

# Investigation on Enhancing Flexural Performance of CFRP Strengthened Concrete Beams

[J.C.P.H. Gamage, M.R.E.F. Ariyachandra]

**Abstract**— Strengthening of reinforced concrete structures is inevitable to preserve structural integrity and protracted service life due to the effects of numerous elements contained within the natural or artificial environment surrounding it. Carbon Fibre Reinforced Polymer (CFRP) composites have been progressively more utilized for decades as a strengthening material due to its outstanding characteristics such as high strength to weight ratio, reduced weight, excellent resistance to corrosion and environmental degradation and ease of handling during construction which have distinguished it well apart from the other strengthening techniques. However, the ultimate load capacity of CFRP strengthened concrete composites is comparatively lower than CFRP material due to premature debonding which reported as the most frequently observed failure mode in CFRP/concrete composites. In the current study, alternative bonding techniques were investigated to achieve enhanced bond performance by delaying premature debonding failure. A total of 18 CFRP strengthened concrete beams with different bonding techniques were tested using three point bending test. The test results show convincing evidence on strength enhancements. Moreover, a numerical model was also developed to inspect the performance of existing CFRP anchors. Finally, a parametric study was carried out and a new type of anchor; “Tri-leg anchor” is introduced. This paper summarizes the overview of the test programme, finite element modeling, results and analysis.

**Keywords**—CFRP, debonding, end wraps, polyester mesh, Tri-leg anchor

## I. Introduction

As reported in literature [1,2,3,4], CFRP/concrete composites exhibit fundamentally two types of failure criterions. In the first category, the full composite action of concrete and FRP is maintained until the failure occurs (i.e. FRP rupture and crushing of compressive concrete). Such failure modes are entitled as “classical failure modes”. The composite action between concrete and FRP is lost prior to failure in the second category, (i.e. de-bonding of FRP) and also known as “premature failure modes.” Separation of concrete cover, separation of FRP plate and interfacial bond failure can be recognized as such failure behaviours of CFRP/concrete composites.

Above all, end-debonding failure (interface failure between CFRP sheet/plate and concrete substrate at the ends of CFRP sheet/plate) is the most commonly reported failure mode [5,6] which significantly declines the ultimate load carrying capacity of CFRP/concrete composites ranging from 60% to 80% [7] while upgrading the brittleness at failure.

To address this decisive phenomenon, a great deal of research studies has been carried out grasping the use of mechanical fasteners, FRP anchors, Near Surface Mount (NSM) reinforcement and End Wraps [6]. End Wraps have been recognized as a beneficial way out to delay premature debonding since it enhances the shear capacity of CFRP/concrete composites [8]. However, previous research studies emphasize the necessity of establishing appropriate design guidelines to predict the strength gains due to end wraps [9] which has led to restrict possible industrial applications. In the current study, alternative bonding techniques were adopted in order to achieve enhanced bond performance by delaying premature debonding failure. A total of 18 CFRP strengthened concrete beams with different bonding techniques were tested using three point bending test. A numerical model was developed using ANSYS to inspect the performance of existing CFRP anchors. A parametric study was carried out via numerical analysis and a new type of anchor; “Tri-leg anchor” is introduced.

## II. Material properties and specimen characterization

A total of 18 concrete beams with 100 mm × 150 mm × 750 mm dimensions (width × depth × length) were prepared using grade 30 concrete mix containing maximum aggregate size of 20 mm and water/cement ratio of 0.55. The configuration of reinforcements of concrete test specimens is shown in Fig. 1. These specimens were immersed in water for maturation period of 28 days. A total of 10 concrete blocks of 150 mm × 150 mm which contains two from each batch of concrete were also prepared and cured under the same condition. The measured average compressive strength of concrete was 33.6 N/mm<sup>2</sup>.

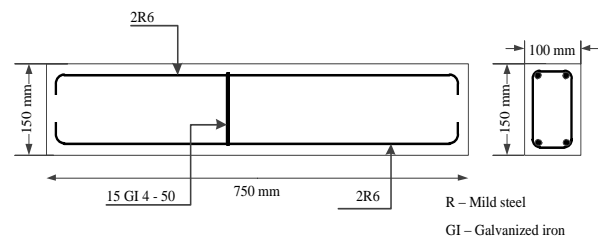


Figure 1. Configuration of reinforcements

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With the completion of curing process, concrete substrates of the beams were sand blasted for strengthening purpose. The properties of the CFRP sheet and two-part epoxy adhesive are listed in Table 1. Primer part A (hardener) and part B (base) were mixed to 1:2 ratio and a thin layer of primer was applied on the sand blasted concrete substrates and they were kept aside for 45 minutes. Saturant part A (hardener) and part B (base) were also mixed to 1:2 ratio. Then, primed concrete substrates and CFRP sheets were properly saturated with epoxy adhesive. Impregnated CFRP sheets were pressed on to the prepared concrete substrates and a ribbed roller was used to remove air entrapped in the bond line. Epoxy adhesive had a pot life of 40 minutes and the prepared CFRP/concrete test specimens were cured for 7 days at room temperature.

In this experimental investigation, alternative bonding techniques were adopted (as explained in section III) to achieve enhanced bond performance by delaying premature debonding failure. The FRP arrangement of CFRP/concrete control test specimens is shown in Fig. 2 and the test set up is illustrated in Fig. 3.

**TABLE 1. MATERIAL PROPERTIES OF CFRP SHEET AND TWO PART EPOXY ADHESIVE [10]**

Parameter	Value		
	CFRP	Primer	Saturant
Fiber Density	2.1 g cm <sup>-3</sup>	-	-
Elastic Modulus	640 GPa	595 MPa	3724 MPa
Thickness	0.19 mm	-	-
Ultimate Tensile Strength	2600 MPa	24.1 MPa	138 MPa
Ultimate Tensile Elongation	0.4%	4%	3.8%
Glass Transition Temperature	-	77 °C	71 °C

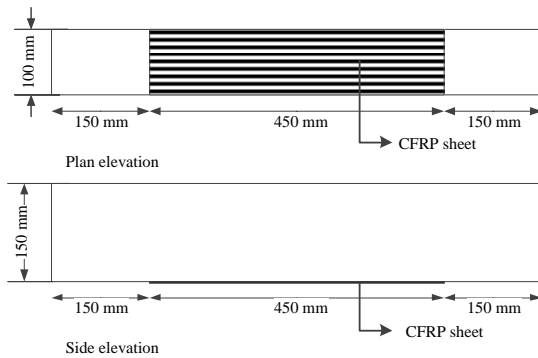


Figure 2. FRP arrangement of CFRP/concrete control test specimens

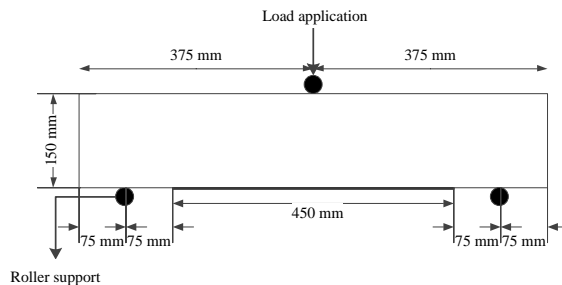


Figure3. Schematic diagram of three point bending test

### III. Test programme

#### A. Non-strengthened control specimens

A total of six non-strengthened concrete test specimens were tested and the average failure loads at 0.3mm crack width was measured. All control specimens were failed due to a single flexural crack which was initiated at the middle of the span as shown in Fig. 4. These six control samples were obtained from three different batches of concrete. The average failure loads observed from batch 1, 2 and 3 were 14.71 kN, 12.36 kN and 14.68 kN respectively.

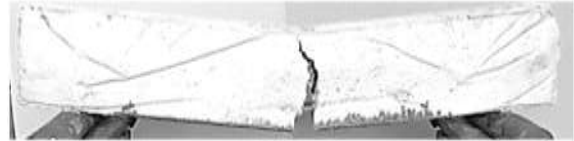


Figure 4. Flexural failure of non-strengthened control beam

#### B. CFRP/concrete control specimens

A total of six CFRP strengthened control concrete beams were tested. Cover separation failure was the typical mode of failure observed for these specimens as shown in Fig. 5. The reported average failure loads at 0.3mm crack initiation were 40.22 kN, 15.89 kN and 31.40 kN corresponding to concrete batches 1, 2 and 3 respectively. The encountered failure mode can be recognized as a premature debonding failure [1, 2, 3, 4]. The overall strength gain was in the range of 60.68% to 213.46%.



Figure 5. Cover separation failure of CFRP-strengthened control

#### C. Use of vertical CFRP U wraps at ends

The first alternative bonding technique was to provide two U shaped vertical CFRP end wraps of 150 mm × 100 mm on top of longitudinal CFRP sheet in transverse direction as shown in Fig. 6. Two test specimens were tested which were cast using concrete from batch 1 and the average failure load was 46.11 kN. The reported failure mode was cover separation failure which originated from shear cracks followed near the supports as illustrated in Fig. 7. This is mainly due to the high stress concentration occurred at the CFRP plate ends. The key objective was to avoid end delamination which is the critical failure mode regarding CFRP/concrete composites. Even though the encountered failure pattern belongs to premature debonding failure category, the use of vertical CFRP U wraps has effectively delayed end delamination with a 14.64% strength increment in comparison of CFRP strengthened control specimens. This is about 213.46% strength gain after strengthening concrete beam with vertical U wraps.

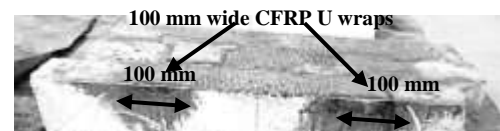


Figure 6. Vertical CFRP U wraps at ends



Figure 7. Cover separation failure of CFRP/concrete beam anchored with CFRP U wraps

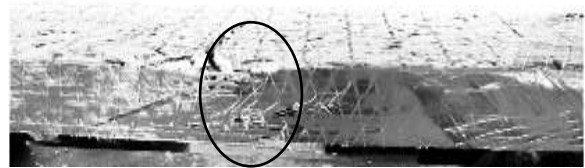


Figure 11. CFRP rupture at mid span

#### D. Use of a polyester mesh at bond line

The second method of alternative bonding technique comprised a bond enhancer which facilitates a reinforcing medium for the bonding agent. Thus, a polyester mesh of 60 mm × 60 mm was placed at the bond line i.e. between two part epoxy adhesive and CFRP sheet as illustrated in Fig. 8. A 1mm thick polymer mesh was selected to be compatible with the existing polymeric materials. The principal aim was to provide a bond enhancing interface which can dissipate energy uniformly before failure. Two specimens which were prepared out of batch no. 2 concrete were tested under this category. The average failure load was 19.86 kN owing 24.98 % strength increment compared to CFRP strengthened control beams. This means an overall strength gain of 60.68% with concrete beam strengthened with CFRP sheet with polymer mesh. The observed flexural failure pattern consisted of mid span debonding (shown in Fig. 9) which propagated to the support ends. Thus, the defensive reason for the end-debonding and its successive strength gain can be directly attributed towards the presence of the polyester mesh which had effectively distributed the interfacial stresses well.

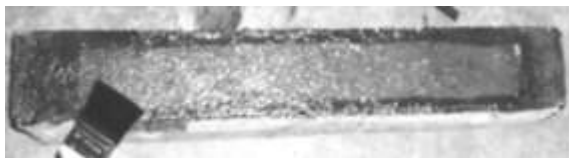


Figure 8. 60 mm wide polyester mesh



Figure 9. Flexural failure of CFRP/concrete beam with polyester mesh

#### E. Use of inclined CFRP U wraps at ends

The third implemented alternative bonding technique was to introduce 60 mm wide inclined CFRP U wraps at ends as shown in Fig. 10. The test specimens were prepared using concrete from batch 3. The reported average failure load was 41.20 kN and the observed failure mode comprised a flexural failure at mid span followed by CFRP rupture as illustrated in Fig. 11. This is mainly due to the enhanced bond strength at plate ends which had prevented the most crucial end-debonding failure mode commendably owing 31.23% strength increment compared to CFRP strengthened control beams. This is about 180.65% strength gain with respect to non-strengthened concrete beam.



Figure 10. Inclined CFRP U wraps at ends

All the bonding techniques have proven their capability of delaying end-debonding failure and subsequent enhancement in ultimate failure loads with strength increments ranging from 60.68% to 213.46% and 14.64% to 31.21% in comparison of non-strengthened control test specimens and CFRP strengthened control test specimens respectively as illustrated in Fig. 12. The highest strength gain of 213.46% with regards to non-strengthened control test specimens corresponds to vertical CFRP U wraps whereas inclined CFRP U wraps achieved the highest strength increment of 31.21% compared to CFRP strengthened control specimens.

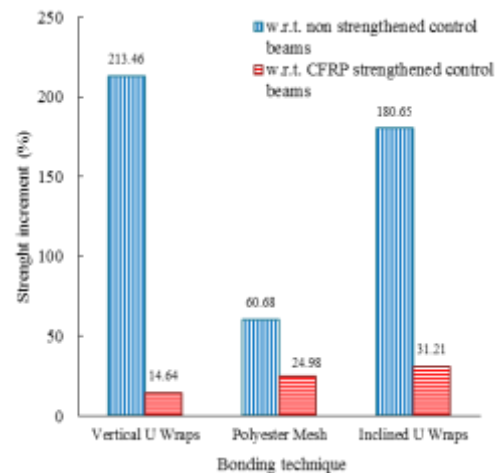


Figure 12. Comparison of strength gains from different bonding techniques

## IV. Finite element modeling of CFRP anchors

A three dimensional numerical model was developed using commercially available finite element package; ANSYS 12.0 performing a nonlinear static analysis. The main objective was to examine the efficiency of CFRP anchors to delay CFRP end-debonding failure and thereby upturn the ultimate failure loads CFRP/concrete composites. Concrete was represented by Solid 65 [11, 12], whereas steel reinforcements and anchor heads were modeled using Link 8 spar [11] element type. CFRP sheet and anchor heads were characterized by the element Shell 41 [11]. Concrete was meshed as hex diagonals of 25 mm × 25 mm and the meshed concrete beam is shown in Fig. 13. The Poisson's ratio of grade 30 concrete was assumed as 0.2 [13]. The elastic modulus of 27156.95 N/mm<sup>2</sup>, uniaxial compressive strength of 29.5 N/mm<sup>2</sup> and uniaxial tensile strength of 4.43 N/mm<sup>2</sup> were obtained using the numerical expressions derived by Desayi and Krishnan [14] together with the measured average compressive strength of 33.6 N/mm<sup>2</sup> experimentally. Open and closed shear transfer

coefficients were assumed as 0.5 and 0.9 [13] respectively. The material behaviour of steel was characterized as isotropic elastic – perfectly plastic material with bilinear Von Mises plasticity failure criterion. For both mild steel and galvanized iron materials, the material properties consisted of a Young’s modulus of  $200,000 \text{ N/mm}^2$ , a Tangent modulus of  $20,000 \text{ N/mm}^2$  and a Poisson’s ratio of 0.3 were assumed [15]. The yield strengths of  $490 \text{ N/mm}^2$  and  $280 \text{ N/mm}^2$  were used for mild steel and galvanized iron materials respectively which were obtained via laboratory experiments. The CFRP sheet was modeled assuming linear orthotropic material behavior with nonlinear Hill plasticity failure criterion.

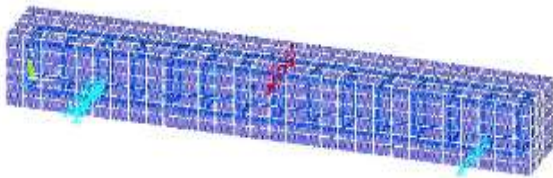


Figure 13. Meshed concrete beam

A three dimensional finite element model with  $100 \text{ mm} \times 150 \text{ mm} \times 750 \text{ mm}$  dimensions was modeled providing 25 mm cover and 50 mm spacing for shear links similar to the experiments. The CFRP/concrete composite beam was simply supported and the supports were located 100 mm inside from two edges. The developed nonlinear finite element model was validated with a considerable higher accuracy with merely 1.43% difference between numerical and experimental failure loads correspond to CFRP strengthened control test specimens. After the validation of the numerical model, three types of CFRP anchors which comprised Fan and Dowel anchor, pi-shaped anchor and tri-leg anchor were characterized as shown in Fig. 14, Fig.15 and Fig. 16 respectively.

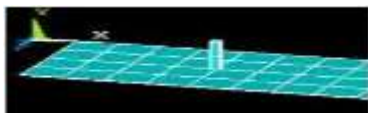


Figure 14. Numerical model of Fan and Dowel anchor

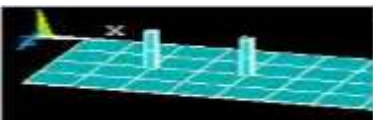


Figure 15. Numerical model of Pi-shaped anchor



Figure 16. Numerical model of Tri-leg anchor

The geometry of newly proposed tri-leg anchor is illustrated in Fig. 17. The numerical analysis of CFRP/concrete composites with the three types of anchors were carried out based on the deflection study, failure load study, fibre strain study and crack pattern study. The obtained crack patterns are presented in Fig. 18.

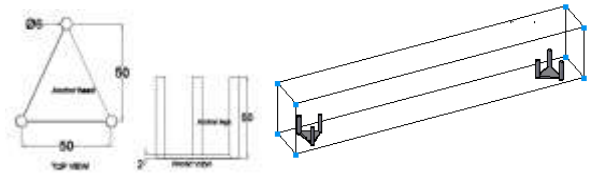


Figure 17. Characterization of Tri-leg anchor

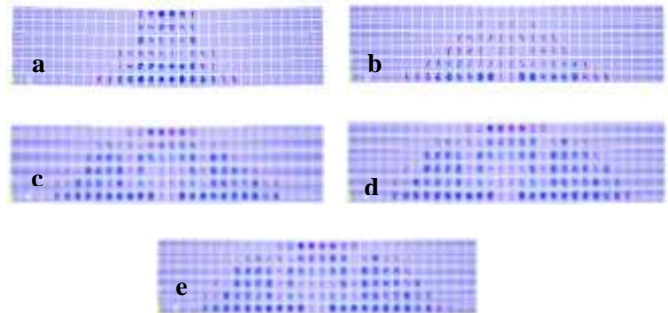


Figure 18. Crack patterns of a) Non-strengthened control beam b) CFRP strengthened control beam c) With Fan and Dowel anchor d) With Pi-shaped anchor e) With Tri-leg anchor

Non strengthened concrete beam showed flexural cracks at mid span as similar to which was observed in experiments. Cracks in CFRP strengthened concrete beams are further extended towards the ends of CFRP sheets. A comparable behavior was observed in experiments since the initiation of cracks occurred at ends of the laminate. Similarly, Fig. 18(c), (d) and (e) show almost similar behaviour as experiments.

All three types of anchors enhanced the failure loads of CFRP/concrete composites effectively reaching more than 211% strength increments in comparison of non-strengthened concrete test specimens. The newly proposed “Tri-leg anchor” has achieved the highest strength increment of 218.84% compared to non-strengthened control composite beams over other two types of anchors as shown in Fig. 19. The corresponding strength gains of Pi-shaped and Fan and Dowel anchors were 214.98% and 211.17% which comply with the previous research findings. Strength gains ranging from 18.6% to 68.7% have been reported for anchored CFRP/concrete composites compared to CFRP strengthened beams [16, 17].

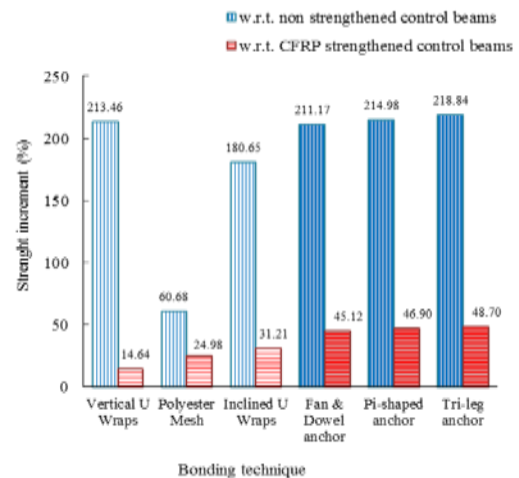


Figure 19. Comparison of strength gains from different bonding techniques including CFRP anchors

## v. Conclusions and recommendations

Premature debonding failure have been identified as the most critical failure mode of CFRP/concrete composites. Many research studies have been focused on investigating techniques to delay debonding of CFRP sheet from the interface. A careful detailing at the CFRP sheet ends can significantly reduce the bond stress concentration which typically occurs at or near the strip ends. In the current study, four such different techniques have been proposed. The use of vertical and inclined U wraps at ends is a promising technique to ensure continuous transfer of force along the CFRP sheet. Moreover, the presence of a polyester mesh at bond line has proven to be a cost effective method which commendably distribute the interfacial stresses well. Three types of anchor systems were also investigated to enhance the performance of CFRP/concrete composites. Fan and Dowel anchor and Pi-shaped anchor have already been studied and the predicted results in the present study are almost comparable with the previous research findings. In the current study, a new anchor type has been proposed by authors which exhibited prominent strength increments over all other presented bonding techniques including two types of anchors. The effectiveness of anchoring systems with respect to non-strengthened control beam is listed below.

Tri-leg anchor ( 218.84%) > PI-shaped anchor (214.98%) > vertical U wraps (213.46%) > Fan and Dowel anchor (211.17%).

Further research studies should be focused on preparation methods, geometry and configuration of Tri-leg anchor improving its competence.

### Acknowledgment

This paper presents a summary of undergraduate research projects carried out at the Department of Civil Engineering, University of Moratuwa, Sri Lanka. The authors would like to convey their appreciation to the research students H.R.D Premarathne, S. Srisangeerthan, D.M.N. Wijerathna and U. Thanasree. The technical staff of Structural Testing Laboratory and Building Materials Laboratory at University of Moratuwa is also greatly acknowledged.

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