Construction and Building Materials 172 (2018) 63–76

Contents lists available at ScienceDirect

Construction and Building Materials

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

Effect of defects in externally bonded FRP reinforced concrete

Baolin Wan [a,1], Cheng Jiang [b,1,2], Yu-Fei Wu [c,*,2]

[a] Dept. of Civil, Construction and Environmental Engineering, Marquette University, USA
[b] Dept. of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong Special Administrative Region
[c] School of Engineering, RMIT University, Australia

HIGHLIGHTS

- Variation of bond workmanship is studied experimentally.
- Bond quality affect debonding failure mode.
- Offset of FRP strip does not cause significant variation of bond.
- Existing cracks in RC beams do not have significant influence on FRP strengthening efficiency.

ARTICLE INFO

Article history:
Received 16 January 2018
Received in revised form 11 March 2018
Accepted 21 March 2018

Keywords:
Concrete
FRP
Cracking
Bond slip relationship
Defect

ABSTRACT

In practical engineering works, external bonding (EB) of fiber reinforced polymer (FRP) composite materials to concrete cannot be as perfect as in laboratory. Defects in bonding, therefore, cannot be avoided. An experimental program including single shear pull-out tests on EB-FRP concrete joints and three-point bending tests on reinforced concrete (RC) beams with/without EB-FRP was conducted. The effects of existing cracks in concrete with different spacing and widths, as well as FRP location relative to the centerline of specimen, were studied. Most of the specimens in the experimental program were prepared by unskilled personnel to simulate the "imperfect" workmanship. Test results show that EB-FRP joints with more than 10% concrete pulled off on the bond surface could have stable strength and ductility. Transverse offset of FRP from longitudinal center line does not have a significant effect on bond behavior. Existing cracks have a two-sided effect on bond-slip relationship. Cracking of concrete causes degradation of the bond slip relationship when crack width is large. However, cracking with smaller crack width could enhance the bond behavior to a certain degree. Existing cracks have limited influence on the load-deflection curves of FRP strengthened RC beams.

1. Introduction

Strengthening of concrete structures by externally bonded (EB) fiber reinforced polymer (FRP) composite materials has become a widely accepted technology in the last three decades [1–4]. The bond between FRP and concrete is a critical factor that affects the behavior of the strengthened members. In order to quantify and analyze the FRP/concrete bond, a significant number of bond strength models and bond slip relationships have been proposed. These models assume "perfect" bonding between FRP and concrete. Perfect bonding here means that specimens are prepared by skilled personnel and FRP laminates are bonded to well treated and undamaged concrete surface so that debonding failure occurs totally in concrete. The perfect bonding condition reduces the uncertainty of bond interface and helps to find the key parameters affecting the behavior of FRP bonded concrete. However, in practice, conditions of the FRP strengthened concrete members, such as temperature [5–7], moisture [8–11] and existing damage [12–14], may not be as good as those tested in laboratories.

The bond quality of the EB-FRP strengthened concrete members largely depends on the workmanship [15,16]. Poor workmanship may cause lower bond strength and unfavorable failure modes, and make the strengthened members less durable. The favorable debonding failure mode is that failure happens in concrete and a thin layer of concrete is pulled off with the FRP laminate. In practice, especially when the bonding work is done by unskilled personnel, undesired failure modes may occur.

* Corresponding author.
E-mail address: yufei.wu@rmit.edu.au (Y.-F. Wu).
[1] These authors contributed to the work equally and should be regarded as co-first authors.
[2] Formerly, Dept. of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong Special Administrative Region.

https://doi.org/10.1016/j.conbuildmat.2018.03.217

Concrete could have been damaged if a reinforced concrete (RC) structure needs to be strengthened. Significant cracking may have occurred in the tensile side of the member. It is difficult to fill such cracks completely because of the viscosity and gravity of the filling material. On the other hand, the width effect exists if the width of FRP (b_f) is smaller than that of concrete member (b_c) [2,17–21]. The width effect is normally considered by multiplying a coefficient into the calculation of bond strength [2,17–21]. Furthermore, the width effect is normally studied by testing specimens with FRP bonded exactly in the middle of a concrete block. In practice, FRP strips may not be exactly in the middle of a concrete member. This may affect the width effect.

In this study, the specimens for the single shear pull-out tests were prepared by unskilled personnel to replicate the uncertainty and poor workmanship in practice. Therefore, different failure modes occurred randomly in different specimens. Concrete surfaces were cut with grooves perpendicular to the FRP fiber direction before bonding to simulate existing damage or cracking of concrete. In some specimens, the centerline of FRP was away from the centerline of the concrete block to study the width effect of eccentrically bonded FRP strip. Furthermore, three-point bending tests were conducted on RC beams to study the effect of existing cracks on the behavior of EB-FRP strengthened RC beams.

2. Experimental program

In this study, thirty-nine EB-FRP joints were tested by single shear pull-out test (Fig. 1a). Two unstrengthened and four FRP strengthened RC beams were tested by three-point bending test (Fig. 1b). All specimens were tested in the Heavy Structure Testing Laboratory at City University of Hong Kong.

2.1. Design of specimens

The main parameters studied in this work are the quality of the FRP/concrete bond, the offset of the FRP and the degree of existing concrete cracking. The quality of the FRP/concrete bond is random if FRP is applied by unskilled personnel. Bonding FRP by unskilled workers is not unusual in developing countries where engineering practices are not well regulated for this relatively new technique. In order to simulate this situation, most of the EB-FRP joints were prepared by an unskilled undergraduate student with minimum training. To study the effect of the FRP offset on the width coefficient, FRP was applied at two different locations (Fig. 2) on the concrete surface. In some specimens, grooves were cut in the transverse direction to simulate existing concrete cracks (Fig. 3). Three grooving spaces (L_g), 40 mm, 60 mm and 80 mm, were tested. The depth of the grooves (d_g) was 5 mm. All grooves were cut 3 mm in width. The groove width of three specimens was reduced to 1 mm by filling epoxy to study the effect of the groove width.

Specimens for the EB-FRP joint tests are listed in Table 1. In the table, $f_{cu,28}$ and f_{cu} are the concrete cube strengths at the age of 28 days and the date of testing of each specimen, respectively. The specimen ID includes three components divided by "–". The first component indicates the individual concrete block. There are totally 12 concrete blocks marked "A" to "L". More than two faces of each concrete block were used for testing. The second component identifies interfacial conditions. "N" refers to the normal concrete surface condition without grooves; and "G40", "G60" and "G80" indicate the concrete surface cut by a 3 mm-thick concrete saw to make grooves with the space of 40 mm, 60 mm and 80 mm, respectively. "1G40", "1G60" and "1G80" mean the width of the grooves was reduced to 1 mm by epoxy filling. "EC" refers to the specimens with eccentrically placed FRP (Fig. 2b). The last term of specimen ID shows the number of identical specimens with the same testing conditions. On the other hand, six RC beams were designed and tested. Two beams were unstrengthened and one of them was cut to make grooves at 60 mm in center. Four beams, two of which were with grooves at 60 mm in center, were strengthened with 2-ply FRP by skilled personnel. Four FRP U-jackets (1 ply CFRP for each with 10 mm in width and 10 mm in corner radius [22,23]) were used to enhance FRP bond for each FRP strengthened beam. Details of the RC beams are shown in Fig. 4 and Table 2.

2.2. Materials properties and specimen preparation

Twelve 500 (length) × 150 (width) × 150 (depth) mm^3 concrete blocks were prepared for the bond tests of EB-FRP joints. More than two faces of each concrete block were used for testing. According to the capacity of the concrete mixer in the lab, three batches of concrete were cast for twelve concrete blocks (six blocks for each batch) and six RC beam specimens (in one batch). Ten 100 × 100 × 100 mm^3 concrete cubes were prepared for each batch to measure the concrete strength at the age of 28 days and at the dates of EB-FRP joint and beam testing.

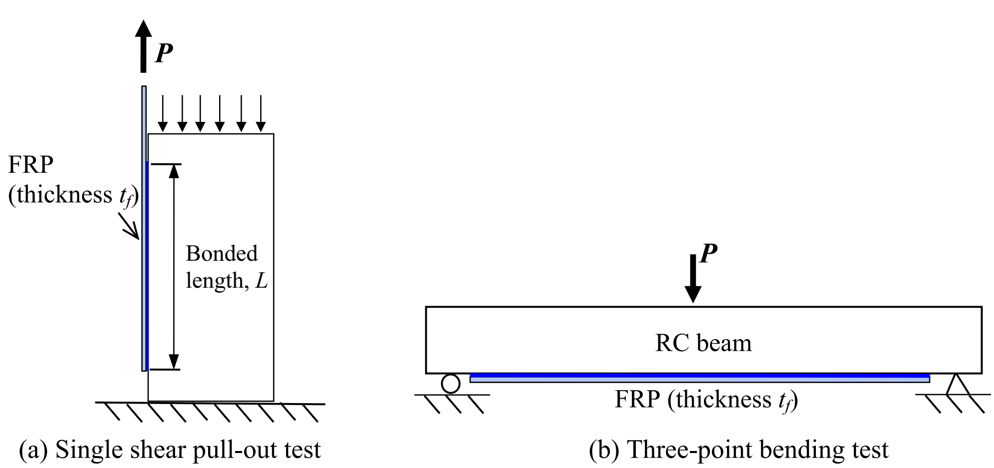

Fig. 1. Schematic diagrams of the test setups.

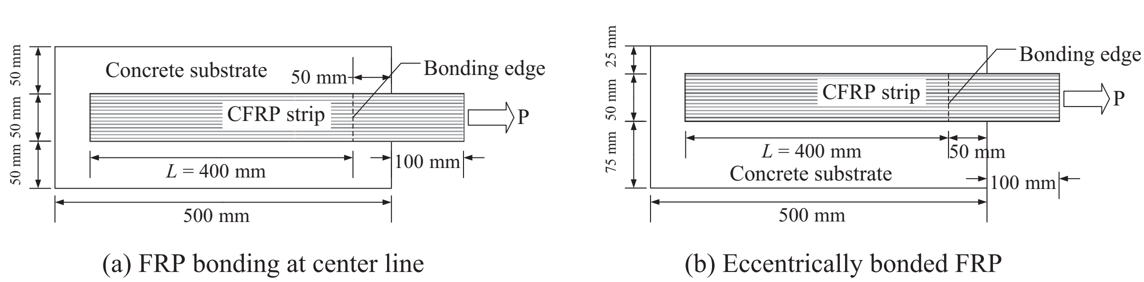

Fig. 2. FRP locations.