A comparative study on different BFRP rebar design methodologies

Sofia Antonopoulou[1], Ciaran McNally[1], Greg Byrne[2]
[1]School of Civil Engineering, University College Dublin, Dublin, Ireland
[2]Burgmann Packings Ltd, Dublin, Ireland
email: sofia.antonopoulou@ucd.ie, ciaran.mcnally@ucd.ie

ABSTRACT: This study compares the physical properties and tensile behaviour of two different basalt fibre reinforced polymer (BFRP) rebar designs. Both types are developed using basalt fibres and epoxy resin as reinforcement and matrix respectively; composites with a constant cross section of 8 mm diameter are manufactured using a vacuum assisted resin infusion technique. The first configuration consists of eight braided layers at various angles, while the second one combines a unidirectional core with four outer braided layers. The latter hybrid design is introduced to improve the elastic modulus of braided BFRP reinforcement used in concrete structures. Tensile performance of all BFRP rebars produced in UCD laboratory is numerically and experimentally evaluated, and results for both approaches are compared. The effective longitudinal in-plane modulus (E_x^{FRP}) and the fibre volume fractions (φ_f) of each sample is calculated using the classical laminate theory and then, tensile tests are performed in accordance to the B2_ACI 440.3R-04 standard to experimentally validate the numerical results. Initial findings indicate that the elastic modulus of BFRP rebar can be enhanced by combining braiding with a unidirectional fibre core while a sufficient tensile strength is obtained, but additional research towards an optimal hybrid design is required.

KEY WORDS: BFRP rebars; Braiding technique; Unidirectional fibres; Tensile behaviour; Characterisation of FRP materials.

1   INTRODUCTION

Degradation of reinforced concrete structures due to corrosion of steel is reported as one of the main causes of structural deficiency that severely affects structural safety of RC elements. Harsh loading conditions and aggressive environmental factors can largely influence the long-term durability of structures in civil engineering applications and eventually lead to undesired repairs, additional costs and shorter service lives. According to IMPACT study, published by NACE International on 2016, a total of about $2.5 trillion is currently spent worldwide each year; approaches that have been taken so far, like stainless steel, epoxy coating, galvanizing procedures etc., have been found to be insufficient to provide a viable solution in a cost-effective way [1-3].

Advanced composite materials, such as basalt fibre reinforced polymer (BFRP), have the capacity to significantly address this problem. Due to both their high strength-to-weight ratio and their excellent corrosion resistance, these materials have the potential to replace traditional steel in civil engineering applications [4-6]. There are however limitations that prevent their use on a larger scale, and lack of ductility is the most significant. The tensile behavior of FRP rebars is characterized by a linear stress-strain behaviour up to failure, thus a direct substitution between FRP and steel rebars is not feasible [2, 7-9].

The overall properties and durability of FRPs are strongly dependent on the constituent materials, the composite's fibre and void content, the fibre-matrix interface and the orientation of fibres, which is strongly related to the used manufacturing technique. FRP reinforcement for concrete structures has traditionally been manufactured using pultrusion process, a low cost method providing composites with a constant cross section and a smooth surface. A detailed investigation on available design methodologies for the optimum development of FRP composites, suggests that a braiding technique could provide the required performance benefits through increased ductility and flexibility; it can also enhance the bond between FRP and concrete, which has a direct influence on both the serviceability and the ultimate load-carrying capacity of the structure. Nevertheless, braided composites exhibit complex damage and failure behavior, mainly due to their textile nature related properties, like multiple curved yarn interfaces, resin rich areas and nesting of different layers. As a result, a decrease on stiffness and strength values can be observed compared to unidirectional composites [1, 9-11]. By combining aspects of pultrusion and braiding into a single manufacturing process, a hybrid FRP rebar consisting of both unidirectional and off-axis oriented fibres can be produced. The stress-strain behaviour of the composite can be tailored by careful selection of raw materials and architectural design for the core structure and the braided sleeve respectively. The final part is a composite rebar with high initial tensile strength, contributed mostly by the high modulus unidirectional core followed by a gradual failure process associated with the outer braided sleeve [12-14].

This study presents a combined experimental and analytical approach for the design and development of two different basalt fibre reinforced polymer (BFRP) rebar types, using braiding technique and unidirectional fibre design. Mechanical properties of laboratory manufactured composites are numerically simulated using Classical Laminate Theory (CLT) and tensile tests are then conducted in order to experimentally evaluate the analytical data. Finally, comparisons are made between the two rebar configurations towards the optimisation of the designing and manufacturing process.

2 MATERIALS, DESIGNS AND MANUFACTURING METHODS

Two different types of basalt fibre reinforced polymer (BFRP) composites for internal concrete reinforcement are developed and mechanically characterised within this study; a fully braided and a hybrid design.

The various raw materials used to develop BFRP rebars are presented in Table 1. Basalt fibres (3 yarns sizes) and epoxy resin are used as reinforcement and matrix respectively. Polyethylene terephthalate (PET) fibres are also used to promote resin flow on samples during impregnation process.

Table 1. Raw material properties.

Product name	Uses	Tensile strength (MPa)	Elastic modulus (GPa)
BASALTEX® - Basalt assembled roving – 300, 600, 2400 tex 13, 17, 19 μm	Fibre reinforcement	2800 – 4800	87 - 89
M183 semi-dull round - PET Monofilament	Impregnation aid	57 – 60	10
Easy Composites - IN2 Epoxy infusion resin/ Slow cure	Resin	65.5 – 73.5	2.95

BFRP preforms in two different configurations are designed and manufactured in Burgmann Packings Ireland, using (i) a pure braiding technique and (ii) a combined approach with a unidirectional fibre core. In particular, the desired rebar configuration consists of a braided or unidirectional core, one or two layers of PET material to promote resin flow, and outer finishing braiding layers to achieve the desired structural geometry. The target is a solid braid of circular cross section with an outer diameter (OD) of 8 mm. In Figure 1, a complete BFRP preform along with resin impregnated rebars are presented, while in Table 2 design details are illustrated.

Figure 1. (a) BFRP rebar preform, (b) Resin impregnated composite rebars.

Table 2. Technical designing details.

BFRP 1 - 8 mm				
Layer	Material	Yarns	OD	Angle
1	300	8	1.6	12
2	300	16	2.7	16
3	600	16	4.0	17
4	PET	32	4.9	12
5	PET	32	5.6	14
6	300	16	6.5	16
7	600	16	7.2	45
8	600	24	7.9	40
BFRP 2 - 8 mm				
Layer	Material	Yarns	OD	Angle
Core	2400	10	4.4	0
1	PET	24	5.3	30
2	600	8	5.8	45
3	600	8	6.5	45
4	600	12	7.2	45
5	600	12	7.8	45

* Note: All values are an average of readings taken at several locations of manufactured samples; OD: Outer diameter (mm); Braid yarns: Basalt (TEX), PET Monofilament; Angle (°).

A vacuum assisted resin infusion method (VARIM) is selected for producing all BFRP specimens. The main reason for that is the minimization of both void content and dry spots in the composite, as well as final rebar products with high fibre content. This method involves placing the preform inside the aluminum mould, which is then completely sealed, and immediately after, epoxy resin is infused using a vacuum. A post-curing procedure is then followed to ensure the composite's quality; the rebar is placed in the oven for 6 hours in 60 °C after 24 hours in room temperature environment. The preforming methods and impregnation procedures were accordingly adjusted in order to reduce defects and optimize the process.

Moreover, a theoretical numerical approach based on CLT was developed to determine the stiffness properties of braided composites, calculating the effective longitudinal in-plane modulus (E_x^{FRP}) and the fibre volume fractions (φ_f) of each braided sample [7, 15, 16].

3 MECHANICAL CHARACTERISATION - TENSILE TESTS

The tensile properties of the manufactured BFRP rebars are determined by testing three representative specimens for each configuration in accordance to B2_ACI 440.3R-04/ ASTM D7205 standard. All tests are performed at room temperature with an Instron 500 Universal Testing Machine of 500 kN capacity, by displacement control and constant loading rate of 1 mm/min. Throughout the whole duration of the test, the applied load, displacement and specimen elongation are electronically recorded. More specifically, an Epsilon 3543-100M-100M-ST Axial Extensometer (100 mm gauge length) attached on the mid-length position of the rebar is used to track the specimen's elongation. Notched metallic jaws are used in order to properly align the sample in the testing machine. During each test, specimen should fail in the test section and slippage should be avoided throughout the length of the

anchors. This is the reason for introducing a special anchoring system prepared in UCD laboratory; the initial length, L_s, of each specimen is 950 mm and both ends are embedded into steel tubes with grip length of 300 mm, L_a, using an anchor filler material - a 1:1 mixture by weight of epoxy resin and clean sand - along with 3D printed caps for alignment (Figure 2). Mechanical treatment - surface sanding - of specimen's ends before mounted into the anchorage is performed to promote adhesion of the rebar with the filler material.
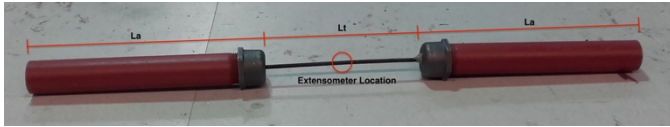

Figure 2. Special anchorage system with specimen dimensions and sensor location.

A total of 6 specimens from 2 different rebar configurations, described on Table 2, are mechanically tested within this study. The sample size is statistically acceptable, as the low coefficients of variation (CoV) ensure the consistency of obtained data. For both series of tests, the average value, standard deviation, and coefficient of variation for each property is calculated. Stress-strain curves are generated for each sample from the load and strain measurements recorded from the extensometer. The tensile strength of the specimens is calculated according to the following equation:

$$f_u = F_u/A \qquad (1)$$

where f_u is the tensile strength (MPa), F_u is the tensile capacity/ measured load (N) and A is the rebar's cross-sectional area (mm^2).

The tensile modulus of elasticity is taken as the linear regression of the data points from 20 to 50% of the rebar's tensile strength and is given by the following equation:

$$E = (f_1 - f_2)/((\varepsilon_1 - \varepsilon_2)A) \qquad (2)$$

where E is the tensile modulus of elasticity (GPa), A is the cross-sectional area (mm^2), f_1 and f_2 are the applied stresses corresponding to about 50% and 20% of the ultimate tensile strength, respectively, and ε_1 and ε_2 are the corresponding strains [17, 18].

4 RESULTS

The results of tensile tests on laboratory manufactured fully braided and hybrid (UN core) BFRP rebars are summarized in Table 3. The critical properties of maximum load and displacement, ultimate tensile strength, strain and elastic modulus per configuration are represented by average values with a sample size of 3. The consistency of results is guaranteed by the relatively low coefficients of variation (CoV) for each measured property, less than 0.1% for all configurations. All specimens failed within the test section area, demonstrating a successful grip system.

Table 3. Test results for the two BFRP composite rebar designs.

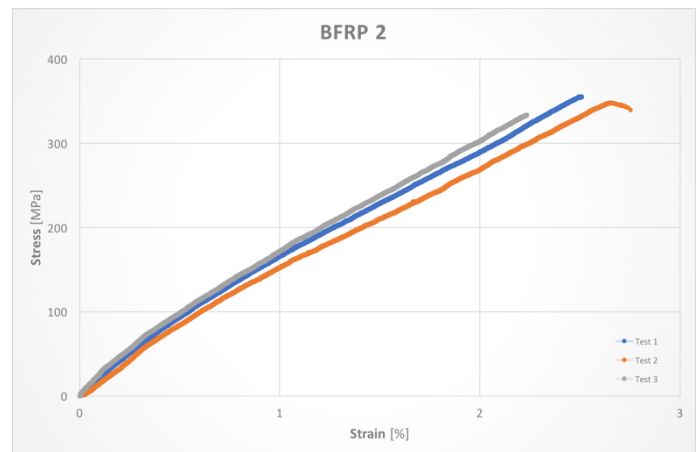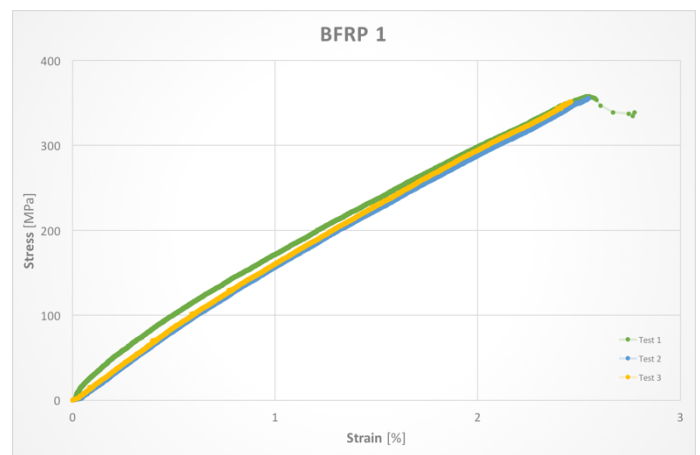| Sample no	BFRP 1	BFRP 2
OD (mm)	8	
Fibre Volume Fraction (%)*	51.63	48.96
	Aver./ CoV	
Maximum Load (kN)	17.84/ 0.01	17.38/ 0.03
Ultimate Tensile Strength (MPa)	354.99/ 0.01	345.73/ 0.03
Maximum Displacement (mm)	10.09/ 0.05	10.50/ 0.06
Ultimate Strain (%)	2.59/ 0.06	2.50/ 0.10
Elastic Modulus (GPa)	14.76/ 0.02	14.27/ 0.06

* Note: Numerically calculated using CLT approach

Figure 3. Stress – Strain curves for all manufactured BFRP rebars with an outer diameter of 8mm.

Figure 3 shows the tensile stress-strain curves for all six specimens of different configurations. The tested rebars showed a linear elastic stress–strain relationship up to failure, typical for all FRP products. Comparing the different design approaches, a similar mechanical behaviour is noticed; as the fibre volume fractions are increased from 48.96 % to 57.76 %, the elastic moduli are also increased from 1427 % to 14.76 %. Both samples exhibited a tensile strength comparable to the one of general steel bars (~ 400 MPa) and the maximum value - 354.99 MPa - obtained for the fully braided configuration. In

addition, the tested specimens showed a strain at failure ranging from 2.50% to 2.59%, almost the same as the 2.5% provided by Elgabbas et al. (2015) for pultruded BFRP bars. Brittle fracture types were noticed on all BFRP rebars, as shown in Figure 4.
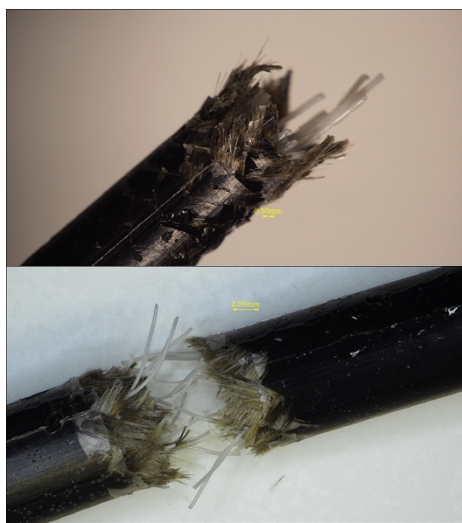

Figure 4. Micrograph of tested BFRP bars - Observed failure modes.

Figure 5. Tensile modulus of elasticity (E_x^{FRP}) for the two different rebar designs - Experimental vs CLT results.

Analytical results gained from Classical Laminate Theory (CLT) calculations [1, 7] have been correlated with average values of 3 test results for each composite rebar design. Figure 5 shows both the experimentally obtained and the numerically calculated tensile modulus of elasticity, E_x^{FRP}, for the two different BFRP rebar configurations. The predicted modulus for the fully braided design – BFRP 1 - is much higher (33.98 GPa) than the test data (14.76 GPa) and overestimate stiffness, whereas the one for the BFRP 2 design - unidirectional core & outer braided layers – is slightly lower (12.96 GPa) than the experimental results (14.27 GPa). CLT method has limitations for use with braided-reinforced composites and is mostly applied to unidirectional fibres designs, where the influence of undulations and orientations of yarns are not taken into account. More specifically, this method relies on the assumption of homogeneous strain and stress distributions in a uniaxial specimen; it applies symmetric properties to braided composites, that do not actually exist, and does not allow any prediction of their locally varying out-of-plane properties.

5   CONCLUSIONS

This paper focuses on the development and characterisation of BFRP composites for internal concrete reinforcement, using both braiding and hybrid designs. More specifically, the aim of this work is to develop an understanding of the mechanical behaviour of composite rebars and correlate it with design and manufacturing process. Two different BFRP rebar design methodologies are introduced in order to obtain similar stress-strain characteristics of steel and maintain ductility in reinforced concrete structures. Both configurations - circular cross section with an outer diameter of 8 mm - are manufactured using either only braiding technique or a combination of high modulus unidirectional fibre core and an outer multilayer braided sleeve, along with a vacuum assisted resin infusion process. The experiments include tensile testing of all manufactured specimens according to B2_ACI 440.3R-04 and ASTM D7205 standard test methods. In particular, the mechanical response and the stiffness of both braided and hybrid BFRP composites is experimentally evaluated and compared with results from CLT numerical analysis.

The results demonstrate a clear dependency of modulus and strength on both designing parameters, like core architecture, no of layers, angle, yarn size, no of carriers, and fibre volume fraction. The mechanical response is mainly dominated by the fibre architecture, which significantly affects localized properties, crack propagation and load redistribution in the material. The maximum tensile strength obtained, is comparable to the one of steel and both design approaches exhibited similar mechanical behaviour, although hybrid types can reach higher values with improved fibre volume fractions. There are also significant discrepancies between theoretical and experimental values for tensile properties on the fully braided type, mainly due to the anisotropic nature and out-of-plane properties of braided composites. The CLT method was instead able to predict the elastic modulus of the hybrid type to a satisfactory degree.

In general, the results obtained contribute to a further understanding on the various available design approaches for FRP composite rebars and their properties. Additional work towards an optimal FRP rebar design should be conducted, taking advantage of both the design flexibility and the wide availability of manufacturing processes. Moreover, a more detailed investigation on the mechanical properties of FRP composites is essential in order to assess the relation between manufacturing parameters and rebar performance for improved rebar design and thus, to generate more confidence on the use of this innovative material in civil engineering applications.

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