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Mauricio Torres [1], Jorge L. González-Velázquez [2], Hilario Hernández-Moreno [3]*

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- ✓ Este suplemento constituye las memorias del congreso "*X Iberoamericano de Metalurgia y Materiales (X IBEROMET)*" celebrado en Cartagena, Colombia, del 13 al 17 de Octubre de 2008.
- ✓ La selección y arbitraje de los trabajos que aparecen en este suplemento fue responsabilidad del Comité Organizador del *X IBEROMET*, quien nombró una comisión *ad-hoc* para este fin (véase editorial de este suplemento).
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Resumen

Los materiales compósitos son ampliamente utilizados en estructuras reticulares, sin embargo su desempeño estructural relacionado con su tolerancia al daño no ha sido estudiado extensivamente. El presente trabajo se enfoca a determinar la resistencia residual de tubos compósitos que tienen defectos circulares. La experimentación involucró la fabricación de láminas unidireccionales epoxy/vidrio con 60% de fibra a diferentes orientaciones utilizando el método de bolsa de vacío. A los especimenes se les indujo un defecto circular para caracterizar la propagación de grietas antes de condiciones de inestabilidad. El comportamiento mecánico fue observado mediante ensayos de tensión hasta la ruptura. La secuencia y el mecanismo de fractura fueron establecidos mediante examen fractográfico. Posteriormente, los tubos fueron modelados acorde a aquellos empleados en fuselajes tipo armadura utilizando Método del Elemento Finito, a fin de estudiar su respuesta mecánica bajo cargas tensiles. Los resultados de la simulación numérica fueron utilizados junto con los datos experimentales para construir los Diagramas de Resistencia Residual correspondientes.

Palabras Claves: *Tubos compósitos, Fractura, Resistencia Residual, Elemento Finito*

Abstract

Composites components are used in reticular structures, however their structural performance related to its damage tolerance has not been studied extensively. The present research is concerned with mechanical strength of composite tubes containing hole defects. Experiments involved fabrication of epoxy/glass unidirectional laminates with at least 60% volume fibre at different orientations using vacuum bagging method. Specimens were induced with different hole defect sizes to characterize crack propagation before instability conditions. Mechanical behaviour was observed in tension tests, loading specimens to failure. Fracture sequence and mechanism were established by fractographic examination. Then, the tubes were modeled according to those employed in tubular fuselages to study their mechanical performance under tensile load using Finite Element Method. Results from numerical simulation were used with experimental data in order to construct Residual Strength Diagrams.

Keywords*: Composite tubes, Fracture, Residual strength, Finite element*

1. INTRODUCTION

Glass fiber reinforced composites (GFRC) offer exceptional properties in structural applications that require high strength to density ratios, so their employment in aeronautics has been rising in recent years. The employment of GFRC has been expanded to numerous aircraft laminated components, however their structural performance related to their damage tolerance has been studied a few [2][3][4], specially when they contain stress concentrators, such as pin holes, drills or notches.

Due to the imminent risk of a crack presence in laminates, the understanding of crack sequence and propagation mechanism is essential to calculated residual strength based on defect size – maximum load ratio in order to design damage tolerant components and establish crack size limits used for inspection on service [1].

Recently, some researches [5][6][7] published investigations considering circular defects as stress concentrators which causes strength weakness as function of non-uniform crack propagation.

However they don't establish physical parameters to define residual strength in composites elements [9][10][11].

The present research is focused to the characterization of fracture behavior of epoxy/glass composites tubes with hole defects. Optimization of the vacuum bagging was necessary to obtain composites laminates with high fiber volume fraction and low porosity. Mechanical characterization was realized by tensile tests loading laminates specimens to failure.

The laminate strength was related to hole defect size for predicting maximum load available in the composite tube. Fracture surfaces formed were analyzed in order to establish rupture sequence and mechanism.

Finally, specimens were modeled and simulated with real conditions to verify experimental data and draw the corresponding Residual Strength Curve (RSC). The proper RSC will aid to establish maximum load with the existence of a hole and the maximum size of defect for a given load.

2. MATERIALS AND LAMINATES MANUFACTURE

The composite used in this work consists of unidirectional E-glass (800 gr/m^2) and EPOLAM 2015 resin. All laminates were manufactured using vacuum bagging process, described next.

The first step, epoxy resin and hardener were degasified in a vacuum chamber at 0.1 atm during 30 min in order to eliminate air inside fluids.

Then a 500 mm X 500 mm X 4 mm glass plate was used as mold to support and covered with Mylar film, which aids to remove the laminates. After preparing a 300 mm X 300 mm composite laminate by hand laying procedure, it was sheltered with nylon fabric (peeling ply). An itched Mylar was placed on, to lead exceeding resin to flow transversely. Then a short fiber glass mat was sited to trap epoxy excess. At the bottom of those plies, a second mylar was positioned and covered with white mantel. Finally polyethylene bag was placed and sealed with buthylene polymer. A retaining valve was connected to a reciprocating vacuum during 2 hrs to obtain uniform thickness laminates as is shown in Fig. 1. Post curing was realized at room temperature (25 °C) for 16 hrs before stripping.



Fig.1 a) Vacuum bagging set up;
b) Hydrostatic method for physical characterization.

Laminates physical characterization was done according to the hydrostatic method established in ASTM D2584 [12] to determinate composite density. Volume fiber fraction was evaluated using the burn-off method, obtaining typical values of 63% fiber fraction and 4% void content.

3. LAMINATES MECHANICAL RESPONSE

3.1 Composite Mechanical Properties

The laminate mechanical properties were measured using 250 mm X 25 mm X 1.5 mm samples using three different orientations (0°, 45°, 90°). Also, a classic lay-up sequence [0°/90°/+-45°] was studied for determine its performance related to defect presence.

Specimens without defects were loaded to failure according to ASTM D3039 [13]. To obtain strength and stiffness values, composite samples were instrumented with polyimide strain gages. Gages were connected to a strain indicator to record data during loading; information was stored with proper software.



Fig.2 a) Specimens free of defects for obtaining mechanical properties; b) Tensile test; c) Specimens with holes for measuring their residual strength.

To improve data acquisition during test, displacement rate of testing machine was adapted;

laminates having 0° orientation and [0°/90°/+-45°] sequence were broken at 2 mm/min; specimens with 45° and 90° were tested at 1 mm/min and 0.1 mm/min respectively. Mechanical properties are summarized in Table 1.

Table 1 Composite Mechanical Properties

Longitudinal Elastic Modulus E_l	47800 MPa
Transverse Elastic Modulus E_t	12400 MPa
Longitudinal Poisson Ratio v_l	0.29
Transverse Poisson Ratio v_t	0.075
In plane Shear Modulus G_{lt}	20400 MPa

3.2 Residual Strength Curves

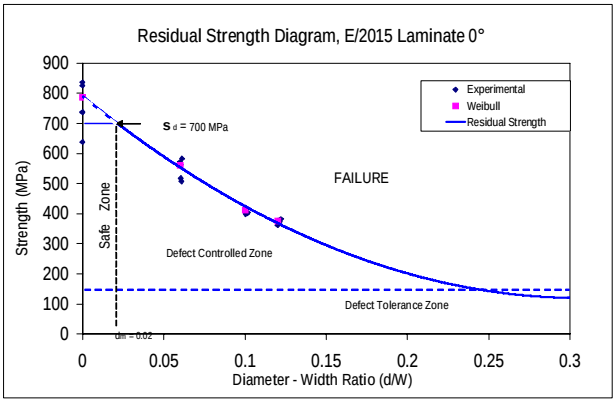
After mechanical characterization, specimens for the studied orientations and the lay-up sequence were induced with different hole defects using a drilling tool to represent stress concentrators in structural components. Hole sizes were 1.5, 2.5, y 3 mm of diameter, located in the center of samples.

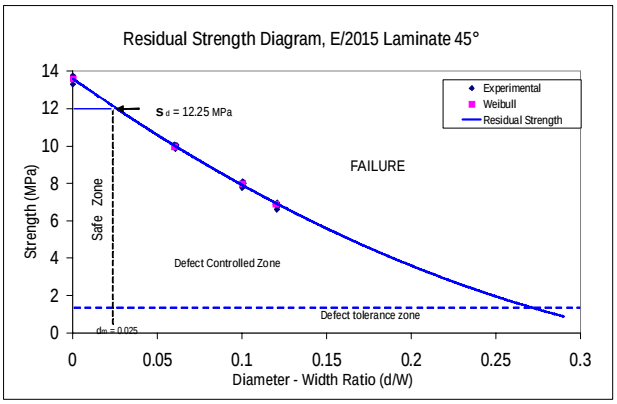
In order to quantify the effect of discontinuity presence in laminate mechanical response, Residual Strength Curves (RSC) for each orientation and ply sequence were drawn. Maximum strength of all specimens was recorded to calculate average strength for each orientation using Weibull statistical method [14]. Residual strength diagrams allow determining fracture load in cracked specimens and maximum crack size for a particular load condition.

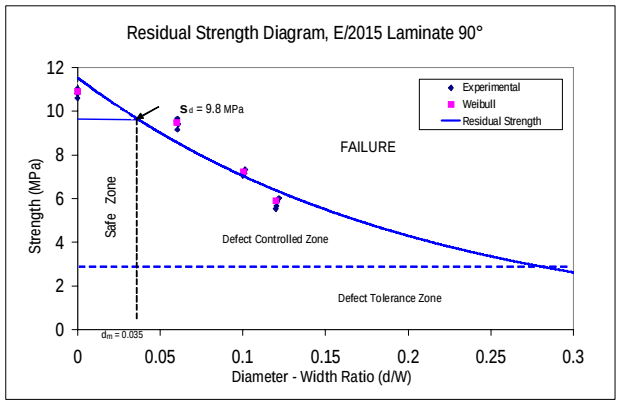
RSC are divided in two main regions, Safe Zone, wherein strength is function of transverse section; and Controlled Defect Zone, wherein strength depends directly on the defect size. Proper identification allows designers to predict maximum strength for specific applications.

For RSC, the following criteria were considered: Residual Strength was calculated with quadratic polynomial regression from experimental data. To generalize composite laminate behavior with hole defects, RSC is plotted as function of diameter – width ratio (d/W). Design strength is set in 90% of experimental ultimate tensile strength. Maximum tolerable defect will be any hole which accomplishes a diameter – width ratio of 0.3.

RSC for each orientation are shown in Fig. 3.







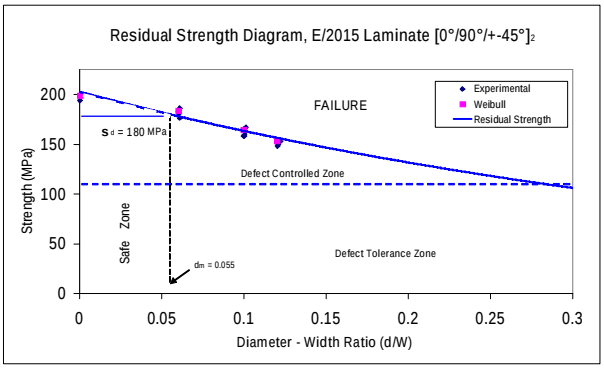


Fig.3 Residual Strength Curve for each orentation, 0°, 45°, 90° and the lay-up sequence [0°/90°/+-45°].

Residual strength for unidirectional laminates shows similar fracture paths. The biggest induced hole (d = 3 mm) produces a diminution on 30% of the laminate strength. The minimum hole size that laminate can hold without considerable damage is d/W = 0.025. RSC predicts that the maximum tolerable defect is related with 80% diminution of laminate strength. Residual strength diagram for lay – up composite indicates a gradual diminution of strength when defect increases its size. The largest hole evaluated diminishes the laminate strength approximately in 25%. In this case, RSC only predicts a diminution of 50% in mechanical strength if the maximum tolerable hole would appear. When the composite laminate is drilled, cross-section diminishes and stress in the flat specimen increases. Additionally, microcracks appear in the circumference nearby zone, producing several discontinuities; those can form a main crack and reach a critical size, propagating itself along the component until failure occurs.

4. FRACTOGRAPHIC EXAMINATION

After the tensile tests, fractographic examination was done to identify the failure path. For macroscopic observation, photographs of the stress concentrator were taken to preserve visual evidence of fracture plane, fracture angle and crack path.

Then, for microscopic evaluation samples were observed by Scanning Electron Microscopy (SEM). Micrographies were acquired to find indications of cracking mechanism related with loading experimental conditions.

Fractografic examination reveals that all unidirectional specimens show fracture surfaces parallel to fiber aligning, running along the test area. They exhibit few plastic deformation and moderate roughness, as is shown in Fig. 4a. Particularly lay-up samples exhibit great delamination, which is more evident around the hole (Fig. 4d).

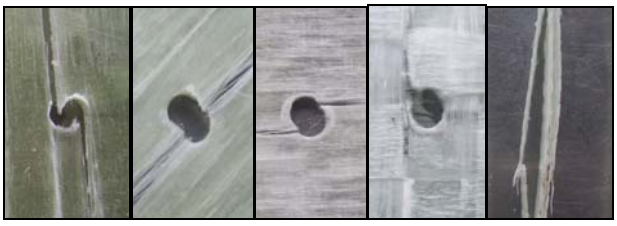


Fig.4 Illustrations of drilled specimens (3mm) to show principal fracture zones and crack paths; also delamination of lay-up specimen is presented.

Samples free of defects show matrix rupture, interlaminar fracture and fiber breaking. In most cases fiber bridging appears and total fragmentation does not occur.

For samples with hole, main crack starts in circumference and extends itself through matrix-reinforcement interface, generating mostly total fragmentation. Also, crack propagates along fiber orientation.

Finally, samples with lay-up sequence reached fracture showing global plastic deformation. Failure of free defect samples shows evidence of matrix rupture and fiber breaking in 0°/90° plates, meanwhile +-45° suffered angular deformation.

General failure sequence starts with main crack nucleation due to microcracks joining at circumference limits causing fibre/resin separation, as can be seen in Fig. 5a. Then, crack propagates along the samples by decohesion of interface, which indicates poor adhesion at matrix-reinforcement. Finally fiber breaking by cleavage appears but sudden fragmentation does not occur, as it is illustrated in Fig. 5b. Delamination is reached when the load is retired at the end of the tensile test, these means that composite structure can carry load even when failure starts due to its damage tolerance properties, as is show in Fig. 5c.

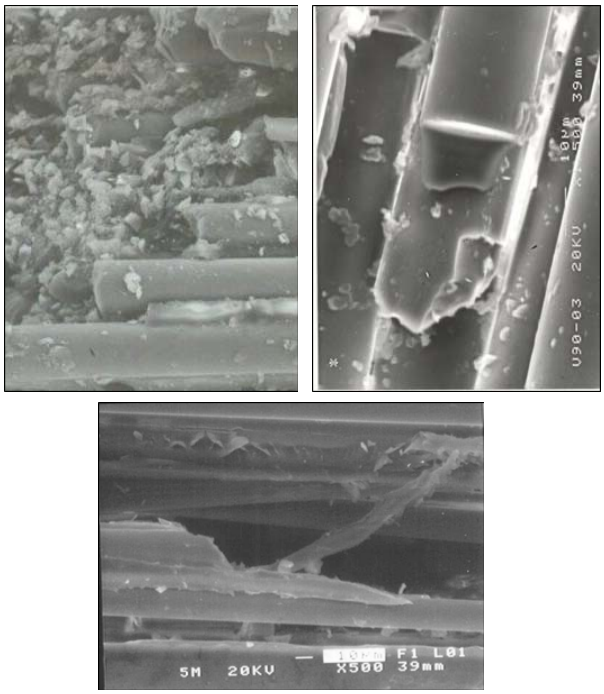


Fig.5 Failure mechanisms identified in fracture surfaces. a) Interface decohesion; b) Cleavage; c) Delamination

5. NUMERICAL SIMULATION

Numeric simulation for composites tubes with hole defects was performed using Finite Element Simulation. Nominal dimensions for the tubes were taken from Cessna-Mooney reticular fuselages [15], as is shown in Fig. 6. ANSYS software was employed to create the finite elements model. Stiffness and flexibility matrix calculus, which defines orthotropic material elastic behavior, was done from experimental mechanical properties in order to have good accuracy in results. Four lay-ups were simulated, one with fibers aligned according to the cylinder axis (0°, unidirectional), other with fibers having a constant 45° angle with cylinder axis (45° unidirectional), the third configuration with fibers in hoop direction (90° unidirectional), and the last lay-up having four plies of plain wave reinforce with orientation [0°/45°]s, this means first layer with fibers in 0°/90°, second and third layers with fibers 45°/-45°, and the last one equal to the first. Plain wave layer mechanical properties were calculated using the classical laminate theory.

The shell configuration was given to structural component to respect the mechanical restrictions of only to support stress in workplane which emerges from applying tension axial load. Also, the use of linear shell elements (SHEL 99) in numerical simulations is justified with the good agreement that these elements can provide for stratified theory resolution and failure criteria. Entire model are built with 2800 tetrahedral elements and 5600 nodes.

Additionally, the model considers the existence of a stress concentrator, represented as a keypoint in hole circumference. This discontinuity will aid to simulate crack tip in hole surroundings.

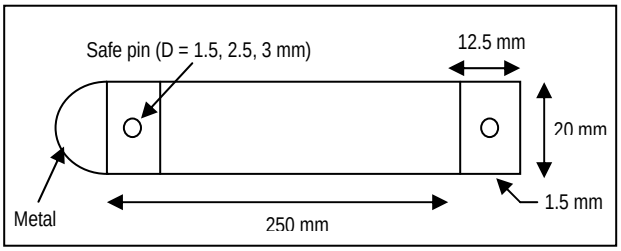


Fig.6 Composite tubes used in reticular fuselages. A metal connector is glued to composite tube and locked by safe pins to complete structural join.

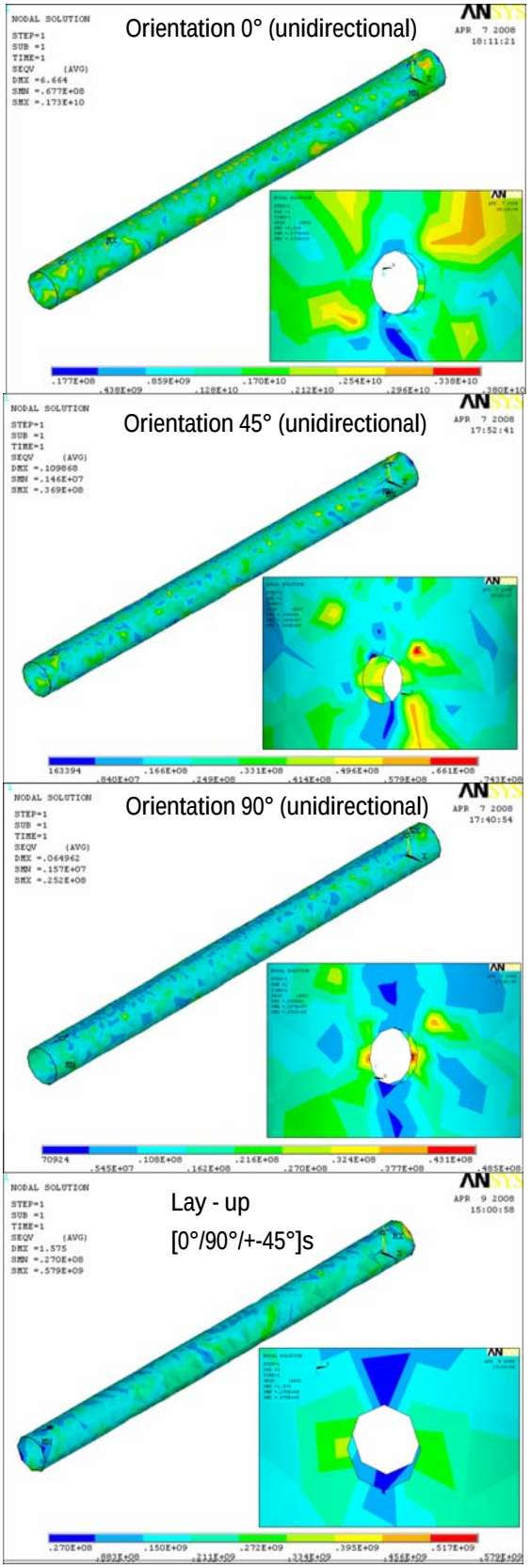


Fig.7 Stress distributions around hole in composite tubes. Orientation at 0° and lay-up sequence show lower stress concentration than 45° and 90°.

For loading conditions, composite tubes were constrained in all degrees of freedom in one side, and applying experimental fracture load in the other one. Numerical solutions for the different holes diameters are presented in Fig. 7. Stress field distribution by nodal solution along the tube is compared qualitatively for the proposed orientations. Special attention is given to stress increments in hole zone.

Numerical simulations show that tubes with 0° and lay-up sequence exhibit a regular distribution of stress around the hole. The intensity of the stress field is smoother and more homogeneous and does not present critical zones. However, tubes with 45° and 90° of orientation have stress intensifications near the crack tip. The discontinuity promotes a higher level of stress in the nearby zone of hole due to the weakness of the matrix-reinforcement interface. Finally, residual strength from experimental procedures and the one predicted by numerical simulations are compared to validate both methods. Table 2 shows the maximum strength carried out from tensile test and the average strength calculated by Finite Element Method.

Table 2 Residual Strength for tubes with 3mm hole

Configuration	Experimental	Numerical
Tube 0°	376 MPa	390 MPa
Tube 45°	6.9 MPa	7.2 MPa
Tube 90°	5.9 MPa	6.1 MPa
Tube $[0°/90°/+-45°]_s$	153 MPa	165 MPa

6. CONCLUSIONS

A study to describe the effect of hole discontinuities in composite tubes is presented here. The remarkable influence of defect size in laminates mechanical response can be measure by drawing the Residual Strength Curve (RSC). With RSC diagrams, it can be affirmed that there is a laminate strength decrement meanwhile hole size is increased. Also, RSC diagrams can provide a critical hole size for further applications.

Hole function as stress concentrator, aiding crack nucleation at its surroundings and causing fibre/resin fracture.

Fractographic evaluation revealed interlaminar fracture by matrix-reinforcement decohesion, and final failure is attributed to fiber breaking.

In lay-up specimens delamination happened when composite is unloaded. This fracture behavior gives stable crack propagation and no sudden fragmentation, showing damage tolerance properties.

Residual strength calculated by numerical simulations shows a good accuracy with the values obtained from experimental procedures.

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