Construction and Building Materials 175 (2018) 610–620

Contents lists available at ScienceDirect

Construction and Building Materials

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

Bond characteristics of different FRCM systems

Adel Younis, Usama Ebead *

Department of Civil and Architectural Engineering, College of Engineering, Qatar University, P. O. Box 2713, Doha, Qatar

HIGHLIGHTS

- Bond behavior was compared for three different FRCM systems.
- The effect of bond length and number of fabric plies was investigated.
- Three different modes of failure were observed.
- The PBO-FRCM showed the highest FRCM/concrete bond capacity.
- A simplified analytical model was proposed to predict FRCM/concrete bond.

ARTICLE INFO

Article history:
Received 8 March 2018
Received in revised form 23 April 2018
Accepted 26 April 2018

Keywords:
Fabric-reinforced cementitious matrix (FRCM)
Direct-shear test
Bond capacity
Prediction model
Concrete
Strengthening

ABSTRACT

Fabric-reinforced cementitious matrix (FRCM) composites are usually applied on the concrete surface for the purpose of strengthening reinforced concrete structures. The efficiency of FRCM as a strengthening material is notably affected by the bond between the FRCM and concrete. In view of that, this paper reports on the results of an experimental study to investigate the bond characteristics between FRCM and concrete. Eighteen specimens with different lengths were prepared and subjected to double-shear test. The parameters investigated included (a) fabric type (carbon, polyparaphenylene benzobisoxazole (PBO), and glass); (b) bond length (75, 100, 125, 150, and 200 mm); and (c) number of fabric plies (single or double).

The modes of failure observed in carbon-, PBO-, and glass-FRCM bond tests are fabric/matrix debonding, FRCM mortar/concrete debonding, and fabric rapture, respectively. The PBO- and glass-FRCM bond failure was more brittle than that of the carbon-FRCM counterpart. Among the three systems, the PBO-FRCM showed the highest FRCM/concrete bond. The bond capacity and the mode of failure were prone to the number of fabric plies and indeed bond length. Theoretically-predicted values for the FRCM bond capacity were obtained based on a proposed analytical model, and showed a reasonable agreement with the experimental results.

1. Introduction

Structural damage is normally encountered in reinforced concrete (RC) structures subjected to harsh environments or unexpected extra loads. Consequently, different strengthening techniques for RC structures were proposed such as ferrocement [1] and fiber reinforced polymer (FRP) [2]. Latterly, fabric reinforced cementitious matrix (FRCM) strengthening systems have emerged as a viable solution for structural rehabilitation and repair [3]. FRCM consists of dry fabrics embedded in an inorganic matrix, which is externally applied to the concrete surface with the aim of strengthening RC structures [4]. In all likelihood, the growing interest in the FRCM strengthening technique is attributed to a number of advantages associated with it such as the ability to resist extremely high temperatures [5–7], the possibility to use recycled materials [8], and the use of cement-based mortar as a binding agent which is well-matched with the original concrete substrate [9].

FRCM systems have been successfully applied in previous research on strengthening RC members such as slabs [10], columns [11–13], and beams critical in flexure [14–18] or in shear [19–24]. In these studies, a noticeable improvement was generally reported in the load carrying capacity and the deformational behavior of the FRCM-strengthened members as compared to those of the non-strengthened benchmarks. Therefore, FRCM progressively attracted the interest of structural engineering community, where design guides have been developed for its use in construction and rehabilitation industry [25,26]. Nonetheless, it is well-agreed that

* Corresponding author.
E-mail addresses: adel.younis@qu.edu.qa (A. Younis), uebead@qu.edu.qa (U. Ebead).

https://doi.org/10.1016/j.conbuildmat.2018.04.216

assessing the FRCM/concrete bond behavior is crucial so as to comprehend the complex mechanism in which forces are transferred from the fabrics to the encompassing matrix and eventually to the concrete substrate [27]. Such familiarity with the FRCM/concrete bond behavior is regarded as a way forward towards the advancement of the current design models in order to maximize the potential use of FRCM in RC strengthening. The current ACI design code [25] accounts for the effect of FRCM/concrete bond merely by limiting the tensile strain of the FRCM to 0.012 in flexural/axial strengthening and 0.004 in shear strengthening applications. However, this approach neither efficiently predicts the failure mode of FRCM/concrete bond nor provides a precise estimate of the load carrying capacity, particularly in case of debonding at concrete/matrix interface, which occasionally occurs even before reaching such limits [14,20]. Therefore, there is a perceptible need to conduct further research so that a more effective model can be achieved to provide an accurate prediction of the FRCM/-concrete bond behavior during the design stage.

Several research studies have been conducted in the past few years to grasp, as possible, the behavior of the bond between the externally-bonded FRCM and concrete [28–41]. The majority of these efforts involved the usage of a single fabric type, commonly the PBO [29–31,33–35,38–40] or carbon [32,36,37], while studies incorporating a comparison between different FRCM systems in this regard are scarce [28]. Two test methods were mainly implemented for the FRCM/concrete bond, namely, single-shear [28–32,34,35,38,40] and double-shear [33,34,36,37,39] tests. Most of the previous studies have investigated the bond length parameter [28,30,32–40], while those considering the effect of the number of fabric plies on the FRCM/concrete bond are less common [35,36]. As far as the mode of failure is concerned, it can be observed that the failure most commonly occurred was in the form of fabric slippage within the mortar [28,30–40], which was generally referred to as 'debonding at the fabric/matrix interface', while the failure due to debonding at the concrete/matrix interface [36] or to fabric rupture [37] was rarely reported.

In view of the aforementioned survey, this paper is aimed at investigating the bond between different FRCM systems and concrete. To achieve this, eighteen FRCM-externally bonded concrete prisms were subjected to double-shear test. The contribution of the effort presented in this paper to the current literature can be outlined in the following highlights: (a) providing, arguably for the first time, a simultaneous comparison in the bond-to-concrete characteristics between carbon-,PBO-, and glass-FRCM systems; (b) further investigation into the effect of the bond length and the number of fabric plies on the FRCM/concrete bond; (c) proposing a simplified model that can be used by structural engineers to predict the bond capacity and the failure mode of the FRCM/concrete joint.

2. Materials and methods

2.1. Test specimens

Ready-mix concrete with an average 28-day compressive strength of 30 MPa was used to cast 18 concrete prisms of dimensions 150 × 150 × H mm. The height of the concrete prism, *H*, was varied according to the FRCM bond length. For each specimen, FRCM was applied on the opposite sides to create a double-shear connection as shown in Fig. 1. A uniform bond width of 100 mm was kept for all test specimens since no width effect was reported on the FRCM/concrete bond based on previous studies [34,40]. Attention was given to maintain a minimum clear unbonded length of 50 mm from the prism edge to avoid local failure at the prism end.

Three types of commercially available FRCM fabrics were considered, namely, glass, carbon, and PBO. Each FRCM system was prepared as per the manufacturers' recommendations by embedding the fabrics in their corresponding cement-based mortars. Water was mixed -per 25 kg of mortar- with an amount of 5 L for the glass-FRCM system and 7 L for both carbon- and PBO-FRCM counterparts. Fig. 2 and Table 1 present the geometrical and mechanical properties for each fabric type, along with the 28-day compressive strength of their associated mortars (f_m) all provided by the manufacturers [42–44]. However, it should be emphasized that the fabric tensile strength and elastic modulus provided in Table 1 are theoretical and obtained for a single fiber filament. An experimental evidence [45] showed that the actual tensile strength and elastic modulus of the overall fabric strips are lower than those provided by the manufacturers. When fabric strips are tested, single fiber filaments within each strip are not equally loaded and therefore, rupture occurs progressively starting from the most stressed filaments. This leads to a tensile strength of the fabric strip lower than that of a single fiber filament [45].

To achieve a profound investigation on the FRCM/concrete bond behavior, the uniaxial tensile characterization of the overall FRCM composites is required. This would corroborate the current study with sufficient knowledge about the behavior of FRCM systems as individually subjected to a uniaxial tensile load, allowing for a more justifiable interpretation of the results of FRCM systems while bonded to the concrete surface. As in most composite materials, the distinct mechanical properties of constituents (i.e., fiber and matrix) do not necessarily imply the behavior of the overall FRCM composite. Therefore, tensile characterization of the entire FRCM composite is important so as to understand the interaction between the fibers and matrix [45]. In view of that, tensile characterization test was performed elsewhere by the authors [20,46] for the same FRCM systems used in this study in accordance with AC 434 [26]. Five tensile coupons of dimensions 410 × 50 × 10 mm were prepared for each FRCM system. Each FRCM tensile coupon encompassed a single textile layer, of which the longitudinal direction was parallel to the coupon's length. The tensile characterization test setup is illustrated in Fig. 3. The specimen was gripped by a double clevis-type connection from one end and a single clevis-type connection from the other. Metal plates were attached to the specimen's ends using epoxy with a 150-mm bond length. Tensile load was uniaxially applied at a rate of 0.25 mm/min. A clip-type displacement transducer was placed to continuously measure the extension of the test coupon. FRCM strain was calculated as the measured coupon's extension divided by the 200-mm extensometer length. Also, the axial tensile stress at any load step was determined as the recorded load divided by the FRCM equivalent area. This FRCM equivalent area is actually the average fabric thickness per unit width (t_f) provided in Table 1 for each fabric type, multiplied by the specimen's width (50 mm).

Accordingly, Table 2 lists the tensile characterization test results for the FRCM systems used in this study [20]. The table includes the mean ultimate strain ($\varepsilon_{FRCM,u}$) tensile strength ($\sigma_{FRCM,u}$) cracked tensile modulus of elasticity (E_{FRCM}) and the tensile failure mode for the FRCM systems. To calculate E_{FRCM} a segment was considered between two data points at stress levels of 0.6 $\sigma_{FRCM,u}$ and 0.9 $\sigma_{FRCM,u}$ within the cracked-section phase of the tensile stress-strain diagram. The slope of the line connecting these two points represents the cracked modulus of elasticity [26]. As shown in the table, the glass-FRCM system exhibited a more brittle failure as well as lower tensile properties than those observed for the carbon and PBO counterparts.

Three test parameters were considered: (a) fabric type (glass, carbon, or PBO); (b) bond length (75, 100, 125, 150, or 200 mm), where this range fairly conforms with that usually considered in previous studies [33,37]; and (c) number of fabric plies (single or double). The test specimens were prepared based on the following rationales:

(a) The effect of the number of fabric plies was investigated for the specimens with bond lengths of 75 and 100 mm.
(b) The effect of the bond length was investigated for the specimens with two fabric plies.
(c) Since the glass fibers have relatively lower mechanical properties (Table 1) and thus a premature fabric rupture was foreseeable [20,46] with high bond lengths, the maximum bond length considered for the glass-FRCM system was 100 mm. The glass fibers showed a premature rupture when lower bond lengths (up to 100 mm) were considered. Therefore, the bond length considered for carbon and PBO-FRCM only were increased.

As shown in Table 3, each specimen is labeled using the "X-Y-Z" format. Here, "X" denotes the fabric type (C for Carbon, P for PBO, and G for Glass); "Y" denotes the number of fabric plies (N1 for a single ply and N2 for two plies); and "Z" denotes the FRCM bond length as provided in Column 2 of Table 3.

Fig. 4 illustrates the procedure followed to prepare the double-shear test specimens. Prior to FRCM application, the concrete surface was roughened using water jetting from two opposite sides of the concrete prism (Fig. 4-a) and then water-saturated for 2 h. After that, the FRCM was applied on each surface via the hand lay-up method (Fig. 4-b) by placing 5-mm thick starting and finishing mortar layers with the fabric impregnated in between [26]. In the case of double-fabric-ply specimens, an intermediate mortar layer of 3 mm in thickness was kept between the fabric plies [26]. Thus, the total thickness of the FRCM plate for the single- and double-fabric ply was 10 and 13 mm, respectively. Fig. 4-c shows a typical double-shear test specimen.

2.2. Test setup and instrumentation

Fig. 5 illustrates the setup of the double-shear test. The FRCM system was axially loaded, simultaneously from both sides of the specimen, by stretching the fabric using a hydraulic jack with a pump operated at an approximate rate of 4 mm/