MULTIAXIAL BEHAVIOR OF NOTCHED COMPOSITE STRUCTURES MANUFACTURED BY DIFFERENT PROCEDURES

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Abstract
Composite structures materials have been traditionally used in the aerospace and aeronautical industries in the hardest working conditions. Nowadays, the use of these materials has increased in a large number of applications such as wind power generation, shipbuilding and automotive industries. In these applications, the composite parts generally have geometrical discontinuities due to different design reasons and develop multiaxial stress states under general loading conditions [1]. In this work, experimental studies are performed in order to analyze the behavior of unnotched and notched composite structures manufactured by different procedures under different loading conditions.

1. Introduction

The design of structural composite elements frequently includes discontinuities as for example fastener holes for joining. The presence of geometrical discontinuities develops stress concentrations, which are the reason why the strength of notched laminates decreases compared with the unnotched laminates. Therefore, the development of stress concentrations due to the presence of notches on the composite laminates is an important topic of study to improve the knowledge about the composites behavior [2]. In order to study this reduction of the strength, a set of experimental tests has been developed on carbon fiber reinforced composite laminates with different stacking sequences, using notched and unnotched specimens and comparing their strengths.

The composite laminate plates tested have been manufactured applying pressure and hot in a hot platen press following the cure cycle recommended by the manufacturer for the material base (prepreg tape) used and maintaining vacuum conditions. The mechanical properties obtained experimentally by the unnotched tests have been compared with the ones provided by Hexcel Composites Ltd., validating the manufacturing process. All results of the notched specimens have been compared with those obtained for a similar material with equal stacking sequences cured by means of an autoclave previously published [3].

In addition, composite structures develop multiaxial stress states due to general loading conditions [4]. For this reason, a preliminary experimental biaxial study has been started to get a better understanding of the composite behavior under complex stress states. With this objective, different stacking sequences have been designed to generate biaxial stresses by means of off-axis loading of unidirectional reinforced laminates [5].

This paper is organized in five sections. Section 1 introduces, in general terms, the steps followed in this work. Section 2 describes the material studied. Section 3 shows the manufacture process and section 4 explains the test facility used and the experimental study developed. Finally, in section 5 the conclusions of the study are discussed.

2. Material

The material studied is an Hexply® M21 carbon-epoxy prepreg fabricated by Hexcel Composites Ltd. and donated by Airbus Operations, S.L. from Illescas (Spain). With this material, Airbus builds the primary composite structures of the A350 XWB, such as fuselage panels, wing covers and the center wing-box (http://www.hexcel.com).

The Hexply® M21, used to manufacture the different composite laminates analyzed in this work, was reinforced with unidirectional continuous high tensile strength carbon fibers (IMA) and it was pre-impregnated into M21 epoxy resin (34 weight% resin content). The prepreg tapes were 300 mm wide. Although the tapes were prepared for developing an automatically lay up, the composite laminates have been laid up by hand in square plates.

A set of tensile uniaxial tests has been developed to characterize mechanically the composite material manufactured, following the “Test Method for Tensile Properties of Polymer Matrix Composite Materials” (ASTM D3039). The results obtained have been compared with the stiffness and strength prepreg properties provided by the manufacturer, obtaining good fitting between both values and verifying the manufacturing process. In Table 1, the elastic properties of the Hexply® M21-IMA and the average tensile properties from uniaxial tests are shown.

Hexply ® M21-IMA	**E_{11} (GPa)**	**G_{12} (GPa)**	**σ_{11T} (MPa)**	**τ_{12} (MPa)**
HEXCEL®	178	5.20	3050	94
Mean value	172	5.15	2218.95	89.65
Standard deviation [%]	9.18	2.52	4.19	3.49

Table 1. Stiffness and strength properties Hexply® M21-IMA.

The difference between the ultimate experimental stress (σ_{11T}) and the ultimate stress value of Hexcel® is due to the difficulty found for obtaining good failure in specimens with all fibers parallel to the loading axis.

As an example, in Figure 1, the results of an uniaxial tensile test developed to characterize the composite material behavior is shown. The material presents a brittle behavior with a yielding stress and strain approximately equal to the ultimate values.

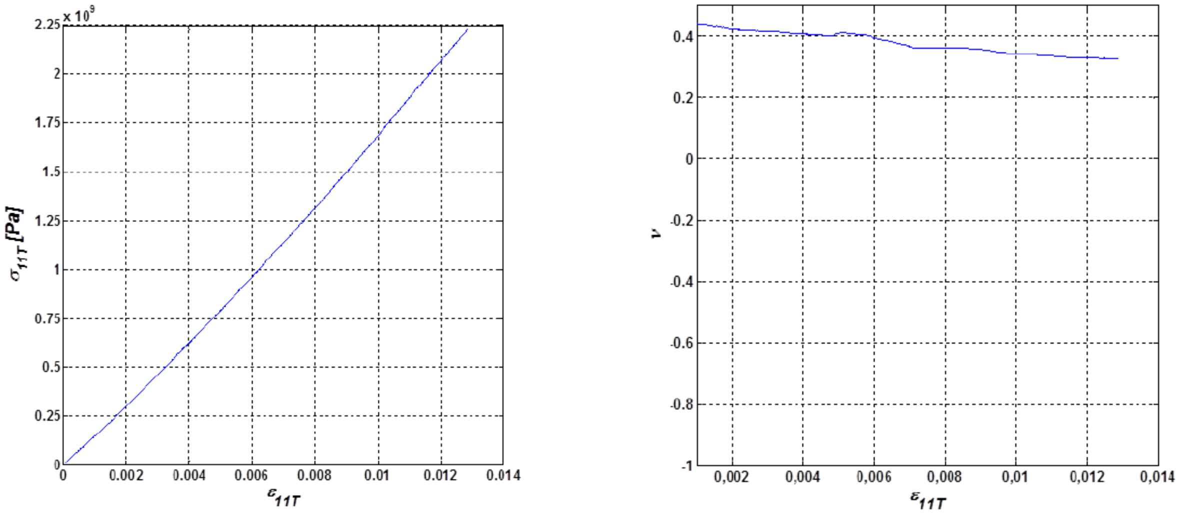


Figure 1. Tensile uniaxial test results on a two-ply unidirectional laminate $[0]_2$: (a) Strain–stress curve, (b) Strain-Poisson's ratio.

3. Manufacturing process

With this scope, a new laboratory has been created for manufacturing different composite laminate plates with epoxy matrix prepreg tapes reinforced by carbon fiber (Hexply® M21-IMA), using a hot platen press and maintaining vacuum conditions. Then, composite laminate plates have been tested experimentally to obtain the material mechanical properties, which have been compared with those provided by Hexcel®.

The manufacturing process has followed the typical cure cycle recommended by Hexcel Composites Ltd. for components with a thickness less than 15 mm (http://www.hexcel.com). The first step has been to lay up by hand the square plates with the stacking sequences decided. The length of the plate's side has depended on the stacking sequences, 300 mm side in cross-ply laminates and 200 mm side in the rest of laminates. After making the laminate, it is introduced into a vacuum bag, where vacuum conditions are achieved using a vacuum pump. Then, the pressurized vacuum plate is placed inside the hot platen press and the curing process is started applying pressure and hot. Vacuum conditions are maintained during the entire cure cycle.

The process has continued preparing cured composite laminate plates for the experimental tests. After cleaning the plates, glass fiber end-taps (50 mm width and 3 mm thick) have been bonded on both sides of each plate (in the correct position for cutting future specimens) to protect the composite surface of the specimen when it is gripped during the tensile tests. Also, the end-taps have helped to prevent the sliding grips. A standard high strength, two component epoxy paste adhesive (Araldite® 2015) has been used for bonding the end-taps. Then, the composite plates with the end-taps bonded have been cut maintaining the dimension recommendations of the ASTM-D3039 tensile method.

4. Experimental study

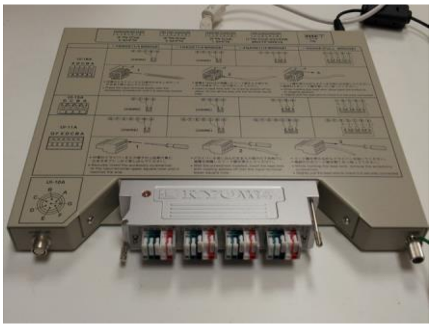
4.1 Test facility

The test facility used in all tests is a triaxial test machine that is able to develop tensile-compression tests in the three space directions. It has six electromechanical actuators and six pneumatic grips, four of them are situated in the horizontal plane and the other two in the vertical direction. Each actuator is driven by an electric gear motor. In this work only have been used two of the actuators placed in horizontal position.

The test machine has specific software which permits to control either the displacement or the force applied on the specimen. The displacement of each actuator is regulated by an encoder and the applied forces are measured by means of loading cells. The maximum operating load and maximum stroke available are 50 kN/axis and 50 mm/actuator, respectively. All tests have been developed controlling the applied force at a fixed loading rate of 50 N/sec.

The measurement of the experimental strain data have been made by uniaxial gages and 45º star rosettes, depending of the strain direction measurement. The gage or rosette chosen is bonded on the specimen's central zone and then, is connected to PCD-300B Data Acquisition System, four channels data recorder. All components (gages and PCD-300B) are from KYOWA™ (Figure 2) [6].

(a)



(b)

Figure 2. (a) Bonding Strain rosette to the specimen. (b) PCD-300B Data recorder.

The test facility described before has been used to study the reduction of the strength due to the geometrical discontinuities. With this objective, four different lay-up notched specimens have been tested. The specimens obtained in the manufacturing process are drilled in the central zone to obtain the notched specimens with 3 mm open hole diameter (Figure 3). The specimen width (W) to hole diameter (D) ratio was W/D = 10.

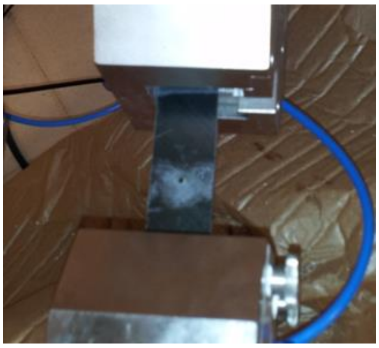


Figure 3. Notched specimen (3 mm hole diameter).

4.2 Experimental results

Finally, the strength results for the unnotched and notched specimens have been compared testing four different laminates. These results are shown in Table 2 where the loading axis is parallel to the 0º fibers and the standard deviation is in brackets.

Hexply ® M21-IMA Lay-up	**[0°]$_2$**	**[90°]$_8$**	**[±45°]$_8$**	**[45°]$_8$**
Unnotched tensile strength [Mpa]	2218.95 (4.19 %)	52.85 (2.42 %)	207.91 (2.37 %)	89.65 (3.49 %)
Open hole tensile strength [Mpa]	1115.32 (4.74%)	25.95 (4.77 %)	193.89 (4.17 %)	48.05 (4.76 %)
Strength reduction [%]	49.74	50.90	6.74	46.40

Table 2. Unnotched and notched average tensile strength.

The notched strength observed is approximately half of the unnotched strength in all the laminates tested, except in the eight plies [±45°]$_8$ laminates, in which the reduction of the strength is less than the 10% of the unnotched strength. All specimens tested have failed in the hole, except the specimens fabricated by means of cross-ply laminates with all fibers parallel to the loading axis that have developed axial splitting at the hole edge.

5. Conclusions

The manufacturing process developed by means of a hot platen press for the material studied has been validated comparing of the mechanical properties obtained experimentally with the ones provided by the prepreg tape manufacturer. The experimental tests (unnotched and notched) have reproduced the characteristic failure modes, with the exception of the laminates loaded in the axis parallel to the fibers in which the failure mode (unnotched and notched) has been very difficult to obtain.

The strength reduction due to a geometrical discontinuity (open hole) has been calculated in laminates with different stacking sequences, obtaining an important decrease in between notched with respect to the unnotched specimens. The notched results have been compared with those obtained by means of an autoclave for the curing process, obtaining correct fitting between both results. Also, by the comparing the results for different configurations, it has observed that there are laminates more notched sensitive than others.

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Acknowledgements

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