ENGINEERING PROPERTIES OF CARBON/EPOXY FILAMENT WOUND UNIDIRECTIONAL COMPOSITES

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Abstract

The aim of this study is to evaluate the engineering constants and strength properties of unidirectional carbon/epoxy composite laminates manufactured by dry filament winding process. After winding, the laminates were cured aided by hot compression. The composites were cut along the fiber direction (0°) and transversely to it (90°). Tensile modulus and Poisson's ratio were measured by using longitudinal and transverse extensometers. Most of the independent elastic constants, major and minor Poisson's ratio and strength properties were obtained, except those related to shear, which were estimated through micromechanical analysis.

1. Introduction

Carbon fiber reinforced polymers (CFRP) are widely used in structural applications for the automotive, oil & gas, wind power, sports and aerospace sector [1]. In spite of their high cost, they are becoming widely employed due to advantages like high specific properties and good damage tolerance [2]. Filament wound parts, in special, attract much attention of the aerospace field and other strength critical applications like high-pressure vessels, commonly applied in rocket motor cases, fuselages, and other structural parts of aircrafts. In general, it can be used to produce nearly any geometry of revolution except those with concave contours [3].

In the filament winding (FW) process, a certain number of filaments are pulled by tensioners and wetted in a resin bath (with curing agent included), and then wound onto a rotating mandrel. Afterwards, the material is cured (in an autoclave or oven) and the wound composite is removed from the mandrel (excepted when the mandrel is a liner). This describes the wet winding variant [4]. By contrast, in dry winding, pre-impregnated filament yarns (towpregs) are wound directly onto the mandrel, leading to advantages like reduction in process time, greater reliability and cleanliness [1].

The production of flat laminates by filament winding is not customary, since there are several composite manufacturing process more readily available for that, even though most of them are not be able to work with towpreg. But there is the need for comprehensive material properties evaluation to properly analyze the mechanical behavior of complex-shaped parts, such as cylindrical, spherical, elliptical and other shapes characteristic of composite overwrapped pressure vessels (COPV) and pipes. In these cases, accurate modelling based on finite element method (FEM) is required to understand their overall behavior under particular loading and boundary conditions.

For the numerical modelling of a composite structure, a set of input parameters is required: i) Engineering constants (elastic properties): Tensile modulus in the fiber direction ($E_{t,1}$), tensile modulus transversely to the fiber direction ($E_{t,2}$), compressive modulus in the fiber direction ($E_{c,1}$), compression modulus transversely to the fiber direction ($E_{c,2}$), in-plane shear modulus (G_{12}), major Poisson's ratio (ν_{12}) and minor Poisson's ratio (ν_{21}); and ii) Strengths: longitudinal and transversal tensile strength ($\sigma_{1,t}$ and $\sigma_{2,t}$, respectively), longitudinal and transversal compression strength ($\sigma_{1,c}$ and $\sigma_{2,c}$) and in-plane shear strength (τ_{12}). Some of them are sometimes obtained mathematically or via simplifications.

Morais et al. [5] manufactured glass/polyester flat laminates by wet filament winding process and measured their mode II interlaminar fracture properties, aiming to represent a COPV's behavior, but they considered curved specimens which hinders the measurement of these properties. Ozdil et al. [6] produced glass/epoxy flat filament wound composites and measured their mixed mode delamination growth to represent the behavior of a glass/epoxy composite pipe. Literature studies focusing on the testing of flat laminates manufactured by filament winding to generate engineering properties are difficult to find.

Thus, the scope of this study is to manufacture flat carbon/epoxy composites by dry filament winding process, aiming to generate representative elastic and strength properties to be used for complex shapes, specifically COPV and composite pipes. The mechanical properties were achieved through tensile, compressive and in-plane shear tests.

2. Materials and methods

2.1 Materials & Composite manufacturing

Carbon/epoxy towpregs from TCR Composites were used in this work. The carbon fiber is Toray T700-12K-50C and the resin system is UF3369. The flat laminates were manufactured on top of a stainless steel rectangular mandrel (Figure 1) using a KUKA robot KR 140 L100 with control and peripheral devices from MFTech. The delivery eye is able to process up to four towpregs simultaneously. The design and manufacturing of the laminates were aided by CADWind2007, which is a CAD and CAM software for filament winding. It converts data input containing all the winding parameters into a simulated model, which can be used for designing and manufacturing optimization. This simulation is then post-processed into a KRL (Kuka Robot Language) code and transferred to the robot.

One of the main reasons why manufacturing simulation is required before processing is that it can predict, and help solving, common problems inherent to filament winding such as fiber slippage, angle deviations and thickness variations. The unidirectional composites with constant fiber volume fraction of ≈70% (experimentally measured following ASTM D3171-11, by digestion with sulfuric acid) were cured by hot compression under 3 ton, for 150 min with heating rate of 3 °C/min, from 25 °C to 125 °C.

Figure 1. Manufacturing of a flat laminate by filament winding process.

2.3 Characterization

The unidirectional composites were cut by water jet, longitudinally and transversely to the fiber direction. All mechanical testing were carried out using an Instron 3382 universal testing machine with a 100 kN load cell.

Tensile testing at constant speed (2 mm/min) of six tabbed samples of controlled geometry dimensions were made following ASTM D3039-08. From this test, the elastic moduli, tensile strengths and Poisson's ratio were obtained. The specimens were tested with two analogical coupled extensometers, one longitudinal and another transversal, which were removed prior to rupture.

The compressive strength was obtained with the combined loading compression (CLC) test according to ASTM D6641-09 in 4 tabbed specimens. The size of the specimens was 140 mm × 12 mm × 1.4 mm, the gauge length was 12 mm and with speed rate of 1.3 mm/min. The in-plane shear properties were characterized using the V-notched rail shear method (ASTM D7078-12), which is recommended for high-modulus fiber-reinforced composite materials. The specimen had 76 mm × 56 mm × 1.4 mm dimensions and was centrally V-notched on both sides. The notch angle is 90° and the radius is 1.3 mm. Speed rate was 1.5 mm/min with 6 samples.

3. Results and discussion

3.1 Tensile properties

Figure 2 shows the stress-strain curves of the tensile specimens tested longitudinally and transversely to the fiber direction. The elastic moduli were collected by the ratio stress/strain ($\Delta\sigma/\Delta\varepsilon$) at a strain range of 0.1-0.2%. All curves show a linear behavior in the range of interest, with similar slopes, as confirmed by the calculations of elastic modulus, $E_{1,t} = 129.8 \pm 5.6$ GPa and $E_{2,t} = 9.1 \pm 0.5$ GPa, which presented low standard deviation. It is valid to mention that these values were considered low, which were credited to the condition of the pre-impregnated material. Indeed, they must be kept under a controlled temperature (typically −18 °C) and for a limited period of storage, which did not happen in this case. For comparison, Hocine et al. [7] reported $E_{1,t}$ = 150 GPa and a $E_{2,t}$ = 11 GPa, for the same T700 towpreg used in this work.

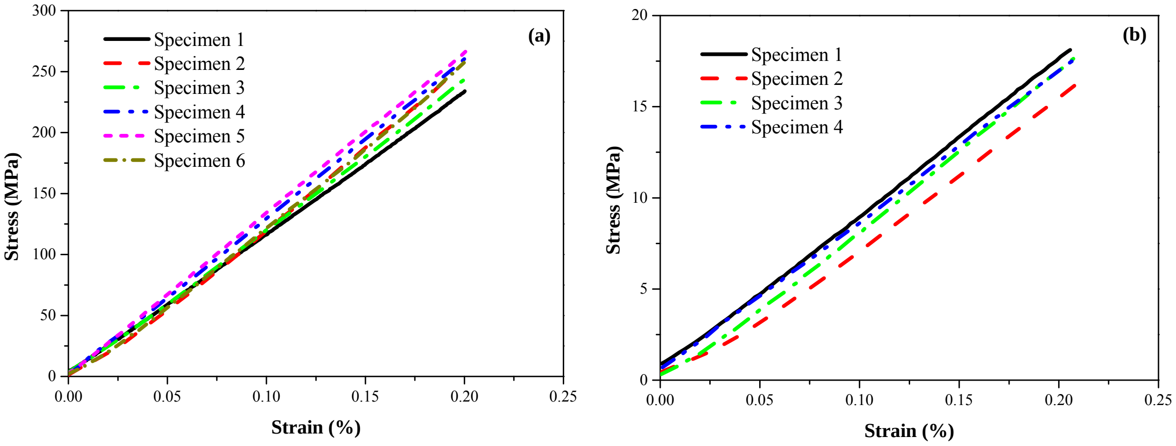

Figure 2. Stress × strain curves of the tensile testing in 0° (a) and 90° (b) directions.

Figure 3 presents the longitudinal (ε_1) and transverse (ε_2) strains obtained for the studied composites. For the 0° laminates, a more linear shape of the curves is noted, since ε_1 is much higher than ε_2 leading to a more consistent relationship between strains. The major Poisson's ratio (ν_{12}) is given by the $\Delta\varepsilon_2/\Delta\varepsilon_1$ ratio in the range of 0.1-0.2%, and then the average of 6 specimens tested pointed to $\nu_{12} = 0.31 \pm 0.02$. For unidirectional laminates, the ν_{21} is not easy to estimate, because the strain is of much lower magnitude. Indeed, this evaluation is considered not as accurate as those of the other elastic constants. Even so, the ν_{21} experimentally measured (0.020 ± 0.001) pointed to values very close to those estimated mathematically through the correlation $\nu_{21} = \nu_{12} \times E_2/E_1$ (i.e. 0.021).

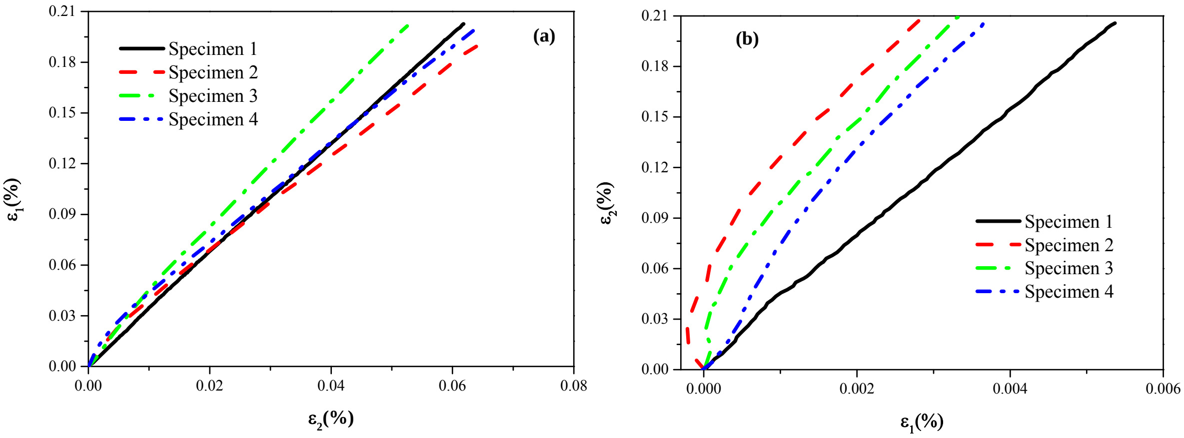

Figure 3. Plot of the longitudinal × transversal strains for determining the major (a) and minor (b) Poisson's ratio.

The overall aspect of the failed specimens is shown in Figure 4. The breaking load was around 25000-35000 N and 800-1000 N, for the 0° and 90° laminates, respectively, leading $\sigma_{1,t} = 1409.9 \pm 131.6$ MPa and $\sigma_{2,t} = 42.5 \pm 3.3$ MPa.

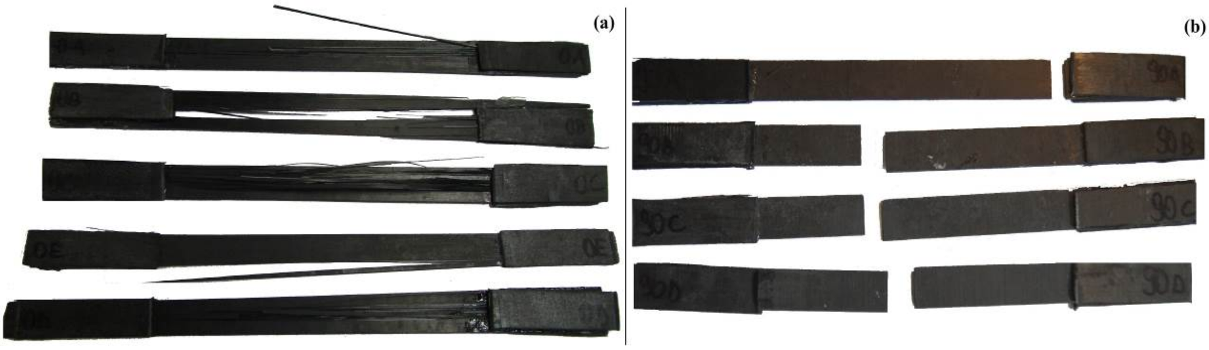

Figure 4. Photographs of the fractured tensile specimens for 0° (a) and 90° (b) specimens.

3.2 Compressive properties

The load × displacement curves from the compression tests for the 0° (Figure 5(a)) and $[90]_2$ (Figure 5(b)) are presented. Since strain gauges were not available for testing, the displacement shown was obtained directly from the movement of the testing machine and therefore was not used to calculate modulus. Thus, the compressive moduli were considered the same as the tensile ones.

In addition, for the 0° specimens, some crushing in the tab region was noticed, which were credited to the use of thin tabs in thin specimens, whereas the 90° specimens presented acceptable failure, in accordance to the referred standard. The observed failure (see Figure 6) were all within the gage section (between the tabs), being characterized as TAT (transverse shear at grip top) and HAT (through-thickness at grip top). The $\sigma_{1,c}$ and $\sigma_{2,c}$ values were 520.0 ± 41.4 and 103.3 ± 2.4, respectively.

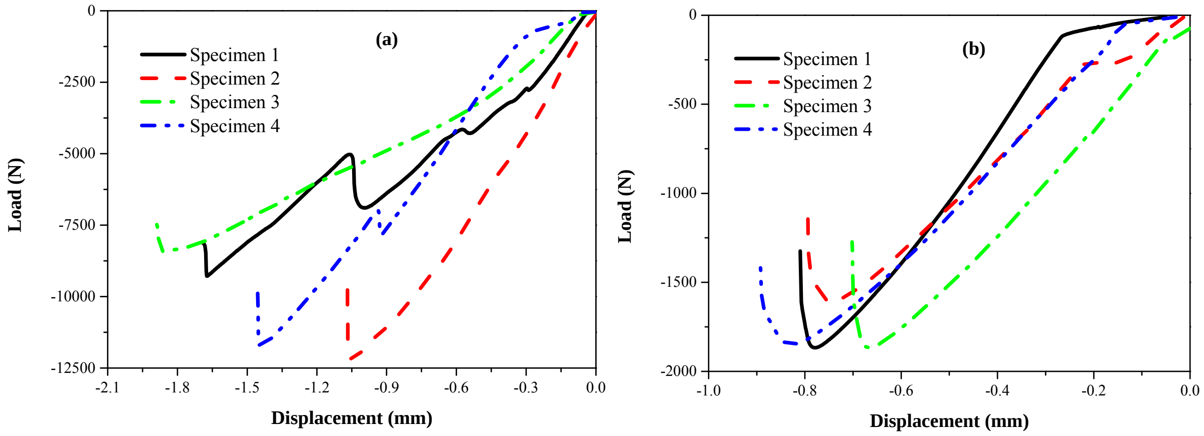

Figure 5. Load × displacement curves of the compression tests used for determining $\sigma_{1,c}$ (a) and $\sigma_{2,c}$ (b).

Figure 6. Photographs of the fractured 90° specimens under compression.

3.3 Shear properties

For the V-notched shear test, inconsistent load displacement curves were obtained for these thin specimens (Figure 7). Observation of the fractured samples indicates that no acceptable failures (as determined by ASTM D7078) were obtained (Figure 8). For instance, most of the specimens failed on the top and bottom of the samples, which can be characterized as VSE failure (vertical cracking on the side region at the top/bottom edge). A strong influence of buckling was observed during testing of these thin specimens (around 1.4 mm) leading to non-representative results. Taking into account only the 3 top curves in Figure 7, the obtained τ_{12} was 74.6 ± 0.9 MPa, which is very close to 70.0 MPa reported in [7].

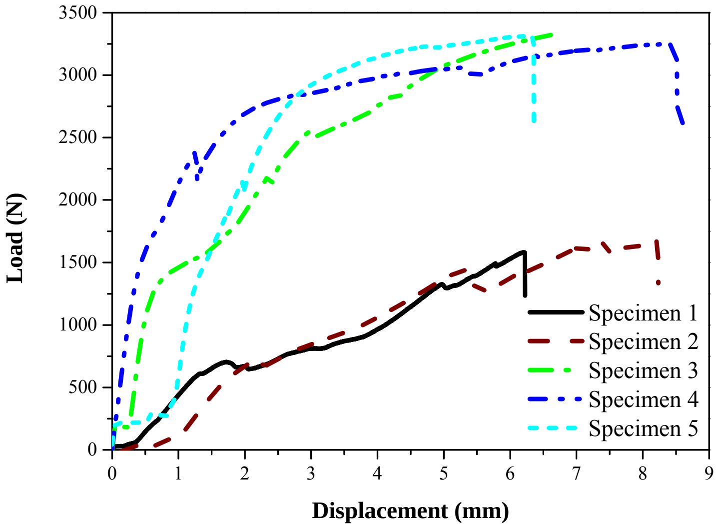

Figure 7. Load × displacement curves of the V-notched shear test specimens.

Considering that proper results could not be obtained from the V-notched test, G_{12} was determined using a micromechanical approach [8]. Based on $G_{12} = \dfrac{E_{t,2}}{2\times\left(1+\nu_{12}\right)}$, the in-plane shear modulus was calculated as 3.16 GPa.

Table 1 shows a compilation of the engineering properties which were obtained or calculated in this work.

Figure 8. Photographs of the fractured V-notched shear test specimens.

Property	*Average*	*Standard deviation*	*Coefficient of variation*
$E_{1,t}$ (GPa)	129.79	5.61	0.03
$E_{2,t}$ (GPa)	9.11	0.49	0.02
$E_{1,c}$ (GPa)	129.79	5.61	0.03
$E_{2,c}$ (GPa)	9.11	0.49	0.02
G_{12} (GPa)	3.16	--	--
ν_{12}	0.31	0.02	0.26
ν_{21}	0.021	--	--
$\sigma_{1,t}$ (MPa)	1409.9	131.6	0.09
$\sigma_{2,t}$ (MPa)	42.5	3.2	0.08
$\sigma_{1,c}$ (MPa)	520.0	41.4	0.08
$\sigma_{2,c}$ (MPa)	103.3	2.4	0.02
τ_{12} (MPa)	74.6	--	--

Table 1. Engineering properties of the flat filament wound laminate.

4. Conclusions

The scope of this study was to obtain the engineering properties of carbon fiber reinforced epoxy unidirectional composites manufactured by filament winding and using carbon/epoxy T700-12K towpreg as raw material. The laminates were cut longitudinally and transversely to the fiber direction, and were characterized by tensile, compression (combined loading compression method) and in-plane shear (V-notched rail shear method) tests.

Analogical extensometers in tensile testing were used for accurately determining the elastic properties. The compression tests presented generally good results, especially for the $[90]_2$ composites, with failure within the gauge section and following acceptable failure modes as suggested by the standard. However, the shear test did not provide consistent results. The negative results obtained were in great part caused by the use of a very thin specimen and the lack of proper tabbing in some cases. Therefore, micromechanics was used to estimate some of the properties. The obtained set of values will be later used for numerical simulation studies.

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