An CFRP Fabrics as Internal Reinforcement in Concrete Beams

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ABSTRACT

This paper presents preliminary results of an experimental programme that investigated mechanical properties of a balanced-symmetric CFRP fabric laminate. Although FRP fabrics have potential to be formed into efficient reinforcement systems that can enable the development of innovative low embodied energy concrete structures, very little research on applications of FRP fabrics has been reported in the literature. In accordance with the classical laminate theory, in a balanced-symmetric laminate there is no coupling between in-plane deformation and curvature, nor between in-plane normal loading and shear deformation. As a result of the choice of lay-up arrangement the flexural reinforcement systems in concrete beams can be designed by considering the conventional section equilibrium analysis.

INTRODUCTION

Despite the successful application of Fibre Reinforced Polymer (FRP) materials for aerospace, marine, automotive and wind turbine blade structures, and the significant market overhaul envisaged when these materials were first introduced in the construction industry, so far FRPs have only achieved limited market penetration in the construction industry. Unlike in aerospace, marine and other structural applications, the light weight of the materials is not a decisive factor except in a few specific applications, for instance, in military or very-long-span bridges or certain all-FRP structures. In addition, repair and strengthening of concrete structures using externally–bonded FRP systems is a notable success where the benefit comes from the reduction in construction costs and that, despite high material costs, FRPs are easier to install [1].

Interest in FRP internal reinforcements is mostly focused on their use as a way to mitigate corrosion in steel reinforced concrete (RC) structures exposed to the environment, especially highway bridge decks [2]. The use of FRPs as a direct substitute for steel tension bars and/or shear links, using the same design principles as in steel RC members, means that designs are often expensive and inefficient [3]. There is a fundamental difference between the characteristics of the two materials that makes an FRP member more difficult to design: FRPs are elastic and brittle whereas steel yields under high stresses. Another major difference is in the bond characteristics; with steel bars having a strong concrete–steel bond, which is advantageous since when the strain in the steel researches the yield strain at a crack in the concrete, the steel yields and no stress concentration can occur. With an FRP, failure of FRP is triggered due to high local strains. Thus, application of an FRP as internal reinforcement bars in concrete beams often resulted in costly and inefficient designs [2].

The flexible nature of FRP fabrics prior to curing with resins provides the prospect of forming novel 2D/3D reinforcement systems, enabling more efficient and innovative material use. FRP fabric reinforcement has particular potential in non-prismatic concrete beams, where conventional steel reinforcement systems are difficult to provide. Recent work at the University of Bath has shown that structurally optimised, non-prismatic concrete beams cast using flexible formwork can make a concrete saving up to 30% [4] over prismatic beams. This advantage provides an opportunity to lower the carbon footprint of concrete structures. Despite the potential of FRP fabrics, little research on their use as internal reinforcement has been reported in the literature. Unidirectional (UD) FRPs, largely used for repair and/or for strengthening of concrete structures, have anisotropic properties with poor strength and stiffness properties in the transverse directions. On the other hand, 2D FRP fabrics, which are either woven or stitched, can be used to achieve more balanced properties including relatively high in-plane strengths and ultimate strains compared to UD FRPs.

Owing to the anisotropic material behaviour, it can be anticipated that complex 2D stress distributions will develop in FRP fabrics when they are used as internal reinforcement. It is not correct to design members using conventional design methods for steel reinforcement. A fundamental understanding of the material behaviour is required under load conditions corresponding to those found in practice. This paper presents test results of an experimental programme that characterises the mechanical properties of a CFRP fabric laminate. The outcome of a theoretical design of a FRP fabric flexural reinforcement system using the mechanical properties determined from the experiments is also presented.

MECHANICAL PROPERTIES OF MULTI-DIRECTIONAL FRP FABRICS

Although multi-directional FRP fabrics have potential to be formed into efficient reinforcement for concrete beams, their mechanical behaviour is complex, and the overall behaviour depends on mechanical and geometric properties of the individual fabric layers and the stacking sequence of the laminates. For instance, 0^0 fibres provide high strength/stiffness properties along the fibre direction, and 90^0 fibres enhance the properties in the transverse direction whereas $\pm 45^0$ fibres provide high in-plane strength. It is anticipated that $\pm 45^0$ multi-layer fabric reinforcement systems (Figure 1) will enhance strength and ductility of concrete beams. In order to design a reinforcement system, mechanical properties of laminates manufactured using commercially available $\pm 45^0$ CFRP fabrics were determined.

Arrangement of Laminates

Unlike homogeneous solids where mechanical properties are isotropic, different layers of fabrics can be arranged in specific orientations to achieve the strength and stiffness properties required for the design. However, the coupling between in-plane loading (*i.e.* extension or membrane) and out-of-plane deformations (*e.g.* bending), and also the coupling between extension and in-plane shear deformation must be considered in the stress analysis. Knowledge of the classical laminate theory [5] was used to design a balanced-symmetric laminate consisting of four layers of $\pm 45^0$ fabric sheets.

The selected laminate was symmetric, since for each layer on one side of the mid-plane there was a corresponding layer at equal distance from the mid-plane on the other side with identical elastic mechanical properties and layer thickness. Since the laminate was symmetric in both geometry and mechanical properties, there is no coupling between in-plane loading and bending deformations. Moreover, the selected laminate was balanced since it had pairs of layers with identical elastic mechanical properties and thicknesses but with $+45^0$ and -45^0 fibre orientations with respect to the longitudinal axis direction. Since the laminate was balanced there is no coupling between in-plane normal loading and in-plane shear deformations.

Preparation of Laminate

All the test specimens were fabricated from a single CFRP laminate of 400 mm x 700 mm (Figure 2) of four layers of $\pm 45^0$ biaxial fabrics purchased from *easycomposites* (Warp fibre : Toray T700Sc, Weft fibre: Toray T700Sc, Weight : 300 g/m^2 and Wave $\pm 45^0$). The laminate was fabricated in a wet lay-up system similar to the methods employed in practical civil engineering applications, using a commercially available (easycomposites) two-part epoxy resin, EL2 Epoxy Laminate Resin with AT30 Slow Hardener. In this process, each layer was individually impregnated with resin and then the subsequent layer added on the top. Each dry fabric layer was 0.35 mm thick and the four-layer laminate was 1.7 mm thick. The laminate was cured for 30 hours in room temperature (18 ± 2 ^{0}C) and pressure and then cut into test pieces using a circular saw of 180 mm diameter with a diamond blade of 16 mm thick. From an analysis of the weight of the laminate and those of the FRP and resin, the fibre volume fraction of the laminate was determined to be ~40%.

Load–Deformation Relationship

The contribution of concrete to the bending stiffness of a beam cross section is significantly higher than that due to the FRP internal reinforcement. Therefore, as a first approximation, it is appropriate to ignore the bending deformation of the FRP fabrics in the equilibrium analysis of beam cross sections. Thus, from the classical laminate theory [5], the load-deformation relationship of the laminate is:

$$\begin{Bmatrix} N_x \\ N_y \\ N_z \end{Bmatrix} = \begin{bmatrix} A_{xx} & A_{xy} & 0 \\ A_{yx} & A_{yy} & 0 \\ 0 & 0 & A_{ss} \end{bmatrix} \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_s^0 \end{Bmatrix} \quad (1)$$

where N_x and N_y are the total in-plane forces in the x and y directions respectively and N_s is the in-plane shear force. ε_x^0 and ε_y^0 are the strains at the mid-plane of the laminate in x and y directions respectively, and γ_s^0 is the x-y shear strain in the mid-plane. A_{xx}, A_{yy}, A_{xy}, A_{yx}, and A_{ss} are the elastic constituent parameters which can be determined from the basic lamina properties in two in-plane principal directions (1, 2) such as the modulus of elasticity (*i.e.* E_1 and E_2), in-plane shear modulus (G_{12}) and major Poisson's ratio (υ_{12}) and the geometric details of the individual lamina [5].

Determination of Mechanical Constituent Properties

Direct tensile tests along the fibre directions (Figure 2) were carried out to determine E_1 , E_2 and υ_{12}. It should be noted that since the fabric reinforcement is symmetric in the x-y plane, E_1=E_2, and direct tensile tests were carried out for one direction only, along the +45^0 fibre direction. Off-axis tensile tests (Figure 2) were conducted to determine G_{12}. In addition to these two tests, a new test, a biaxial continuous fibre tensile test (Figure 2) was carried out using a relatively large 250 mm x 275 mm specimen. In this test, the zones of fibres that cross the centre of the specimen are continuous through its length, unlike fibres in the off-axis tensile test. The aim is to represent the loading and boundary conditions active on relatively long and wide fabric sheets when used as flexural reinforcement in concrete beams.

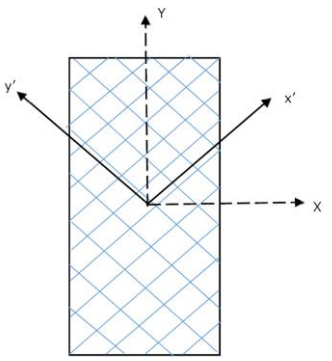


Figure 1. Fibre orientation in a ±45^0 fabric

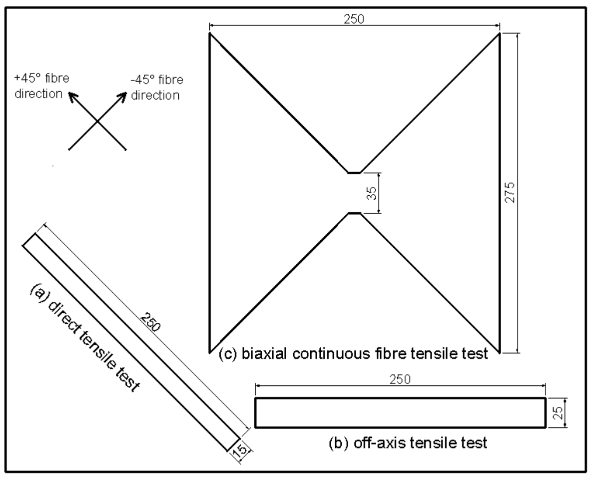


Figure 2. Three types of test specimens (all dimensions in millimetres)

Direct Tensile Test

The direct tensile test along the fibre direction was carried out in accordance with ASTM D3039/D3039M [6], with specimen dimensions 250 mm long and 15 mm wide. As shown in Figure 3a, aluminum end-tabs were used so that the effective test length of the specimen was ~140 mm. Three specimens cut from the same large laminate (Figure 2) were tested in a servo-hydraulic Instron test machine at a stroke rate of 2 mm/min. Test specimens were instrumented with strain gauges in the main fibre direction and the transverse direction on one side, and in the main fibre direction only on the opposite side.

Figure 3b shows longitudinal stress–strain relationship in the three test specimens. As expected, all samples responded linear-elastically until ultimate failure. The stress–strain relationships of the three specimens are similar, and the ultimate tensile strengths were determined to be 774, 834 and 800 MPa (Table 1), giving an average value of 803 MPa as the design value. The computed E_1 are very similar, with magnitudes of 46.3, 46.8 and 47.8 GPa (Table 1), and an average of 47 GPa was used in the subsequent analysis. Poisson's ratio (υ_{12}) determined from the strain gauge readings is 0.1. It should be noted since only three specimens were tested in this experimental programme the average value of each mechanical property was used rather than attempting to predict characteristic values.

Comparison of longitudinal strain data on opposite sides show that the two strain data match each other with an error less than 5% suggesting that the specimens did not experience significant bending during tensile loading. Therefore, the mechanical properties determined above are judged to be sufficiently accurate for design. It should also be noted that the calculated E_1 of 47 GPa is smaller than that of commercialy available uni-directional CFRP prepreg sheets (typically 100–150 GPa) due to the relatively low fibre volume fraction (~20%) in the longitudinal direction compared to 50-60% for commercially-available CFRP prepregs.

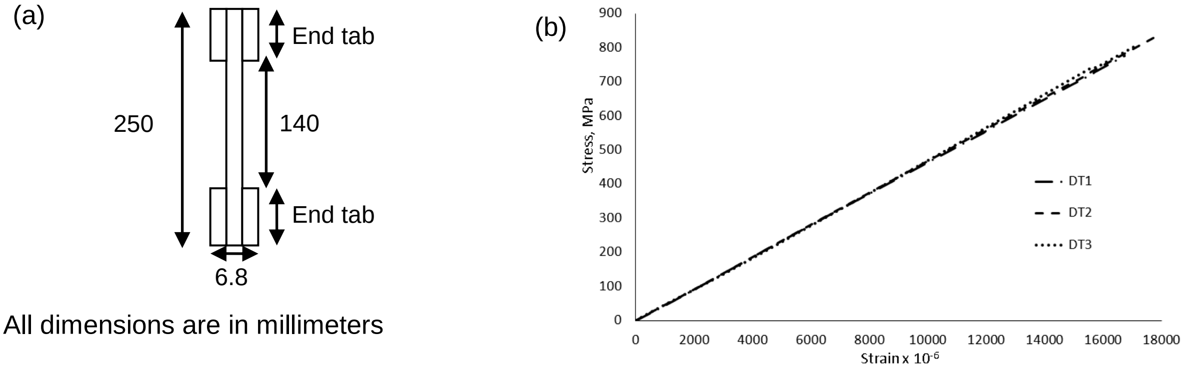


Figure 3. Direct tensile test along the fibre direction (a) Test specimen (b) Stress vs strain relationship

Table 1. Test results for elastic mechanical properties

Direct tensile test			Off-axis tensile test			Biaxial tensile test		
Test specimen	E_1 (GPa)	Tensile strength (MPa)	Test specimen	G_{12} (GPa)	Shear strength (MPa)	Test specimen	Modulus (GPa)	Tensile strength (MPa)
DT1 DT2 DT3	46.3 46.8 47.8	774 834 800	OA1 OA2 OA3	5.5 5.8 5.6	49.1 52.4 59.8	BA1 BA2	23.3 23.9	468 446
Average	47	803		5.6	53.8		23.6	457

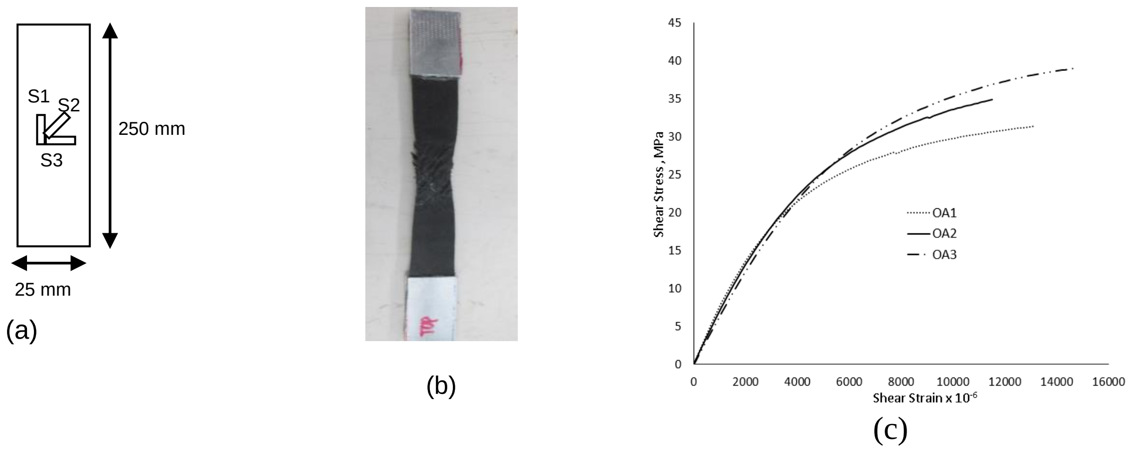


Figure 4. Off-axis tensile test (a) Strain gauge rosette (b) Shear failure of test specimen (c) Shear stress–strain relationship of the three test specimens

Off-axis Tensile Test (In-plane Shear Test)

This test was conducted in accordance with ASTM D3518/D3518M [7]. Test specimen dimensions were similar to those used in the direct tensile test but with specimen width 25 mm. As shown in

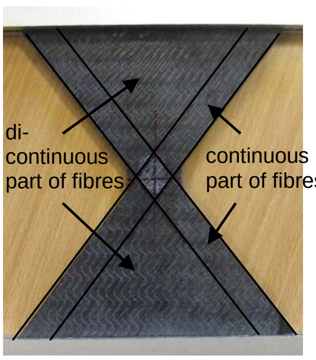
Figure 4a, a strain gauge rosette was used to measure strain in the longitudinal (S1) and the transverse (S3) directions and also in the 45^0 direction (S2). Three specimens were tested in this programme, and measurements obtained from a strain gauge in the longitudinal direction on the other side suggested that no significant bending took place during loading. As expected, all three samples failed in in-plane shear (Figure 4b).

Shear strains were determined using the data from the strain gauge rosette, and Figure 4c shows the shear stress–shear strain relationships. As expected, the results show that each specimen experienced (approximately) linear behaviour at lower loads (up to shear stress ~22 MPa and shear strain ~0.004). The linear responses of all three samples were very similar (Figure 3c) and G_{12} determined to be 5.5, 5.8 and 5.6 GPa respectively, with an average value of 5.6 GPa taken for subsequent analysis. It is worth noting that shear stress–strain behaviour of the specimens beyond the linear portion was notabley different with failure shear stresses of 49.1, 52.4 and 59.8 MPa respectively. However, it is anticipated that the design shear stresses will be limited to the linear region and therefore the non-linear behaviour close to failure is not relevant in the current work.

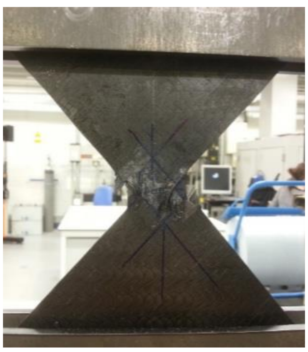
Biaxial Continuous Fibre Tensile Test

In the off-axis tensile test, the response largely depends on the matrix, since the short fibres in the specimen (note: width of the test specimen = 25 mm) are not fully contributing to the load carrying unlike in the direct tensile test. FRP fabric internal reinforcement systems may consist of relatively wide and long fabric sheets and the bond between the fabric and concrete means it is anticipated that the contribution of the fibres to load carrying is significant. A new test specimen, a biaxial continuous fibre tensile test (Figures 2 and Figure 5a), was designed to characterise the contribution of a region of continuous fibres at $\pm 45^0$ to load carrying.

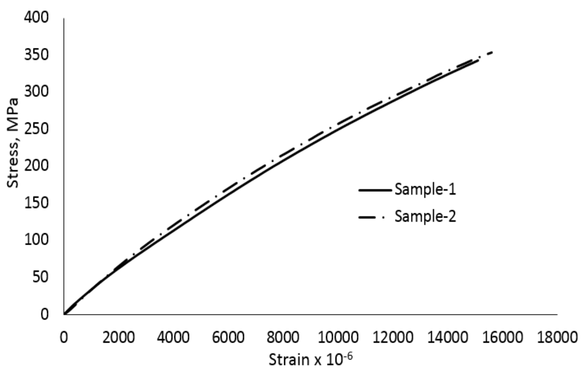
Figure 5c shows the longitudinal stress–strain relationship for the central region of the two specimens tested. Results show that the behaviour is approximately linear, and the stress–strain relationships of the two samples are very similar. The elastic modulus in the longitudinal direction was determined to be 23.3 and 23.9 GPa (average 23.6 GPa). Tensile strength (calculated over the minimum cross section perpendicular to the applied load) was determined to be 468 and 446 MPa (average 457 MPa). The results suggest that, as expected, strength and elastic modulus from this test (457 MPa and 23.6 GPa respectively) are higher than from the off-axis tensile test (53.8 MPa and 5.6 GPa) but smaller than from the direct tensile test (803 MPa and 47 GPa). The strength and elastic modulus in the longitudinal direction of the bi-directional laminate may also be determined by transforming the elastic mechanical properties determined from the direct tensile test. However, it should be noted that this simplified transformation does not take into account the different failure modes of the two laminate. Nevertheless, the values determined from the transformation of the results of the direct tensile test were found to be 401.5 MPa and 18.4 GPa respectively. Thus, the mechanical properties obtained from the biaxial continuous fibre tensile tests (457 MPa and 23.6 GPa respectively) are 12% and 20% higher than those derived from the knowledge of 2D stress transformation theory. A possible explanation for this discrepancy is a small load-carrying contribution of the discontinuous fibres outside the central cross section area. In addition, uncertainty with regard to Poisson's ratio effects in the stress transformation analysis may have a contribution.



(a)



(b)



(c)

Figure 5. Biaxial continuous fibre tensile test (a) Test specimen (b) Failure of test specimen (c) Longitudinal stess–strain relationship of the two test specimens

DESIGN OF FRP FABRIC FLEXURAL REINFORCEMENT SYSTEM

The results described above provide mechanical properties of an FRP fabric laminate under specified static load cases and known simplified boundary conditions. The loading and boundary conditions active when the material is used as internal reinforcement in a concrete beam can be complex and the conditions different to those experienced in small-scale material coupon tests. S*ize effects* of the material may also mean the results of small test specimens might not be represntive. In order to investigate the appropriateness of the mechanical properties obtained from the above tests to model the load response of FRP fabric reinforcement in a real concrete beam, a simply-supported beam was designed using these mechanical properties.

A simply supported beam loaded in 4-point bending with dimensions depicted in Figure 6 was designed to fail by rupture of the FRP in tension at mid-span due to the bending moment. FRP strength values used in the design were (1) 53.8 MPa (average strength from off-axis tensile tests); (2) 457 MPa (average strength from biaxial continuous fibre tensile tests); and (3) 401.5 GPa (strength computed by transforming the average tensile strength obtained from the direct tensile test). The compressive strength of the concrete used in the design was 25 MPa. From equilibrium analysis of the beam cross section, ultimate moment capacity was determined to be 1.79, 2.55 and 2.19 kNm respectively for the design strength values (1) to (3), with corresponding failure loads P = 7.0, 10.0, and 8.6 kN respectively. A control beam reinforced with conventional steel bars was also designed to compare its ductility with the FRP-reinforced beam. The testing programme is still ongoing; the authors will discuss the results in the conference presentation.

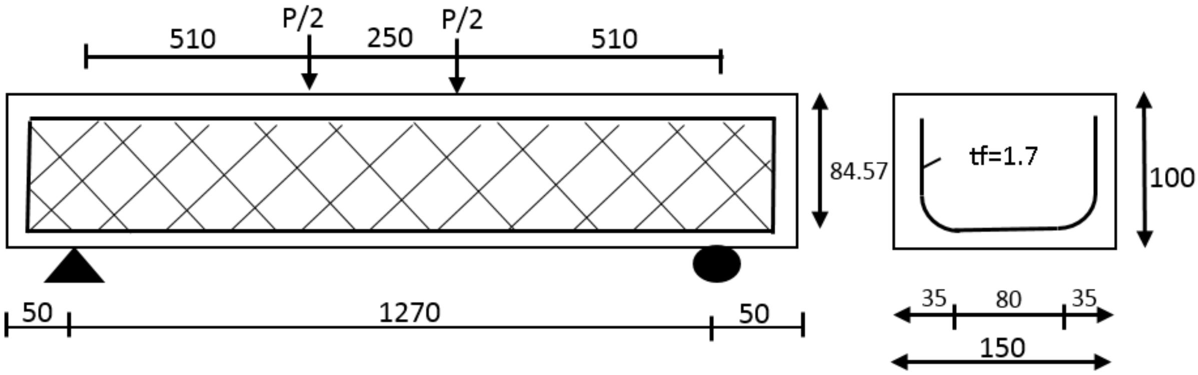


Figure 6. Dimensions of concrete beam (all dimension in millimetres)

CONCLUSIONS

This paper has shown that by combining the knowledge of basic mechanical properties of FRP fabrics with classical laminate theory and carrying out a series of relevant laboratory materials characterisation tests, strength and stiffness properties of a flexural reinforcement system suitable for use in a concrete beam can be determined. A beam has been designed using the properties obtained, and results from testing it will be presented at the ACIC 2015 conference.

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