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Optimisation of carbon and glass FRP anchor design

H.W. Zhang [a], S.T. Smith [a,*], S.J. Kim [b,1]

[a] Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, China
[b] Industrial Composite Contractors (ICC) Pty Ltd., 15 Pavers Circle, Malaga, Western Australia, Australia

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ABSTRACT

The strengthening and repair of reinforced concrete (RC) civil infrastructure with externally bonded fibre-reinforced polymer (FRP) composites is an established technology. One of the limitations of this technology though is the propensity of the FRP to prematurely debond at strains well below its rupture strain. Anchorage of the FRP strengthening is therefore a logical remedy to prevent or delay debonding failure. A promising type of anchor, which is made from bundles of fibre or rolled fibre sheets and can be applied to virtually any shaped structural member, is the FRP anchor. Limited fundamental characterisation of FRP anchors has, however, been undertaken to date. In this paper a series of tests aimed at optimising the FRP anchor design within the confines of the experimental variables are reported. The anchors are tested in an FRP-to-concrete single-lap joint shear test set-up and the main parameters varied are fibre type, fibre content and method of anchor construction. The behaviour as well as strength and failure of the test specimens are discussed and generic load–slip responses are provided which can form the framework for the future development of analytical models. Criterion with which to assess the optimal design of FRP anchors is also provided.

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1. Introduction

Reinforced concrete (RC) members strengthened with externally bonded fibre-reinforced polymer (FRP) composites are susceptible to premature failure by debonding of the FRP. An effective means to delay or halt the propagation of debonding in an FRP strengthened member is by anchorage of the FRP strengthening with FRP anchors [e.g. 1–7]. An FRP anchor (also referred to as an *anchor*) is essentially a rolled fibre sheet or a collection of bundled fibre strands in which one end of the anchor is inserted into an epoxy filled hole in the concrete member and the other end is threaded through and splayed onto the surface of the FRP strengthening plate (herein *plate* unless indicated otherwise). Fig. 1 is a schematic representation of a typical installed anchor system, in the context of an FRP shear-strengthened RC beam, in which the individual components of the anchor are clearly identified. Of importance to note in Fig. 1 is the orientation of the anchor fan in the main load carrying direction of the U-jacket. A much more detailed background on the application of FRP anchors to FRP-strengthened RC members is provided in Smith et al. [6].

Research on the fundamental strength and behaviour of FRP anchors in isolation has, however, been much more limited and such research has been predominantly experimental in nature. Studies to date have reported the pullout strength and behaviour [8–11] as well as the shear strength and behaviour [12–15] of FRP anchors. It is the result of such limited fundamental understanding and associated design guidance, especially in the case of the shear strength and behaviour of FRP anchors, which is hindering the rational design and wide-scale use of FRP anchors.

In a bid to examine the strength and behaviour of FRP anchors, Smith and Kim [15] reported the results of 20 FRP-to-concrete joint tests anchored with FRP anchors. The main variables in these tests were (i) method of plate and anchor installation, (ii) anchor fibre content, and (iii) anchor position. The tests showed the anchored joints to fail in predominantly two different modes, namely (i) complete debonding of the FRP plate followed by near simultaneous failure of the anchor (known as Mode 1 failure), and (ii) complete debonding of the FRP plate followed by failure of the anchor after substantial slippage of the debonded plate (known as Mode 2 failure). Within each of these two major modes the anchors were found to fail differently. More specifically, detailed classifications of all failed specimens were proposed by Smith and Kim [15] as Mode 1A (herein *simultaneous plate debonding and anchor rupture*), Mode 1B (herein *simultaneous plate debonding and anchor fan debonding*), Mode 2A (herein *plate debonding followed by anchor rupture*), Mode 2B (herein *plate debonding followed by anchor fan debonding*), and Mode 2C (herein *plate debonding followed by anchor pullout*).

The main test variables considered in the experimental study reported herein are aimed at optimising the performance of the

* Corresponding author. Tel.: +852 2241 5699; fax: +852 2559 5337.
E-mail address: stsmith@hku.hk (S.T. Smith).
[1] Formerly of affiliation (a).

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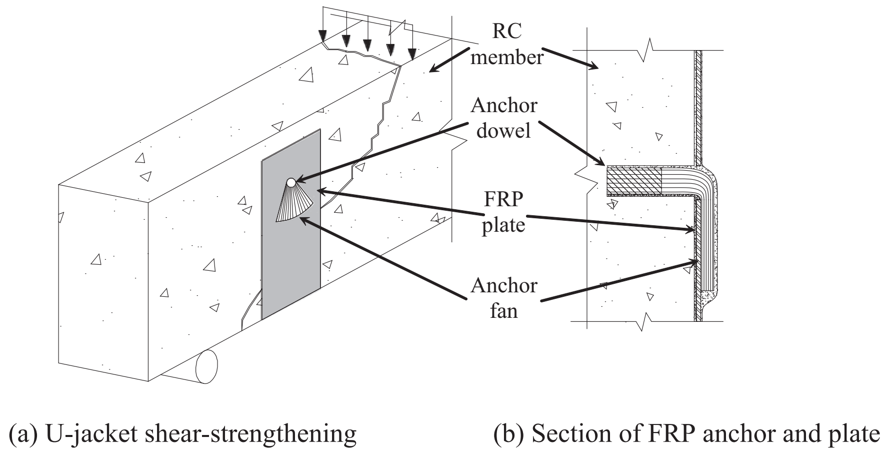

Fig. 1. Schematic of FRP-strengthened RC member and anchor.

FRP anchor. Such variables consist of (i) anchor fibre type, (ii) anchor fibre content, and (iii) method of anchor construction. In addition, criterion is established with which to optimise the anchor design upon. All test specimens are extensively instrumented with an array of linear variable displacement transducers (LVDTs) and electric strain gauges. The resulting experimental behaviours and failure modes are presented in addition to selected LVDT and strain results. Finally, generic load–slip responses are proposed which form the basis of future load–slip and bond-slip model development.

2. Experimental details

2.1. Details of test specimens and test set-up

The experimental program consisted of 27 FRP-to-concrete single shear joint tests in which three joints were unanchored (i.e. control joints) and 24 joints were anchored with a single anchor. The resulting test matrix is given in Table 1 in which the three main variables are evident, namely, (i) fibre type (i.e. glass or carbon), (ii) anchor fibre content (fibre sheet widths of 134, 200, and 259 mm), and (iii) method of anchor construction (dry or impregnated anchor). Three tests series were established, namely (i) Control Series, (ii) Glass Series, and (iii) Carbon Series. In addition, three tests were undertaken for each set of variables for repeatability.

The Control Series tests on unanchored FRP-to-concrete joints were quite standard and numerous experimental studies have been reported in the open literature on such testing e.g. [16]. No further comment is therefore warranted here.

For the Glass Series, two different types of anchors were tested. The anchors were either dry FRP anchors or impregnated FRP anchors. Detailed descriptions of the dry and impregnated FRP anchors are contained in Section 2.2 although brief comments are included as follows. Dry anchors were essentially formed from rolled fibre sheets in which the epoxy was omitted in the manufacturing stage. Impregnated anchors were also formed from rolled fibre sheets, however, the anchor dowel component of the anchor was impregnated with epoxy during the anchor manufacture stage so as to form a solid 'dowel'. In the case of the glass anchor series, the same width of fibre (i.e. 200 mm wide glass fibre sheet) was used in order for the method of anchor construction to be directly compared.

For the Carbon Series, both dry and impregnated FRP anchors were also tested and the anchors were manufactured in the same manner as the Glass Series anchors. In addition, three different amounts of fibre were used in the construction of the carbon anchors for comparison with the glass anchor counterparts. The three different carbon fibre sheet widths corresponded to equivalent glass anchor properties of (i) equal tensile force capacity (based on flat FRP coupon properties) (i.e. 134 mm wide sheets), (ii) equal fibre sheet width (i.e. 200 mm wide sheets), and (iii) equal fibre content (based on equal cross-sectional area of fibre sheet) (i.e. 259 mm wide sheets). The FRP coupon specimens were made from impregnating the fibre sheet with epoxy of which more detailed information is contained in Section 2.4. Table 2 provides a detailed summary of the tensile properties of the tested glass FRP and carbon FRP coupon specimens though in addition to the nominal fibre sheet thickness and the equivalent fibre sheet widths. Also contained in Table 2 is the amount of carbon fibre to produce an equal axial rigidity as the glass fibre anchor in which the axial rigidity is defined as the elastic modulus of the FRP coupon multiplied by the fibre sheet cross-sectional area. As this value (i.e. 121 mm in Table 2) is quite similar to the carbon fibre sheet width to produce equivalence in FRP coupon force capacity (i.e. 134 mm in Table 2), tests on anchors constructed from such amount of fibre have been omitted from the test program as there is not expected to be any noticeable difference to anchors made from 134 mm carbon fibre sheet width.

The test set-up and a typical test specimen are shown schematically in Fig. 2a and b, respectively. All concrete prisms were nominally 200 mm wide, 200 mm deep and 400 mm long. The FRP plates were formed from the same roll of carbon fibre used for the construction of the carbon FRP anchors. The plate, of 50 mm width and 250 mm bonded length, was made from three layers of carbon fibre sheet in a wet lay-up procedure. For such an arrangement, the effective bond length (i.e. the limiting length of plate with which an increase in plate length will not increase the strength of the joint) was 111.7 mm when calculated in accordance with Chen and Teng's [17] commonly referred to model. An unbonded zone of 40 mm was maintained at the loaded free end of the concrete prism in order to reduce edge effects of the concrete prism and to minimise the formation of a concrete wedge at failure. In all anchored joint tests, the anchor was positioned 75 mm from the bonded loaded end of the plate (i.e. 115 mm from the loaded free end of the concrete

Table 1
Test matrix.

Test series and specimen identification[a]		Concrete		FRP plate		FRP anchor		
		f_{cu}[b] (MPa)	Width (mm)	Bond length (mm)	Width (mm)	Fibre type	Anchor type	Fibre sheet width (mm)
Control Series	CN-1–3	50.3	200	250	50	–	–	–
Glass Series	GD-200-1–3	50.3	200	250	50	Glass	Dry	200
	GI-200-1–3						Impregnated	200
	CD-134-1–3						Dry	134
	CD-200-1–3							200
Carbon Series	CD-259-1–3	50.3	200	250	50	Carbon		259
	CI-134-1–3						Impregnated	134
	CI-200-1–3							200
	CI-259-1–3							259

[a] CN = control, G = glass fibre, C = carbon fibre, D = dry anchor, I = impregnated anchor, 1–3 = specimens 1, 2, 3.
[b] f_{cu} = concrete cube compressive strength (cylinder strength ≈ 0.8 f_{cu}).

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