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A study of the effect of fiber orientation on the torsional behavior of RC beams strengthened with PBO-FRCM composite

Meyyada Y. Alabdulhady, Lesley H. Sneed *

Department of Civil, Architectural and Environmental Engineering, Missouri University of Science and Technology, Rolla, MO, USA

HIGHLIGHTS

- RC beams strengthened with PBO-FRCM composite were tested under torsional moment.
- The effect of composite fiber orientation on the torsional response was studied.
- Internal and external reinforcement strains were presented.
- Longitudinal elongation of the strengthened beams was examined.

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ABSTRACT

Repair and rehabilitation of reinforced concrete (RC) structures with different types of external reinforcement has been investigated widely. Fiber reinforced cementitious matrix (FRCM) is a new type of composite system that contains continuous fibers embedded in inorganic matrix. This system has been proven to be effective for strengthening RC members under flexure, shear, and axial loadings. However, studies on the use of FRCM composite for torsional strengthening are very limited. This study investigated experimentally the torsional behavior of solid rectangular RC beams strengthened with externally bonded PBO-FRCM composite in different wrapping configurations. The study focused on the effect of fiber orientation as well as other parameters that influence the torsional strength, torsional moment-twist per unit length response, and mode of failure including fiber continuity and number of composite layers. The strains in the internal and external reinforcement and the longitudinal elongation of the strengthened beams were examined, and a comparison with other types of fiber reinforced composite was also discussed. The 90° fiber orientation (perpendicular to the beam longitudinal axis) was more effective in increasing the torsional strength than the 45° fiber orientation since premature debonding of the fibers occurred at the ends of the 45° strips, which contrasted the potential benefits from optimizing the fiber orientation and led to the underutilization of the composite. The 90° fiber orientation was also more effective than the 0° fiber orientation.

1. Introduction

Fiber reinforced cementitious matrix (FRCM) composite material has been used recently in repair and strengthening of reinforced concrete (RC) members in buildings and bridges [1–3]. This type of composite, which is comprised of continuous fibers embedded in an inorganic matrix, has favorable features over fiber reinforced composites with organic resin, such as fiber reinforced polymer (FRP) composites, due to its higher temperature resistance and reversibility, ability to be installed onto wet surfaces or in low temperatures, and good vapor permeability due to compatibility with concrete and masonry substrates. Therefore, FRCM composites appear to be highly promising, especially for application to historical constructions [4]. Different types of fibers have been used in FRCM composite systems including carbon, glass, basalt, steel, and polyparaphenylene benzobisoxazole (PBO). The use of FRCM composites has been studied for flexural [5–8] and shear strengthening [9–15] of RC members and confinement of axially and eccentrically loaded elements [16–18]. On the other hand, very few studies are available in the technical literature on its use for torsional strengthening [19].

Torsional behavior of RC beams strengthened with externally bonded FRP composites has been investigated since the early 2000s [20–24]. Some authors have studied the effect of the FRP

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* Corresponding author.
E-mail addresses: mymxw7@mst.edu (M.Y. Alabdulhady), sneedlh@mst.edu (L.H. Sneed).

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Table 1
Concrete mixture proportions.

Material	Quantity
Water, lb/yd^3 (kg/m^3)	270 (160)
Cement type I/II, lb/yd^3 (kg/m^3)	517 (307)
Coarse aggregate, lb/yd^3 (kg/m^3)	1700 (1009)
Fine aggregate, lb/yd^3 (kg/m^3)	1450 (860)

fiber orientation on the torsional strength. Panchacharam and Belarbi [25] studied the behavior of RC beams with a square cross-section strengthened with glass FRP (GFRP) composite in different fiber orientations (0° and 90° relative to the longitudinal axis of the beam) and wrapping configurations. The results showed that fibers with 0° orientation increase the torsional moment associated with concrete cracking, although they were ineffective for increasing the torsional strength. Ghobarah et al. [26] investigated the behavior of RC beams with a rectangular cross-section strengthened with GFRP or carbon FRP (CFRP) composite with different fiber orientations (45° and 90° relative to the longitudinal axis of the beam) and wrapping schemes (continuous along the length or discrete strips with different widths and spacings). Findings showed that spiral wrap with a 45° fiber orientation is more efficient in terms of increasing the torsional strength than fibers a 90° orientation. Deifalla et al. [27] tested rectangular, T-shaped, and L-shaped beams strengthened with CFRP composite with fibers oriented in the 45° and 90° directions to study the effectiveness of the strengthening technique on increasing the torsional strength of beams with various cross-sections. The results showed that the torsional strength and rotational capacity of L-shaped RC beams with anchored, inclined U-jackets were increased by 12% relative to those with anchored, vertical U-jackets. Furthermore, anchored 45° U-jacket strips were found to be more effective than unanchored 45° U-jacket strips, while anchored 45° U-jacket strips were comparable to 45° fully wrapped strips.

This study investigates the torsional behavior of RC beams strengthened with PBO-FRCM composite. The experimental results of 10 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 aim of the present study is to investigate the effect of fiber orientation and wrapping configuration on the torsional strength, behavior, and failure mode of FRCM strengthened RC beams.

2. Experimental program

2.1. Material properties

The RC beams in this study were constructed with normal weight concrete. The coarse aggregate was a crushed dolomitic limestone with 1 in. (25.4 mm) maximum aggregate. The fine aggregate was natural river sand. The beams were constructed in two batches, named Batch 1 and Batch 2, with the same concrete mixture proportions summarized in Table 1. The compressive strength, splitting tensile strength, and modulus of elasticity of each batch of concrete were determined from the average of three 4 in. (101.6 mm) diameter × 8 in. (203.2 mm) long cylinders cast at the same time and cured in the same manner as the concrete beams and tested at 28 days in accordance with ASTM C39 [28], ASTM C496 [29], and ASTM C469 [30], respectively. The measured concrete properties are summarized in Table 2. The concrete beams and cylinders were covered with wet burlap for four days then kept together in the laboratory under the same atmospheric conditions until testing.

Reinforcing bars were ASTM A615 Grade 60 (Grade 420) deformed steel bars of sizes No. 3 (dia. = 9.5 mm, area = 71 mm^2) and No. 5 (dia. = 15.9 mm, area = 199 mm^2) [31]. Reinforcing bars of the same size were from the same heat of material. Three coupon samples of each bar size were tested according to ASTM A370 [32] to obtain the material properties, and the results are provided in Table 2.

The FRCM composite used in this study was comprised of a bidirectional PBO fiber net embedded in an inorganic matrix [33]. The

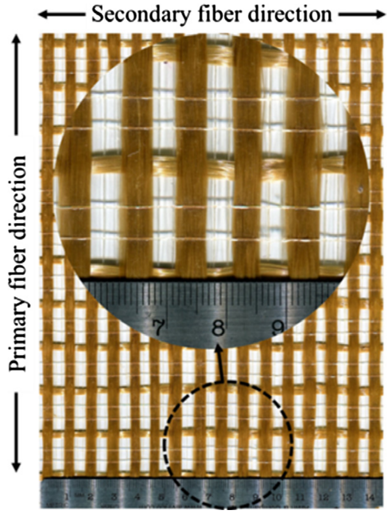

Fig. 1. PBO unbalanced fiber net.

Table 3
Measured PBO-FRCM composite material properties.

PBO fibers		
Ultimate tensile strength, ksi (MPa)	440 (3015)	
Modulus of elasticity, ksi (GPa)	29,900 (206)	
Ultimate strain, in./in. (mm/mm)	0.0145 (0.0145)	
Mortar		
	Batch 1	Batch 2
Compressive strength, psi (MPa)	3600 (24.8)	2200 (15.2)
Splitting tensile strength, psi (MPa)	670 (4.6)	520 (3.6)

Table 2
Measured concrete and steel reinforcement material properties.

Material	Concrete		Steel reinforcing bars	
	Batch 1	Batch 2	No. 3	No. 5
Compressive strength, psi (MPa)	5700 (39.3)	5000 (34.5)	–	–
Splitting tensile strength, psi (MPa)	460 (3.2)	400 (2.8)	–	–
Modulus of elasticity ksi (GPa)	4150 (28.6)	4150 (28.6)	29,000 (200)	28,000 (193)
Yield strength, ksi (MPa)	–	–	65.8 (454)	68.0 (469)
Ultimate strength, ksi (MPa)	–	–	104 (717)	107 (738)