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Effect of fiber orientation on the structural behavior of FRP wrapped concrete cylinders

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Abstract

In this study, 27 concrete cylinders with a diameter of 152.4 and a height of 304.8 mm were prepared. Among them, 18 cylinders were wrapped using two layers of fiber reinforced polymer (FRP) with six fiber orientations; six cylinders were wrapped using four layers of FRP with fibers in axial or hoop direction only; the remaining three cylinders were used as control. The FRP used was E-glass fiber reinforced ultraviolet (UV) curing vinyl ester. Fifteen coupon specimens were prepared to experimentally determine the tensile strength of the FRP with fibers oriented at 0°, 45°, and 90° from the loading direction. Co-axial compression tests were conducted on the wrapped cylinders and control cylinders. The test results were compared with existing confinement models. It is found that the strength, ductility, and failure mode of FRP wrapped concrete cylinders depend on the fiber orientation and wall thickness. Fibers oriented at a certain angle in between the hoop direction and axial direction may result in strength lower than fibers along hoop or axial direction. A larger database is desired in order to refine the existing design-oriented confinement models.

Keywords: FRP; Concrete; Composite cylinders; Compression; Structural behavior; Confinement model; Fiber orientation

1. Introduction

Concrete columns are fundamental structural components in civil structures. In recent years, repair, retrofitting, and strengthening of damaged concrete columns using fiber reinforced polymer (FRP) composite wrapping or jacketing are increasingly becoming important in civil infrastructures due to the high strength/stiffness to weight ratio, corrosion resistance, and ease of installation of FRPs [1–4]. Additionally, the structural capacity of FRP can be tailored and maximized by aligning fibers along the optimal orientation. For an ideal column, i.e., a column subjected to a co-axial compressive load, it is well established that fibers should be aligned along the hoop direction to confine the dilation of the concrete core. In practice, however, almost all the columns are subjected to an eccentric axial load, which can be resolved into a co-axial compressive load and a bending moment. Because of this, almost all the columns should be treated as beam-columns. For beam-column repairing/retrofitting/strengthening, hoop direction is the optimal fiber orientation only for co-axial compressive load; for a bending moment, fibers in the axial direction are more favorable. Therefore, fiber orientation is an important variable in the structural design of FRP wrapped concrete columns.

A number of studies have been conducted using fibers aligned along a direction other than the hoop direction. Mirmiran and Shahawy [5] used fibers oriented at ±15° from the hoop direction in their FRP tube encased concrete columns. In the study by Rochette and Labossiere [6], fibers oriented at [±15°/0°] were used to wrap square concrete cylinders. Pessiki et al. [7] employed [0°/±45°]

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fibers to warp both small-scale and large-scale square and circular concrete columns. Fibers in both hoop and axial directions were used by Dias da Silva and Santos [8] to repair concrete columns. Fam and Rizkalla [9] and Fam et al. [10] studied filament wound FRP tube-encased concrete columns. In their tubes, fibers in various directions and stacking sequences were utilized to provide both hoop confinement and axial reinforcement. Li et al. [11] used ±54° filament wound tubes in their FRP tube-encased concrete cylinders. Although angle fibers other than the hoop direction have been used in FRP repaired or FRP tube-encased concrete columns, less attention has been paid to systematically investigate the effect of fiber orientation on the structural behavior of FRP wrapped concrete columns.

Recently, Li et al. [12] conducted a 3-D finite element analysis of FRP wrapped concrete columns. They found that the structural behavior of FRP wrapped concrete columns depends on the fiber orientation and interfacial bonding strength. They also found that the effect of fiber orientation is coupled with the effect of interfacial bonding strength between the FRP shell and the concrete core. When the interfacial bonding strength is very weak, fibers in hoop direction are optimal; when the interfacial bonding strength is very high, fibers in axial direction play an important role.

The objective of this study was to experimentally investigate the effect of fiber orientation on the structural behavior of thin-walled FRP wrapped concrete columns. The test results were also compared with the existing confinement models to validate their effectiveness in predicting the compressive strength of FRP wrapped concrete cylinders.

2. Experiments

2.1. Raw materials and specimen preparations

Type I Portland cement, gravel, natural sand, water, and air entraining agent DARAVAIR 1000 were used to prepare the concrete. Concrete with a 28-day compressive strength of 40 MPa was designed as a control mix. The mix design followed ACI Standard 211.1 (“Standard” 1991). The mix ratio by weight for control concrete was cement:water:gravel:sand:admixture = 1:0.51:3.49:1.88:0.001. The concrete was cast, compacted, finished, demolded, and cured for 28 days in a standard curing room. The test results of the slump, air-content, and 28-day compressive strength were 15.2 cm, 8.1%, and 45.60 MPa, respectively. A unidirectional E-glass 7715 fabric, which has an areal weight of 200 g/m^2 and a thickness of 0.2 mm/ply, was used as fiber reinforcement. The resin used was an ultraviolet (UV) curing vinyl ester. For a thin film of pure resin, the curing time is 20 s under direct sunshine. The physical/mechanical properties of the E-glass fiber and UV curing vinyl ester resin provided by the manufacturers are given in Table 1.

Table 1
Physical/mechanical properties of the raw materials

Materials	Viscosity at 25 °C (cps)	Tensile strength (MPa)	Modulus of elasticity (GPa)
UV curing resin	450	85	3.2
E-glass fabric	–	3000	70.0

2.2. Wrapping and curing of FRP jacket

The wet lay-up technique was used to wrap the FRP layers. This technique started with applying a layer of resin (about 200 g/m^2) to the surface of the concrete cylinder. Next, a unidirectional E-glass 7715 fabric of 304 mm long (axial) by 504 mm wide (hoop) was wrapped to fully cover the resin. A 25.4 mm extra length was used in the hoop direction to provide an overlap. It is noted that no roller was used. The viscosity of the resin was proper to wet through the fabric without excessive running. Only a brush was used to help wrap the fabric. On the top of the fabric, another layer of resin was applied. This completed one FRP repair layer. The procedure was repeated to apply the subsequent layers. Because the unidirectional E-glass fabric was used in this study, it was easy to form various winding angles. In this study, six fiber orientations were used to investigate the effect of fiber orientation on the structural behavior of FRP wrapped concrete cylinders, as demonstrated in Table 2. From Table 2, samples were divided into eight groups. Each group contained three specimens. Groups 1–6 contained two-layer FRP wraps, while groups 7 and 8 contained four-layer FRP wraps. This was to investigate the effect of FRP thickness on the structural performance of the jacketed concrete cylinders.

The 24 wrapped samples were cured using UV-A fluorescent bulbs. Six 160-W UV-A fluorescent bulbs were installed onto three UV lamp high-output fixtures. The three fixtures were attached to a frame and positioned vertically at each point of an equilateral triangle. The side-length was about 0.36 m. The radiance was estimated at 80 mW/cm^2. Fig. 1 shows two cylinders being cured. While the vinyl ester resin can be cured in 20 s, 20 min were used to cure two layers of FRPs and 40 min were used to cure four layers of FRPs. The reason for this is that the existence of fibers blocked the penetration of UV light, therefore longer curing times were required to maximize the number of free radical chains and achieve a higher degree of cure. The test results from this study show that the curing time is adequate to fully cure the FRP wraps. Similar curing times were used previously [13].