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Bend-strength of novel filament wound shear reinforcement

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ABSTRACT

The winding of Fibre Reinforced Polymer (FRP) tows around longitudinal reinforcing bars provides a novel method for the fabrication of reinforcement cages. Complex geometries of internal reinforcement can be fabricated using this technique, a particular advantage for the construction of optimised concrete beams.

A key limitation on the contribution of FRP to the shear capacity of a concrete member is found at corners, where the presence of stress concentrations in different directions can lead to premature failure. A new test methodology was developed to allow for rapid testing of the samples as well as sample re-alignment during load application, reducing the effects of eccentricities and imperfections created during their fabrication. An experimental program, comprising 30 test samples, was undertaken to assess the bend capacity of filament wound FRP (W-FRP) shear links manufactured using a carbon tow impregnated with epoxy resin. A fixed bend radius of 5 mm and six non-circular fibre cross sectional areas having different width-thickness ratios were considered. Additionally, 18 samples were tested to measure the tensile properties of the straight reinforcement.

The test results indicate that W-FRP shear links exhibit improved bend strength as compared to conventional stirrups with circular sections (up to +53%), as a larger width-thickness ratio of the reinforcement provided more strength for a given cross sectional area. A good correlation between the test results and predictions of the W-FRP bend strength was observed when the specimens were modelled as a collection of transformed individual circular sections.

1. Introduction

Optimising the cross-section of reinforced concrete elements, by tailoring their shear and bending capacities at every cross-section to withstand the applied load can result in material savings of up to 40% [1]. During this process, the self-weight of the structural elements is reduced, leading to lower material costs. However, such optimised sections are often non-prismatic, creating practical and technical issues associated with reinforcement cages.

Reinforcement solutions utilising traditional steel shear links are hard to achieve in non-prismatic sections due to construction costs and practicality issues [2]. Subsequently, Fibre reinforced polymers (FRP) reinforcement has received a lot of attention, as the flexibility of the raw fibres prior to the application of resin allows reinforcement to be shaped precisely as required [3]. FRP also has a number of physical advantages over steel: it is non-magnetic, has a very high strength to weight ratio, and is not susceptible to corrosion [4,5].

A complication with FRP shear reinforcement is its linear stress-strain behaviour and anisotropic properties. Bends in shear reinforcement, which help to develop sufficient anchorage with the concrete, are associated with additional stress concentrations: transverse stresses due to bearing on the concrete; longitudinal stresses along the length of the fibres due to tensile forces in the shear reinforcement; and kinking of the inner fibres due to the bend generation during manufacture As FRPs do not yield, the combination of these three factors creates an intrinsically weak point at the corners of the reinforcing cage. Bend strength capacities as low as 30–40% of the tensile strength in the direction of the fibres are often reported for FRP stirrups with circular cross section [6–10]. As a consequence, strength of the bend governs the capacity of FRP shear reinforcement.

It has recently been suggested that the use of FRP stirrups with a rectangular cross sections and large width-to-thickness ratio can result in a bend strength up to 76% of the tensile strength of a straight portion of FRP, due to the lower number of kinked fibres at corners achieved by reducing the difference between the outer and the inner radius [8]. Another major parameter reported to affect the bend strength of FRPs are ratio between radius of bend and bar diameter.

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Techniques such as filament winding, which is often used in aeronautical engineering, can be applied to wind fibres coated in resin around longitudinal reinforcement bars to create reinforcement cages for concrete structures (Fig. 1). The winding process forms the fibres in wide and thin cross sections, the ideal geometry identified by Lee et al. [8,11]. This method also allows for quick and accurate fabrication of reinforcement cages with consistent quality. Traditional FRP stirrups are made by bending pultruded bars prior to full polymerization of the resin. The filament winding technique allows the radius of curvature of the bend to be tighter than for traditional open stirrups as the fibres do not need to slide over each other as is required when bending a straight pultruded bar before the resin polymerizes

In the majority of FRP design codes, the shear capacity of flexural members is normally divided into contributions from the concrete and reinforcement [12]. A limiting factor in the contribution of the reinforcement is the strength of the FRP at the corners.

In this paper, the performance of filament wound CFRP shear links of a realistic size are investigated. The specimens tested simulate a slice of the optimised T-beam web recently tested by the same research group [13,14] and including a combination of shear and longitudinal reinforcement. As filament winding was used to create the test samples, the corner radius of the shear links was determined by the diameter of the longitudinal reinforcement. The bend radius was therefore kept constant, with the variable investigated being a change in the number of wound layers. It is expected that as cross-sectional area increased the failure capacity of the link increases proportionally. However, when the cross-sectional area is increased, it is anticipated that there will be a larger volume of kinked fibres on the inside surface, resulting in a lower bend strength at failure. Tests were also performed on straight samples to measure the tensile properties of the W-FRP reinforcement. Experimental results are compared to theoretical predictions made using the guidance provided in ACI 440.1R [15] and a predictive equation proposed by Lee et al. [8]. The suitability of applying the test methodology to future local bend strength investigations is also reviewed.

2. Materials and predictions

2.1. Manufacturing

The W-FRP reinforcement was manufactured using an automated filament winding technique, which consist on wrapping continuous fibres under tension over a rotating mandrel. Although this method of fabrication has recently been proposed to create reinforcement cages for concrete structures [13,14,16], it is generally used to produce continuous hollow shapes with constant cross section.

Fig. 1. Filament Wound FRP (W-FRP) reinforcement.

Four #3 CFRP reinforcing bars [17] were attached longitudinally to the mandrel to form the corners of an idealized prism. The CFRP bars, having 10 mm diameter, aim to simulate the longitudinal reinforcement of a realistic concrete beam during the manufacturing of W-FRP cages. A refined system of control was employed to wind one or more carbon fibres layers impregnated with resin. The carbon fibres are wound around the bars in the form of closed rectangular stirrups with curved corners (bending radius, r_b, equal to 5 mm), a process very similar to the one employed to produce optimised reinforcement cages.

2.2. Tensile properties predictions

A continuous 50 k carbon fibre tow with a 240 GPa modulus of elasticity and a two-component epoxy were employed. This class of epoxy resin is applied at room temperature and is air cured, both considerable advantages for this application. A summary of the properties of the raw materials and the estimated characteristics of the final composite are reported in Table 1.

As the component densities are known, the resin content was determined by weighing reinforcement of known length, subtracting the weight of fibres employed (based on fibre volume and density) and converting the value into a volume. A consistent fibre-to-resin volume-fraction-ratio of 0.45/0.55 (VF_f/VF_r) was observed.

Under the assumption of all fibres stressed uniformly up to failure and negligible contribution of the resin, the expected tensile capacity of the reinforcement $f_{u,WFRP}$ is computed as:

$$f_{u,WFRP} = \frac{f_{u,f}}{A_{WFRP}} A_f, \tag{1}$$

where $f_{u,f}$ and A_f are the tensile strength and the cross section of the carbon fibre tow, respectively, whereas A_{WFRP} is the cross section of the whole WFRP (fibre tow and resin).

The expected modulus of elasticity in the direction of fibres is computed according to the mixture law, assuming that all fibres are perfectly straight and aligned:

$$E_{CFRP} = VF_f \cdot E_f + VF_r \cdot E_r, \tag{2}$$

where E_f is the Modulus of elasticity of the fibres and E_r is the Modulus of elasticity of the resin.

Knowing the modulus of elasticity and tensile strength, and assuming a linear elastic behaviour up to failure, the expected ultimate strain of the composite, ε_u, is finally computed as:

$$\varepsilon_u = \frac{f_{u,WFRP}}{E_{CFRP}}. \tag{3}$$

All these predictions assume perfect fibres alignment and uniform stresses in the different fibres, which will inevitably result in an overestimation of the mechanical properties of the composite.

Table 1
Material Properties.

Property	Carbon Fibre tow (x_f)	Epoxy Resin (x_r)	W-FRP (x_{WFRP})
Commercial Name	C T50-4.0/240-E100	Fyfe S	
Density (ρ, kg/m^3)	1800	1100	1415
Area per layer (A, mm^2)	1.92	2.35	4.28
Volume Fraction (VF)	0.45	0.55	1.00
Tensile Strength (f_u, MPa)	4000	72	1800
Tensile Modulus (E,GPa)	240.0	3.2	109.8
Elongation at break (ε_u,%)	1.7	5.0	1.64