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