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Torsional behavior of RC beams strengthened with PBO-FRCM composite – An experimental study

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ABSTRACT

The use of fiber reinforced cementitious matrix (FRCM) composites has been studied for flexural and shear strengthening of reinforced concrete (RC) members, but currently there are no studies on its use for torsional strengthening. This paper presents the results of an experimental study in which solid rectangular RC beams were externally strengthened with PBO-FRCM composite material in different wrapping configurations to investigate the torsional behavior in terms of strength, rotational ductility, and failure mode. Increases in the cracking torque, torsional strength, and corresponding values of twist were achieved by beams strengthened with a 4-sided wrapping configuration relative to the control (unstrengthened) beam. On the other hand, the 3-sided wrapping configuration was found to be largely ineffective in improving the torsional performance due to excessive fiber slippage. The contribution of the strengthening system to the torsional strength was reasonably predicted (±20%) by the strain measured in the composite fibers. Provisions used to estimate the torsional strength of RC beams with fully-wrapped, externally-bonded fiber reinforced polymer (FRP) composites were found to be applicable to beams strengthened with PBO-FRCM composite.

1. Introduction

In recent decades, repair and strengthening of reinforced concrete (RC) buildings and bridges have become increasingly common. Deficiencies in RC members may exist for several reasons, including changes in use of the structure, design and constructions errors, and degradation due to environmental conditions. RC members are commonly strengthened in flexure, shear, and/or confinement depending on the member loading conditions and type of enhancement needed. In some cases, RC members are subjected to significant torsional moments, and the torsional strength needs to be enhanced. Accordingly, methods and design provisions for strengthening RC members in torsion are needed.

Torsional behavior of RC beams strengthened with externally bonded fiber reinforced polymer (FRP) composites has been investigated since the early 2000s. Ghobarah et al. [1] investigated the behavior of RC beams with a rectangular cross-section strengthened with carbon FRP (CFRP) or glass FRP (GFRP) composite, and a simple design approach was also introduced. Panchacharam and Belarbi [2] studied the behavior of RC beams with a square cross-section strengthened with GFRP composite and proposed an analytical design equation. Salom et al. [3] tested RC beams with an L-shaped cross-section strengthened by CFRP composite to study the effectiveness of this technique on increasing the torsional strength of spandrel beams. Hii and Al-Mahaidi [4] used photogrammetry measurements to prove that externally bonded CFRP composite improves the torsional strength of RC beams by limiting crack width development and increasing aggregate interlock. Hii and Al-Mahaidi [5] investigated RC beams with solid and box sections that were strengthened in torsion with CFRP composite and compared the results with those obtained from the nonlinear finite element program DIANA. Chalioris [6] tested rectangular and T-shaped RC beams without internal transverse reinforcement and strengthened with CFRP composite in order to evaluate the contribution of the composite material to the torsional strength. Ameli et al. [7] investigated the behavior of rectangular RC beams strengthened with CFRP or GFRP composite and compared the results with those obtained from the nonlinear finite element program ANSYS. Deifalla et al. [8] tested rectangular, T-shaped, and L-shaped beams strengthened with CFRP composite to study the effectiveness of the strengthening technique on the torsional strength of beams with various cross-sections.

FRP composites have several attributes such as high strength and stiffness, light weight, resistance to corrosion, and flexibility

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of use that make it a suitable structural strengthening material. On the other hand, disadvantages of FRP composites include difficulty to install on wet surfaces or in low temperatures, low fire resistance, low glass transition temperature, and lack of vapor permeability, which are associated with the use of organic matrix. Recently a new type of composite called fiber reinforced cementitious matrix (FRCM) composite has been developed to overcome or reduce some of the shortcomings associated with FRP composites. In contrast to organic matrix, inorganic cementitious matrix can be applied in low temperatures and on wet surfaces, allows vapor permeability, and has better heat resistance. Different types of fibers have been used in FRCM composites systems such as carbon, glass, aramid, basalt, steel, and polyparaphenylene benzobisoxazole (PBO). The use of FRCM composites has been studied for flexural [9–11] and shear strengthening [12–15] of RC members and confinement of axially/eccentrically loaded elements [16,17], but currently there are no studies in the technical literature on its use for torsional strengthening.

The tensile force in an externally bonded composite strengthening system is transferred to the substrate through the fiber-matrix and matrix-concrete interfaces through shear. Recent studies on the fundamental bond behavior of PBO FRCM-concrete joints [18–26] indicate that the debonding failure mode is quite different from that of FRP-concrete joints. For FRP-concrete joints, failure occurs in a quasi-brittle manner within a thin mortar-rich layer of the concrete substrate, whereas with PBO FRCM-concrete joints failure occurs at the fiber-matrix interface with significant fiber slippage relative to the matrix. This difference in failure mode warrants investigation of the fundamental torsional behavior of RC members strengthened with PBO-FRCM composites to examine the potential differences with respect to RC members strengthened with FRP composites.

The aim of this study is to investigate the torsional behavior of RC beams externally strengthened with PBO-FRCM composite in terms of torsional strength, rotational ductility, and failure mode. In this paper, the experimental results of four solid rectangular RC beams externally strengthened with PBO-FRCM composite material in different wrapping configurations are presented and compared with those of an unstrengthened control beam. The torque-twist load response and strains measured in the internal and external reinforcement are evaluated, and the applicability of design provisions for torsional strengthening using FRP composite is examined.

2. Experimental program

2.1. Experimental design

A total of five RC beams were included in the experimental program. The beams were designed based on the ACI 318 code [27] provisions. All beams had a rectangular cross-section with the same nominal dimensions of b = 8 in. (203.2 mm) wide × h = 12 in. (304.8 mm) tall × 84 in. (2133.6 mm) long and the same internal reinforcement. Dimensions and details of the RC beams are shown in Fig. 1. The beams had a test region in which the composite was applied of 60 in. (1524.0 mm) long that was reinforced with minimum torsional reinforcement in transverse direction in accordance with the ACI 318 code [27]. The volumetric reinforcement ratios of the longitudinal and transverse reinforcement were $\rho_{sl} = A_{sl}/A_c = 1.29\%$ and $\rho_{st} = \frac{A_{st}}{A_c}\frac{p_t}{s} = 0.92\%$, respectively, where A_{sl} is the total area of longitudinal bars, A_c is the gross concrete area ($A_c = bh$), A_{st} is area of one leg of a stirrup, p_t is perimeter of a stirrup, and s is the center to center spacing of stirrups. The end regions of the beam (12 in. [304.8 mm] long each end) were more heavily reinforced to prevent failure in the clamp regions.

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 60 (Grade 420) deformed steel bars [28]. 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. Table 1 shows the properties of the longitudinal and transverse reinforcement, which were determined based on the average of three coupon samples for each size tested according to ASTM A370 [29].

All beams were constructed at the same time with normal weight concrete without admixtures. The coarse aggregate type was crushed dolomite with 1 in. (25.4 mm) maximum aggregate size, and the fine aggregate was river sand. The compressive strength, splitting tensile strength, and modulus of elasticity of concrete were determined based on the average of three 4 in. (101.6 mm) diameter × 8 in. (203.2 mm) long cylinders tested at 28 days in accordance with ASTM C39 [30], ASTM C496 [31], and ASTM C469 [32], respectively. The concrete properties are listed in Table 1. The beams and cylinders were moist cured for four days under wet burlap then kept together in the laboratory under the same atmospheric conditions until testing.

2.2. FRCM composite material

The FRCM composite was comprised of PBO fibers with an inorganic matrix [33]. The PBO fibers were in the form of an unbalanced fiber net as shown in Fig. 2. The net is formed with rovings spaced at 0.4 in. (10 mm) and 0.8 in. (20 mm) on center in the longitudinal and transversal directions, and the free spacing between rovings is 0.2 in. (5 mm) and 0.6 in. (15 mm), respectively. The nominal thicknesses (which is obtained by assuming the fibers are distributed evenly over the entire width of the composite) in the two fiber directions are 0.0018 in. (0.046 mm) and 0.0005 in. (0.012 mm), respectively. The total weight of PBO fibers in the mesh is 0.00013 lb/in.^{2} (88 g/m^2), with 0.00010 lb/in.^{2} (70.4 g/m^2) in the longitudinal direction and 0.000025 lb/in.^{2} (17.6 g/m^2) in the transversal direction.

The FRCM material properties are listed in Table 2. Tensile strength, ultimate strain, and elastic modulus of the fibers determined from tensile tests of the bare fibers were 440 ksi (3015 MPa), 0.0145, and 29,900 ksi (206 GPa), respectively [21], [23]. Mortar compressive and splitting tensile strength properties were determined from of a representative sample of matrix used to cast the FRCM composite using the average of three 2 in. (50.8 mm) diameter × 4 in. (101.6 mm) long cylinders tested at 28 days in accordance with ASTM C39 [30] and ASTM C496 [31], respectively.

2.3. FRCM composite installation and wrapping schemes

The corners of the RC beams were chamfered with a radius of 0.75 in. (19 mm) in order to reduce stress concentrations at the corners, which have been reported to lead to fiber rupture and failure of beams strengthened in torsion with FRP composites [34]. The PBO-FRCM composite material was installed on the beams after the beams were 28 days old. The strengthening process is summarized as follows:

- The surface of the beam was sandblasted to achieve a target profile of 0.1 in. (2 mm).
- The surface of the beam was cleaned of dust and dirt.
- The surface of the beam was saturated with water before applying the first layer of matrix.
- In order to control the location and total thickness of the composite, foam strips of 0.2 in. (5 mm) thickness were mounted to the beam as shown in Fig. 3.