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Development of a testing methodology for the design and quality control of carbon fiber reinforced polymer (CFRP) anchors

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HIGHLIGHTS

- Develop a standard test methodology to determine the quality of CFRP anchors.
- Provide recommendations for the design of CFRP anchors.
- Propose a proper installation procedure.

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ABSTRACT

Using CFRP anchors to prevent the premature debonding failure of CFRP strips from concrete substrate is gaining acceptance. Although adequate CFRP anchors can fully develop the strength of CFRP strips, few recommendations for designing CFRP anchors are available. Based on experimental results obtained from 38 tests, a testing methodology using design strip strength is presented to evaluate the quality of CFRP anchors and to identify the design parameters including the strength ratio of CFRP anchor to CFRP strip, the strip width, the concrete strength, the fan angle, the embedment length, the bend radius, the hole diameter, the CFRP patch, the bond length and the bond condition. Design recommendations and installation procedures are also presented to ensure the desired performance of the anchorage system.

1. Introduction

Over the past decade, using carbon fiber-reinforced polymer (CFRP) in the rehabilitation of concrete members has gained widespread acceptance because CFRP is lightweight, has high strength, and is relatively easy to install [1–8]. Based on installation methods, CFRP composites can be divided into wet layup systems and pre-cured systems. Wet-layup FRP systems refer to FRP strips consisting of dry fiber fabrics impregnated with a saturating epoxy resin on site [4–6]. Pre-cured systems refer to FRP plates consisting of a variety of composite shapes fabricated off site [5–8]. Typically, adhesive (epoxy resin) is used to bond those CFRP composites onto concrete substrate with the fibers oriented in the direction that requires additional tensile strength. It should be noted that premature failure of CFRP debonding from the concrete substrate is likely to limit 50–60% of the CFRP tensile strength if the CFRP material relies exclusively on the CFRP-concrete bond [9–11]. Extensive studies were conducted to determine the bond strength of the CFRP-concrete interface for the design of CFRP-strengthened concrete structures [12–18].

Anchorage systems were introduced to prevent premature CFRP composite debonding failure. Mechanically fastened joints, consisting of steel plates and bolts, are generally used to anchor pre-cured CFRP plates. Those joints have been proven as a logical solution to prevent the debonding failure of CFRP plates [19–21]. Fiber-reinforced polymer (FRP) U-jacket anchors [22–24] and patch anchors [25] apply unidirectional or bidirectional fibers to the ends of wet-layup CFRP strips to limit the occurrence of premature debonding. These two non-destructive anchors prevent CFRP strips from debonding due to the tensile peeling stress or crack propagation towards the end of the CFRP strip. However, multiple anchors might be required to limit the considerable slip between the anchors and the anchored CFRP strip. Increasing the number of anchors is unappealing due to the high installation costs, the increased need for CFRP material and the longer installation time. Versatile CFRP anchors, as shown in Fig. 1, are made by inserting a strip of CFRP material into a predrilled hole and then fanning the strip out to cover the wet-layup CFRP strip; these anchors were

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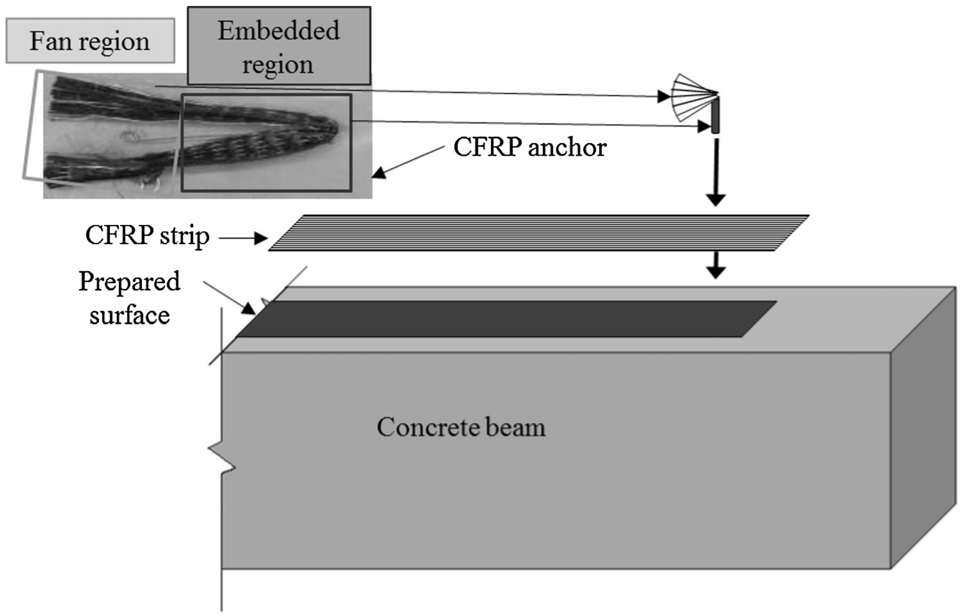

Fig. 1. A typical CFRP anchor.

introduced to gradually transfer the tensile force from the strip to the concrete via the anchorage system after debonding [26–31]. Experimental studies have illustrated that shear strength gains exceeding 40% were achieved by using the CFRP anchored CFRP U-wraps, while no significant increases were observed when using the same CFRP U-wraps without anchorage applications [32]. Moreover, CFRP anchors were able to fully develop the tensile strength of CFRP strips used for flexural strengthening concrete beams [29]. CFRP anchored U-wraps were able to achieve an effectively continuous wrapping application for those columns at the end of a wall [26].

Although CFRP anchors have demonstrated superior performance in strengthening CFRP strips, information regarding anchor design and installation is limited. An inadequate anchorage system could prematurely fail before the CFRP strip has developed the desired strength. A testing methodology is therefore developed in this paper to 1) validate the quality of CFRP anchors and 2) identify the design parameters. Moreover, wet-layup CFRP with epoxy as the resin is applied in all experimental specimens to make CFRP strips and anchors.

2. Previous research

Although they are few in number, previous studies provide insight into the CFRP anchor properties and indicate that the anchor size, anchor hole size, embedment length, details of the anchor fan, bend radius and bond condition are the critical parameters for CFRP anchors. Pull-out tests (Fig. 2) are generally used to investigate the performance of anchors with various geometries and material properties. Pull-out tests have shown that tensile strength gains of up to 53% and slip gains exceeding 900% can be achieved by using CFRP anchors to strengthen CFRP strips [33]. The anchor size directly determines the amount of tensile force transferred at the anchor from the CFRP strip into the concrete. An anchor that contains less CFRP material than the CFRP strip could rupture before the CFRP strips fracture [34]. An embedment depth of 51 mm was used in Niemitz's tests, and only one anchor failed in pull-out mode [34]. CFRP anchors are intended to fan out and cover the entire width of the CFRP strips to effectively transfer the tensile force from the strip to the anchor [30]. However, pull-out tests require 1) careful alignment to avoid eccentricities; 2) careful design of the clip used to grab the CFRP strip to avoid stresses concentrated around the clipped zone; and 3) careful fixing of the concrete block to restrict block movement and to avoid the concrete block failing in shear, which could limit the feasibility of pull-out tests in a general laboratory.

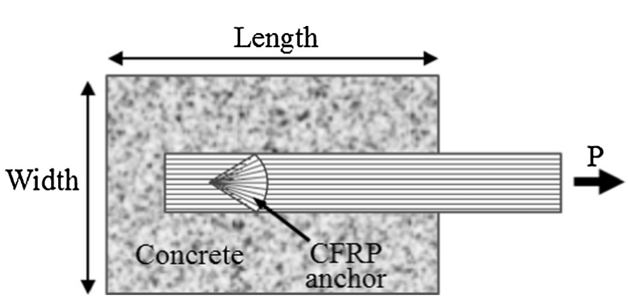

Fig. 2. A typical pull-out test.

A modified version of the ASTM C293 standard (ASTM International 2007b) for the flexural strength of concrete was used to study the behavior of CFRP anchors. Test specimens were loaded at their mid-span with a pin support at one end and a roller support at the other end. Since the concrete block did not contain any steel reinforcement, the tensile force was carried by the anchored CFRP strips applied to the tensile surface of the blocks. This methodology was designed to achieve a qualified test using specimens that were simple to make and could be handled by a single staff member in a general laboratory [10,35–37]. Flexural tests have shown that to fracture the CFRP strip, the anchor should have a total cross-sectional area that is at least two times greater than that of the longitudinal strip if the same CFRP material is used for both the anchor and the strip [10]. The hole used to insert the anchor has been suggested to have at least 1–2 mm of free space between the hole and the CFRP anchor for saturating the epoxy resin [35] or to be at least 1.4 times larger than the cross-sectional area of the CFRP anchors [37]. Anchor fans have been recommended to extend 13 mm beyond the width of the CFRP strips to achieve a more effective cover [32,37]. The fan angle was