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An experimental investigation of the mechanical behavior and damage of thick laminated carbon/epoxy composite

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ABSTRACT

In this study, mechanical behavior and damage of thick laminated carbon/epoxy composite are investigated through static and fatigue three-point bending tests. In order to supply a maximum of information about the mechanical behavior of these materials, which have been little studied in the literature, and to provide an accurate description of the different mechanisms involved during their damage process, three non-destructive evaluation and monitoring techniques were used in this study. The acoustic emission for damage assessment, identification, and their threshold detection, the infrared thermography for fatigue damage evaluation and fatigue limit estimation and the digital image correlation for strain and displacement fields measurements.

1. Introduction

Currently, the substitution of metal materials by composites in aeronautics is no longer reserved for secondary structures, but it was extended to some primary structures, such as the fuselage and wings of the Airbus A350 and Boeing 787. This progress is considered as a major step towards the aim of building a whole aircraft structure from composite materials. However, during this development, the thickness of the composite laminates used in this area has greatly increased and led to several difficulties in the manufacturing and understanding of the mechanical and damage behavior of these materials. The industrial research has already made great strides in this sense, nevertheless, the state of the non-academic art is inaccessible.

The major challenge in the manufacturing of thick thermoset composites is the management of the heat generated during cure. It is also difficult to avoid the presence of porosities, low fiber volume fraction and dry zones in the manufacturing of thick composites. Indeed, there are many studies that are performed under this subject [1–9]. The mechanical behavior of these materials has been the subject of several research works. However, most of this work has been concentrated on the effect of specimen thickness on the mechanical properties of thick composites [10–19]. An extensive literature review of size and scale effects in composites is given in Ref. [20]. It was found in the most of these works that the mechanical properties decrease with increasing thickness of the composites laminates. According to these works, the observed decrease in the mechanical properties is due to the influence of test configuration that are not designed for thick composites [10–12], the cure gradients [14–16], the interlaminar shear, manufacturing defects and matrix dominated failures [17–19]. In another hand, the effect of impact damage on the mechanical properties of thick composites, can be found in [21,22]. It was found that the residual compressive strength is considerably lower for an edge impact than for a central impact, and the residual tensile strength for a central impact is less than for an edge impact. The nondestructive evaluation of thick-section composites and sandwich structures has been reviewed by Ibrahim in Ref. [23]. This paper mentioned that the NDE of thick composite materials appears to be relatively immature compared to that of thin composites. It is also noted in this paper, that there are no references in the literature to inspection reliability or acceptance criteria for thick composite structures.

On the other hand, there are some authors who have investigated the damage behavior of thick composites under compressive loading [24–26], it was observed that the first failure mechanism appears is shear failure in the matrix precipitated by pre-existing fiber misalignment, and that the kink bands and delaminations are predominant failure mechanisms. However, very limited studies are available on the fatigue of thick composites, and most of these works have been focused on the effects of thickness [27,28], impact damage [28], curing cycles [16], and heat generation [29] on the fatigue-behavior of these materials.

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The increased use of the thick composites laminates in the aircraft industry requires a full understanding of their mechanical and failure behavior, and the bending test is the most representative test of real load condition on a structural component such as an airplane wings and fuselage. However, to date, most of the work on these materials has been concentrated around the effects of manufacturing process, thickness and pre-existing damage on the mechanical behavior of these materials under compressive loading. In this regard, the objective of the present study is to investigate the mechanical and damage behavior of thick laminated carbon/epoxy composite through static and fatigue three-point bending tests. Three non-destructive evaluation and monitoring techniques that have proven their effectiveness in the study of composite materials were used in this study.

2. Experimentation

2.1. Specimens

The material used in this study is a unidirectional carbon/polymeric Hexply M21 T700 (reference: M21/35%/268/T700GC) prepreg manufactured by Hexcel Composites. The laminate was prepared in a controlled atmosphere (white room) and compaction was carried out using vacuum pump. A mould for the laminate was prepared and placed in a vacuum bag and evacuated to 0.7 bars. Curing was then conducted at 180 °C (raising at the rate of 2 °C/min) for 120 min during which the pressure was maintained at 7 bar in an autoclave and 0.7 bar of vacuum inside the mold (as recommended by Hexcel Composite Company). The M21 matrix is a mixture of epoxy and thermo-plastic. The carbon fibers are the Toray T700GC. This prepreg is used in the aeronautical industry to manufacture primary and secondary aircraft parts of some aircraft, such as the A380 and A400M. The mechanical properties of the used prepreg are listed in Table 1 [31]. The composite plate is made up of 36 layers. For the stacking sequence, a typical aeronautical sequence with a thickness of 9.4 mm was adopted (Fig. 1). The specimens were water-jet cut into a rectangular shape with dimensions of (182 mm × 15.2 mm × 9.4 mm) according to ASTM standard (D790-03) [30].

2.2. Instrumentation

2.2.1. Digital image correlation

A high-speed camera two-dimensional (2D) digital image correlation system (StrainMaster, LaVision Inc.) was used for in situ measurement of displacement and surface strain fields in the thickness of the specimens during testing. The CCD cameras of this system have a sensor of 7.2 × 5.4 mm^2, with a resolution of 1628 × 1236 pixels and rate of 14 frames per second. A speckle pattern provided by the system manufacturer was applied on the side surface of the test specimens. The post processing of the results was performed by means of the commercial software Davis 8.2.3 (LaVision). The correlation parameters used for the measurement of the displacement field are 9 pixels for the scanning step and 16 pixels for the digital gauge. The calculation of the strain field is carried out after the measurement of the displacement field.

Table 1
Mechanical properties of HexPly T700-M21-GC.

Mechanicals properties of the materials (T700-M21)	
Young's modulus in the L direction (GPa)	E_{ll} = 142
Young's modulus in the T direction (GPa)	E_{tt} = 8.4
Shear modulus (GPa)	G_{lt} = 3.8
Poisson's ratio	ν_{lt} = 0.33
Ply thickness (mm)	h = 0.26
Fiber content (%)	V_f = 59
Critical strain energy release rate in mode I (J/m^2)	G_{Ic} = 440

2.2.2. Infrared thermography

The evolution of the temperature field at the surface of the specimens during tests was recorded using a Flir A35 infrared camera. The thermal resolution of the camera was 50 mK with temperature operating range from −25 °C to 135 °C and images resolution of 320 × 256 pixels. The emissivity is taken as 0.98 [32].

2.2.3. Acoustic emission

A two-channel MISTRAS data acquisition system from Physical Acoustics Corporation with a sampling rate of 4 MHz and a 40 dB pre-amplification was used to record AE data. AE measurements were achieved by using two resonant MICRO-80 sensors with an operating frequency range of 100–1000 kHz. The sensors are coupled on the faces of the specimens with a thin layer of silicon grease and grasped with two small clamps. A threshold of 35 dB was used to suppress background noise. The peak definition time (PDT), hit definition time (HDT) and hit lockout time (HLT) were set at 50, 150 and 300 µs, respectively. A three pencil lead break tests were performed before each test out to calibrate the source location of AE events and check the coupling state between the specimen and the sensors.

3. Experimental setup and procedure

3.1. Quasi-static bending tests

Three-point bending tests were performed at room temperature with a loading rate of 1 mm/min and a span length of 150.4 mm, according to the ASTM-D790-03 standard test method [30]. The testing machine was an Instron model LM-U150, equipped with a 10 kN load cell. These tests were carried out to investigate the mechanical and damage behavior of thick laminated carbon/epoxy composite under quasi-static loading. The tests were instrumented with infrared camera, two acoustic emission sensors and CCD camera (Fig. 2). A RFDA Professional system from IMCE was used for measurement of the resonant frequency in the flexural and torsional vibration modes of specimens. The resonant frequencies were used to calculate their elastic properties according to ASTM standards (E1876) [33,34].

3.2. Bending fatigue tests

Fatigue tests were conducted in an MTS-370.10 servo-hydraulic testing machine equipped with a 100 KN load cell. All fatigue tests were performed in sinusoidal displacement control at room temperature and constant displacement ratio R of 0. The displacement ratio is defined as δ min/δ max, where δ min and δ max are the minimum and maximum applied displacement, respectively. To prevent thermal effects, the tests frequency was set at 5 Hz [29]. The specimens were subjected to three-point bending tests with displacement ranging from 35% δ_U to 85% δ_U, with step of 5% and each for blocks of 10,000 cycles. The load blocks were interspersed with rest period of 10 min to let the specimens returned to its initial temperature (Fig. 3). A calibrated thermocouple was placed in the middle of the specimen lower surface to continuously monitor the temperature at this location. The thermocouple is used to ensure that the calibration of the infrared camera is satisfactory. The objectives of these tests were to investigate the mechanical and damage behavior of thick laminated carbon/epoxy composite under fatigue loading, and estimate the endurance limit with thermographic data analysis. The tests were instrumented with infrared camera, thermocouple and two acoustic emission sensors (Fig. 4).

4. Results and discussions

4.1. Quasi-static bending tests

The experimental results of quasi-static three-point bending tests are reported in Fig. 5. This figure gives the evolution of the stress versus