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Shear resistance of RC circular members with FRP discrete hoops versus spirals

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ABSTRACT

Nowadays, *design guidelines and codes* contain valuable shear provisions for the design of concrete bridge members reinforced with fiber-reinforced-polymer (FRP) bars. Limited researches seem to have assessed the shear strength of circular concrete members reinforced with FRP reinforcement. Therefore, these standards do not provide specific formulae for circular RC members designed with FRP bars, hoops and spirals under shear loads. This paper reports experimental data about the shear strength of circular concrete specimens reinforced with FRP bars, discrete hoops and continuous spirals. Full-scale circular concrete specimens with a total length of 3,000 mm and 508 mm in diameter were constructed and tested up to failure. The test parameters included the type of reinforcement (glass FRP and carbon FRP versus steel) and configuration of the shear reinforcement (discrete hoops versus continuous spirals). The investigation revealed that the specimen reinforced with FRP hoops exhibited high load-carrying capacity comparable to the counterpart reinforced with FRP spirals. The experimental shear strengths of the FRP-reinforced concrete specimens were compared to theoretical predictions provided by current codes, design guidelines. The results of this study can be used as a fundamental step toward code provisions for using GFRP or CFRP spirals and hoops as internal shear reinforcement.

1. Introduction

Discrete hoops or continuous spirals are usually used as shear reinforcements in the transverse direction for circular reinforced-concrete (RC) members. These members are often used in piers and piles because they are easy to build and provide equal strength in all directions under shear resulted from braking and accelerating forces, wind and seismic loads [1,2]. Hoop and spiral reinforcement is well known for its better confinement effectiveness and restraint for longitudinal bar buckling than rectilinear hoop or tie transverse reinforcement. Moreover, hoop and spiral reinforcement can effectively resist concrete expansion and longitudinal bar buckling by developing tangential tension along hoop or spiral perimeter through the height of the members, whereas rectangular stirrups or tie reinforcements are only effective at corners or bends [3–5].

In North America, the majority of department-of-transportation manuals prefer discrete hoop reinforcement over continuous spiral reinforcement due to ease of construction. The discrete nature of hoops provides an advantage in seismic-critical elements, since the failure of one hoop does not lead to premature plastic-hinge failure. Any break at a single location in spiral reinforcement may render a considerable length of the spiral ineffective and lead to plastic-hinge failure. Spiral reinforcement, on the other hand, increases confinement and rebar-cage stability relative to discrete hoops, which is critical for seismic design, which depends on this extra ductility. Continuous spiral reinforcement requires fewer anchorages than discrete hoops, which minimizes the probability of pullout failure [5–8]. Moreover, due to the difference in the configuration between spirals and hoops—particularly the continuity and the inclination of spirals with respect to the longitudinal axes—the shear strength contribution of spirals is less than that of hoops to resist shear force. This is attributed to the fact that the shear plane will usually cut a spiral link twice in each revolution, but one side of the spiral will be less beneficial than the other side at resisting shear because of its inclination to the shear plane [9,10].

In North America in particular, the corrosion of steel reinforcement in concrete bridges subjected to deicing salts and/or aggressive environments constitutes the major cause of structure deterioration, leading to costly repairs and rehabilitation as well as a significant

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Fig. 1. GFRP cages fabrication and pile soft-eye driving process.

reduction in service life [11,12]. Estimates indicate that the United States spends billions of dollars annually to repair and replace bridge substructures such as pier columns ($2 billion), and marine piling systems ($1 billion) [13,14]. In addition, the United States Federal Highway Administration (FHWA) estimates that eliminating the nation's bridge deficient backlog by 2028 would require an investment of $20.5 billion annually because of corroded steel and steel reinforcement. Problems related to expansive corrosion could be resolved by protecting the steel reinforcing bars from corrosion-causing agents or by using noncorrosive materials such as fiber-reinforced-polymer (FRP) bars [15,16]. Nowadays, the use of FRP bars in soft-eyes, which are openings of retaining walls to be penetrated by tunnel boring machines (TBMs), is gaining popularity in the field of tunnel excavation. Fig. 1 shows the construction application of FRP soft-eyes at TTC Subway North Tunnels, Toronto, ON, Canada. Glass FRP (GFRP) bars were used to build cages up to 19.0 m long (diameters from 600 to 920 mm). These soft-eyes are subjected to a significant lateral loads resulted from the earth and water pressure, and hence a considerable shear force is applied to the cross-section [7,17].

Recent years have seen valuable research work on shear behavior of FRP RC structures [6,7,18–22]. Accordingly, *AASHTO LRFD Bridge Design Specifications* [23] and the *Canadian Highway Bridge Design Code* [24] provide flexural and shear provisions for the design of concrete bridge members reinforced with FRP bars and stirrups. Due to a lack of research, these standards do not provide specific formulae for circular RC members designed with FRP bars, hoops, and spirals under shear loads [6]. The bend strength of bent FRP bars (rectangular stirrups) is a main factor in designing FRP RC members under shear and torsion [22,25] Fabrication process of FRP spirals and hoops is similar to that the bent FRP stirrups. The difference is only in the configuration of the mandrel used (cylindrical or square shape) to fabricate the spirals or stirrups, respectively. Nowadays, it is well defined that the FRP stirrups have lower tensile strength than regular straight FRP bars. This is due to the significant reduction in tensile strength at the bend portions as a result of the unidirectional characteristics of the FRP-material portions [26–28]. The reduced strength of the bent portion of FRP stirrups is attributed to the comparative kinking of the innermost fibers compared to those along the outermost radius, resulting from the curvature and the intrinsic weakness of FRP fibers perpendicular to their long axis [29]. The bend capacity of FRP bars is influenced by the bending process, bend radius (r_b), bar diameter (d_b), and type of reinforcing fibers [26]. The bend strength of FRP stirrups can be obtained experimentally according to ACI Test Method [26]. In addition, the bend tensile strength ($f_{fu,bent}$) can be estimated according to ACI [26] and CSA [24] design equations for FRP bent bars. Yet, a standard test method for FRP hoops or spirals has not been introduced. Moreover, very limited experimental research on the shear behavior of circular concrete members reinforced with FRP hoops or spirals has been reported yet. A combined experimental and analytical investigation on shear performance of circular concrete members reinforced with FRP hoops or spirals has been conducted at the University of Sherbrooke. The program has been designed to quantify the shear strength contribution of different types of FRP hoops and spirals through testing full-scale circular RC specimens under shear load.

2. Objectives

The current design provisions in the design guidelines and codes have no provisions regarding shear strength to bridge concrete members with circular sections reinforced internally with FRP reinforcement. Moreover, there are very limited experimental research results on the shear strength and behavior of circular RC members reinforced with FRP. Our study aimed at yielding experimental data on the shear strength contribution of FRP (glass and carbon) discreet hoops and continuous spirals in full-scale concrete members with circular sections. The shear strengths of test specimens were compared to the available design equations in the literature. The test results and outcomes of this study can be used to assess and explore the feasibility of using noncorrosive FRP hoops and spirals as shear reinforcement in circular RC members to resist shear loads.

3. Experiments

3.1. Materials

The sand-coated GFRP and CFRP bars, hoops, and spirals used in this study were manufactured by pultrusion process using E-glass and carbon fibers, respectively, impregnated in a modified vinyl-ester resin. Number 4 GFRP spirals and hoops and #4 CFRP spirals were used as a transverse reinforcement for the GFRP RC and CFRP RC specimens, respectively (see Fig. 2). The lap splice length (L_d) of hoops was $40d_h$, where d_h is hoop diameter. High-modulus (HM) GFRP bars (CSA [24] Grade III) of 20 mm designated diameter and CFRP bars of 15 mm designated diameter were used in this study as longitudinal reinforcement. The tensile strength and elastic modulus were calculated using nominal cross-sectional area. Grade 60 steel bars were used to reinforce the steel-reinforced control specimen. Deformed #6 (M20) and #4 steel bars were used as longitudinal and spiral reinforcement, respectively. Table 1 provides the guaranteed properties of GFRP and CFRP reinforcements, as reported by the manufacturer. In addition, the bent tensile strength ($f_{fu,bent}$) was calculated according to ACI [26] and CSA [24] design equations for the bend strength of FRP bent bars. Also, the mechanical properties of the steel bars were obtained according to ASTM [30]. Table 1 shows the mechanical properties of the steel bars. All of the designed specimens were cast with normal-weight, ready-mixed concrete.

3.2. Test matrix and specimen preparation

The experimental program of this study was designed to provide experimental data on the shear strength of circular concrete specimens reinforced with FRP bars, hoops and spirals. The present work addressed the worst (critical) case when the flexural demand prevails over the axial load in bridge piles and piers. In design concrete members for shear, codes and standards included an additional multiplier to account for axial compression loads [24,31,32,39]. AASHTO LRFD [31] (Clause 5.10.11.4.1c—Column Shear and Transverse Reinforcement) and AASHTO LRFD [31], axial compression tends to increase the shear strength. In addition, in AASHTO LRFD Bridge Design Specifications [31] (clause 5.7.3.4), it was stated that “when computing the actual stress, axial tension effects shall be considered, while axial compression effects can be neglected”. Clause C 5.8.2.9 also states that the axial load can be ignored in calculating the effective depth for circular members.