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FRP-strengthened RC slabs anchored with FRP anchors

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ABSTRACT

An abundance of tests over the last two decades has shown the bending capacity of flexural members such as reinforced concrete (RC) beams and slabs to be enhanced by the bonding of fibre-reinforced polymer (FRP) composites to their tension face. The propensity of the FRP to debond, however, limits its effectiveness. Different types of anchorages have therefore been investigated in order to delay or even prevent debonding. The so-called FRP anchor, which is made from rolled fibre sheets or bundles of lose fibres, is particularly suitable for anchoring FRP composites to a variety of structural element shapes. Studies that assess the effectiveness of FRP anchors in anchoring FRP strengthening in flexural members is, however, limited. This paper in turn reports a series of tests on one-way spanning simply supported RC slabs which have been strengthened in flexure with tension face bonded FRP composites and anchored with different arrangements of FRP anchors. The load–deflection responses of all slab tests are plotted, in addition to selected strain results. The behaviours of the specimens including the failure modes are also discussed. The greatest enhancement in load and deflection experienced by the six slabs strengthened with FRP plates and anchored with FRP anchors was 30% and 110%, respectively, over the unanchored FRP-strengthened control slab. The paper also discusses the strategic placement of FRP anchors for optimal strength and deflection enhancement in FRP-strengthened RC slabs.

1. Introduction

Numerous experimental investigations have proven the ability of fibre-reinforced polymer (FRP) composites to increase the flexural capacities of beams and slabs when bonded to their tension faces [1,2]. Numerous studies have also observed the FRP to debond at strains well below its rupture strain. Such premature failure, which has been observed to initiate at the base of flexural and flexural-shear cracks along the length of the member (e.g. IC debonding, [2]) or at the FRP plate end (e.g. concrete cover separation, [2]), can occur in a relatively sudden manner and constitutes an under-utilisation of the strength and strain capacity of the FRP. Mechanical anchorage of the FRP offers a real solution to the debonding problem and several different systems have been trialed to date. They include, but are not limited to, embedded metal threads [3], nailed plates (also known as hybrid bonding [4]), U-jackets [5], near-surface mounted rods [6], and anchors made with FRP [7] (also known as spike anchors but herein referred to as *FRP anchors* or *anchors*). FRP anchors are versatile as they are non-corrosive and can be applied to wide dimensioned elements such as slabs and walls. A recent review of FRP anchors is provided in [7] while a review of other anchorage methods (including FRP anchors) is presented in [8]. The anchorage of steel strengthening plates using metallic bolts is a related field of research (e.g. [9]), however, it is outside the scope of this paper and is therefore not considered further.

Fig. 1. is a schematic representation of the face of a concrete member which has been strengthened with an externally bonded FRP plate and anchored with an FRP anchor. Such an anchor is essentially made from glass or carbon fibres in which fibre sheets are folded or rolled, or lose fibres are bundled together. One end of the anchor (herein *anchor dowel*) is inserted into an epoxy filled hole in the concrete substrate (Fig. 1(b)) and the other end of the anchor is passed through the externally bonded FRP strengthening plate (herein *FRP plate* or *plate*). The free ends of the fibres (herein *anchor fan*) are splayed and epoxied onto the surface of the plate in order to disperse local stress concentrations. The double anchor fan arrangement (herein *bow-tie*) shown in Fig. 1 has been tailor made for the test slabs reported herein. As a precursor to the bow-tie anchor fan form, Smith [10] reported FRP anchors with a single fan component to increase the shear strength and slip capacity of FRP-to-concrete joints by up to approximately 70% and 800%, respectively, over unanchored control joints. The relative difference between the strength and the behaviour of single fan and bow-tie anchors in FRP-to-concrete joint tests has also been summarised in [10]. While Smith [10] reported both types of

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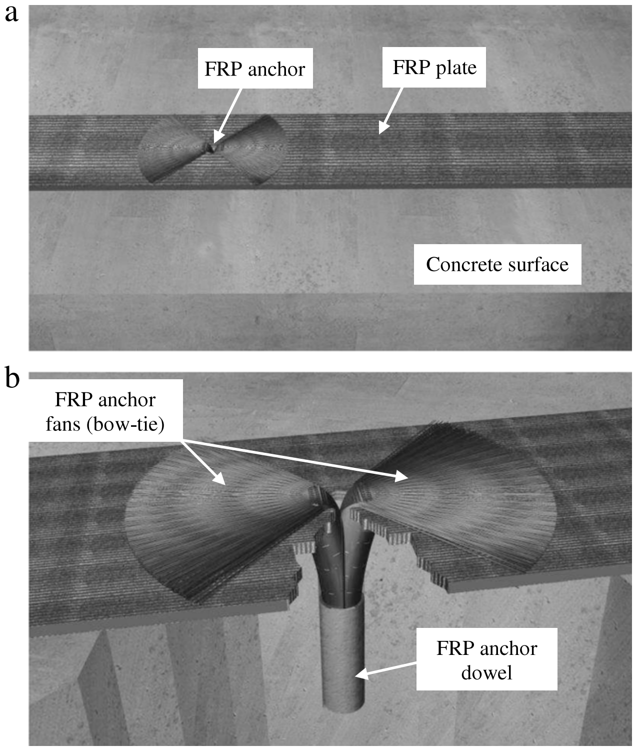

Fig. 1. FRP anchor and plate: (a) overall view; (b) cut-away view.

anchors to exhibit similar load–slip characteristics over most of the responses, the bow-tie anchors were ultimately able to resist much greater slips (while maintaining limited strength) before failure. Such an extensive slip capacity is a desirable feature of an FRP anchor especially when large slips are expected between the FRP strengthening and concrete substrate in structural members. Another benefit of the bow-tie anchor alternative is that slip may be in the other direction for members where the applied load can move. Here the minimum criterion is to position the anchor fan on the side of the anchor in the direction of load. There has been limited research though conducted to date on characterising the fundamental behaviour of FRP anchors (e.g. [7,11–14]) and more work is clearly required. Such work is, however, outside the scope of this paper.

The majority of the research conducted to date on FRP anchors has been on the anchorage of flexurally strengthened RC beams [15,16], slabs [17,18], slab–column connections [19], confined columns [20], and concrete and masonry walls [21,22]. In such research, FRP anchors were generally shown to be effective in enhancing the strength and deformability of the strengthened members, however, the FRP anchors were generally not the focus of these studies. Also, in many cases, the FRP was not observed to fail and as a result the limits of the anchors were not established. Brief reviews of some of the literature of FRP-anchored FRP flexurally strengthened RC beams and slabs are provided as follows.

Teng et al. [23] reported seven cantilever RC slabs tests of 700 mm span of which six slabs were strengthened in flexure with glass FRP (GFRP) composites formed in a wet lay-up manner. The unanchored slabs were found to fail by IC debonding with debonding initiating at the fixed end of the slab. Two of the strengthened slabs were anchored with FRP anchors positioned 150 mm and 300 mm from the fixed end. In both cases, the FRP anchors were observed to reduce the rate of debonding crack propagation. In the first case, the GFRP plate ruptured after the debonding crack had propagated to the second anchor. The low tensile strength of the GFRP (i.e. 428 MPa) made it susceptible to rupture failure. The second anchored slab test utilised an extra layer of GFRP. In this case the anchors failed after the debonding crack had propagated along the plate. In both anchored slab cases the slope of the load–deflection curve clearly decreased as debonding propagated. The two anchored slabs experienced a 24% and 61% increase over the unanchored but strengthened control slab respectively, however, the deflection at failure for both anchored slabs was 76% of the control.

Lam and Teng [17] then reported an additional five RC cantilever slabs tests of 700 mm span in which fours slabs were strengthened in flexure with wet lay-up GFRP and anchored with FRP anchors positioned in the same locations as Teng et al.'s [23] test slabs. The main test variables were preloading as well as internal tension steel ratio and position. In all strengthened slab tests the FRP was observed to rupture. In some cases, debonding was halted by the first anchor and in other cases no debonding was observed.

Eshwar et al. [24] strengthened ten beams of varying soffit curvature with carbon FRP (CFRP) tension face plates. The span of the beams was 6 m, the length of FRP was 5.2 m, and the failure mode was IC debonding. Of the three beams with greatest curvatures, two were strengthened with identical configurations of wet lay-up FRP and one of these beams was additionally installed with FRP anchors at 500 mm centres. The increase in strength and mid-span deflection of this anchored beam to its unanchored counterpart was 34% and 74%, respectively. The anchored beam appeared to fail by complete debonding of the FRP followed by anchor rupture, however, the effectiveness of the FRP anchor in enhancing load and deflection had been proven.

Oh and Sim [15] reported tests on eleven simply supported beams each of 2 m span. Ten of these beams were strengthened in flexure with tension face GFRP plates formed in a wet lay-up manner. The beams were susceptible to concrete cover separation failure, so two FRP anchors were positioned at 500 mm centres at the end of one beam specimen. The anchors were not successful in delaying the occurrence of concrete cover separation and as a result they did not enhance load or deformation capacity of the beam. More recently, Micelli et al. [16] showed FRP anchors spaced at 250 mm centres in 2.2 m spanning beams to increase the load carrying capacity of the FRP-strengthened beams by 13% above the strengthened but unanchored control beams. The strengthened beams ultimately failed by IC debonding after which the behaviour of the beams resorted to that of the unstrengthened (and unanchored) control beam.

While Brunckhorst et al. [25] did not consider FRP anchorage, their research is still applicable and is therefore reviewed here. Brunckhorst et al. [25] presented a diagram of a generic moment–displacement (analogous to load–deflection) response of an RC beam strengthened in flexure with a tension face bonded CFRP pultruded plate comprising of multi-directional fibres. The plate was also anchored with regularly spaced metal screw-bolts. In order to install the bolts, holes were drilled through the initially bonded (and cured) FRP plate at regular intervals along the whole length of the plate and then metal bolts were inserted. The generic response consisted of several key features, namely (i) first cracking of the tensile concrete, (ii) initiation of debonding of the FRP plate via 'gliding fracture' (this translation appears to be consistent with IC debonding), (iii) a sharp drop of moment upon initiation of debonding, (iv) residual strength (above the plain unstrengthened RC beam) provided by the remaining bonded FRP, and (v) residual strength provided by the bolts (after complete plate debonding).

In light of the overall success of FRP anchors in delaying or suppressing IC debonding failures, a clear understanding surprisingly still does not exist about the exact role the FRP anchors play when used in structural members. Also, there is no rational methodology for the design and placement of the anchors. Such is the motivation for the experimental program reported in this