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Experimental investigation into the size effect of bidirectional fiber patch anchors in strengthening of concrete structures

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ABSTRACT

The strengthening of existing reinforced concrete structures using fiber reinforced polymers (FRP's) as externally bonded reinforcement is gaining increasing attention due to the materials superior mechanical properties and light weight. However, a serious limitation in the use of FRP as a strengthening material comes from separation of the FRP from the concrete surface by premature debonding at a strain level which is well below the ultimate tensile strength of the material. A logical means to improve the performance of externally bonded FRP by mitigating the processes of debonding is by the provision of end anchorage. Of the many anchorages investigated by researchers, the use of bi-directional fiber patch anchors has shown exceptional promise. Due to the limitations of experimental data in this area, the current paper presents the first comprehensive experimental program into the size effect FRP patch anchors.

1. Introduction

Over the last two decades, extensive research has demonstrated the effectiveness of externally bonded (EB), fiber-reinforced polymer (FRP) composites for strengthening and repairing reinforced concrete (RC) structures. The main advantages of EB FRP for strengthening applications, when compared to strengthening using traditional engineering materials such as steel, are their high strength-to-weight ratio (up to ten times stronger than steel and about 20% of the weight) and high corrosion resistance.

A commonly documented failure mode of FRP strengthened RC is premature debonding, which generally occurs at fiber elongations well below the tensile strength of the FRP. Failure by debonding is usually rapid and represents a significant underutilisation of the materials strength properties. Design guidelines around the world are strongly influenced by such behaviours and adopt a preventative approach by limiting the design strain in the FRP to a level where debonding will not occur. A logical means to improve the performance of externally bonded FRP by preventing end debond is by anchorage. However, research in the field of anchorage systems has been very limited to date.

Following the thorough review of the existing forms of anchorages available [7], it was found that the majority were limited by a labour intensive installation process, subject to corrosion and ongoing maintenance or required mechanical fasters. As a result, anchorages in the forms of patch anchors consisting of unidirectional and bidirectional fibers were conceived conceptually and examined via a 2 stage experimental program, followed by extensive numerical simulations and parametric studies. Of the six types of anchorages tested in stage 1 of the experimental program, the use of bidirectional fiber patch anchors was proven to be the most effective in increasing the anchorage strength by up to 195%. Such a large increase in anchorage strength was achieved by the patch anchors ability to distribute the adhesive-to-concrete bond stresses, typically localised to the width of the FRP laminate, over a wider area of concrete.

Since the stage 1 experiments were limited by case dependency and the relatively small sample sizes employed. Many parameters remain to be investigated which could influence the performance of the patch anchors when applied to structures consisting of different material properties and design configurations. Factors such as: Concrete strength, laminate thickness, laminate modulus and patch anchor size and their effect on anchor performance remain to be quantified. Consequently, a further experimental study was designed (herein stage 2) to investigate factors such as patch anchor size, laminate thickness, laminate width and concrete strength.

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2. Experimental program

2.1. Specimen design

The following stage of the experimental program (stage 2), consisted of patch anchor configurations similar to those used in stage 1 – which were based on 2 plies of bidirectional fabric, with the laminate sandwiched in between. However, the study was designed to investigate a more commonly used laminate thickness (1.4 mm) as opposed to (2 mm) which was used in stage 1. The laminate width adopted was also reduced from 120 mm (stage 1) to 100 mm in stage 2. The reduction in laminate width was chosen specifically to observe the effect of laminate width and its relation to anchorage strength.

Another objective was to determine the size effect of the FRP patch anchor on the overall anchorage strength. In shear strengthening applications, FRP laminates are often installed to beams webs, side-by-side at a predefined spacing. Such situations require a continuous form of anchorage applied to the FRP ends and the question naturally arises regarding the relationship between laminate spacing and anchorage effectiveness. Where continuous patch anchors are used, it is apparent that each laminate will transfer bond stresses to a width of patch anchorage which is governed by the distance between adjacent laminates (laminate spacing). In order to assess the performance of patch anchorages under such situations, three alternative concrete block widths: 420, 320 and 220 mm were chosen for further study.

Appropriate boundary conditions of symmetry at the concrete block left and right edges were applied by replicating restraint normal to the concrete sides (x direction) whilst allowing movement in the vertical plane (y direction). Such boundary conditions are typically applied to replicate symmetry – in this case, symmetry meaning continuity of the anchorage and enabling full utilisation of the fabric-to-concrete bonded area without the adverse effects of development length of the bidirectional fibers. This was accomplished by the construction of steel angle slotted movement joints, the details of which are presented in Fig. 1. Each angle ($100 \times 100 \times 10$ mm) contained 2 no. 50×11 mm slots which were placed between two greased steel plates with 10 mm holding dowels to create the movement joint. The result of this symmetric boundary was that the effects of the patch anchors used to anchor multiple laminates spaced at 420, 320 and 220 mm apart could be investigated by simulating symmetry. In addition, 2 different patch anchor lengths: 300 mm in types (1, 3 and 4) and 250 mm (type 2) were investigated in an effort to determine the minimum anchorage length required. With the above criteria in mind, a control specimen together with 4 types of anchorage specimens were designed, the properties of which are presented in Fig. 1.

2.2. Specimen preparation

The specimens were prepared using the same techniques adopted in stage 1 to ensure consistency in the experimental results. The surface of the concrete blocks was sandblasted to expose the aggregate and achieve a surface roughness of approximately 1.5 mm. Installation commenced with the application of a primer. Once the primer reached a tacky state, application of the first layer of bidirectional fabric commenced. The fabric was thoroughly impregnated with saturant and any voids within the bond line were removed with the assistance of a hard rubber roller. The FRP laminate was applied to the surface of the first layer of bidirectional fabric, together with 50 mm adhesive tapers to achieve a smooth transition of the final layer of bidirectional fabric sheet. Finally, the second layer of bidirectional fiber was placed and 7 days of curing at a temperature of above 25 °C.

2.3. Experimental setup

The near end supported (NES) single pull test configuration was adopted for direct shear testing of each anchorage specimen. The same test rig which was used in stage 1 was also used in stage 2 of the study with some slight modifications, including a 200 mm high steel chair welded to the bottom of the rig, to account for the smaller concrete block sizes. This ensured a snug fit of the concrete blocks within the testing rig. The rig was fastened to an MTS 1MN universal testing machine using M24 high tensile bolts, which clamped the specimen into place. The final testing configuration is presented in Fig. 2.

2.4. Test preparation and material properties

Concrete blocks were reinforced nominally with 4 no. 12 mm diameter bars at 100 mm centres each face. The reinforcement cover used was 30 mm. All specimens consisted of a single laminate strip bonded to the surface of the concrete block with a bond length of 370 mm. Tables 1 and 2 summarises the material properties used as per manufacturers specifications.

2.5. Instrumentation and loading procedure

A series of 7 strain gauges (G1–G7) were applied to the length of the FRP laminate at 50 mm intervals. An additional 4 gauges were placed either side of the laminate (2 each side) to measure strains in the bidirectional fibers (G8–G11). Gauges G1 and G12 were installed at the front and back of the laminate to monitor any bending in the FRP plate during testing indicating the presence of tilting. The strain gauge locations can be seen in Fig. 1.

2.6. Image correlation photogrammetry

Optical measuring techniques are increasingly being used to provide full field monitoring of strain and deformation over a predefined area. The technique is particularly suited to capture hot spots and stress concentrations, which typically occur in non-homogenous and anisotropic materials. 3D image correlation photogrammetry used a pair of high resolution digital CCD cameras in combination with a randomised high contrast speckle pattern applied to the surface of the test specimen for the 3D deformation measurements. Stage 2 of the experiments used the image correlation system Vic3D [5] as opposed to ARAMIS which was used in stage 1. Specialised software processing involved first defining a subset size, which was essentially a grid covering the entire image area. Each subset was approximately 20 pixels in size and the speckles within each subset were used to define its centroid for monitoring and correlation with surrounding subsets. Image correlation principles were used in the Vic3D software to precisely calculate the strains and deformations to a level of resolution dependent largely on the speckle pattern, subset size, image contrast and image flatness.

The overall strain accuracy that could be achieved was found to be highly sensitive very to the speckle pattern. The pixel size, randomness, contrast, highly influence the noise in the data, which could be observed as random, sharp increases or decreases in strain output during loading. Various methods were trailed with the aim of producing an optimal speck pattern. The prepared surface was then spray-painted flat white in preparation for speck application.

The method of speckle application used in stage 1 of the experimental program utilised black spray paint, which resulted in the speckle pattern depicted in Fig. 3(a). Using a half pressed nozzle, a spluttering effect of black paint was created resulting in a randomised speckle pattern applied to the surface. Although this method provided acceptable results, the resulting speckle pattern