SHEAR STRENGTH OF CIRCULAR CONCRETE BEAMS REINFORCED WITH GFRP BARS

Ahmed H. Ali  
Ph.D. Candidate, Université de Sherbrooke, Canada

Hamdy M. Mohamed  
Postdoctoral Fellow, Université de Sherbrooke, Canada

Brahim Benmokrane  
Professor, Université de Sherbrooke, Canada  
NSERC Research Chair in FRP Reinforcement for Concrete Infrastructure  
Tier-I Canada Research Chair in Advanced Composite Materials for Civil Structures

ABSTRACT

This paper presents the results of an investigation of the shear strength and behavior of three circular concrete beams reinforced with glass-FRP (GFRP) bars and spirals. The beams, which measured 3,000 mm in length by 500 mm in diameter, were tested under four-point bending. The test parameters included the GFRP-spiral-reinforcement ratio (different spiral spacings [150 and 200 mm] and spiral diameters [13 and 15 mm]). As designed, the beams failed in shear due to GFRP-spiral rupture. The test results indicated that the higher the GFRP spiral reinforcement ratio, the higher the enhancement of the shear strength due to the confinement, which controls shear cracks and improves aggregate interlocking.

Keywords: Circular concrete beams, Shear, FRP bars, and spirals.

1. INTRODUCTION

Reinforced concrete (RC) members with circular cross section are often used in civil engineering structures, for instance as laterally loaded bridge piers and piles because they are easy to build, have a pleasing appearance, and provide equal strength characteristics in all directions under wind and seismic loads. These members have limited service lives and high maintenance costs when used in harsh environments due to corrosion of steel reinforcement. In North America, it has been estimated that the repair and replacement of piling systems costs billions of dollars annually (Benmokrane et al. 2015). In the last decade, the use of fiber-reinforced polymer (FRP) as an alternative reinforcing material in RC structures has emerged as an innovative solution to the corrosion problem (ACI 440.1R-15). FRP bars offer many advantages over conventional steel bars, including a density of one-quarter to one-fifth that of steel, greater tensile strength than steel, and no corrosion even in harsh chemical environments (Rizkalla et al. 2003; Benmokrane et al. 2007; Drouin et al. 2011; Mohamed and Benmokrane 2012; Beaulieu-Michaud et al. 2013; Benmokrane and Mohamed 2014).

In recent years, extensive research programs have been conducted to investigate the shear behavior of concrete members reinforced with GFRP bars and stirrups with rectangular cross sections (Razaqpur and Spadea 2015, Alam and Hussein 2010, Ahmed et al. 2010, Fico et al. 2008, El-Sayed and Benmokrane 2008, El-Sayed et al. 2006, Shehata et al. 2000, Alkhrdaji et al. 2001, Guadagnini et al. 2006, Tottori and Wakui 1993). As a result, several guidelines and code standards have been published, including design equations for assessing total shear resistance ($V_r$): ACI 440-1R-15, CSA S806-12, CSA S6-14, and JSCE (1997). They all follow the traditional ($V_{cf} + V_{sf}$) philosophy, but significantly differ in the manner in which they estimate the contributions of concrete ($V_{cf}$) and diagonal tension reinforcement ($V_{sf}$) to the total shear resistance ($V_r$). In contrast, studies on the shear behavior of circular concrete members that can be reinforced with GFRP bars and spirals have not yet been introduced.
Moreover, none of the aforementioned FRP design standards have incorporated specific formulae for circular RC members. In general, FRP shear design provisions can be applied to circular members by using an equivalent rectangular cross section. The accuracy of such an approach should, however, be assessed, because circular GFRP spirals may not contribute to shear strength in the same way as rectangular bent stirrups. That being said, limited research has been carried out during the last decade on the shear behavior of circular steel-reinforced-concrete members (Jensen et al. 2010, Khalifa and Collins 1981, Clark and Bijandi 1993, Priestley et al. 1994, Collins et al. 2008, Felthem 2004, Merta and Kolbitsch 2006, Turmo et al. 2009).

The experimental study reported on herein is part of an ongoing comprehensive research program at the University of Sherbrooke, in which full-scale circular concrete beams are tested under shear loading to investigate different variables and design parameters. The variables include the type of reinforcement (glass, carbon FRP, and steel), ratio of longitudinal reinforcement, ratio of shear reinforcement (spiral diameter and spacing), and shear-span-to-depth ratio. This paper describes the results of full-scale concrete beam internally reinforced with longitudinal GFRP bars spirals to study the effect of GFRP-spiral-reinforcement ratio (spiral spacing and diameter).

### 2. EXPERIMENTAL WORK

#### 2.1 Material

GFRP bars and spirals were used to reinforce three circular concrete beams in the longitudinal and transverse directions, respectively. The GFRP longitudinal bars were pultruded, while the transverse reinforcement was fabricated with a bending process (BP Automation, Inc. 2014). The reinforcement was made of continuous glass fibers impregnated in a thermosetting vinyl-ester resin, additives, and fillers. The GFRP reinforcement had a sand-coated surface to enhance bond performance between the bars and the surrounding concrete. GFRP bars (#6; 20 mm designated diameter) were used as longitudinal reinforcement. GFRP spirals (#4; 12.7 mm and #5; 15.8 mm) were used as shear reinforcement. The tensile properties of longitudinal GFRP bars were determined by performing the test method in ASTM D7205 (ASTM 2011) and CSA/CSA S6-12, Annex C, as reported in Table 1. In addition, the bent tensile strength ($f_{fu, bent}$) of the #4 and #5 bars was calculated according to ACI 440.1R-15 and CSA/CSA S6-14 design equations for the bend strength of bent FRP bars. Table 1 presents the measured and calculated bent tensile strength of the spirals. All beam specimens were cast on the same day with normal-weight, ready-mixed concrete with an average compressive strength of 49.5 MPa. The actual compressive strength was determined based on the average test results of ten concrete cylinders (150 x 300 mm) tested on the same day as the start of testing of the beam specimens.

<table>
<thead>
<tr>
<th>Bar Size</th>
<th>Diameter (mm)</th>
<th>Area (mm²)</th>
<th>Straight Portion</th>
<th>Bent Portion $f_{fu,bent}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$f_{fu,*}$ (MPa)</td>
<td>$E_v$ (GPa)</td>
</tr>
<tr>
<td># 4</td>
<td>13</td>
<td>127</td>
<td>1019</td>
<td>47.0</td>
</tr>
<tr>
<td># 5</td>
<td>15</td>
<td>198</td>
<td>1003</td>
<td>49.5</td>
</tr>
<tr>
<td># 6</td>
<td>20</td>
<td>285</td>
<td>1103</td>
<td>62.8</td>
</tr>
</tbody>
</table>

* $f_{fu,*}$ is the guaranteed tensile strength of the straight portion; $f_{fu,bent}$ is the ultimate tensile bend strength.

#### 2.2 Specimens Details

A total of three full-scale circular RC beams totally reinforced with GFRP bars and spirals were constructed and tested under monotonically increasing shear load. The test matrix was arranged to assess the influence of the GFRP-spiral-reinforcement ratio (spiral spacing and size) on the shear strength and behavior of circular concrete beams. Each beam was simply supported over a 2,400 mm span and had a total length of 3,000 mm, an equivalent effective...
flexural depth \((d)\) of 377 mm, an equivalent effective shear depth \((d_e=0.9d)\) of 340 mm, and a diameter of 500 mm. The equivalent effective depths were estimated based on the shear provisions (Clause 5.8.2.9) in the 2012 edition of the AASHTO LRFD Bridge Design Specifications. Table 2 provides the test matrix and reinforcement details of the beam specimens. Each specimen was identified a code consisting of two letters (B and S) and two numbers. The letters B and S refer to beam specimen and spiral, respectively. The first number refers to the spiral diameter. The second number represents the spiral spacing. As shown in Table 2, the effect of the GFRP-spiral-reinforcement ratio was investigated using #4 spirals at a spacing of 150 and 200 mm and using #5 spirals at a spacing of 150 mm. These beams were reinforced longitudinally with 10 #6 (20 mm) GFRP bars. Figure 1 shows the dimensions, various configurations, and reinforcement details of the test specimens.

GFRP cages were assembled for the various beam configurations. The clear concrete cover was kept constant at 40 mm. The circular beams were prepared for casting in very stiff Sonotubes. Wooden plugs were used to seal the ends. The Sonotubes were placed in an inclined position and the concrete was cast from the top. External and internal vibration was used.

<table>
<thead>
<tr>
<th>Beam ID</th>
<th>Shear Reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(f'_c) (MPa)</td>
</tr>
<tr>
<td>BS4-200</td>
<td>49.5</td>
</tr>
<tr>
<td>BS4-150</td>
<td>49.5</td>
</tr>
<tr>
<td>BS5-150</td>
<td>49.5</td>
</tr>
</tbody>
</table>

Figure 1: Dimensions and reinforcement details of the tested circular specimens

2.3 Instrumentation and Test Setup

Strains in the longitudinal reinforcing bars were measured using electrical-resistance strain gauges with gauge lengths of 6 mm. In addition, three strain gauges with a gauge length of 6 mm were mounted on the concrete top surface at three different levels \((D, D/8, \text{and } D/4)\) at the mid-span to measure compressive strains. Furthermore, three strain gauges were placed on each shear span to measure concrete diagonal strains at the mid-shear span. These strain gauges were installed at mid-depth \((D/2)\) of the cross section. Beam deflection was measured with three LVDTs placed at the mid-span and at mid-shear span. The crack width was monitored by visual inspection during the test until the first crack appeared which was initially measured with a handheld microscope. Then, seven high-accuracy LVDTs (±0.001 mm) were installed at the crack location (three at each shear span and one at the mid-span).
The test setup was designed and fabricated in the University of Sherbrooke’s structural laboratory. Steel saddles were designed in order to accommodate the circular geometry at the loading and support points. Rubber and aluminum sheets were used as an intermediate layer between the saddles and the test specimen to ensure a smooth, uniform distribution of the applied load at the loading point. Moreover, prior to specimen testing, a thin layer of high-strength cement grout was applied to the supports for leveling and to compensate for any geometrical imperfections in the saddles and specimens. The beams were loaded in four-point bending, as shown in Figure 2, using a servo-controlled, hydraulic 1000 kN MTS actuator attached to a spreader beam. The load was applied at a displacement-controlled rate of 0.6 mm/min. An automatic data-acquisition system monitored by a computer was used to record the readings of the LVDTs, load cells, and strain gauges.

3. EXPERIMENTAL RESULTS

3.1 Mode of Failure

In all of the specimens, flexural cracks first appeared between the two concentrated loads, where the flexural stress is highest and shear stress is zero. As loading increased, additional vertical cracks appeared on the beam surface, followed by the formation of diagonal cracks. The formation of diagonal cracks did not immediately lead to final collapse. Instead, these cracks continued to develop with each increment of the applied load, and the ultimate loads sustained by the beam were, in general, considerably higher than the load at which the diagonal tension cracks first formed. The initial flexural cracks at the pure bending moment zone remained narrow throughout the tests. Failure occurred after the formation of two or more significant diagonal shear cracks near the mid shear span that propagated through the compressive zone, leading to diagonal tension failure combined with rupture of GFRP spirals. Removing the concrete cover revealed the rupture of the GFRP spirals, with at least two of the GFRP spirals crossing a diagonal crack. The concrete cover under the layer of longitudinal reinforcement at the bottom of the beam was lost. The main difference in the final crack patterns of the three beams was the number and spacing of diagonal cracks that developed in the shear span: the higher the failure load, the greater the number of induced shear cracks. Figure 3 shows the typical failure mode of the beam specimens.
4. EFFECT OF SPIRAL-REINFORCEMENT RATIO ON LOAD–DEFLECTION BEHAVIOR

Figure 4 shows the shear behavior of three circular RC beams (BS4-200, BS4-150, and BS5-150) that were reinforced with different spiral-reinforcement ratios (0.26, 0.35, and 0.53, respectively). In general, the behavior of these beams can be divided into two stages. In the first—the “prior-to-flexural-cracking stage”—all the beams behaved similarly and approximately linearly. Beam stiffness at this stage was almost identical regardless of spiral-reinforcement ratio, representing the behavior of the uncracked beam with the gross moment of inertia of the
concrete cross section. After cracking, the beams behaved nearly linearly with reduced stiffness up to failure. This is attributed to the linear-elastic characteristics of the GFRP reinforcement. Beam stiffness in this stage was insignificantly dependent on the spiral-reinforcement ratio as well as the stiffness of the flexural reinforcement, which was constant for the three beams. Figure 4 indicate that the ultimate shear strength increased as the spiral-reinforcement ratio increased. Increasing the shear reinforcement from 0.26 to 0.35 and 0.53 increased the shear capacity of the tested beams by 9% and 30.7%, respectively. Moreover, BS4-150 and BS5-150 evidenced enhanced stiffness when the major diagonal shear crack compared to BS4-200, which had a lower shear-reinforcement ratio. This can be attributed to the higher spiral-reinforcement ratio that tends to control crack opening and propagation. Increasing the shear-reinforcement ratio in BS4-150 and BS5-150 helped redistribute internal stresses, forming a truss action in which the reinforcement acts as tensile links and the concrete acts as compression diagonals.

![Figure 4: Load–deflection response at mid-span for the effect of the spiral-reinforcement ratio](image)

5. MID-SPAN FLEXURAL STRAINS

Figure 5 shows the measured applied load on the beams versus the strain relationships for the GFRP longitudinal bars. As shown in this figure, the strain was minimal until the concrete section cracked. The specimens exhibited similar strain behaviors up to this stage. After cracking, the figure indicated that, there was no significant different between the tested beams. The maximum strains in the GFRP bars for beams were approximately 8,130, 7,340, and 9,670 microstrains for BS4-200, BS4-150, and BS5-150, respectively. In general, this strain at ultimate shows that shear failure was not triggered by the GFRP bars rupturing. No signs of anchorage problems were observed in any of the beams.
6. CONCLUSIONS

The experimental results concerning the shear behavior of full-scale circular beams reinforced with GFRP bars and spirals are presented and discussed. The main variable was the GFRP-spiral-reinforcement ratio (different spiral spacings [150, 200 mm] and spiral diameters [13 and 15 mm]). The beam specimens were tested under shear loading. The main findings of this investigation can be summarized as follows:

1. In all tested beams, the mode of failure was GFRP-spiral rupture. However, the main difference in the final crack patterns of the three beams was the number and spacing of diagonal cracks that developed in the shear span: the higher the failure load, the greater the number of induced shear cracks.

2. The presence of GFRP spirals in the beam specimens enhanced the concrete contribution after the formation of the first diagonal crack.

3. The test results indicate that the higher the GFRP spiral reinforcement ratio, the higher the enhancement of the shear strength due to the confinement, which controls shear cracks and improves aggregate interlocking. The shear strengths increased linearly with the increase in $\rho_s E_s$ for each spiral size. Increasing the GFRP spiral-reinforcement ratio from 0.26 to 0.53 increased the shear strength of the tested specimens by 30.7%.

ACKNOWLEDGMENTS

The authors would like to express their special thanks and gratitude to the Natural Science and Engineering Research Council of Canada (NSERC), the NSERC/Industry Research Chair in Innovative FRP Reinforcement for Concrete Structures, and BP Automation Inc. (Edmonton, AB) for their financial support, and for the technical help provided by the staff of the structural lab of the Department of Civil Engineering at the University of Sherbrooke.
REFERENCES


Mohamed, H. M., and Benmokrane, B. 2012. Recent field applications of FRP composite reinforcing bars in civil engineering infrastructures. Proc., Int. Conf. ACUN6–Composites and Nanocomposites in Civil, Offshore and Mining Infrastructure, 14 – 16 November 2012, Monash University, Melbourne, Australia, 6 p.


