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Flexural behavior of RC beams strengthened with steel-FRCM composite

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ABSTRACT

This paper presents the results of an experimental investigation of the flexural response of reinforced concrete (RC) beams strengthened using externally bonded steel fiber reinforced cementitious matrix (steel-FRCM) composite. Steel-FRCM composite strips were bonded to the tension face of four RC beams, which were tested in four-point bending. Parameters varied were the presence/absence of the external (coating) layer of the matrix, presence/absence of U-wrap anchorages, and loading rate. Results are compared with those from single-lap direct-shear tests conducted on the same composite. The direct-shear tests showed that debonding of steel-FRCM joints is characterized by fiber slippage and fracture of the matrix layer at the internal matrix layer-fiber interface. In the beam tests, the strengthening system increased the yield load by 15–21% relative to the unstrengthened beam. The ratio of the load at which debonding occurred to the load at yielding ranged from 1.11 to 1.19 for each strengthened beam. The load rates employed and the presence of the external matrix layer did not appear to significantly affect the failure mode or the load and midspan displacement at debonding. The presence of the U-wraps helped restrain the peel-off of the composite observed in strengthened beams without the U-wrap, however, they did not restrain the fiber slippage at the ends of the composite, which inhibited composite action. Average values of the maximum fiber strain at composite debonding determined using strain profiles from strain gages, an approximate method, and moment-curvature analysis were 0.54%, 0.73%, and 0.83%, respectively.

1. Introduction

Fiber reinforced composites have been widely used to strengthen reinforced concrete (RC) members since they have a high strength-to-weight ratio, require relatively limited time to cure, and have mechanical properties that can be engineered to meet the desired structural performance. Fiber-reinforced polymer (FRP) composites, which are comprised of continuous fibers (usually carbon, glass, or aramid) and a thermosetting (organic) resin, are currently the most common type of composite system used for structural strengthening applications. Another type of composite that was recently developed is referred to as fiber reinforced cementitious matrix (FRCM) composite, which contains continuous fibers with a cementitious (inorganic) matrix. The use of inorganic matrix was proposed to address some of the inherent disadvantages associated with the use of organic resin in FRP composites, such as lack of moisture vapor transmission [1].

A new class of composites that is being explored includes steel fiber sheets with either an inorganic matrix or an organic matrix described above. The use of steel fibers was proposed as a lower-cost alternative to other fiber types used in FRCM or FRP composites such as carbon, aramid, glass, or polyparaphenylene benzobisoxazole (PBO). The resulting composites have been referred to in the recent literature by different names, but are herein referred to as steel-FRCM and steel-FRP, respectively. Published literature on steel-FRCM and/or steel-FRP composites dates from 2004 [2,3]. Different authors have studied the use of steel-FRCM and/or steel-FRP for flexural strengthening of RC beams [2–11] and RC slabs [12]. These studies have shown that steel-FRCM and steel-FRP composites are effective in increasing the flexural strength of the member, although debonding of the composite tends to limit the effectiveness except in cases of relatively low fiber density where fiber rupture has been observed [12]. Experimental evidence in the literature reports that debonding of steel-FRCM composite can occur within the composite [12] instead of within a thin matrix-rich layer of the concrete substrate as is typically the case with FRP composites [1]. Interestingly, the limited number of studies that have investigated mechanical anchorage

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of steel-FRCM composites have shown that anchorage did not significantly improve the performance of the strengthening system [3,7,13]. Therefore, for design purposes it is important to understand the debonding process and potential factors that may help mitigate this mode of failure.

This paper presents the results of an experimental investigation conducted to study the flexural response of RC beams strengthened using externally bonded steel-FRCM composite. Steel-FRCM composite strips were bonded to the tension face of four RC beams, which were tested in four-point bending. Parameters varied were the presence/absence of the external (coating) layer of matrix, presence/absence of U-wrap anchorages, and loading rate. The strengthened beam load responses are presented and compared, and the contribution of the composite to the flexural strength is examined. Debonding of the steel-FRCM composite strips is also discussed. Results are compared with those from single-lap direct-shear tests conducted on the same composite.

2. Experimental campaign

2.1. Material properties

The concrete beams and prisms were constructed with normal weight concrete with Portland cement (Type 1) without admixtures. The concrete water-cement ratio was 0.44, and the maximum aggregate size was 25 mm. The beams and prisms were cast from the same batch of concrete. The average compressive strength [14] and splitting tensile strength [15] determined at 28 days from six (3 + 3) 100 mm × 200 mm concrete cylinders were 31.5 MPa (CoV = 0.023) and 3.1 MPa (CoV = 0.046), respectively, and values are summarized in Table 1.

Reinforcing bars in the beam specimens were No. 3 (dia. = 9.5 mm, area = 71 mm^2) and No. 5 (dia. = 15.9 mm, area = 199 mm^2) ASTM A615 Grade 420 deformed steel bars [16]. All reinforcing bars of the same size were from the same heat. Tension tests were conducted on three samples of each bar size to determine the mechanical properties. The measured yield strength f_y and ultimate strength f_u of the No. 3 bars were 454 MPa (CoV = 0.015) and 716 MPa (CoV = 0.003), respectively. For the No. 5 bars, the measured values of f_y and f_u were 469 MPa (CoV = 0.011) and 740 MPa (CoV = 0.011), respectively.

The composite material consisted of steel fibers and a cementitious matrix. The steel fibers were produced in the form of a sheet that consisted of unidirectional twisted steel wire cords. Each cord included five filaments, three of which were straight, and the remaining two were wound around the other three at a high twist angle. The weight of fibers was 2000 g/m^2, the cord density was 0.472 cords/mm, and the cross-sectional area of each cord was 0.538 mm^2. The tensile strength, ultimate strain, and elastic modulus of the fibers reported by the manufacturer [17] were 3000 MPa, 1.5%, and 205 GPa, respectively. The matrix employed in this study, which was designed to attain high bond with the steel fibers, was an inorganic, thixotropic mineral mortar. The compressive strength and tensile strength of the matrix given by the manufacturer [17] are summarized in Table 1.

Table 1
Material properties of matrix and concrete.

	f_c (MPa)	f_t (MPa)	f_r (MPa)
Matrix	>50[a]	–	>9[a]
Concrete	31.5 (CoV = 0.023)	3.1 (CoV = 0.046)	–

Note: f_c = average compressive strength at 28 days; f_t = average splitting tensile strength at 28 days; f_r = average flexural strength at 28 days.
[a] Value reported by the manufacturer [17].

2.2. Direct-shear tests

Seven specimens presented in this paper were tested using the single-lap (direct) shear test set-up. The composite strips were externally bonded to concrete blocks (prisms). The push-pull configuration was adopted where the concrete prism was pulled while the fibers were restrained [18] (Fig. 1). The concrete prisms had a cross section b = 125 mm width × h = 125 mm depth and length L = 375 mm. Only the three faces of the prisms cast directly against the formwork were used to bond the composite strips; the face of each prism that was troweled smooth after casting was disregarded.

The concrete blocks were sandblasted prior to applying the first (internal) layer of matrix. The target roughness profile was 5 mm in accordance with the composite manufacturer's recommendation [17]. The roughness depth was measured at several discrete locations to ensure the requirements were met. Per the manufacturer's instructions [17], the concrete surface was thoroughly wetted before applying the composite. The matrix was applied only to the bonded area to embed the fibers and bond the composite to the concrete substrate (Fig. 1a). The composite was bonded starting at a distance d = 38 mm from the prism edge at the loaded end (Fig. 1a). The matrix was applied from the edge of the external longitudinal cord on one side of the fiber strip to the edge of the external longitudinal cord on the other side of the fiber strip. Fibers were bare outside the bonded area. A 4 mm thick layer of matrix (internal layer) was applied to the concrete using molds to control the composite width and thickness. A single layer of steel fibers was applied onto the internal matrix layer, and the fibers were pressed onto the matrix to maintain their alignment and assure proper impregnation by the matrix. The fiber strip was positioned such that it extended slightly beyond the end of the matrix at the free end of the composite strip as shown in Fig. 2. A second (external) 4 mm thick layer of matrix was applied over the steel fibers. The thickness of the composite strip t = 8 mm was in accordance with the manufacturer's recommendations [17]. Several specimens were cast with the external matrix layer omitted. For these specimens, after applying the fiber strip to the internal matrix layer a thin (i.e., less than 1 mm) layer of matrix was applied over the strip only to cover the fibers, and then the excess material was scraped off at the level of the fiber strip backing to minimize the amount of material on top of the fibers.

The bonded width b_1 of each composite strip was 50 mm (with n = 24 longitudinal fiber cords), and the bonded length ℓ was 330 mm. The bonded length was based on results of preliminary direct-shear tests of the same composite that indicated that the bonded length selected was longer than the effective bond length (i.e., the length over which the stress transfer zone is fully established) because a plateau was reached in the load response, as has been observed in the case of FRP-concrete joints [19,20]. Table 2 lists the direct-shear test specimens. Specimens are named following the notation DS_K_X_Y_(L_)Z, where DS indicates that the specimen was tested in single-lap direct-shear, K is used to identify the specific composite in this paper, X = bonded length (ℓ) in mm, Y = bonded width (b_1) in mm, L (if present) indicates the external layer of matrix was omitted, and Z = specimen number.

Steel plates were attached to the end of the steel fiber strip with a thermosetting epoxy resin to grip the bare steel cords during testing (Fig. 1). The plates were also bolted together with four through-bolts at the plate corners to assure a uniform pressure on the gripped fibers and to prevent slippage within the plates. The concrete prism was restrained against movement by a steel frame bolted to the testing machine base. The steel frame was made with flat bars of width w_s = 48 mm and thickness t_s = 9 mm. A 9 mm thick steel plate was inserted between the steel frame and