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Bond characteristics of carbon fabric-reinforced cementitious matrix in double shear tests

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HIGHLIGHTS

- Double shear tests were conducted to study the bond between textiles and concrete.
- Fabric delamination from the matrix governed the failure of mortar-based specimens.
- Fabric rupture at free length governed the failure of epoxy-based specimens.
- Bond stress at failure was 28% less in mortar-based than in epoxy-based specimens.
- For the same bonded area, bond stress at failure decreased when bonded length increased.

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ABSTRACT

This study examined the bond characteristics between fabric-reinforced cementitious matrix (FRCM) systems and concrete. Twenty-seven double-shear specimens were tested under direct shear loading. Two types of cementitious mortars (FRCM specimens) and one type of epoxy (FRE specimens) were used as a matrix. Fabric delamination governed the failure of the FRCM specimens without debonding at the concrete/matrix interface. The FRCM specimens experienced cracking prior to failure whereas the FRE specimens failed suddenly by fabric rupture without cracking. The bond stress of the FRCM specimens at failure was on average 28% lower than that of the FRE specimens. For the same width of the bonded area, the bond stress at failure typically decreased with an increase in the bonded length of the fabric. Similarly, for the same bonded area, the bond stress at failure tended to decrease by increasing the bonded length. This reduction in the bond stress at failure was more pronounced in the FRE specimens than in the FRCM specimens.

1. Introduction and background

Externally bonded fiber-reinforced polymers (FRP) have received wide acceptance as an efficient strengthening technique for reinforced concrete structures (RC) due to the excellent mechanical properties of the FRP materials and their relative ease of application in the field. Despite the effectiveness of FRP in restoring the integrity of RC structures, concerns about their sustainability and durability in harsh environments have been raised [11,1,19,25]. The toxic nature and flammability of epoxies used to bond FRP sheets and plates to the concrete substrate are drawbacks that necessitate the examination of alternative techniques.

Recently, fabric-reinforced cementitious matrix (FRCM) systems have emerged as promising alternatives to the epoxy-based FRP products [28,18]. The FRCM systems consist of open fabric meshes made of carbon, alkali-resistant glass, polymeric fibers (such as Polyparaphenylene benzobisoxazole, PBO), or hybrid fibers embedded into cementitious matrix based on Portland cement [2]. The matrix impregnation in the fabric strands creates a mechanical interlock that can be controlled by varying the spacing and the volume fraction of roving that makes up the fabric. The FRCM surmounts the epoxy-based FRP systems in their resistance to environmental conditions as the embedded fabric in FRCM is

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shielded between the matrix layers [14]. More importantly, the compatibility between the FRCM matrix and the concrete substrate is inherited since both materials have cement as a common base [1].

The characteristics of the FRCM systems subjected to direct tensile forces have been the focus of many studies [22,7,27,6,16,26]. Colombo et al. [5] investigated the effect of the fabric geometry (warp and weft spacing and cross section), the loading rate, and the curing method on the tensile strength and ductility of the FRCM system. It was concluded that the bonded surface of the warp roving strongly influenced the strength of the system, while the weft roving controlled the cracking distance and the overall ductility of the system. Curing conditions also affected the matrix shrinkage and consequently, the strength and mode of failure of the system. The higher strength was achieved when the systems were cured for 28 days at room temperature. The researchers also reported on the loss of strength and ductility while decreasing the displacement rate during testing.

In a more recent study, De Santis and De Felice [10] carried out tensile tests on eight types of FRCM systems. The researchers reported that the tensile strength, the modulus of elasticity, and the failure mode of FRCM systems made of strong fabrics were governed by the properties of the fabric rather than the matrix. However, stiffer matrices led to high stiffness in both the uncracked and cracked stages. The interlocking between the fabric and the matrix ensured better crack distribution in stiff matrices than in systems with flexible matrices having poor bonding between the fabric and the matrix.

When FRCM systems are externally bonded to the concrete substrate, the stress transfer is accomplished through bonding between the fabric and the matrix and between the matrix and the concrete substrate [9]. Many researchers have investigated the bond performance and failure mechanisms of FRCM systems [29,21,23,15,12,24]. Typical bond specimens included beam tests [21,20], single shear tests [13], and double-shear tests [8,9]. Single shear tests involve bonding the fabric to one side of a concrete block and applying a pull or push force, while double-shear tests involve bonding the fabric on both sides of concrete specimens.

Hashemi and Al-Mahaidi [13] investigated the bond strength of carbon FRCM and FRP fabric in single-lap shear tests using cement-based and epoxy-based adhesives, respectively. The ultimate load achieved by the FRCM system was around 80% of that of the FRP system. All specimens failed by debonding after initiation of cracks at the fabric/matrix interface rather than at the concrete/matrix interface. D'ambrisi et al. [8,9] carried out double shear tests to examine the bond of FRCM made of PBO fabric encapsulated in a cement-based matrix with different bond lengths. It was reported that failure of specimens was governed by the debonding at the fabric/matrix interface after a considerable fiber slippage. Ombres [20] confirmed similar mode of failure in RC beams strengthened with FRCM systems externally bonded to the soffit of the beams. Despite the premature debonding of the FRCM systems, the researchers reported an increase of 30% in the ultimate capacity of the strengthened beams. D'Ambrisi et al. [9] and Ombres [20] reported that the bond strength increased with an increase in the length of the bonded fabric, up to a certain length referred to as the effective length, beyond which insignificant increase in the bond strength occurred. The effective length was identified as 250–300 mm in the case of a single FRCM layer. Choi et al. [4] and Li et al. [17] previously reported similar findings for FRP systems.

In the present study, the bond performance of a newly developed FRCM strengthening system has been investigated. The study consists a preliminary investigation of the FRCM system prior to being used in strengthening large-scale concrete elements. Bond tests were carried out on double-shear specimens designed with different bond lengths, widths, and mortar types. Specimens with fabric bonded to concrete using epoxy were also tested for the purpose of comparison and will be referred to as the FRE specimens (Fabric Reinforced Epoxy). The study reports on the bond performance of both systems with a focus on the failure mechanism, the strain distribution, and the maximum bond stress of the tested system.

2. Experimental program

The test specimens consisted of a pair of concrete cubes of 150 mm side placed apart at a clear distance of 370 mm as shown in Fig. 1. Every two fabric meshes made of carbon fibers were cut to predetermined lengths and widths and attached to the parallel sides of the cubes to constitute double-shear specimens with various bonded areas. The specimens were divided into three groups according to the type of the bonding matrix. The test program is given in Table 1. A combination of three bonded lengths and three bonded widths of 75 mm, 100 mm, and 150 mm were used. Based on the combination of the investigated parameters, a total of 27 specimens were tested. The specimens were labeled in the order of the matrix type (M1, M2, and E for epoxy), width of the bonded area, *W*, and length of the bonded area, *L*. For instance, specimen M2–100–150 refers to a specimen with cementitious mortar M2 and a fabric bonded area having a width of 100 mm and a length of 150 mm.

2.1. Test specimen fabrication

Fig. 2 depicts the procedure used in preparing the double-shear specimens. Prior to attaching the fabric to the concrete substrate, the concrete surface was manually roughened with an electrical saw as shown in Fig. 2a. This step was necessary to increase the mechanical interlock between the concrete substrate and the cementitious matrix as recommended by Bissonnette et al. [3]. For the FRCM specimens, the concrete cubes were dampened into tap water for two hours prior to mortar application. A dual shaft electrical mixer was used to prepare the mortars and to ensure the uniformity of the mix. The mixing operation lasted for 3–5 min. The hand lay-up method was used to attach the FRCM/FRE to the concrete substrate. The length and width of the bonded area were marked on the concrete cube surface. A mortar layer of 4 mm thickness was manually applied on the concrete surface using a metal trowel before laying up the fabric pre-cut in lengths and widths as shown in Fig. 2b. Hand pressure was applied to ensure full impregnation of the fabric in the mortar (Fig. 2c). A second layer of mortar was laid on top of the fabric and a bearing weight was applied on the sandwiched fabric for a few minutes (Fig. 2d). The FRCM specimens were cured for 24 h using damp burlap covered with plastic sheets to prevent the evaporation of the curing water. Similar procedure was adopted to bond the fabric to the other side of the cube. The hardened specimens were air-cured for 28 days at a temperature of 20 ± 2 °C and a relative humidity of 95%. The total thickness of the FRCM layer was on average 10 mm.

At the other end of the specimen, referred to as the anchored end, the fabric was bonded to the concrete using epoxy with a bonded length equal to the side dimension of the cube (150 mm). The FRCM/FRE was further wrapped transversally with glass-fiber reinforced polymer (GFRP) sheets to create a confined anchored end as shown in Fig. 2e. This technique was implemented in all FRCM and FRE specimens to ensure that the failure occurred at the other specimen's end, referred to as the loaded end. Similar procedure was adopted to bond the fabric in FRE specimens except that these specimens were not damped before epoxy application. The total thickness of the FRE layer was approximately 5 mm. Prior to testing, the edges of the bonded areas were trimmed to the predetermined dimensions using an electrical cutter as shown in Fig. 2f.

2.2. Material properties

The cubes were cast using concrete with an average compressive cubic strength of 55 MPa. Carbon fabric commercially known as Sigratex® 600 was used in preparing the specimens. The fabric was a bidirectional mesh made of carbon fibers joined together to form rovings in two orthogonal directions as shown in Fig. 3. Rovings in the strong direction were spaced at 10 mm and held together with stitches whereas rovings in the other direction were spaced at 18 mm (Fig. 3). The physical and mechanical properties of the fabric as obtained from the manufacturer are given in Table 2.

Table 3 lists the mechanical properties of the commercial matrices and epoxy used in preparing the specimens (data was obtained from the manufacturer). The cementitious matrix, M1, was a non-shrink metallic aggregate mortar produced by BASF® and commercially known as Embeco® 885. As per the manufacturer datasheet, the mortar has a compressive strength that ranges between 62 MPa and 76 MPa after 28 days of curing, depending on the amount of water used during mixing. The tensile strength and modulus of elasticity of M1 were 3.4 MPa and 25.4 GPa, respectively. The other cementitious mortar used in preparing the FRCM2 specimens was also produced by BASF® and commercially known as MasterEmaco® S466. The mortar has a compressive strength, tensile strength, and modulus of elasticity of 65 MPa, 3.5 MPa, and 40.7 GPa, respectively (data was obtained from the