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Measurement of the *in situ* transverse tensile strength of composite plies by means of the real time monitoring of microcracking

T.A. Sebaey [b,c,*], J. Costa [a], P. Maimí [a], Y. Batista [a], N. Blanco [a], J.A. Mayugo [a]

[a] AMADE, Polytechnic School, Universitat de Girona, Campus Montilivi s/n, 17071 Girona, Spain
[b] Mechanical and Industrial Department, College of Engineering, Qatar University, P.O. Box 2713, Doha, Qatar
[c] Mechanical Design and Production Department, Faculty of Engineering, Zagazig University, P.O. Box 44519, Zagazig, Sharkia, Egypt

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ABSTRACT

Failure of a ply due to transverse loading is one of the mechanisms that was taken into account in physically-based failure criteria, used in composites design. However, experimental data are scarce and the measurement techniques used in the past are time consuming and involve a lot of specimen handling during testing. While some physical information is currently well consolidated (such as the dependence of the strength on ply thickness, or *in situ* strength), there still remain relevant open questions. This work presents a methodology, which does not interfere with the tensile test, to detect transverse cracks by optical means. Four different configurations of CFRP are considered. The results show that the *in situ* strength depends on the thickness of the ply and the orientation of the adjacent layers. In the case of thick transverse plies, the strength is controlled by full-width transverse cracks whereas, in thin plies cracking parallel to the specimen's mid-plane occurs before transverse matrix cracking.

1. Introduction

The popularity of laminated composites in the aerospace and aircraft industries evokes the need for reliable and accurate simulation techniques. simulation accuracy depends on correctly defining the properties of a material. One of the terms that determine the damage onset in the progressive failure analysis of laminated composites is the *in situ* strength, and is defined as the strength of the ply when taking into account its thickness, its position in the whole laminate and the stiffness of the adjacent plies (see for example the models developed in [1–4]).

To measure the transverse *in situ* strength, the specimen must be designed to have a 90° ply in the middle of the laminate and be surrounded by plies of other orientations at the surface. In the late 1970s, Bailey and co-authors [5–9] studied the formation of microcracks in $[0_m/90_n]_s$ laminates of both glass and carbon fiber reinforced thermoset composites. For specimens with a thick 90° layer, the first decrease in stiffness corresponded to the formation of transverse cracks. On the other hand, for specimens with a thin 90° layer the transverse cracks were not the driving force behind stiffness reduction. For specimens with a very thin 90° layer (0.1 mm) no transverse cracks could be observed up to failure.

In the past the methodology techniques used to observe microcracks have included acoustic emission [7,8], X-ray radiographic inspection [10–13], electronic speckle pattern interferometry [14,15], video microscope [16] and embedded piezoelectric actuator [17]. Most of these techniques are based on measuring the initiation of cracking by loading and then unloading the specimen for inspection. Such methodology is time consuming. In addition, unloading and handling of the specimen during inspection could cause some damage to the instantaneous state of the specimen. Moreover, the use of these results to validate *in situ* strength criteria and/or damage models is limited by the lack of a complete set of material properties.

This paper aims to present a simple technique for measuring the *in situ* transverse tensile strength of an embedded 90° ply as a function of the ply thickness and the stiffness of the neighboring plies. Neither unloading nor handling the specimen for inspection is required. The technique is applied to characterize the *in situ* strength of a carbon fiber composite commonly used in aeronautic structures. Once the experimental technique has been described and the obtained results presented, the concordance of the data with the existing analytical models is discussed. The agreement between both of them supports the usefulness of this technique, in spite of the fact that the monitored area of the specimen is only its edge.

* Corresponding author. Current address: Mechanical and Industrial Department, College of Engineering, Qatar University, P.O. Box 2713, Doha, Qatar. Tel.: +974 66816364.
E-mail addresses: sepaey@hotmail.com, sepaey@qu.edu.qa (T.A. Sebaey).

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2. Methodology

2.1. Material and stacking sequences

The material used in this study was a carbon/epoxy material, Hexcel M21/T800, widely used in aeronautic structures. The pre-impregnated plies were laid in the desired configuration and cured according to the Hexcel's specifications. Once the specimens had been cured at 180 °C in an autoclave they were then cut into their final dimensions with a diamond disk. The unidirectional elastic properties and strengths were measured according to the corresponding ASTM standards in the testing laboratory at the University of Girona (ISO 17025 and NADCAP – "Non-Metallic Materials Testing" accredited), Table 1. The thermal and fracture properties were taken from the literature [18,19].

Four symmetric and balanced stacking sequences were selected; $[\pm 45/90]_s, [\pm 45/90_2]_s, [\pm 45/90_4]_s$ and $[0_2/90_4]_s$. The first, the second and the third laminates were used to check the effect of the thickness of the 90° layer with the same adjacent layers (±45°). The third and the fourth laminates were used to check the effect of the orientation of the adjacent layers for the same 90° layer thickness. The specimens were 180 mm long and 30 mm wide.

After being cut and measured, the specimens' sides were polished. The polishing process was performed under wet conditions with medium grit (474 mesh) followed by fine grit (1200). Then the specimens were placed in a furnace for 1 h at 50 °C and finally, stored in silica desiccator, to prevent any moisture uptake. Three specimens for each configuration were tested.

2.2. Test procedure

The specimens were loaded using a universal testing machine (MTS INSIGHT100) with a 100 kN load cell. The longitudinal strain was measured using an axial extensometer (MTS 634.25 F-24) with 50 mm gage length and 50% maximum extension. An 18 Megapixel Canon digital camera (EOS 550D) with macro-lenses (100 mm f/2.8 Macro L IS USM) was used to monitor 40 mm of the specimen edge (the middle of the zone between the grips). A picture was taken every 5 s with the aid of the camera's Software Development Kit (SDK) which was connected via a USB port to a PC.

The precision of the resulting image resolution enabled any transverse cracks to be identified. Fig. 1 shows an example of the images obtained in both reduced and full resolution.

The specimen was loaded at 1.0 mm/min. During loading, the camera took a picture every 5 s, which equates to an image approximately every 500 με. The process continued, uninterrupted, until the final failure of the specimen (neither stop nor unloading was required). The image acquisition was synchronized with the reading of the load and the strain from the testing machine, so that each image could be easily attributed to the load and strain on the specimen at the moment where the picture was taken. The number of cracks within 30 mm of the specimen edge were counted throughout the loading history and the crack density (number of cracks per unit length) was calculated.

Table 1
M21/T800 carbon/epoxy unidirectional properties.

Elastic properties	$E_1 = 130.7$ GPa; $E_2 = 8.01$ GPa; $G_{12} = 3.95$ GPa; $\nu_{12} = 0.35$
Strength	$Y^T = 40.5$ MPa; $S^L = 69.6$ MPa
Thermal properties	$\alpha_1 = 2.1$ με/°C; $\alpha_2 = 24$ με/°C
Fracture properties	$G_{Ic} = 250$ J/m^2; $G_{IIc} = 500$ J/m^2
Nominal ply thickness	0.184 mm

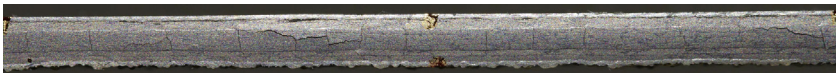
2.3. Calculations of the in situ strength

In order to obtain the *in situ* strength from the experimental data, the procedure summarized in [10], which is based on the Classical Lamination Theory (CLT), was used. CLT takes into account the thermal induced stress caused by the curing process. They should be estimated based on the difference between the room temperature (T_r) and the stress free temperature (T_{sf}). These stresses are highly dependent on the curing temperature [20,21]. At curing temperature, the laminate cannot be considered as stress free due to the existence of chemical residual stresses. The value of T_{sf} is usually 15 °C higher than the curing temperature [22]. Through the current analysis, the value of 195 °C was used as T_{sf} and, consequently, the value of ΔT was −172 °C ($\Delta T = T_r - T_{sf}$ where $T_r = 23$ °C).

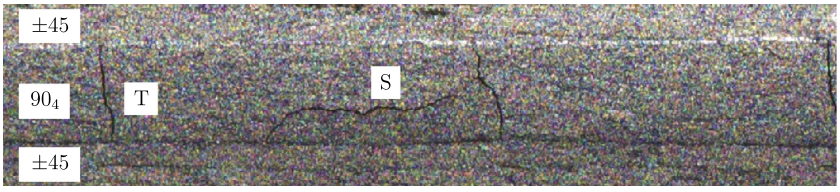
3. Results

To illustrate the outcome of the experimental methodology described above, Figs. 2 and 3 show some of the sequences of pictures obtained for the configurations $[\pm 45/90_4]_s$ and $[0_2/90_4]_s$, respectively. The length of the specimen shown in each picture is 30 mm. In both figures, matrix cracks can be easily detected on the images. The configuration $[\pm 45/90_2]_s$ behaves in the same manner as the configuration $[\pm 45/90_4]_s$.

A different response is observed in the images obtained for $[\pm 45/90]_s$. The transverse crack openings are too small to be observed in the reduced resolution. However, the cracks are clearly identified in the full resolution, Fig. 4.



(a) Image of the zone of the specimen edge acquired with each picture



(b) Image in full resolution

Fig. 1. Example of the images obtained from the prescribed methodology at reduced and full resolutions. T corresponds to transverse crack and S corresponds to crack parallel to the specimen's mid-plane).