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Genetic programming in the simulation of Frp-to-concrete patch-anchored joints

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ABSTRACT

Although fiber reinforced polymer composites (FRPs) have proven to be one of the most efficient materials for strengthening existing reinforced concrete (RC) structures against various loading actions, premature debonding remains the major factor limiting their full utilization. Experiments have demonstrated that anchorage systems such as bidirectional fiber patch anchors are an effective method to improve the bond performance of FRP when bonded to concrete substrates and they can be applied to existing strengthening systems to achieve a given level of strengthening using less material. The present research aims to use available experimental data on patch-anchored joints to develop a new anchorage strength model using genetic programming. The model incorporates a number of input parameters which have been found to influence the strength of the anchor: concrete strength, laminate thickness, laminate width, patch anchor size and strength of adhesive. The genetically programmed model is compared with predictions from a semi-empirically derived model and provides less error and better correlations with the available data.

1. Introduction

In recent years, fiber reinforced polymer composites (FRPs) have become the world's leading material for strengthening reinforced concrete (RC) members against flexure, shear and torsion. The materials' superior mechanical properties, high tensile strength, light weight, resistance to corrosion and durability allow them to be used as either externally-bonded or near-surface mounted reinforcement. Despite the inherent strength of FRP materials, the bond between the FRP and the concrete remains a weak link in the strengthening system, largely due to the concrete substrate, which possesses relatively low tensile strength to resist the interfacial shear and peeling stresses generated in the FRP bond line. Hence, the majority of research into FRP-strengthened RC has shown that premature debonding is the controlling failure mode, as opposed to FRP rupture. The occurrence of debonding often limits the degree of strengthening that can be achieved, results in lower member ductility, and is an inefficient use of material, since only 10–30% of the ultimate tensile strength (UTS) of the FRP is reached prior to debonding. Recent studies have demonstrated that anchorage systems have the potential to significantly improve the bond performance of FRP-to-concrete substrates and mitigate the occurrence of premature debonding. This is accomplished by a confining mechanism to resist interfacial peeling and shear stresses, that typically result in end debond. In this category are anchors such as mechanically fastened steel plates, U-wraps and spike anchors. Other anchors developed more specifically for shear strengthening applications, where interfacial shear stresses in the bond line predominate, are flange embedment, bidirectional fiber anchors and anchoring around an embedded FRP bar. Recent tests by Al-Mahaidi and Kalfat [2] have shown that ±45° oriented bi-directional fabric anchorages (herein patch anchors) result in gradual debonding of FRP laminates as a result of FRP-adhesive stresses being distributed over a greater area of the concrete. The anchored joints experienced increases in strength of up to 93–109% as well as loaded end slippage of 4 to 8 times above that of the unanchored counterparts. The ±45° oriented bi-directional fabric configuration has been successfully applied to strengthen the West Gate Bridge in Melbourne [3,28], which represents the world's largest application of FRP strengthening to date.

Alongside the importance of carrying out experimental studies on FRP anchorage systems and designing and testing new, more effective anchorage methods is the development of prediction models and design guidelines so that the outcomes of the research can be incorporated into design codes and used in future designs. Based on a limited amount of test data, Kalfat and Al-Mahaidi

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[13] derived a semi-empirical prediction model for patch-anchored joints. Although the model provided reasonable strength predictions based on the experimental data at the time, further experimental tests required the model to be modified to account for the strength of the saturant adhesive, which was found to influence the failure mode of the anchor and the overall strength achieved [15]. The present paper aims to develop a better model using a genetic programming modeling technique and evolve a mathematical formulation in accordance with the available data set.

2. Summary of experimental work on patch-anchored joints

To date, many anchorage systems investigated by researchers have been limited by the labor-intensive installation process, are subject to corrosion and ongoing maintenance, or require mechanical fasteners [16]. Therefore, a research project was implemented to devise a new FRP anchorage system which is non-destructive, low maintenance, easy to install and able to mitigate the process of premature debonding. Patch anchors consisting of unidirectional and bidirectional fibers were conceived conceptually and examined via a three-stage experimental program, which was later followed by extensive numerical simulations and parametric studies.

The first stage of the experimental program by Al-Mahaidi and Kalfat [2] consisted of testing both unidirectional and (±45°) bidirectional fiber patch anchors. The anchorages were used to anchor 2 mm thick × 120 mm wide FRP laminates bonded to concrete and were tested in a near-end supported single-shear pull test. The study determined that the patch anchors were successful in improving the strength of the FRP-to-concrete joint by up to 195%. The use of (±45°) bidirectional fabric patch anchors applied to the ends of FRP laminates resulted in a more efficient distribution of FRP-adhesive stresses, which were typically localized to the width of the FRP laminate, to a greater area of concrete.

Further experimental work focused on developing the (±45°) bidirectional fiber patch anchor concept by investigating influencing parameters. The influence of patch anchor size, laminate thickness and laminate width was investigated in Kalfat and Al-Mahaidi [12]. FRP-to-concrete joints were constructed using 1.4 mm thick × 100 mm wide laminates which were anchored and tested using a similar test set-up to that depicted in Fig. 1(a). By examining the strain distributions within the bidirectional fibers, it was found that laminates could be spaced as closely as 250 mm without any reduction of anchorage strength. The study revealed two possible failure modes whereby the anchored FRP laminate may separate from the concrete: (1) complete debonding of the sandwiched laminate and bidirectional fabric structure from the concrete block (patch anchor debond), or (2) slippage of the laminates from between the two layers of bidirectional fibers (laminate slippage). Of the two failure modes observed, laminate slippage occurred at a lower load when laminate widths less than 120 mm and anchor lengths less than 300 mm were used. Laminate slippage was attributed to an insufficient bond strength and contact area between the FRP laminate and the two layers of bidirectional fiber sheet. The typical failure mode of patch anchor debond is depicted in Fig. 1(b) below:

Numerical finite element simulations were conducted which were able to capture the pre-peak and post-peak response of the patch-anchored joints to a high level of accuracy, once calibrated with the numerical data [14]. Parametric studies on concrete strength were also performed to expand on the experimental data, resulting in an approximately linear relationship between the concrete compressive strength and the maximum laminate strain achieved prior to debond. Both the experimental data from stages 1 and 2, as well as the information derived from the finite element simulations, were used to develop a theoretical anchorage strength model for (±45°) bidirectional fiber patch-anchored joints [13]. The model is capable of offering anchorage strength predictions for alternative material and geometrical properties and was verified with the existing experimental and numerical data.

Following the publication of the first anchorage strength prediction model, further experimental studies were conducted to investigate the effect of using a higher strength saturating resin on the performance of the patch-anchored joints. As a result, the tensile strength of the saturating resin was increased from 47.8 MPa (used in earlier experimental tests) to 63.1 MPa. The higher strength saturant was discovered to prevent laminate slippage in all cases,

Fig. 1. Specimen testing rig details (a) configuration of test rig (front view); (b) Photograph of typical patch anchor debond failure.