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Material properties

Scaling effect on the tensile properties of [±45/0/±45/0/±45] Polypropylene/Twaron laminates

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ABSTRACT

The effects of scaling on the mechanical response under tension of balanced nonsymmetrical laminates were investigated for a thermoplastic composite: Polypropylene reinforced with Twaron® fibers. The composite baseline was an 8-ply laminate which consisted of unidirectional plies arranged in the sequence [±45/0/±45/0/±45]. The influence of specimen size on the tensile properties was studied for one (thickness), two (in-plane) and three (volume) dimensional scaling. The stress-strain curves suggested some variation in laminate behavior owing to the dimensional scaling; nevertheless, a further analysis with the classical lamination theory demonstrated that the observed effect was due to small variations in the fiber volume fraction of the laminates. It was concluded that the mechanical properties of these thermoplastic laminates do not exhibit scaling effects. The failure mechanism of the laminates was studied at macroscopic level; a scale effect of the fracture mechanism was observed.

1. Introduction

Environmental concerns have led to a strong interest in the development and use of thermoplastic composites for structural applications due to their recyclability. The development of a thermoplastic composite based on a polypropylene matrix reinforced with Twaron fibers and the route for its manufacture have been established [1,2]. Some modeling of the mechanical behavior of PP/Twaron laminates has been published [3,4], which is useful to predict the elastic and plastic response under tension of this thermoplastic composite. However, a further step may be required to validate the design phase of new components, namely, the evaluation of small scale models to predict the behavior of a full size prototype. Predicting the behavior of full scale prototypes from experimental results on small scale models is a powerful tool to identify possible corrections to the design before full scale manufacture; however, composite materials often exhibit scaling effects, in which the mechanical properties of the model and the mechanical properties of the prototype present some variation due to their difference in size. Therefore, the performance of full scale prototypes from small scale data requires that the material's scaling effects be known and included in the analysis to establish a correspondence between the model behavior and the behavior of the prototype.

A comprehensive review on the topic of scaling effects in composites has been presented by Sutherland and Shenoi [5,6]. Most research on scaling effects in composites has been undertaken in the aerospace field, involving carbon/epoxy thermoset systems. Reports in the literature do not follow a particular study pattern; often the phrase “scaling effects in composite materials” is used to refer to a variety of properties, methods, test parameters and material systems. Considering these facts, it is not uncommon to find contradictory results [7–10]. The Weibull theory [11] has proved useful, within certain limits, to describe the scaling effects of unidirectional composites; however, the simple

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laws for scaling models become inappropriate in the case of composite laminates since the scaling effects are complex [12].

Martin-Barrera and Gonzalez-Chi have found scaling effects in symmetrical and balanced $[\pm 45]_{2nS}$ PP/Twaron laminates [13]. Nevertheless, for some composites, the scaling effects are more evident in laminates in which the load is carried by off-axis plies than for laminates with a high percentage of 0° plies [14]. Hence, the present paper addresses the effects of the dimensional scaling on the tensile properties of PP/Twaron laminates with a stacking sequence $[\pm 45/0/\pm 45/0/\pm 45]_n$ where the 0° plies carry most of the applied load.

2. Experimental procedure

2.1. Materials

The thermoplastic laminates were molded with polypropylene (VALTEC from INDELPRO) reinforced with continuous aramid fibers (TWARON 2200 from TAIJIN). The PP was supplied in the form of pellets and its specific weight was 0.9 g/cm^3. The Twaron fiber was supplied in the form of filament yarn with a monofilament diameter of 12 μm and specific weight of 1.45 g/cm^3. Table 1 presents the average mechanical properties of these constituent materials.

2.2. The scaling program

Table 2 shows the scaling program used to determine the tensile behavior of the PP/Twaron laminates as a function of their dimensional scaling. Nine specimens were tested at each scaling level. An 8 ply laminate with the stacking sequence [±45/0/±45/0/±45], nominal thickness of 1.3 mm and in-plane dimensions 1x = 120 mm gage length × 25 mm width was designated as the baseline composite (denoted as "8 layers 1x" in Table 2). Scaling in one dimension (thickness) was studied, increasing the stacking sequence of the baseline to $[\pm 45/0/\pm 45/0/\pm 45]_2$ and $[\pm 45/0/\pm 45/0/\pm 45]_3$, denoted in Table 2 as "16 layers 1x" and "24 layers 1x", respectively. The thickness of the 16 and 24 layer laminates was set to 2.6 and 3.9 mm, respectively. Scaling in two dimensions was carried out by increasing the gage length and width of the 8 layers baseline to the dimensions 2x and 3x specified in Table 2. The tridimensional scaling program was accomplished by increasing the number of layers (thickness) and the in-plane dimensions simultaneously as shown in Table 2.

Table 1
Mechanical properties of Twaron fiber and PP matrix.

Property	Fiber	Matrix
Young's modulus	113.90 GPa	1.56 GPa
Shear modulus	42.20 GPa	0.57 GPa
Poisson's ratio	0.35	0.38
Ultimate stress	3.01 GPa	25.5 MPa
Ultimate strain	3.01 %	304 %

2.3. Molding of the laminates

The PP was ground and the Twaron yarn was impregnated with the powder in a continuous impregnation line using the dry powder impregnation method. The nominal fiber weight fraction at the impregnated yarn (preform) was 0.15 g/g, equivalent to a fiber volume fraction in the composite of 0.1 cm^3/cm^3. The preform was cut and fitted into the mold; each layer of the laminates was stacked in accordance with Table 2. The laminates were compression molded at 230 °C for 30 min with no pressure and for a further 3 min at 40 kPa. The mold was then cooled gradually for 20 min to room temperature and the composite was removed from the mold.

2.4. Tensile tests

The specimens for the mechanical characterization were cut from the molded laminates with a band saw and the edges were polished to eliminate any irregularities. Fig. 1 shows the specimen geometry and dimensions of the scaled samples. Dimensions of the baseline specimen are according to ASTM D-3039 for the mechanical characterization under tension of polymer composites reinforced with continuous fibers.

Tensile tests were performed according to ASTM D-3039 in a Shimadzu universal testing machine (model AG-1). The crosshead speed was set for the different specimen sizes to obtain a strain rate of 8.33×10^{-3} min^{-1} in all specimens. The tensile load and strain were simultaneously monitored to estimate tensile strength and Young's modulus of the laminate specimens. The extensometer's knife edges could only fit the specimens 1x, consequently, specially designed knife edges were made from aluminum for the 2x and 3x specimens.

2.5. Composite fiber content

Sections of 25 × 45 mm were cut from the tested laminates, taking care not to select the fractured zone of the specimens. The samples were dried to a constant weight by removing moisture in a convection oven. The PP matrix was removed from the samples with a Soxhlet extractor using xylene (120 °C) as solvent; after removing the PP, the remaining fiber was dried to constant weight. The fiber volume fractions of the laminates were calculated from the weight of the dry samples and the fiber specific weight (1.45 g/cm^3).

2.6. Morphological study of the fractured specimens

The process of deformation and failure of the scaled laminates was recorded with a video camera during testing. After the test, a stereo microscope MOTIC was used to observe evidence of the initiation and propagation of the failure in the fractured specimens; the microcracks and fractures were observed with a 10x objective and reflected light.