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INFLUENCE OF DISPLACEMENT RATE ON MODULUS AND STRENGTH OF 2D KEVLAR® TUBULAR BRAIDED COMPOSITES

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ABSTRACT

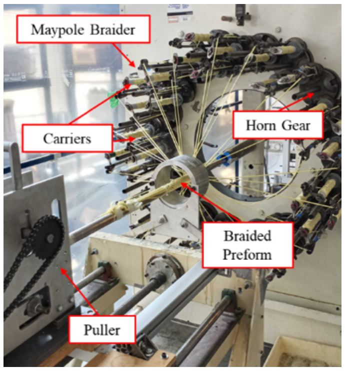
Tubular Braided Composites (TBCs) are manufactured by interlacing yarns on a cylindrical mandrel and curing the formed textile with an epoxy matrix. Although several studies have investigated the mechanical properties of TBCs, no studies have explored the influence of displacement rate on these materials. Displacement rate is hypothesized to influence the variation in the mechanical properties documented in the literature. In this preliminary experimental study, Kevlar®/epoxy TBCs were manufactured at three braid angles (35°, 45° and 55°) and tested in tension at three rates (1 mm/min, 2 mm/min and 6 mm/min). Stress-strain curves were plotted and used to calculate the elastic moduli and its deviation. Results from the study suggest that displacement rate does not have a significant effect on mechanical properties at lower braid angles. At higher braid angles, the influence of displacement rate is more pronounced. This is theorized to be a result of the influence of the matrix phase at these angles. Further studies investigating more braid angles and materials should be conducted to validate the initial findings.

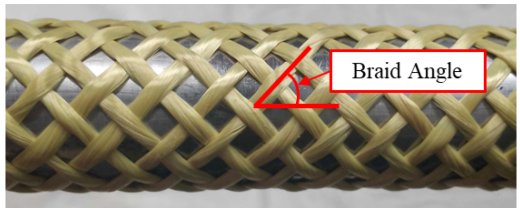
1 INTRODUCTION

Composite materials consist of two or more constituents joined together to produce a non-homogenous complex material with tailorable mechanical and physical properties. Braiding is a textile composite manufacturing technique in which three or more yarns are intertwined over the length of a mandrel to create a preform. Braided preforms are typically manufactured using a maypole braider. In these machines, carriers spooled with a fibrous material move along predefined paths. As the carriers move along the tracks, the yarns are deposited and interlaced on a translating mandrel to create the preform. Figure 1a shows a typical braiding manufacture line.

Once braided, the preform is impregnated with a matrix, typically a polymer, to form the final braided composite. Several manufacturing parameters influence the properties of the final braided composite. Of these parameters, braid angle is the most significant in determining the final tensile and compressive strength, stiffness and rigidity of the composite. Braid angle is defined as the angle formed between the yarns and the longitudinal axis of the braid. Figure 1b shows the braid angle labelled on a braided preform.

TBCs are the most common type of braided composites and are manufactured using a cylindrical mandrel. Due to their high specific strength and specific stiffness, TBCs have numerous applications including construction, sports, medicine, and aerospace. Figure 1c shows a typical TBC manufactured using the equipment shown in Figure 1a.





(a) (b) (c)

Figure 1. Images showing (a) a typical braided preform manufacturing line showing the maypole braider, horn gears, carriers, puller and the braided preform, (b) a preform with braid angle labelled and (c) a cured Kevlar®/Epoxy TBC.

2 LITERATURE REVIEW

The characterization of TBCs has been thoroughly explored in literature. These studies have investigated the tensile, compressive, torsional, creep and fatigue behaviour of TBCs[1–8]. One aspect not investigated is the large variation between samples, often exceeding 10%. An explanation for the variations in TBC properties is the testing procedure followed by studies. ASTM standard D3039 is typically followed to test and measure the tensile properties of polymer matrix composite materials. Section 11 of this standard describes the recommended procedure for conducting the test. For one parameter, "Speed of Testing", the standard document suggests selecting a rate "so as to produce failure within 1 to 10 min[utes]"[9]. This is a wide range of sample displacement rates.

The influence of displacement rate on the behavior of composite materials, most studies have looked into very high rates that mimic impact. May and Kilchert studied the effect of displacement rate on the in-plane shear stress of carbon fibre triaxial braided composites. Samples were manufacture at three different braid angles (30°, 45° and 60°) and tested at two strain rates (0.001 s^{-1} and 3 s^{-1}). The results showed that samples tested under higher strain rates had higher shear strength and more scattering in the data collected[10]. Böhr et al. experimentally investigated the strain rate dependent behavior of 2D biaxial and triaxial carbon fibre braided composites. Biaxial samples were manufactured at three braid angles (30°, 45° and 70°) and triaxial samples were manufactured at two braid angles (30° and 45°). Samples were tested at four different strain rates (2 mm/min, 10 mm/s, 100 mm/s and 1 m/s). The results of the study concluded that tensile strength and damage onset were significantly dependent on strain rate[11]. Jiang et al. investigated the influence of strain rate on the dynamic tensile properties of braided carbon fibre composites. Samples were tested at six strain rates (1 s^{-1}, 10 s^{-1}, 100 s^{-1}, 250 s^{-1}, 500 s^{-1}, and 800 s^{-1}). The study found that increasing strain rate resulted in an increase in tensile elastic modulus by 10-30% and tensile strength by 30-40%[12]. Some other studies have investigated the influence of strain rate on the properties of woven and laminate composites, but similarly high strain rates were used[13–16].

Although some studies have investigated the relationship between displacement rate and the tensile properties of composites, the tested strain rates are not reflective of the rates used during tensile testing of composites. Additionally, the results of the studies that have been conducted seem to indicate a relationship between testing rate and the elastic modulus and tensile strength, though the results are inconclusive. This relationship provides a plausible explanation for the variation seen in the experimental data collected from TBCs. Accordingly, the objective of this study is to experimentally investigate the influence of displacement rate on the elastic modulus of TBCs.

3 METHODOLOGY

3.1 MATERIALS

TBCs in this study were manufactured using 1420 den Kevlar® 49 fibres (DuPont, Wilmington, Delaware, USA), Epon 826 epoxy resin (Hexion, Ohio, USA) and Lindau LS-81K hardener (Lindau Chemicals Incorporated, South Carolina, USA). Material selection was based on the previous work done by Ead et al.[4].

3.2 TBC MANUFACTURING

Samples were manufactured following the procedure highlighted in previous work by Ead et al.[4]. Yarns were interlaced onto a 7/16-inch diameter aluminium mandrel. Preforms in this work were manufactured at three different braid angles (35°, 45° and 55°) in a diamond (one-over one-under) pattern. Epon 826 and LS-81K were mixed in a 1:1 ratio, massaged onto the preforms and cured vertically in an oven. After curing, samples were cut down to a length of 7 inches and their edges filed. Sample dimensions were measured and recorded using a microscopic gauge and a digital Vernier caliper.

3.3 SAMPLE PRE-TEST PREPARATION

Prior to testing, TBC samples were attached to steel end tabs using two-part epoxy (Henkel AG & Company, KHaA, Düsseldort, Germany) and left to fully set in for 24 hours. Samples were secured on an aluminium rail with hose clamps to ensure sample alignment during testing. To prepare samples for strain measurement during testing, settled samples were spray-painted in a black matte paint (Painter's Touch Flat Black, Rust-Oleum Corp, Concord, ON, Canada) and speckled with white paint (4230 Transparent White, Auto Air-Colors, East Granby, CT) using an airbrush (Paasche H Series, Paasche Air Brush Co., Chicago, IL). Air pressure and nozzle outlet size for speckling were selected to ensure sufficient speckle density and contrast for accurate strain measurement during the tensile test. Figure 2 shows a zoomed in image of the samples after painting and speckling.

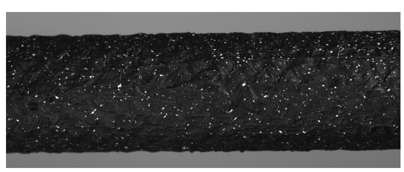


Figure 2. Zoomed in image of a 55° speckled TBC sample.

3.4 DISPLACEMENT-RATE PILOT STUDY

Prior to testing, a pilot study was run to ensure the tensile testing machine was calibrated and correctly output the displacement rate specified by the user. Furthermore, the pilot study was necessary to determine an acceptable range of displacement rate values that ensured samples failed within the specifications of ASTM standard D3039. Based on these pilot tests, three displacement rates were determined for this work (1 mm/min, 2 mm/min and 6 mm/min). These speeds have been used in characterization studies and also ensured that samples failed within 1-10 min of loading. For each testing configuration, three samples were to be tested.

3.5 TENSILE TEST AND STRAIN MEASUREMENT

Quasi-static testing of the samples was performed using an Instron tensile testing machine (Instron 1000, Instruments and Systems for Advanced Materials Testing, Canton, Massachusetts). To measure strain, a stereo digital image correlation (DIC) setup was used. DIC is a contact-free strain measurement method in which correlation fields are used to measure displacement of the sample. Two scientific cameras (Basler acA3800-10gm, Basler AG, Ahrensburg, Germany) were used to take images of the sample were taken at two-second intervals. Testing was conducted until sample experienced yielding or failure. Figure 3 shows a schematic of the setup used for applying loads at the specified displacement rates and collecting images for DIC.

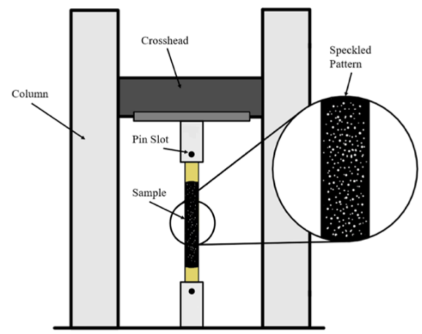
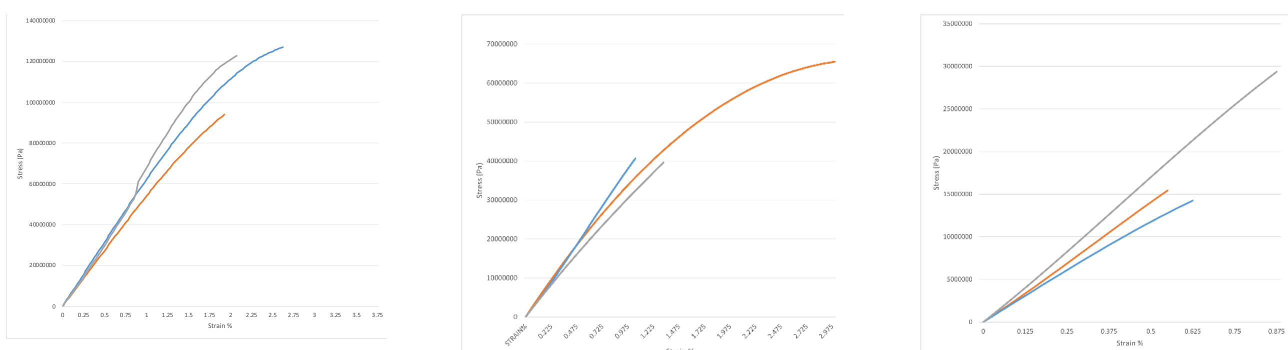


Figure 3. Schematic of experimental setup used for quasi-static tensile testing of TBC samples

4 RESULTS AND DISCUSSION

Strain data collected from DaVis® was matched to the stress data by using the time stamps from the MATLAB® code. Stress-strain curves were then plotted and averaged to produce a single plot. The averaged plot for each of the configurations is shown in Figure 4.



(a) (b) (c)

Figure 4. Averaged stress-strain plots for the (a) 35°, (b) 45° and (c) 55° TBCs. The colours of plots indicate displacement rates with blue representing 1 mm/min, orange representing 2 mm/min and grey representing 6 mm/min.

To calculate the elastic modulus for each sample, a regression-based formula was used following ASTM standard D3039. The calculated results are shown in Table 1.

Table 1. Average modulus values calculated from the tested tbc samples.

Braid Angle (°)	Displacement Rate (mm/min)	E_x (GPa)	s_x (GPa)
35	1	5.49	0.560
	2	6.32	0.438
	6	5.91	0.453
45	1	3.74	0.364
	2	3.67	0.243
	6	3.24	1.20
55	1	2.83	0.135
	2	2.41	0.581
	6	3.40	2.11

The stress-strain plots in Figure 3 coupled with the values in Table 1 describe the typical behavior of TBC under tensile testing. As can be seen, the longitudinal elastic modulus is higher at lower braid angles and decreases as the braid angle increases. The influence of displacement rate on the elastic modulus of TBCs can also be observed from Table 1. The average elastic modulus values seem to be independent of the displacement rate. Within a particular braid angle, displacement rate does not result in a clear increase or decrease in the averaged elastic modulus values. The data, however, suggests that displacement rate can influence the variation between the samples. The standard deviation for the 45° tested at 6 mm/min is 1.20 GPa (compared to 0.364 GPa and 0.243 GPa at 1 mm/min and 2 mm/min respectively) and for the 55° tested at 6 mm/min is 2/11 GPa (compared to 0.135 GPa and 0.581 GPa at 1 mm/min and 2 mm/min respectively). These preliminary results indicate that at higher braid angles the influence of displacement rate on the variation is more pronounced. At higher braid angles, the matrix has a more significant impact on the overall behavior of the composite. The results from the study might provide an explanation for the variation documented in the tensile properties of braided composites. Samples tested with higher displacement rates may exhibit higher variation due to the more pronounced contribution of the viscoelastic matrix phase. These results seem to support the findings in the literature, however, further experimental work and analysis is required to verify these initial findings[15].

5 CONCLUSION

Although the tensile behavior of TBCs has been thoroughly investigated in literature, documented properties of these materials exhibit large variations. These variations often exceed 10% for identical samples. The purpose of this study was to investigate the hypothesis that testing rate influences the tensile properties of TBCs. TBC samples were manufactured at three braid angles (35°, 45° and 55°) and tested in tension at three displacement rates (1 mm/min, 2 mm/min and 6 mm/min). Load and extension data were collected and used to plot stress-strain curves and calculate the elastic moduli of the tested samples. Initial results from this work suggest that displacement rate does not have a significant effect on TBCs at lower braid angles. At higher braid angles tested in this work (45-

degrees and 55-degrees), no significant difference in deviation was noted for the 1 mm/min and 2 mm/min displacement rates. At the higher displacement rates of 6 mm/min, deviation increased significantly to 37% for the 45-degree braids and 62% for the 55-degree braids. These large deviations at the higher displacement rate are theorized to be a result of the pronounced effect on the matrix phase of the composites. The results of this work suggest that this manifests as increased scatter of the data. When measuring the elastic properties of 2D TBCs, the initial results of this work indicate that higher displacement rates of 6 mm/min should be avoided to reduce data scatter.

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