Engineering Structures 133 (2017) 133–150

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Influence of FRP anchor configuration on the behavior of FRP plates externally bonded on concrete members

Togay Ozbakkaloglu *, Chengfeng Fang, Aliakbar Gholampour

School of Civil, Environmental and Mining Engineering, University of Adelaide, SA 5005, Australia

ARTICLE INFO

Article history:
Received 8 March 2016
Revised 2 December 2016
Accepted 6 December 2016

Keywords:
Fiber-reinforced polymer (FRP)
FRP plate
Delamination
FRP spike anchor
Single shear test
Load capacity
Load-displacement curves
Plate strain variation

ABSTRACT

This paper presents an experimental study on the influence of fiber-reinforced polymer (FRP) anchor configuration on the behavior of FRP plates externally bonded on concrete members. Single shear pull-off tests were conducted on 33 test specimens that were designed with different carbon FRP anchor configurations. The effects of embedment depth, and number and configuration of FRP anchors were examined. Results indicate that all of the investigated parameters influence the peak load capacities of carbon FRP plate, with particularly significant influences on the second peak load capacity. Load-slip behaviors of FRP plates are significantly influenced by the number and configuration of anchors. Distribution and magnitude of the longitudinal FRP plate strains recorded at the initial and second peak load capacities of anchored plates are affected by the anchor configuration. FRP plates with a longitudinal anchor configuration develop higher maximum strains than those of plates with a transverse anchor configuration.

1. Introduction

Fiber-reinforced polymer (FRP) composites are recognized for their high tensile strength, strength-to-weight ratio, corrosion resistance, easy installation, and versatility, and these properties make them an attractive option for use in modern construction. A great number of studies have been undertaken on FRP-strengthened concrete members, where carbon and glass FRP laminates or strips were externally bonded on concrete surfaces to improve shear, bending, or torsional capacities of concrete members [1–12]. These studies have shown that the presence of FRP laminates resulted in significant increases in the load capacities of the retrofitted members compared to the control group. However, due to high interfacial shear and normal stresses at the FRP-to-concrete interface, debonding failure modes such as plate end debonding, concrete cover separation, and intermediate crack-induced debonding were frequently reported in previous studies [1–3,5,6,8,12–20]. Such debonding failure results in the premature failure of the FRP plate strengthening system before it develops its full strength, thereby resulting in inefficient use of the material. It is now broadly accepted that there is a need to develop FRP strengthening systems that are able to overcome the summarized shortcomings of externally bonded FRP laminates.

The use of anchorage has emerged as one of the most promising techniques for delaying or preventing interfacial debonding failure in concrete members retrofitted with externally bonded FRP laminates through increasing the bond strength between the FRP plates and concrete substrate [1,14–19]. A number of techniques have been used previously to prevent delamination of FRP laminates in FRP-strengthened concrete members. These included the use of transverse FRP wraps as anchors [1], U-shape FRP anchors [1,18,21,22], steel bolt anchors [23,24], near surface mounted anchors with FRP bars [25–28], U-shape FRP sheets with additional FRP plates to fix the sheets at the flange of concrete beams [29], mechanical fasteners with steel capping plates and anchors [30], and FRP spike anchors [1,22,23,26,31–35]. Among these techniques, the use of FRP spike anchors has been found to be particularly attractive due to the technique's applicability to a wide range of concrete members, and that the anchors possess the same material properties, installation techniques, and benefits as the original FRP laminate [1,17–19]. FRP spike anchors with a 90° angle between the anchor dowel and anchor splay (refer to Fig. 1) are commonly used for anchorage throughout the entire length of the FRP laminate to delay or prevent interfacial debonding, and 180° FRP spike anchors are typically used in concrete members with geometric complexities to provide a sufficient stress transfer mechanism [1,17–19]. The use of FRP spike anchors results in

* Corresponding author.
E-mail address: togay.ozbakkaloglu@adelaide.edu.au (T. Ozbakkaloglu).

http://dx.doi.org/10.1016/j.engstruct.2016.12.005
0141-0296/

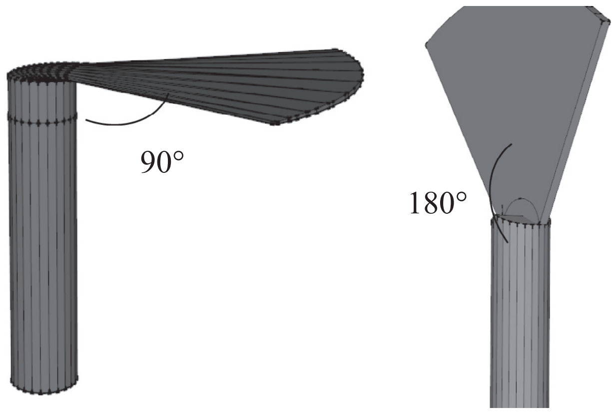

Fig. 1. 90° and 180° FRP spike anchors.

increases in both the bond strength at the FRP-concrete interface and axial strain in the FRP plate, thereby allowing a more efficient use of the FRP material [17–19].

A large number of experimental studies have been undertaken to investigate the behavior of FRP anchors used in concrete members under axial tension [36–41] and shear [38,42–49]. The studies on the axial tension behavior of anchors have found that the anchor embedment depth, anchor fiber content, and quality of workmanship in anchor installation are the major parameters affecting the magnitude of the maximum pullout load. Based on a database of experimental results, Kim and Smith [41] proposed pullout strength models for FRP anchors in uncracked concrete to predict anchor pullout capacities and anchor failure modes. The study by Kim and Smith [42] showed that in FRP plates with a single anchor, the bond strength between the plate and concrete decreased when the anchor was positioned away from the loaded end of the plate.

Following from the work by Kim and Smith [42] on the use of a single FRP anchor, a number of studies have been reported on the use of multiple FRP anchors [43–49] to secure FRP plates to concrete. These studies have identified the spacing, diameter, configuration, and fabrication method (i.e. impregnated or dry fiber anchors) of anchors as important parameters affecting the performance of the anchor strengthening system. The results also showed that the specimens with a longitudinal FRP anchor pattern develop a more ductile system behavior before failure, whereas the transverse FRP anchor pattern leads to the development of higher forces in the FRP plate. In addition, the overall effectiveness of FRP anchors was shown to be dependent on the ratio of the FRP anchor splay diameter to FRP anchor diameter, with a larger ratio engaging a wider region of the FRP plate and increasing the likelihood of the failure to shift to the anchor [43]. Following from these studies, Zhang and Smith [47] proposed analytical models for predicting the bond capacity of the single and multiple FRP-anchored plate strengthening systems based on the bond-slip model proposed by Chen and Teng [50]. A careful review of the existing literature indicates that no study has investigated the effect of anchor configuration along the length of the plate for FRP plates with multiple anchors.

This paper presents an experimental study that investigated the behavior of FRP-anchored FRP plates bonded to concrete. This is the most comprehensive experimental study to date to investigate the effect of anchor configuration on the behavior of FRP plates anchored to concrete using single or multiple anchor(s). The study also introduces a carefully designed instrumentation arrangement that enables close monitoring of the strain development on the FRP plates throughout the loading history. The paper initially provides a summary of the experimental program, including material properties, specimen properties, and testing procedures. Subsequently, the results of the experimental program are presented followed by a detailed discussion of the results.

2. Experimental program

2.1. Test specimens

33 identical 350 mm long, 150 mm high, and 250 mm wide rectangular concrete blocks were prepared for the single shear tests of FRP-anchored plates. Based on cylinder tests, the average test-day compressive strength (f_c') of the concrete was established as 49.6 MPa. In the preparation of the specimens, 33 identical FRP plates were manufactured using 0.167-mm thick unidirectional carbon fiber sheets. Carbon FRP plates, shown in Figs. 2(a) and (b), were prepared using a manual wet layup process to adhere four layers of carbon fiber sheets together, resulting in an over-engineered plate with a width of 100 mm, a length of 500 mm, and a thickness of 2.6 mm. This was done to ensure the FRP plate rupture did not occur and the plate failed by debonding, so that the influence of FRP anchors on the bond behavior of the FRP plate strengthening system could be studied. As shown in Fig. 2(a), a 270 mm-long section of the plate was bonded on the concrete block, whereas a 40-mm long section of the plate near the edge of the concrete block was left unbonded to prevent concrete wedge failure from the high-stress concentration effects around the concrete edge areas [47–49]. Aluminum tabs measuring 140 mm long and 100 mm wide were bonded at the loaded side of the FRP plate to ensure that load was applied to the FRP plate evenly and without any damage from the machine grip [42–49].

The same unidirectional carbon fiber sheets used in FRP plates were used to manufacture the FRP anchors. Anchors with two different embedment depths (i.e. h_{ef} = 40 mm and 60 mm) were considered. As can be seen in Fig. 3, the anchors with 40 mm and 60 mm embedment depths were prepared by rolling 150 × 100 mm and 150 × 120 mm fiber sheets, respectively.

Table 1 shows the test parameters, which included: the number of FRP anchors (i.e. 1, 2, or 4), anchor position on the FRP plate (i.e. Regions 1, 2, or 3), and anchor pattern (i.e. longitudinal or transverse). Three nominally identical specimens were tested for the control group with no FRP anchors and the anchored specimens with a single-anchor configuration, and two nominally identical specimens were tested for specimens with multiple anchor configurations.

2.2. Materials

2.2.1. Carbon FRP sheet

Three flat coupon tests were performed to determine material properties of carbon FRP. The same method used in the fabrication of the FRP plates was adopted for the preparation of the FRP coupons using four layers of fiber sheets, which resulted in a 25 mm wide and 140 mm long coupons with an average thickness of 1.94 mm. The coupons were cured for 7 days in the room temperature, after which 25 × 85 mm aluminum tabs were glued to the coupon at both ends using the Araldite K330-1 adhesive. After an additional curing time of 7 days at 25 °C, the FRP coupons were tested under axial tension in accordance with ASTM standard D3039M-08 [51]. The data recorded in the coupon tests were used to establish the ultimate tensile strength (f_{frp}), ultimate tensile strain (ε_{frp}), and elastic modulus (E_{frp}) of the FRP composites based on nominal fiber thickness, as listed in Table 2. The manufacturer-supplied properties of the carbon fibers are also given in the same table.