TENSILE PROPERTIES OF FLAX FRP COMPOSITES

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Abstract
In this study, the effects of the polymer matrix properties and shape of test specimens on mechanical properties of flax fiber-reinforced polymer (FRP) composites are examined. A total of 30 flax FRP coupons were fabricated using three different types of matrix (epoxy resin, bio-based epoxy resin, and polyester resin) and two different specimen types (dumbbell-shape and tabbed coupons). Also, 15 unreinforced dumbbell-shape coupons were fabricated using the same resins. The specimens were all tested in uniaxial tension to determine whether there is a significant relationship between the properties of the composites and the matrix type or specimen shape. It was observed that the stress-strain curves of flax FRPs are nonlinear and can be simplified to a bilinear behavior. It was determined that the matrix type had a significant effect on the maximum tensile strength, but is not the source of the nonlinear behaviour. Additionally, 30 strands of the flax fabric were also tested in uniaxial tension. The results of these tests indicate that the source of the nonlinear behaviour could be the short length of flax fibres, however more research is required to quantify the source of nonlinearity.

1. Introduction

Interest in sustainable materials is increasing around the world. One new material type that is currently being studied is natural fibre-reinforced polymers (FRPs), specifically flax FRPs. Flax is a plant that is grown in many locations around the world and its fibres have moderate strength and stiffness [1]. In Canada, the use of the flax fibres is often over-looked and the fibres are mainly considered a waste product of the flax seed industry. An interesting property of flax FRPs reported by numerous authors is that stress-strain behavior is nonlinear [2][3][4]. The objective of this study was to determine the source of the nonlinear behavior of flax FRPs. It was first hypothesized that as flax fibres are weaker and less stiff than glass or carbon fibres, there is the potential that the matrix has a larger influence over the composite mechanical properties, specifically on the nonlinear properties of flax FRPs. Another hypothesis was that the nonlinear behaviour was influenced by the shape of the test specimens. Finally, the third hypothesis was that the source of the nonlinearity was the flax fibre material. A series of coupons were prepared and tested to evaluate the aforementioned hypotheses.

2. Experimental Study

A unidirectional flax fabric with a reported unit weight of 275 g/m^2 (gsm) was used. The technical fibre diameter, tensile strength and modulus were not available from the manufacturer, but are typically cited as 50 – 100 µm, 500-900 MPa and 50-70 GPa, respectively [1]. Three different resins, namely, West System Epoxy, Super Sap ONE Epoxy, and Altek General Purpose Polyester resin were used. West System Epoxy has a reported tensile strength, modulus and elongation of 50.33 MPa, 3.17 GPa and 4.596 %, respectively. Super Sap ONE has a reported tensile strength, modulus and elongation of approximately 53.23 MPa, 2.65 GPa and 6 %, respectively. Altek General Purpose Polyester Laminating Resin has a reported tensile strength, modulus, and elongation of 84 MPa, 3.9 GPa, and 3.6%, respectively.

A total of 45 tension coupons (9 groups x 5 identical specimens) were fabricated and tested. To manufacture the unreinforced specimens, the resin was first mixed with the hardener and placed into a vacuum chamber for degassing. The degassed resin was then poured into a template in accordance with ASTM D638 [5]. Both types of reinforced specimens started as a 300 mm by 300 mm square sheet of polymer reinforced with two layers of unidirectional flax fibres manufactured using the wet lay-up technique as shown in Figure 2a. After performing the wet lay-up, parchment paper was placed on top of the sheets and any additional resin and air was removed by a steel roller as shown in Figure 2b. After the sheets had cured, they were cut and made into either the tabbed specimen shape as prescribed by ASTM 3039 [6] or the dumbbell specimen shape as prescribed by ASTM D638 [5].

The specimens in this study were all tested in uniaxial tension at a rate of 2 mm/min using an Instron 8501 test frame. This testing rate was chosen as it satisfied the requirements for both ASTM D638 [5] for the dumbbell-shaped unreinforced and reinforced polymers and ASTM D3039 [6] for the tabbed reinforced polymers. The elongation of the coupons was measured using an Instron extensometer with a gauge length of 25 mm and a maximum travel of 25 mm in tension. To directly compare the data of the different reinforced specimens, a nominal thickness of 1 mm was used. The test results for the study are presented in Table 1.

Table 1. Mechanical properties of test specimens.

Group ID	Thickness (mm)		Tensile Strength (MPa)		Ultimate Strain (mm/mm)		Primary Modulus (GPa)		Secondary Modulus (GPa)		
	AVG	SD	AVG	SD	AVG	SD	AVG	SD	AVG	SD	Red.
E-R-D	1.74	0.03	186.0	14.8	0.0134	0.0011	18.95	0.42	12.66	0.60	66.8
B-R-D	1.53	0.11	159.5	14.0	0.0126	0.0008	16.46	0.96	11.45	0.37	69.5
P-R-D	1.36	0.07	144.1	4.9	0.0106	0.0006	17.83	2.00	11.09	0.68	62.2
E-R-T	1.66	0.07	192.5	7.6	0.0165	0.0025	17.49	2.41	10.73	1.34	61.4
B-R-T	1.97	0.09	198.0	9.3	0.0153	0.0006	17.09	0.63	11.93	0.39	69.8
P-R-T	1.57	0.02	167.7	6.7	0.0136	0.0011	17.74	2.48	10.83	1.05	61.1
E-U-D	2.95	0.42	55.6	0.6	0.0234	0.0005	3.84	0.06	N/A	N/A	N/A
B-U-D	3.49	0.29	57.9	0.4	0.0287	0.0018	3.20	0.13	N/A	N/A	N/A
P-U-D	4.07	0.37	48.4	4.8	0.0185	0.0032	3.55	0.37	N/A	N/A	N/A

AVG=average, SD=standard deviation, E=epoxy, B=bio-based epoxy, P=polyester, R=reinforced, U=unreinforced, D=dumbbell, T=tabbed, Red.=percent reduction, NA=not applicable.

3. Results and Discussions

As seen in Figure 1a, the flax FRPs displayed bi-linear mechanical behavior. It was hypothesized that the type of polymer would have an effect on the mechanical properties of the flax-FRPs, specifically on the secondary modulus. The mechanical behavior of the tabbed specimens was proven to be unaffected by the matrix type with 95% confidence by a single factor analysis of variance (ANOVA). Contrary to the results of the tabbed specimens, an ANOVA analysis with 95% confidence showed that the secondary moduli of the dumbbell specimens were affected by the matrix type. Another ANOVA analysis showed with 95% confidence that there was a significant difference in the maximum tensile strengths of the composites manufactured with different matrices for both of the specimen types. Also, a series of ANOVA analyses at 95% confidence were performed to determine if there was a significant difference in any of the mechanical properties between different specimen shapes. For both the bio-based epoxy and polyester specimens the maximum tensile strength was significantly reduced for the dumbbell type specimens when compared with the tabbed specimens of the same matrix type.

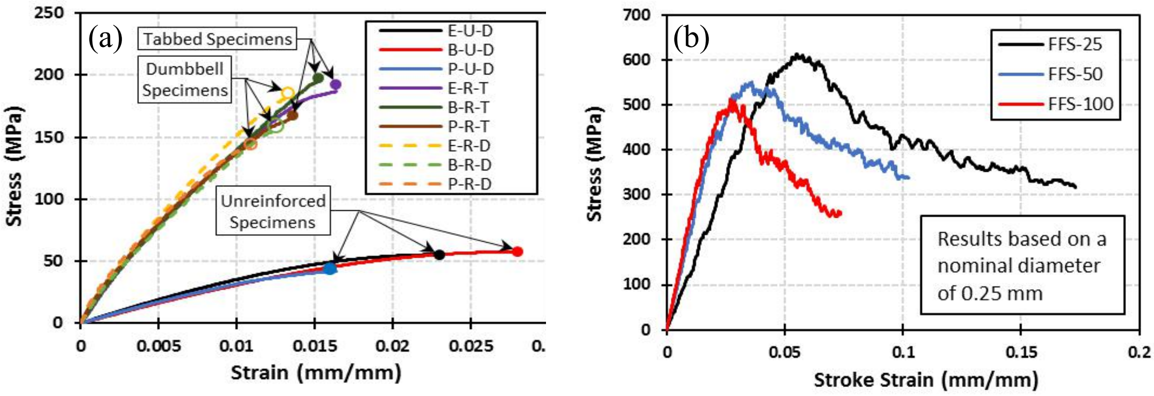

Figure 1. Stress-strain plots: (a) averages of all coupons (b) averages of fibre strands (FFS = Flax Fibre Strand, (25,50,100) = gauge length in mm).

Based on the analysis of the data, it was determined that the matrix type was not the source of the nonlinear behavior of the flax FRPs. While it was shown that, for the dumbbell specimens, the matrix type affected the secondary modulus, it was not the cause of the reduction in modulus. It was also determined that the specimen shape was not the source of the nonlinear behavior. Though, the specimen shape for the epoxy specimens seemed to have some effect, it was not the source of the nonlinear behavior.

A series of flax fibre strands, as seen in Figure 2e, were tested in uniaxial tension to determine whether the source of the nonlinear behavior was the flax fibres. Each fibre strand in the unidirectional fabric is a group of single short flax fibres bound together. A total of 30 strands were tested: 10 tests at three different gauge lengths. The stress was calculated using a nominal strand diameter of 0.25 mm and the strain shown in Figure 1b is based on the stroke of the test frame as a more accurate method was not available at the time. Three gauge lengths were selected to account for the fact that the single flax fibres within each strand are short. It was hypothesized that as the gauge length increased, the peak load would decrease due to the fact that at shorter gauge lengths, some fibres could span the full gauge length.

As shown in Figure 1b, each specimen tested reached a peak stress in the range of 500-600 MPa, after which the stress reduced while the strain continued to increase. These peak stresses are in agreement with the previously reported strengths in the range of 500-900 MPa [1]. The reduction in strength after the peak load could be indicative that the fibres are the source of the nonlinear behavior of the composites as this reduction in fibre strength could cause the reduction in the secondary modulus of a composite. A single factor ANOVA analysis was performed to determine whether there was a significant difference in the peak loads between the different gauge lengths. Due to the high variability of the results, the ANOVA analysis could not prove there to be any difference between the peak loads. However, looking at Figure 1b, there is a trend showing that as the gauge length increases, the peak load decreases. To more accurately compare the data, a new set of tests will include the diameter of the flax strands and a two-way ANOVA analysis will be performed.

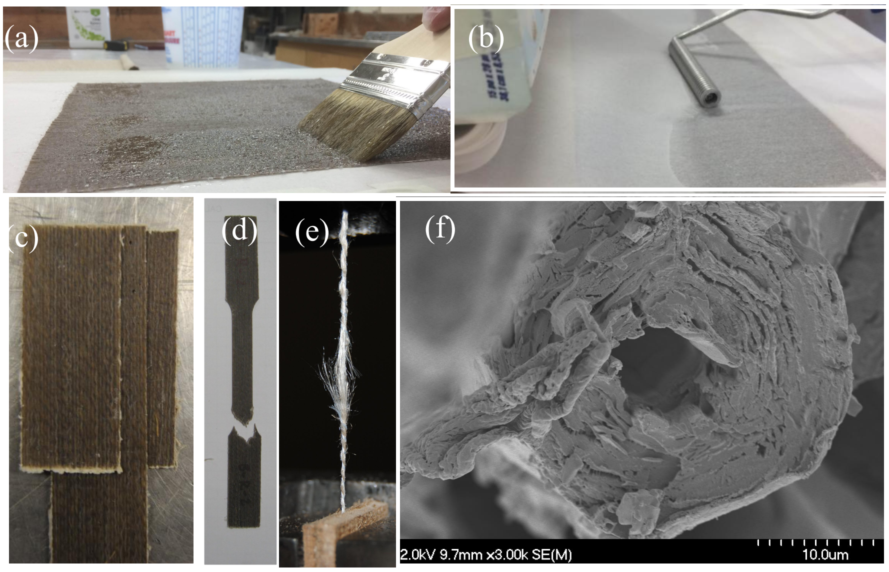

Figure 2 – Experimental procedure: (a) Applying epoxy (b) air removal (c) tabs before placement (d) tested reinforced specimen (e) tested flax fibre strand (f) SEM of tested flax FRP.

4. Conclusions

In this paper, a series tensile tests was performed on flax strands, pure polymer, and composite coupons in order to identify the source of materials nonlinearity. It was verified that the mechanical behavior of flax FRPs are nonlinear and can be simplified to an approximately bi-linear behavior. The primary modulus of the specimens is typically in the range of 16 to 19 GPa. The secondary modulus of each specimen was approximately two thirds of the primary modulus. The nonlinear mechanical behavior of the flax FRPs was not significantly affected by the matrix type or the specimen shape. It was determined that there is the potential that the nonlinear behavior is caused by the fibres. This is an ongoing research project. To further this research, the following tests will be performed: more strand tests including an accurate measurement of strand diameter and strain, uniaxial tension tests of single flax fibres, and strips of dry fabric will be tested in uniaxial tension.

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