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INTERFACIAL FRACTURE PROPERTIES OF FRCM COMPOSITES BONDED TO A QUASI-BRITTLE MATERIAL

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Abstract: Newly-developed composites that employ cementitious, i.e. inorganic, matrices have gained a momentum in the last decade in an attempt to overcome some drawbacks related to fiber-reinforced polymer (FRP) composites. This broad category of composites is referred to in the literature as fiber-reinforced cementitious matrix (FRCM) composites or textile reinforced mortar (TRM) composites. The premature debonding of FRCM composites remains a critical issue as it is for FRPs and the phenomenon is even more complex than what observed in FRP materials because a hierarchy of interfaces exists as the fibers might debond from the inorganic matrix as well as the entire composite might debond from the substrate. This paper is a preliminary study that aims at investigating the feasibility of employing optical fibers to measure the strain in the fibers of the FRCM system. The research focuses on one FRCM that is comprised of a cement-based mortar and steel fibers. FRCM strips are bonded to concrete to study their bond behavior using a single-lap shear setup. The readings of the optical fibers are compared with the experimental strain derived from the applied load to understand if optical fibers can be used to understand the stress transfer between the steel fibers and the matrix.

1 INTRODUCTION

Fiber-reinforced polymer (FRP) composites are the most common type of composite used world-wide as an externally-bonded reinforcement to strengthen existing reinforced concrete and masonry structures. The weak link in this technology is the premature debonding of the FRP strip from the substrate that typically involves a thin layer of the substrate itself and occurs at a stress level lower than the rupture of the fibers. The study of the bond behavior is usually tackled within the framework of a fracture mechanics mode-II problem [1]. FRP have been used successfully to strengthen reinforced concrete structures and their high strength-to-weight ratio make them an ideal technique to intervene on existing structures. However, FRP exhibit some drawbacks, such as a poor vapor permeability, low glass transition temperatures, and difficult application of the composite onto a wet surface, that made researchers and manufacturers seek alternative solutions. Fiber-reinforced cementitious matrix (FRCM) composites are a suitable alternative to FRPs because they employ an inorganic matrix instead of epoxy. FRCMs can be applied to wet surfaces and the absence of the organic matrix make them resistant to high temperatures. The premature debonding of FRCM composites remains a critical issue as it is for FRPs and the phenomenon is even more complex than what observed in FRP materials because a hierarchy of interfaces exists as the fibers might debond from the inorganic matrix as well as the entire composite might debond from the substrate [2]. For most of the FRCM systems available in the market, debonding occurs at the matrix-fiber interface. The fibers slip with respect to the matrix and in some cases they fracture the matrix causing an *interlaminar failure* that is characterized by the detachment of the external layer of matrix with the fibers while the internal layer of matrix remains attached to the substrate. In other FRCM composites, the slippage of the fibers occurs without fracturing of the matrix and the fibers pull out of the two layers of matrix.

This paper presents a preliminary work to attempt to measure the strain in the fibers of one FRCM system that exhibits interlaminar failure. The external layer of the matrix in FRCMs hinders direct measurements of the strain in the fibers. For FRPs, strain gauges or innovative techniques such as digital image correlation can be used to measure the strain on the surface of the composite, which can be assumed equal to the strain in the fibers as the total thickness of the composite is in the range of 1 to 3 mm. In FRCMs, the thickness of each matrix layers is typically 4 mm and, as the fibers slip with respect to the matrix, measuring the strain on the surface of the matrix layer does not provide information on the slippage of the fibers. The FRCM here studied is comprised of steel fibers embedded in an inorganic cementitious mortar and is also known as steel reinforced grout (SRG) composite. Optical fibers with one fiber Bragg grating (FBG) located at the beginning of the bonded area are glued to one of the steel fibers prior to applying the mortar that is used to bond the fibers to the concrete block. Single-lap shear tests (Figure 1) are conducted to study the bond of the FRCM to concrete and the readings of the FBG (Figure 2) are used to determine the strain in the fibers when debonding occurs. Interlaminar failure is observed for the SRG and strain in the fibers are used to compute the applied load.

2 MATERIALS AND METHODS

2.1 Materials and specimen preparation

Concrete prisms and cubes were cast from the same batch of concrete used for the tests presented in [3]. The mean compressive strength of concrete [4], obtained from three 150 mm × 150 mm × 150 mm cubes cast from the same batches used to construct the concrete prisms was equal to 24.88 MPa (CoV = 0.087). Dimension of concrete prisms used for single-lap direct shear tests were 150 mm (width) × 150 mm (depth) × 600 mm (length). The composite material was comprised of steel fibers embedded in a cementitious matrix. Mechanical properties of fibers (Table 1) and matrix (Table 2) were provided by the manufacturer [5, 6].

Table 1 Mechanical properties of steel fibers

Mechanical properties	Steel fiber
Ultimate strain [%]	1.50
Tensile Strength [MPa]	2850
Elastic Modulus [GPa]	190
Equivalent thickness [mm]	0.126

Table 2 Mechanical properties of matrix mortar

Mechanical properties	Mortar
Compressive strength [MPa]	55
Elastic Modulus [GPa]	25
Tensile Strength (28 days) [MPa]	10

To cast the SRG strip, a first layer of mortar was applied to the bonded area, then a steel fiber sheet was placed on the top of it, and a trowel was used to gently press the fiber sheet against the mortar in order to guarantee a good impregnation of the fibers. Each fiber sheet consisted of 16 chords across the width. Each chord had a cross-sectional area A_{chord}= 0.538 mm^2. A second layer of mortar was applied tofully cover the fiber sheet. To assure the desired thickness of each layer, i.e. 4 mm, cardboard molds were used (Figure 2b). Bonded width b_f and bonded length ℓ were kept constant for all specimens, and were equal to

50 mm and 300 mm, respectively. The fibers were left bare outside the bonded area and extended for 350 mm. For two specimens out of the total 6 specimens herein presented, an optical fiber was attached to one of the middle chords with a bi-component glue. The fiber Bragg grating (FBG) placed at a distance of 30 mm from the laoded end of the bonded area (Figure 2a).

The SRG composite strips were cured under wet cloths for 28 days at T = 20 ± 5°C.

2.2 Methods

Six specimens were tested using the single-lap test set-up represented in Figure 1. Prior to testing, a 7.5 mm-long epoxy tab was constructed for each specimens to facilitate the gripping by the machine jaws during the test.

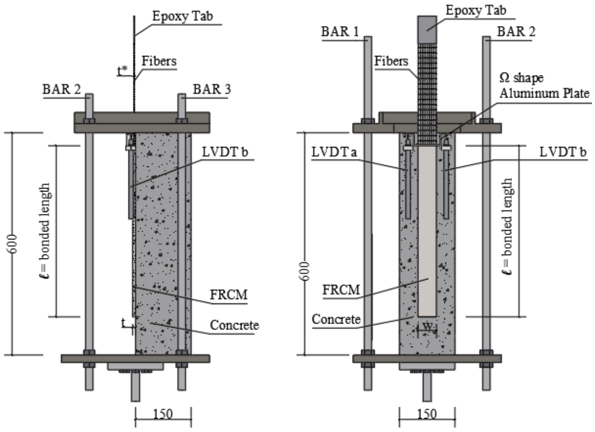


Figure 1: Sketch of the test set-up

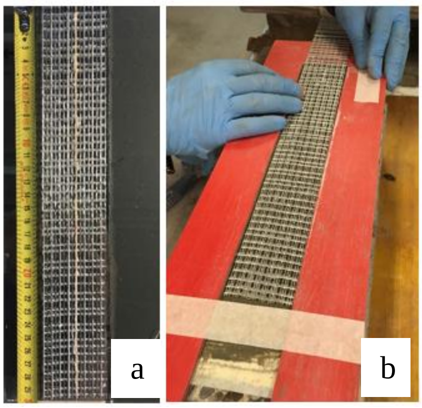


Figure 2: a) Application of FBG on the steel chord, b) Casting of the bond strip

Fibers were pulled while the concrete prism was restrained against movements by two steel plates. The bottom plate was bolted to a cylindrical element gripped by the bottom jaws of the machine. The top C-shaped steel plate was designed to have the centroid as close as possible to the bottom plate, reducing the effect of the eccentricity during the test. The two plates were connected through four steel bars. Single-lap shear tests were conducted under displacement control using a close-loop servo-hydraulic universal testing machine. Two LVDTs were mounted on the concrete prism, and reacted off a Ω-shaped plate, which was glued to the bare steel fibers at the loaded end just outside the bonded area. The average of the two LVDTs measurements is named the global slip *g*. The global slip was increased at a constant rate equal to 0.00084 mm/s. As already mentioned, two specimens out of six, had optical fibers attached to one steel chord. For these specimens, a FBG interrogation system was used, with the end of the optical fibers connected to it, which measure the wavelengths of the FBG during the test.

3 EXPERIMENTAL RESULTS

3.1 Load responses

The load-global slip response of all the specimens is represented in Figure 3. For four specimens out of six, the load responses show an initial linear portion followed by a non-linear ascending branch that either continues up to failure or transitions into a nominally constant final branch up to failure. For the remaining two specimens, which were instrumented with optical fibers, the first part of the load response is not reliable because the LVDTs slipped with respect to the Ω-shaped plate. The remaining portion of the response for these two specimens was always increasing up to failure.

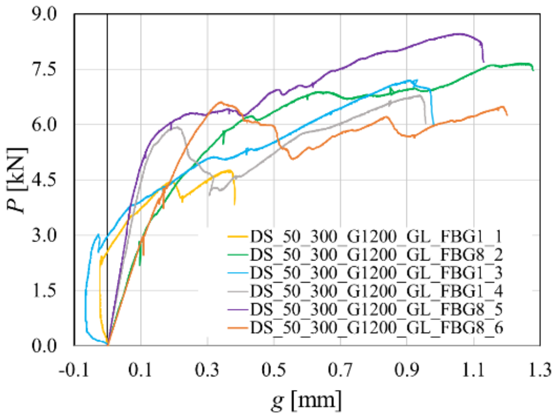
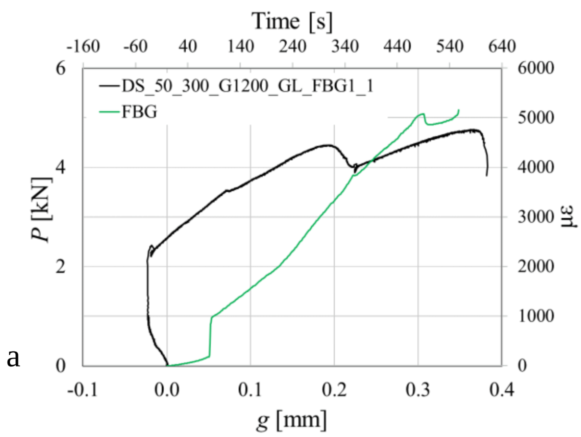


Figure 3: Load-global slip responses

As observed for other FRCMs composites [7], the inorganic matrix is prone to high variability as the FRCM strips are cast. Thus, it is expected that the load response are quite scattered although the failure load (i.e. the maximum load) is typically consistent among the specimens. It should be pointed out that the effective bonded length for SRG and other FRCM composites is typically in the range of 200 mm to 300 mm. The effective bond length is the minimum length required to fully establish the stress transfer at the matrix-fiber interface. As the bonded length of the specimens was 300 mm, it is possible that the scatter of the results and the absence of the nominally constant response could be attributed to the variability of the effective length that in turn is related to the inherent variability of the matrix. Figure 4a and b shows the load versus global slip, and microstrain versus time responses for the two specimens with one FBG.



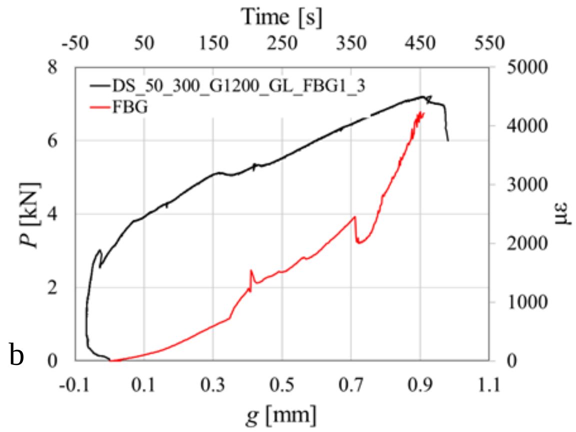


Figure 4: Load versus global slip and FBG microstrain versus time for a) DS_50_300_G1200_GL_FBG1_1 and b) DS_50_300_G1200_GL_FBG1_3

The strain measured by the FBG increases almost linearly with time, which indicates that the as the steel chord debonds the effective bond length has not been established. In fact, if the interlaminar failure was associated with a self-similar propagation of the interfacial crack, the load response would exhibit a nominal constant response and the strain would have reached a constant value at the loaded end.

3.2 Failure modes

For all specimens, interlaminar failure occurred and was characterized by the detachment of the external layer of matrix with the fibers still attached to it, while the internal layer of matrix remained attached to the concrete prism as shown in Figure 5.

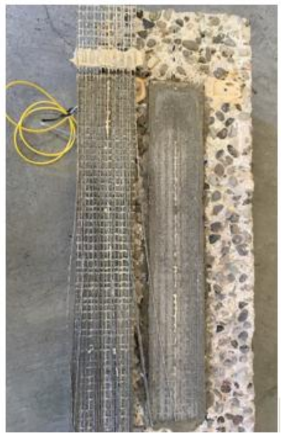


Figure 5: Failure mode of representative specimen

4 DISCUSSION

4.1 Fracture energy

The maximum strain ε_{max} measured by the FBG can be used to determine the applied load P_ε and compare it with the maximum experimental applied load P_{max} measured by the load cell embedded in the testing machine:

$$P_\varepsilon = \varepsilon_{max} A_{chord} n E_f \tag{1}$$

N=16 is the number of the chords across the width and E_f is the elastic modulus of the fibers reported in Table 1. Equation 1 provides P_ε=8.4 kN and P_ε=6.9 kN for specimens DS_50_300_G1200_GL_FBG1_1 and DS_50_300_G1200_GL_FBG1_3, respectively. The experimental maximum load P_{max} for these two specimens was 4.8 kN and 7.2 kN, respectively. The FBG was able to measure correctly the strain in the fibers for one of the specimens and provided an overestimate of the load for the other. It should be observed that the strain in the fibers might not be same for all chords. Additional tests will be carried out with optical fiber glued to more than one chords and multiple readings on one chord to study the stress transfer along the bonded length.

5 CONCLUSIONS

This paper presents a preliminary study to investigate the stress transfer at the matrix-fiber interface of FRCM composites. Single-lap shear tests are performed on six specimens that consist of a FRCM strip bonded to a concrete prism. For two specimens, optical fibers are glue to the fiber sheet to measure the strain at the beginning of the bonded area. The results indicate that optical fibers can be successfully used to measure the strain in the fibers but due to the variability of the matrix mortar and a possible non-uniform distribution of the load among the fibers the optical fiber readings should be carefully interpreted.

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