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TENSILE STRENGTH OF STRAIGHT FRP ANCHORS IN RC STRUCTURES

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ABSTRACT

Structural strengthening using externally bonded fibre reinforced polymer (FRP) materials is an established method to enhance the performance of existing structures. Although standardised design methods are available for the strengthening of simple elements, limited guidance is available to apply these designs to the complex geometries which are common in realistic applications. In particular, a current limitation of existing FRP design guidance emerges where the force carried by the FRP needs to be transferred into or through an adjacent structural element. Straight FRP anchors feature a number of advantages over other methods to transfer the load, but their behaviour is poorly understood and the lack of available design guidance hampers efficient design. Reported here are a series of experiments performed as part of on-going research aimed to develop design equations for straight FRP anchors that will assist engineers to utilise straight FRP anchors and design efficient and reliable FRP strengthening schemes for structures with complex geometries.

The focus of these experiments was primarily on the fibre rupture failure mode developing in the key portion of the anchor, with fibre content having the most influence on capacity for this failure mode. The concrete used as a substrate to bond the FRP sheets was fabricated with two different strengths. The objective was to trigger different failure modes by varying the bonding strength between the FRP sheet and the concrete substrate and to compare the results obtained for both sub-failure modes. Next the efficiency of each anchor test was calculated as the measured capacity of the anchor divided by the ultimate tensile capacity of the bundles as specified by the manufacturer. Finally, the measured ultimate capacity and the efficiency were compared for different anchor sizes. As a result, the efficiency of the anchors was found to reduce for larger fibre contents, and an efficiency equation was developed based on the experimental results.

1 INTRODUCTION

The application of Fibre Reinforced Polymer (FRP) as Externally Bonded Reinforcement (EBR) for structural strengthening of existing Reinforced Concrete (RC) structures is a widely used technique and its effectiveness when compared to more conventional methods is well documented[1]–[3]. For strengthening purposes, externally bonded FRP is most commonly applied using the wet lay-up method which involves saturating carbon or glass fibre fabric sheets with epoxy resin and applying the wet sheets to the structure before the resin cures. The epoxy hardens to form a matrix that is adhered to the external surface of the structural member and the fibres perform as tensile reinforcement.

The primary deficiency of externally bonded FRP is the premature debonding of the FRP sheets from the concrete substrate prior to the development of the full strength of the FRP fibres[1],[4]. More effective use of the FRP sheets can be made either by enhancing the bond between the fabric and the concrete (bond enhancement anchors), or by using an anchor located at the end of the FRP sheet to transfer the load carried by the FRP sheet directly into the structure. Methods to transfer the loads from the FRP sheets into the structure been tested over the last 15 years and while several of these techniques have proven to be effective, straight FRP anchors have often been highlighted as a highly compatible and practical solution to improve the overall behaviour of wet lay-up externally bonded FRP[2],[3]. In addition to terminating the force into the structure, straight FRP anchors can also be used as ties to join FRP sheets and provide a continuous tensile element when the sheet is intersected by structural or non-structural elements such as walls or floors. FRP anchors can be used to enable effective FRP strengthening solutions to be developed for a wide range of RC structural elements with complex geometries[1],[5],[6].

2 STRAIGHT FRP ANCHORS

Straight FRP anchors consist of a bundle of fibres having one end splayed out in a circle or fan shape and bonded to the FRP sheet and the other end of the bundle being embedded with epoxy resin into a pre-drilled hole. Alternatively the anchor may be passed through an epoxy filled hole in the structure and anchored on the other side using a second splay. FRP anchors consist of three components. The fan portion is bonded to the FRP sheet and transmits the forces from the sheet to the dowel, which is introduced into the structural element. The small portion where all the fibres enter the hole and are bent from the anchor fan into the dowel is usually referred to as the key portion. In addition to the inherent angular changes of fibres in the key portion, fibres are also generally less aligned thus reducing the capacity of the anchor in this area. See **Figure 1** for a graphical description.

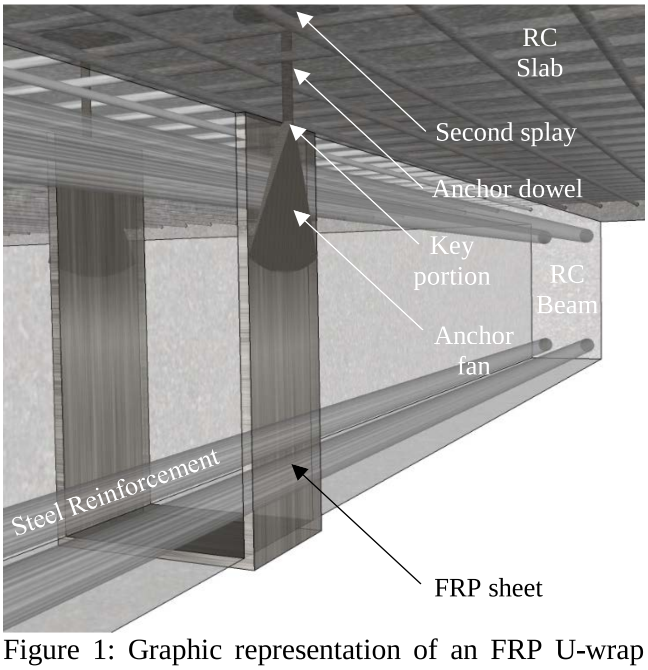

Figure 1: Graphic representation of an FRP U-wrap anchored with a straight FRP anchor

Several previous studies have been published regarding the properties and behaviour of the dowel component of straight FRP anchors[7]–[10] and a design model using predictive mathematical equations was developed by Kim[10]. However, the key and the fan portion of the anchor have received comparatively little attention. The Kobayashi[5] study on the force transfer mechanism and the Niemitz[11] study on fan engagement are notable exceptions. Two primary failure modes occur outside the dowel of the anchor, being fibre rupture in the key portion or debonding between the fan portion and the FRP sheet. The research reported herein concentrated on the fibre rupture failure mode.

Multiple parameters influence the capacity of the key portion of straight FRP anchors but only two parameters were considered. The primary parameter under consideration was the fibre content of the anchor because it is has the most significant influence on the tensile capacity of straight FRP anchors. The second parameter under investigation was the concrete mechanical properties which have an influence on the bond strength between the FRP sheets and the concrete substrate.

3 TEST SET-UP AND ASSEMBLY PROCESS

The primary considerations in design of the test set-up were to replicate the construction and fibre alignment conditions of realistic structural applications and to avoid or minimise loading eccentricities that could induce shear stress in the FRP materials. Having these two premises in mind, the concept was to duplicate the FRP and anchor configuration from one side of the beam shown in **Figure 1.**

In order to determine the strength of the FRP anchor accurately, the RC beam and slab had to be separated, while maintaining the configuration and bond conditions existing in realistic applications. This separation was achieved by introducing a discontinuity between the RC beam and the RC slab so that the only connection was provided by the FRP anchor. The beam was then pulled away from the slab while ensuring that the load was applied concentrically with the FRP anchor. The test setup is shown in **Figure 2**, where the realistic arrangement (from **Figure 1**) is turned upside-down to facilitate installation and testing of the anchor. The RC beam had a bar protruding from the top to apply the load directly to the concrete (as occurs in reality). Loading directly from this point would have caused undesirable eccentricity in the FRP anchor so a very stiff steel plate connector was secured to the RC beam with a nut. The loading bar was screwed into the steel connector aligned with the FRP anchor and the steel connector transferred the load and minimised rotation of the RC block during loading, which would have induced undesirable stresses in the FRP anchor. A layer of plaster was placed between the RC block and the steel connector to make the joint stiffer. Little rotation was observed in the concrete blocks during testing, indicating that the anchor was loaded in pure tension as desired.

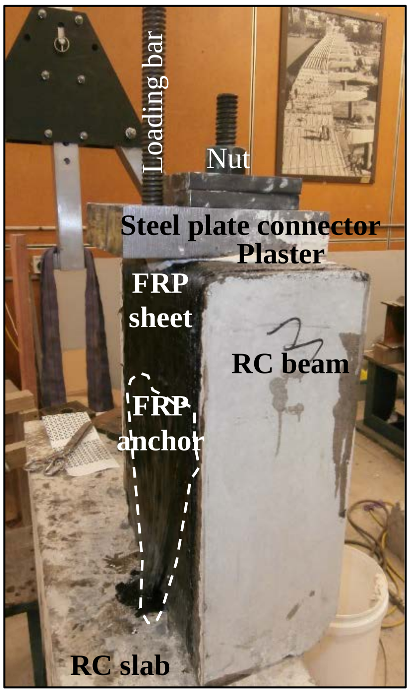

Figure 2: Test set-up

Assembly. The first step in the assembly process for each specimen was to grind the surface of the concrete to eliminate imperfections and loose material, exposing the aggregate and the pores in the concrete. The hole was then drilled. The next step was to place a plastic sheet as a bond breaker layer between the two concrete surfaces before placing the RC beam over the RC slab. The CFRP sheets were cut into the required width and length and the anchor fibres cut to desired length and bundled to the required size. The anchor end was tied using a metal wire, in order to simplify insertion of the anchor into the drilled hole. Once the epoxy resin was prepared a small part was mixed with thickener to use as a primer layer on the concrete surface. After applying the primer layer, the CFRP sheets were saturated with epoxy resin and installed onto the concrete beam in the correct alignment. Note that the sheets covered the main side of the RC beam where the anchor was installed plus the top side and a portion of the back, similarly to the anchored U-wrap situation being modelled. A spatula was used to straighten the sheets as much as possible and to remove excessive resin and eliminate air bubbles. After saturating the FRP anchor in epoxy resin and draining the excessive resin, the anchor was installed in the hole with the help of the metal wire. When the anchor had reached the bottom side of the RC slab, the wire was cut and removed. The anchor was then adjusted to the desired length and the fibres were arranged into the anchor fan. For the tests under study, the fanning angle (commonly referred to as angle α) was set to 30 degrees on either side of the fibre direction, with the bonding area having been determined to be large enough to prevent debonding between the fan portion and the FRP sheet. As before, a spatula was used to straighten the fibres in the fan portion, and to remove excessive resin and air bubbles. The specimen was ready for testing after at least 3 days of curing.

The FRP anchor product used in these experiments was supplied as a bundle of fibres with a standard fibre content, the bundles were then combined to produce anchors with greater fibre contents. The manufacturer-specified material properties for the FRP products used in this research are given in **Table 1**. The properties are expressed as net-fibre laminate properties.

Table 1 Manufacturer-specified FRP material net-fibre properties

	Net fibre thickness (mm)	Tensile Modulus (GPa)		Tensile strength (MPa)		Ultimate strain	
		Ave	Design[1]	Ave	Design[1]	Ave	Design[1]
CFRP fabric 1	0.343	-	64.8	1241	1055	0.016	0.010
CFRP fabric 2	0.331	75.7	68.1	968	833	0.013	0.011
CFRP Anchor	28 mm^2	-	230	-	2100	-	0.016

[1]Design values defined as average values minus two standard deviations

Two concrete strengths were used to investigate the influence of concrete strength on the capacity of the anchors. The compressive and tensile strength of each concrete mix was determined using NZS 3112-2[12]. The results are detailed in **Table 2**.

Table 2: Concrete mechanical properties

Batch	Characteristic ultimate compressive strength (MPa)	Characteristic ultimate tensile strength (MPa)
Weak 1	25.7 SD=2.1 CoV=0.08	3.2 SD=0.15 CoV=0.05
Weak 2	24.9 SD=0.7 CoV=0.03	2.9 SD=0.17 CoV=0.06
Strong	42.5 SD=3.4 CoV=0.08	2.4 SD=0.00 CoV=0.00

4 RESULTS

Experimental results were obtained as part of an on-going research project aiming to investigate the performance of straight FRP anchors used in the strengthening and repair of existing RC structures. The objective was to investigate the influence of anchor fibre content and concrete strength on the fibre rupture failure mode capacity of FRP anchors. The full manufacturer-specified material properties of the FRP anchors cannot be relied upon when calculating the capacity of FRP anchors for several reasons. Firstly, the manufacturer-specified material properties are obtained through tests undertaken in idealistic laboratory conditions on anchor bundles with straight fibres, where the installation process is highly controlled and fibre alignments can be optimised. The tests performed in this research closely mimic the fibre alignments and installation processes of straight FRP anchors in realistic applications. In these applications each fibre in the fan is installed with a different fanning angle α, being the efficiency of the fibres reduced in relation to this angle α. In addition, the concentration of stresses due to the angular change of fibres in the key portion plays a significant role on the final tensile strength of the anchor.

The fibre content of the anchors was varied in terms of the number of bundles used to manufacture each anchor, with anchor fibre content having the biggest influence on the capacity of the anchor when fibre rupture is the governing failure mode. The capacity of the anchor increased as the fibre content was increased but the relationship was not linear. The anchor efficiency was defined in this research as the ratio of measured failure load over the calculated failure load using the manufacturer-specified material properties. The primary objective of the tests was to investigate the efficiency of the FRP anchor for a range of different fibre contents. The results can be seen in Table 3, where the ultimate load is expressed in kN while the numbers in brackets are the efficiency of the anchor. The average (AV), standard deviation (SD) and coefficient of variation (CV) for each set of values are also provided.

The second parameter investigated in the tests was concrete strength. The RC blocks used as substrate to bond the FRP sheets were made of two different strengths (hereafter referred to as strong and weak). The objective was to obtain two different sub-failure modes related to the fibre rupture failure mode. For the one and three-bundle series, when the RC block was made with strong concrete the sub-failure mode observed was pure fibre rupture (R), without debonding between the FRP sheet and the concrete substrate. When weak concrete blocks were used the sub-failure mode observed was debonding between the FRP sheet and the concrete substrate followed by fibre rupture in the key portion of the anchor (CD+R). For the six-bundle series, the load was too large for debonding between the FRP sheet and the concrete substrate to be prevented, even when strong concrete was used. As can be seen in **Table 3**, the sub-failure mode did not have an influence on the ultimate capacity of the anchors. This behaviour suggests that debonding between the FRP sheets and the concrete substrate does not affect the capacity of the FRP when anchored with properly designed straight FRP anchors.

Table 3: Summary of capacity, efficiency and failure mode for every test

One-bundle (28 mm^2)			Two-bundle (56 mm^2)			Three-bundle (84 mm^2)			Six-bundle (168 mm^2)		
ID	Capacity[1]	FM[2]	ID	Capacity[1]	FM[2]	ID	Capacity[1]	FM[2]	ID	Capacity[1]	FM[2]
FC1a weak	**55.1 kN** (93.6%)	CD+R	FC2a strong	**94.6 kN** (80.5%)	R	FC3a strong	**122.7 kN** (69.5%)	R	FC6a weak	**143.1 kN** (40.6%)	CD+R
FC1b weak	**55.2 kN** (93.9%)	CD+R	FC2b strong	**82.8 kN** (70.4%)	R	FC3b weak	**111.1 kN** (63.0%)	CD+R	FC6b weak	**145.6 kN** (41.3%)	CD+R
FC1c weak	**52.4 kN** (89.2%)	CD+R	FC2c weak	**78.1 kN** (66.4%)	CD+R	FC3c weak	**105.1 kN** (59.6%)	CD+R	FC6c weak	**164.5 kN** (46.6%)	CD+R
FC1d strong	**51.2 kN** (87.0%)	R	FC2d weak	**78.1 kN** (66.4%)	CD+R	FC3d weak	**113.1 kN** (64.1%)	CD+R	FC6d strong	**144.0 kN** (40.8%)	CD+R
FC1e strong	**57.3 kN** (97.4%)	R	FC2e weak	**81.6 kN** (69.4%)	CD+R	FC3e weak	**123.1 kN** (69.8%)	CD+R	FC6e strong	**168.2 kN** (47.7%)	CD+R
AV	**54.2 kN** (92.2%)		AV	**83.0 kN** (70.6%)		AV	**115.0 kN** (65.2%)		AV	**153.1 kN** (43.4%)	
SD	2.43 kN (4.1%)		SD	6.82 kN (5.8%)		SD	7.77 kN (4.4%)		SD	12.2 kN (3.5%)	
CV	0.04		CV	0.08		CV	0.07		CV	0.08	

[1]Capacity in kN and efficiency in brackets expressed in terms of percentage of capacity specified by manufacturer
[2]Failure Mode: R=Pure rupture CD+R=Rupture after debonding between the FRP and concrete substrate

The efficiency for small anchors made with one standard bundle was 92.2 % of the capacity specified by the manufacturer. As the fibre content was increased the efficiency reduced. The reduction in efficiency was significant at the beginning, from 92.2 % for one-bundle anchors to 70.6 % for two-bundle anchors and 65.2 % for three-bundle anchors. The decrease in efficiency was more moderate as the anchor size continued growing, reaching 43.4 % in six-bundles anchors. The efficiency for the range of anchor sizes under consideration can be seen graphically in **Figure 3** along with the equation for the best fit line.

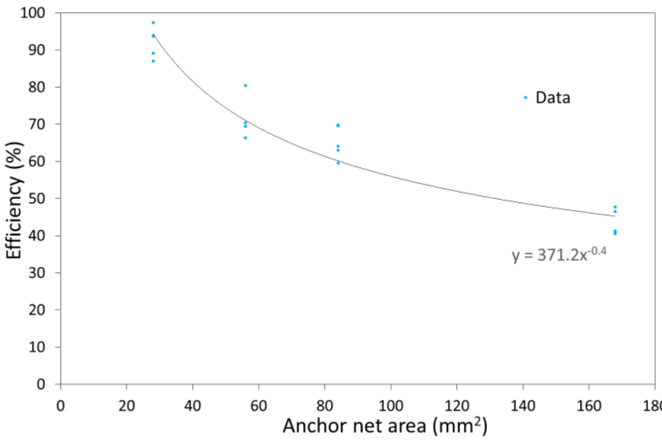

Figure 3: Strength efficiency of anchors with varying net-fibre area

The anchor sizes tested in this research were determined by the number of bundles used in each anchor, but is expressed as the net-fibre (excluding resin) cross sectional area of each anchor so that the data can be more easily applied to anchors made with different CFRP anchor products.

5 CONCLUSION

A series of experiments investigating the fibre rupture failure mode in the key portion of straight FRP anchors was detailed. The efficiency of straight FRP anchors with a range of fibre contents was presented as a percentage of the measured capacity divided by the manufacturer-specified capacity. The influence of anchor fibre content on the efficiency of the straight FRP anchor was discussed. Smaller anchors were found to be more efficient than larger anchors. While larger anchors provided greater capacity overall, the efficiency of the anchors was significantly reduced as anchor fibre content was increased. Measured efficiencies ranged from an average of 92.2% for small anchors (single bundles), to an average of 43.4 % for large anchors (six-bundles). Therefore efficient anchor design should balance the cost efficiency of installing fewer large anchors with the increased anchor material requirements due to the reduced efficiency of larger anchors. Future work will aim to increase the anchor size further and to refine the efficiency equation including the effect of other parameters such as fanning angle alfa or the offset distance between the anchor dowel and the fan portion.

The mechanical properties of the concrete substrate were found to have no influence on the ultimate capacity of the fibre rupture failure mode of FRP straight anchors. Weaker concrete allowed the FRP to debond from the substrate before failure, but did not influence the capacity of the anchors. This behaviour suggests that debonding from the substrate does not affect the capacity of the FRP when anchored with properly designed straight FRP anchors.

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REFERENCES

[1] Koutas L, Triantafillou TC. Use of Anchors in Shear Strengthening of Reinforced Concrete T-Beams with FRP. J Compos Constr. 2013;17(1):101-107.
[2] Mofidi A, Chaallal O, Benmokrane B, Neale K. Performance of End-Anchorage Systems for RC Beams Strengthened in Shear with Epoxy-Bonded FRP. J Compos Constr. 2012;16(3):322-331.
[3] Kalfat R, Al-mahaidi R, Smith ST. Anchorage Devices Used to Improve the Performance of Reinforced Concrete Beams Retrofitted with FRP Composites : State-of-the-Art Review. J Compos Constr. 2013;17(1):14-33.
[4] Lau KT, Dutta PK, Zhou LM, Hui D. Mechanics of bonds in an FRP bonded concrete beam. Compos Part B Eng. 2001;32(6):491-502.
[5] Kobayashi K, Fujii S, Yabe Y, Tsukagoshi H, Sugiyama T. Advanced wrapping system with CF anchor-Stress transfer mechanism of CF anchor. Proceedings of FRPRCS-5. Cambridge; UK:2001
[6] Witt S. Developments in fiber roving anchors for use with externally bonded fiber reinforced polymers. Proceedings of FRPRCS-8. Patras, Greece: 2007
[7] Kim SJ, Smith ST. Behaviour of Handmade FRP Anchors under Tensile Load in Uncracked Concrete. Adv Struct Eng. 2009;12(6):845-865.
[8] Ozdemir G, Akyuz U. Tensile capacities of CFRP anchors. In: Advances in Earthquake Engineering for Urban Risk Reduction. Springer Netherlands; 2006:471-487.
[9] Ozbakkaloglu T, Saatcioglu M. Tensile Behavior of FRP Anchors in Concrete. J Compos Constr. 2009;13(2):82-92.
[10] Kim SJ, Smith ST. Pullout Strength Models for FRP Anchors in Uncracked Concrete. J Compos Constr. 2010;14(4):406-414.
[11] Niemitz CW. Anchorage of Carbon Fiber Reinforced Polymers to Reinforced Concrete in Shear Applications. 2008;(2008):335.
[12] NZS 3112-2. Methods of Test for Concrete. Wellington, New Zealand: New Zealand Standards (NZS); 1986.