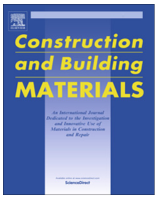
Construction and Building Materials 177 (2018) 522–534

Contents lists available at ScienceDirect

Construction and Building Materials

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



Numerical study on the bond between CFRP rod panels (CRPs) and concrete

Akram Jawdhari [a],*, Amir Fam [a], Issam Harik [b]

[a] Dept. of Civil Engineering, Queens University, Kingston, ON, Canada
[b] Dept. of Civil Engineering, University of Kentucky, Lexington, KY, USA

HIGHLIGHTS

- CFRP rod panel (CRP) is a promising retrofit system for concrete structures.
- Finite element models were developed to study the bond between CRP and concrete, and several parameters.
- A bilinear bond-slip model is proposed, with a maximum shear stress of 6.25 MPa and maximum slip (δ_f) of 0.45 mm.
- Decreasing rod diameter or increasing rod spacing/diameter ratio increases the ultimate strength.
- Debonding load of CRP is 51% higher than that of an externally bonded conventional CFRP plate with same FRP area.

ARTICLE INFO

Article history:
Received 19 March 2018
Received in revised form 13 May 2018
Accepted 15 May 2018

Keywords:
Concrete
Fiber reinforced polymer
Rod panels
Finite element
Bond
Development length
Bond-slip relation

ABSTRACT

In this study, finite element (FE) models are developed to examine the interfacial behavior of a new retrofitting system comprised small diameter carbon fiber reinforced polymer (CFRP) rods spaced apart a distance larger than the rod diameter. The CFRP rod panel (CRP) is adhesively bonded to the concrete surface. The study explores several key parameters, including bond-slip (τ-δ) relation, effective bond length, rod diameter (D), and rod spacing-to-diameter (S/D) ratio. The models were validated against previous double-lap CRP-concrete block tests. A bilinear (τ-δ) model that provides a good correlation to the failure loads of the entire range of specimens was established. The effective bond length was found for two commonly used CRPs, and was 85 mm for one with D = 2 mm and S = 6.35 mm, and 115 mm for that with D = 4 mm and S = 9.50 mm. A parametric study using 20 FE models was carried out, considering four rod dimeters (1–4 mm) and five S/D ratios (2.2–3.18). It was found that although debonding failure consistently governs; decreasing (D) or increasing (S/D) ratio increases the ultimate strength. The effect of (S/D) ratio is more pronounced for D = 1 mm than other diameters. The study also found that debonding load of CRP is 51% higher than that of an externally bonded conventional CFRP plate of similar cross-sectional area and mechanical properties.

1. Introduction

The use of fiber reinforced polymers (FRPs) in the infrastructure industry has advanced tremendously over the past few decades, as a result of their superior properties [1–10]. In addition to the well-known retrofit systems such as the externally bonded (EB) plates and near surface mounted (NSM) FRPs, a relatively new system comprising small diameter carbon-FRP (CFRP) rod panels, referred to as CRPs, has been developed [11–16]. The rods are bonded to a light fiber glass mesh designed to maintain a spacing between rods, greater than the rod diameter [15] as shown in Fig. 1. The fiberglass backing, which is a commercially available product such as drywall tape, can be either self-adhesive or sprayed with a bonding agent, and is assumed to have negligible structural contribution.

Generating a CRP consists of: (a) aligning the rods at the required spacing using a guiding device, and (b) placing the backing on top of the rods and applying pressure to ensure a good bond between the rods and the backing. Like EB FRP, CRPs are externally bonded to the structural member with a two-part epoxy paste. The application of CRPs as a retrofit technique involves the following typical steps: (a) surface preparation of the substrate (e.g. by sand-blasting or grinding), (b) application of the fist adhesive layer, (c) setting CRP into position and pressing down to force the adhesive

---

* Corresponding author.
E-mail address: akram.hassan@uky.edu (A. Jawdhari).

https://doi.org/10.1016/j.conbuildmat.2018.05.138
0950-0618/

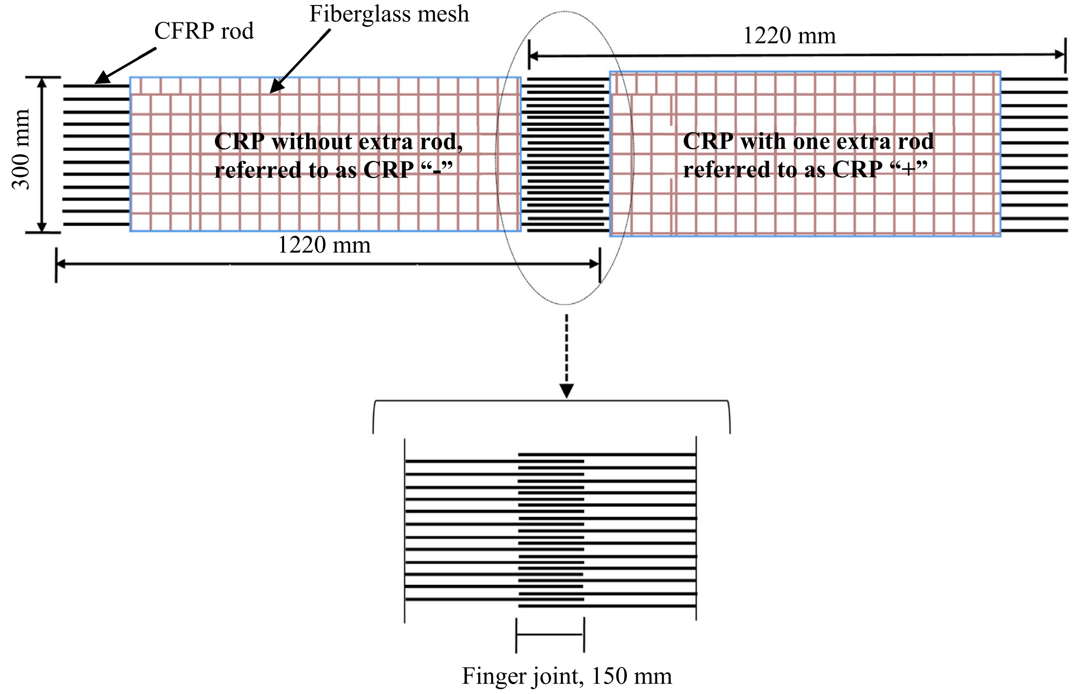


Fig. 1. CFRP rod panel (CRP) strengthening technique.

to flow around and fill between the rods, and (d) coating with a second layer of adhesive to completely embed the rods.

One of the advantages of the CRP technique over conventional CFRP plates is the improved bond performance because the surface area of the CFRP rods is larger than that of a plate with a similar cross-sectional area [14]. Another benefit of CRP is the modular concept, achieved by using short-length panels made continuous by a finger joint (overlap) (Fig. 1). Panels with a length of 1.22 m are used to facilitate ease of shipping and handling and enable rapid installation using few workers. A finger joint of 150 mm was found to be sufficient in providing continuity and composite action between adjacent panels [11,13]. When retrofitting bridges with long-spans or accessibility restrictions (e.g. over waterways or multi-lane freeways), CRP application can be conducted in stages by stopping the application at any panel, leaving the finger joint exposed without epoxy, then resuming installation at a later stage [15]. For conventional EB systems, continuous CFRP plates are typically used. The cost of labor and equipment required to attach the continuous laminate can be high. Issues related to premature debonding and large length of splice, have prevented the full utilization of spliced conventional CFRP plates [17–20].

Few studies assessed the bond and structural effectiveness of the CRP system in strengthening RC members [11,14,17]. Jawdhari and Harik [12] tested RC beams retrofitted with EB CFRP plates and CRPs, including continuous and spliced configurations for both systems. The study found that the increase in strength was 112% (for continuous CRP), 106% (for spliced CRP), in contrast to 49% (for continuous EB plate) and 32% (for lap-spliced EB plate). Unlike EB plates, CRPs did not experience debonding failure, neither at the finger joint region nor at the CRP ends. Peiris and Harik [15] also conducted tests on three RC beams, which were unstrengthened, strengthened with full-length CRP, and strengthened with spliced CRPs. Compared to the control specimen, the full-length and spliced CRPs resulted in 95% and 68% increase in ultimate load, respectively. Both strengthened specimens failed by concrete cover separation, with no debonding at CRP ends or the finger joint.

Jawdhari et al. [13] carried out a bond study of CRPs using concrete blocks. Two panels were investigated, namely CRP 070 (made from 2 mm rods at 6.35 mm spacing), and CRP 195 (made from 4 mm rods at 9.5 mm spacing). The development length was found to be 100 mm and 119 mm for CRP 070 and CRP 195, respectively. However, this bond study was limited in scope to finding the development length and bond strength of two rod diameters only. Also, strain gages were installed on the surface of adhesive and not directly on the small CFRP rods. The bond-slip relation for the FRP-concrete joint, which is of primary importance for determining the interfacial and structural properties, including ultimate loads was established from the adhesive strains, assuming they are equal to rod strains, which may not be quite accurate.

This study aims at developing an in depth understanding of the bond characteristics of this new CRP system. A robust nonlinear finite element (FE) model is developed and calibrated using the experimental results available to examine the interfacial behavior of CRPs bonded to concrete. The goal is to accurately determining the bond characteristics, including the effective bond length, bond-slip relation, and the distribution of stresses in the rod panel. A parametric study is also conducted to examine a variety of CRP configurations, including various rod diameters and rod spacing and their effect on ultimate loads.

2. Summary of experimental program

In the experimental study by Jawdhari et al. [13], 18 double-lap shear specimens were prepared and tested under pull-out tension load to measure the development length and bond strength of CRPs attached to concrete. Each specimen comprised two 300 mm long concrete blocks with a 100 × 100 mm square cross-section (Fig. 2). A 25 mm diameter central steel rebar was embedded in the block and used to transfer the pull-out force to the specimen. On two opposite faces of the blocks, as per the double-lap configuration, CRPs with a varied bond length (l_b) ranging from 25 mm to 175 mm, were installed (Fig. 2). To ensure failure at the bond length