Mechanical characterisation of braided BFRP rebars for internal concrete reinforcement

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ABSTRACT: This study investigates the tensile behaviour of basalt fibre reinforced polymer (BFRP) composites that were developed using braiding as a manufacturing technique. Those materials will be introduced in concrete reinforcement applications. Three BFRP rebar sizes with a circular constant cross section and different braided configurations are developed and characterised with respect to their internal architecture. The braid angle on each layer of the rebar, varying from 10° to 45°, is an important parameter that has a direct impact on its performance characteristics. The effective longitudinal in-plane modulus (E_x^{FRP}) of each braided sample is calculated numerically using the classical laminate theory (CLT) approach and then, tensile tests are performed according to the relevant standard. Comparisons between analytical and experimental data demonstrate a significant influence of braiding parameters, like braiding angle and number of braiding layers, on the mechanical properties of BFRP rebars. In addition, it is noteworthy that all predicted moduli determined with CLT numerical approach are found to be higher than the test results and overestimate rebar's stiffness, most probably due to the degree of undulation from braiding process.

1 INTRODUCTION

The increasing rate of degradation of reinforced concrete structures due to corrosion of steel is identified as one of the main causes of structural deficiency that severely affects structural safety of RC elements. It is noteworthy that the global cost of corrosion is estimated at about \$2.5 trillion and current approaches (stainless, epoxy coating etc.) have been found to be unable to successfully address this problem in a costeffective way (Afifi et al. 2015, Antonopoulou & McNally 2017, Benmokrane & Ali 2016, Koch et al. 2016).

Advanced composite materials, such as Basalt Fibre Reinforced Polymer (BFRP), were recently introduced as a potential replacement to traditional steel in civil engineering applications, due to both their high strength-to-weight ratio and their excellent corrosion resistance. These materials can be used as internal concrete reinforcement to overcome the inherited corrosion-related deficiency of steel reinforced concrete structures and thus, to extend infrastructure's longterm durability and total service life (Elgabbas et al. 2015, Fiore et al. 2015, Hollaway 2010, Whitehead & Ibell 2005).

However, the mechanical behavior of FRP reinforcement differs from the one of conventional steel, so a direct substitution between FRP and steel rebars is not feasible. The tensile behavior of FRP rebars is characterized by a linear stress-strain behaviour up to failure. The lack of ductility under tension along with their anisotropic nature, are the main issues to be addressed when considering their use in concrete structures. 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. A detailed investigation of manufacturing technologies and design methodologies for the optimum development of BFRP composites, indicates that braiding methods could provide the required performance benefits and improve their brittle nature and low elastic modulus through increased ductility and flexibility; it can also enhance the bond between FRP and concrete (Antonopoulou et al. 2016, Benmokrane & Ali 2016, Ibell et al. 2009, Portnov et al. 2013).

Mechanical in-plane properties are influenced by the textile nature of braided composites, as out-ofplane and in-plane waviness is evident on interlacing yarns. As a result, a decrease on stiffness and strength values can be observed compared to unidirectional composites. Moreover, 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. Therefore, a more detailed investigation on the mechanical properties of braided FRP composites, such as Young's Modulus, tensile strength, etc. is essential to understand their behavior and generate higher confidence in these innovative materials (Antonopoulou & McNally 2017, Birkefeld et al. 2012, Portnov et al. 2013, Seo et al. 2016).

This study presents the results of an experimental evaluation for the tensile properties of braided Basalt Fibre Reinforced Polymer rebars. BFRP reinforcement is designed and developed using braiding as manufacturing technique. The mechanical behavior of braided BFRP rebars is numerically simulated using Classical Laminate Theory and their stiffness properties are assessed. Tensile tests were then conducted in order to evaluate their mechanical performance and comparisons are made between numerical and experimental data.

2 DEVELOPMENT OF BRAIDED BFRP REBARS

Basalt fibre reinforced polymer (BFRP) composites for internal concrete reinforcement were developed and mechanically characterised within this study, using braiding as a manufacturing technique.

2.1 Materials

Materials used to develop BFRP rebars are shown in Table 1. Basalt fibres and epoxy resin were used as reinforcement and matrix respectively. Polyethylene terephthalate (PET) fibres were also used to promote resin flow on FRP samples during impregnation process.

Table	1.	Material	properties	used	in d	levelop	oment	of
BFRP	rel	oars.						

Product name	Uses	Tensile strength (MPa)	Elastic modulus (GPa)
BASALTEX® - Basalt assem- bled roving - 300tex 13µ, 600tex 17µ	Fibre rein- forcement	2800 - 4800	87 - 89
M183 semi-dull round - PET Monofilament	Impregna- tion aid	57 - 60	10
Easy Compo- sites - IN2 Epoxy infusion resin/ Slow cure	Resin	65.5 - 73.5	2.95

2.2 Manufacturing method

BFRP rebars are manufactured using braiding technique and vacuum assisted resin infusion process.

Braided BFRP preforms in three different sizes and configurations are designed and manufactured in

Burgmann Packings Ireland, while changing key braiding parameters (yarn size, no. of carriers, angle, no. of layers), in order to meet the performance characteristics of existing rebar reinforcement. More specifically, the desired rebar configuration consists of a braided core, two or three layers of PET material, 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 5, 8 and 10 mm. In Table 2, technical braiding details are illustrated, while in Figure 1 a complete braided BFRP preform along with resin impregnated rebars are presented.



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

Table 2. Techn	cal braiding	details
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BFRP 1 - 5 mm					
Layer	Material	Carriers	OD	Angle	
1	600	8	2.5	14	
2	PET	24	3.8	15	
3	PET	24	4.0	15	
4	600	16	4.9	45	
	BFI	RP 2 - 8 mm			
Layer	Material	Carriers	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 3 - 10 mm					
Layer	Material	Carriers	OD	Angle	
1	300	16	2.6	14	
2	600	16	4.2	16	
3	PET	32	5.0	13	
4	PET	32	5.4	14	
5	600	16	5.8	34	
6	600	16	6.2	36	

7	600	24	7.1	30
8	PET	24	8.0	35
9	600	24	8.8	34
10	600	24	9.8	38

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

For resin impregnation, the vacuum assisted resin infusion method (VARIM) was selected to minimize both void content and dry spots in the composite, as well as to obtain rebars with high fibre content. In details, the preform is placed inside the aluminum mold, which is then completely sealed, and immediately after, epoxy resin is infused using vacuum, as illustrated in Figure 2. A post-curing procedure is also 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.



Figure 2. Resin impregnation process set-up.

Moreover, a theoretical numerical approach based on Classical Laminate Theory 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 (Antonopoulou et al. 2016, Bank 2006, Valentino et al. 2013).

3 TENSILE TESTS

3.1 Experimental Methodology

The tensile properties of the manufactured BFRP rebars were determined by testing three representative specimens for each type in accordance to B2_ACI 440.3R-04/ ASTM D7205 standard. A total of 9 specimens and 3 different configurations and sizes of braided rebars, described on Table 2, were mechanically tested within this study. The sample size is statistically acceptable, as the low coefficients of variation (CoV) ensure the consistency of obtained data.

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:

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

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 (mm²).

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:

$$E = (F_1 - F_2)/((\varepsilon_1 - \varepsilon_2)A) \quad (2)$$

where E is the tensile modulus of elasticity (GPa), A is the cross-sectional area (mm²), F_1 and F_2 are the applied loads corresponding to about 50% and 20% of the ultimate tensile strength, respectively, and ε_1 and ε_2 are the corresponding strains.

For each series of tests, the average value, standard deviation, and coefficient of variation for each property is calculated.

3.2 Test set-up

The tensile tests on different BFRP configurations were carried out within this study in accordance to B2_ACI 440.3R-04/ ASTM D7205 standard. All tests were 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 were electronically recorded. Figure 3 shows the test setup.



Figure 3. Typical tensile test set-up.

The initial length, Ls, of each specimen was fixed to 850 and 950 mm for 5 mm and 8, 10 mm rebar diameter respectively. The proper alignment of specimen in the testing machine is achieved with the use of notched metallic jaws. A special anchoring system prepared in UCD laboratory (Fig. 4), is introduced to all BFRP rebars in order to impose the failure to occur in the test section and to avoid slipping throughout the length of the anchor during the test. Both specimen ends are embedded into steel tubes with grip length of 300 mm, La, using an anchor filler material - a 1:1 mixture by weight of epoxy resin and clean sand along with 3D printed caps for alignment. Mechanical treatment of specimen before mounted into the anchorage is performed to promote adhesion of the rebar with the filler material, by the means of surface sanding at both ends.



Figure 4. Special anchorage system with specimen dimensions and sensor location.

An Epsilon 3543-100M-100M-ST Axial Extensometer was used in order to record specimen's elongation during testing. The extensometer was attached on the mid-length position of the rebar and its gauge length was 100 mm, according to the relevant standard.

4 RESULTS AND DISCUSSIONS

The results of tensile tests on laboratory manufactured braided BFRP rebars are summarized in Table 3. The critical properties of maximum load and displacement, ultimate tensile strength, strain and elastic modulus per braiding 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, indicating a successful grip system.

Sample no	BFRP 1	BFRP 2	BFRP 3
OD (mm)	5	8	10
Fibre Volume Fraction (%)*	57.76	51.63	54.59
	Aver./ CoV	Aver./ CoV	Aver./ CoV
Maximum Load (kN)	5.46/ 0.05	17.84/ 0.01	30.60/ 0.02
Ultimate Ten- sile Strength (MPa)	277.84/ 0.05	354.99/ 0.01	389.64/ 0.02
Maximum Dis- placement (mm)	7.49/ 0.03	10.09/ 0.05	21.58/ 0.07
Ultimate Strain (%)	2.98/ 0.03	2.59/ 0.06	3.73/ 0.09
Elastic Modu- lus (GPa)	10.65/ 0.03	14.76/ 0.02	12.39/ 0.04

Table 3. Test results for braided BFRP reba	rs.
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* Note: Numerically calculated using CLT approach







Figure 5. Stress – Strain curves for braided BFRP rebars with an outer diameter of (a)5mm, (b)8mm, (c)10mm.

Figure 5 shows the tensile stress-strain curves for all nine specimens of the different configurations. The tested rebars showed a linear elastic stress-strain relationship up to failure, typical for all FRP products. Comparing the different types of braided BFRP rebars, as the fibre volume fractions are increased from 51.63 % to 57.76 %, the elastic moduli are decreased from 14.76 % to 10.65 %. Though the maximum tensile strength obtained was 389.64 MPa, this value is comparable to the one of general steel bars (~ 400 MPa). Furthermore, the tested specimens showed a strain at failure ranging from 2.59% to 3.73%, higher than 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 6.



Figure 6. Observed failure modes in tested BFRP bars.

Analytical results gained from Classical Laminate Theory (CLT) calculations (Antonopoulou et al. 2016, Antonopoulou & McNally 2017) have been correlated with average values of 3 test results for each braiding configuration. Figure 7 shows both the experimentally obtained and the numerically calculated tensile modulus of elasticity, E_x^{FRP} , for the three different braided rebar types. All predicted moduli with CLT approach are always much higher than the test data and overestimate stiffness, as this method is mostly applied to unidirectional composites, where the influence of undulations and orientations of varns are not taken into account. In particular, this method has limitations for use with braided-reinforced composites, since it 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-ofplane properties.



Figure 7. Tensile modulus of elasticity (E_x^{FRP}) - Experimental vs CLT results.

5 CONCLUSIONS

This paper demonstrates the results of the research that is currently in progress at University College Dublin regarding the design, development and characterisation of braided BFRP composites for internal concrete reinforcement. More specifically, the aim of this work is to develop an understanding of the mechanical behaviour of braided composite rebars and correlate it with textile processing conditions. Three different BFRP rebars of circular cross section and outer diameter of 5, 8 and 10 mm are manufactured using braiding technique and vacuum assisted resin infusion process. The experiments included 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 braided 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 braiding parameters, like no of layers, angle, yarn size, no of carriers, and fibre volume fraction. The mechanical response is mainly dominated by the textile 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, although pultruded rebars can reach higher values, but with lower strain rate. There are also significant discrepancies between theoretical and experimental values for tensile properties, mainly due to the anisotropic nature and out-of-plane properties of braided composites. In general, the results obtained contribute to further understanding the properties of braided FRP rebars. Additional work on different BFRP composites should be conducted to generate more confidence on the use of this material in civil engineering applications. Since, the prediction of failure in braided materials is still a major challenge, further investigation should be conducted to develop finite element analysis (FEA) models for braided BFRP composites and to assess the relation between braiding parameters and rebar performance for improved rebar design.

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