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Experimental study on RC beams strengthened with CFRP rod panels

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ABSTRACT

Externally bonded (EB) fiber reinforced polymer (FRP) laminates and fabrics have become a mainstream method for retrofitting and upgrading concrete structures. Nevertheless, when strengthening long-span members or members with limited access, labor, traffic, and equipment demands may hinder the use of continuous EB FRP. The use of carbon FRP (CFRP) rod panels is a recent application of FRP material intended to overcome the above limitations. CFRP rod panels are developed from small diameter rods and are made continuous by means of a finger joint. This study leveraged four-point bending tests to determine whether spliced CFRP rod panels can effectively serve as flexural reinforcement for concrete members. Testing included a control beam and beams strengthened with the following FRP reinforcement layouts: (1) continuous rod panel, (2) spliced panel (two half-length panels with a 150 mm finger joint), (3) spliced panel anchored at ends with CFRP fabric, (4) continuous CFRP laminate, and (5) lap-spliced CFRP laminate system. Beams bonded with either continuous or spliced rod panels failed by concrete cover separation. The beam with spliced and anchored rod panel failed by intermediate crack-induced debonding of the panel. No local debonding or other signs of distress were observed at the finger joint for the two beams strengthened by spliced rod panels. For beams bonded with continuous and lap-spliced CFRP laminates, the failure was by laminate debonding. Compared to a control specimen, the maximum load increase of the strengthened beams was as follows: 112% for the continuous rod panel; 106% for spliced rod panel; 158% for the spliced/anchored rod panel; 49% for continuous laminate; and 31.8% for lap-spliced laminate.

1. Introduction

Concrete structures may require structural repairs or upgrades for a number of reasons, including aging-related deterioration; severe environmental exposure, vehicular impacts, and errors in design or/and construction. When the need for repairs or upgrades arise, one of the alternatives is the deployment of fiber reinforced polymer (FRP) composites.

FRP composites, as externally bonded reinforcement (EBR), in the form of pultruded laminates (strips, plates) and fabrics, have been successfully deployed to strengthen existing concrete structures, and it is generally more economical and convenient than traditional repair systems [1,2]. The embrace of FRP, as an alternative repair and strengthening method, stems from its excellent attributes including high strength and/or stiffness, lightweight, immunity to corrosion, and ease of handling and installation [3–9].

Based on the authors experience in retrofitting more than thirty bridges with EB FRP systems since 2001 [10], one of the limitations of using laminates is the manpower and equipment required to attach a continuous laminate along the entire length of long members with limited access (e.g., bridge girder over waterways, multi-lane freeways, etc., [11]). Although splicing FRP laminates is an option, it is not commonly used in practice because splice plate debonding may occur prematurely [12,13].

Several experimental, numerical, and field studies have examined the viability of using lap spliced EB FRP in retrofit applications of concrete and steel members [14–20]. Stalling and Porter [17] performed laboratory tests on large-scale RC beams strengthened with lap-spliced CFRP plates. They proposed limiting the shear stresses in the splice to within 15% of ultimate stress to prevent debonding of the splice. They also concluded that, for the splices to be fully functional and to avoid shear failure in the splice, the average shear stress in the adhesive should be kept below 15% of the adhesive's shear strength. This leads to relatively long splices.

Recent work has identified carbon FRP (CFRP) rod panels (CRPs) as an externally bonded reinforcement and an alternative to splicing laminates. CRPs are made from small diameter CFRP rods that are placed side by side at discrete spacing to form a panel (Fig. 1). The rods are

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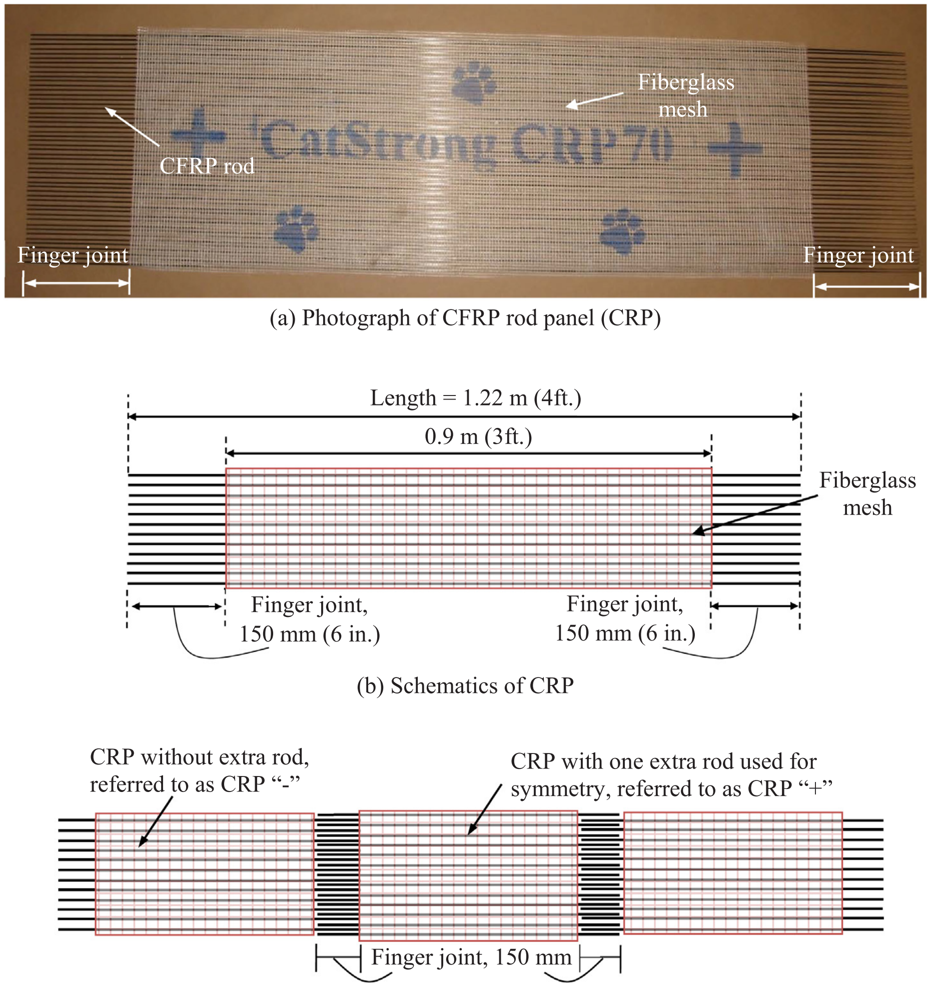

(a) Photograph of CFRP rod panel (CRP)

(b) Schematics of CRP

(c) Schematics of three CRPs made continuous by means of overlapping

Fig. 1. CFRP rod panel (CRP) strengthening technique.

then mounted to a fiberglass backing to facilitate the handling of the panel and to keep rod spacing consistent [11,13,21]. Neighboring panels are brought together and made continuous by a finger joint mechanism (Fig. 1).

Rods are spaced so that, in the finger joint region, they can easily be placed leaving sufficient room for the adhesive to completely cover the rods. Every other panel is produced with an extra rod to provide symmetry on both sides of the finger joint region. CRPs are 1.22 m (4 ft.) long including a 150 mm (6 in.) finger joint on both ends of the panel (Fig. 1). The finger joint length is selected based on bond studies carried out on double-lap shear concrete specimens bonded to small-scale CRPs as well as individual rods [11,22]. Although CRPs can be produced in any length, the 1.22 m length is convenient when a single worker in a bucket mounted on a truck is deploying them on a member traversing a waterway or other crossings with limited access.

A previous study by Peiris and Harik [11] validated the proof of concept through experimental tests. Bond tests were conducted using double-lap shear specimens on individual rods with both steel and concrete substrates. Flexural tests were carried out under four-point bending on small-scale reinforced concrete beams that were strengthened using continuous carbon fiber reinforced polymer rod panels (CRPs) and spliced CRPs with an overlapping finger joint. Case studies of four bridge retrofit projects involving CRPs were also carried out in order to evaluate the feasibility of field deployment.

This study investigates experimentally the effectiveness of spliced CRPs for strengthening RC members. Six RC beams are tested to assess the flexural behavior of CRP-bonded beams at cracking, service, and ultimate load stages, and to compare the performance of CRPs with laminates.

2. Experimental program

2.1. Test specimens

The tested RC beams are 3042 mm (120 in.) long and have a square cross-section of 150 × 150 mm (6 × 6 in.). The dimensions were designed to ensure that the specimens failed in flexure rather than in shear, following specifications of the ACI code [23]. The clear span between supports was 2742 mm (108 in.), while 150 mm (6 in.) of extra length was added beyond the clear span on each side of support to provide an anchorage for internal reinforcement and adequate seating area. The shear span was 990 mm (39 in.), corresponding to a shear span-to-effective depth ratio of 7.80. The pure flexural region measured 762 mm (30 in.).

Flexural reinforcement consisted of two No. 10 [nominal diameter 10 mm (0.39 in.)] deformed steel rebars located near the beam's tension face. The shear reinforcement consisted of No. 3 [nominal diameter 3 mm (0.12 in.)] steel stirrups located within the shear span. The stirrups were spaced at 150 mm (6 in.) along most of the shear span. For locations at supports and loading points, the stirrups were spaced 76 mm (3 in.) apart to avoid shear failure at those critical locations. To facilitate the placement and vertical alignment of shear stirrups, two