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Strain field measurement of filament-wound composites at ±55° using digital image correlation: An approach for unit cells employing flat specimens

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ABSTRACT

Testing of filament-wound composites (FWC) with simplified methods is studied until now in order to generalize the mechanical response of FWC structures. To assure a good analogy between meso- and macro scales, it is necessary to design a representative specimen that include the characteristic winding pattern. This research aims at characterizing the strain field of FWC pattern at ±55° using flat specimens by measuring the displacement field with digital image correlation. Experimental procedure involves tensile testing of epoxy/glass specimens with two unit cells aligned at hoop and axial direction of the winding pattern. Validation of the strain values from digital image correlation is carried out by comparing them with strain gauge measurements and FEM simulations. Failure sequence and modes of FWC flat unit cells show good concordance with those observed in FWC cylinders exposed to buckling in previous works [1].

1. Introduction

In recent years, filament-wound composites (FWC) are mostly used in oil-extraction, fluid transport, aerospace and aeronautic industries due to their specific strength ratio [1–3]. On all these applications, the FWC structures are designed according to their variables, such as the winding pattern, ply sequence and number of cells [1–4].

Nowadays, the structural behavior of FWC has been investigated by testing the whole structure and imposing the real service loads [1,5–10]. Nonetheless, as there is a difficulty in reproducing the real conditions in a laboratory, this kind of tests requires specific equipment, which increases the cost and time of the study. These difficulties also exist for computational approaches, because the solution of complex structures has a consequence in the processing time of the algorithms.

With the objective to test FWC with simplified methods, the conception and design of a representative specimen, which includes the winding pattern cells, is necessary. The structural behavior of FWC at constituting cell level with flat specimens is studied until now [11] in order to generalize the mechanical response of FWC structures. The understanding of the mechanical performance of FWC unit cells is a priority for composite designers, because it can lead to infer the correct failure mechanisms and to conceive new structures more tolerant to damage [12,13].

Also, the benefit would be increased if the mechanical response is measured using digital image correlation (DIC), which will aid to localize over-strain zones in the unit cells which can be related to crack initiation and damage evolution in the pattern of FWC.

Recently, the researchers of ICA & IPN [1,14–16,24–26] invest their efforts studying the pattern influence in FWC pipes, comparing DIC measurements and numerical models. These researches have the interest for calculating FWC strength as a function of the geometry of the structure, material properties, service loads and environment conditions. Additionally, they are focused on the designing of multi-instrumented specimens to assure safe operational conditions and health monitoring in industrial components.

In order to study the mechanical behavior of the composites fabricated with filament winding process taking into account the specific pattern generated (detailed cell structure), an experimental multi-instrumented study coupled with numerical analysis is proposed here, using flat specimens with the characteristic filament winding rhomboid pattern. The main purpose will be the characterization of the strain field of FWC cells at ±55°. The strain field will be calculated by measuring the displacement field with digital image correlation.

For a better understanding of the goals of this research, this paper is organized as follows. The first part explains the basic fundaments of digital image correlation. The second part deals with the

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experimental setup. The third part shows the strain fields obtained by DIC and FEM simulations. After that, a fractographic comparison is made in order to infer the crack sequence and failure mechanisms. Finally, the paper finishes with the concluding remarks.

2. Fundamentals of digital image correlation

In most of the engineering applications, the strain measurement in structural components is based on well-known surface techniques such as strain gauges or mechanical extensometers. Nonetheless, the acquired information is just valid for a small region (punctual information) and it cannot be generalized to the whole component due to the heterogeneities of the geometry and the material. With the aim of having a more complete visualization of strain distribution in complex structures, the optical techniques are being applied [14–18]. The most employed technique for laboratory purposes is the full-field speckle photography [19–23] known as digital image correlation (DIC).

The DIC has been used to analyze mechanical phenomena such as strain concentration, crack propagation, material phase changes and combined failure modes. One outstanding contribution of this method is that it offers the opportunity to make a direct and reliable comparison between experimental data and computational simulations.

The DIC method employs a setup of cameras and a controlled white-light source to capture images of a specimen loaded at different charge levels. The images are captured with a charged coupled device (CCD) that contains a sensor with small photoelectric cells that acquires the images in focal storage unities (pixels). The images contain information of the light intensity for each pixel. The light intensity of the zone of interest (ZOI) can be related in two different images, one before loading (reference image) and one after loading (deformed image) [14,15,19,20].

The DIC has the mathematical fundament in the maximization of the cross-correlation coefficient which is determined examining the light intensity of a pixel array in two consecutive images and extracting a displacement function which relates the analyzed images. The cross-correlation coefficient (r_{ij}) is defined by Eq. (1) [19,20]:

$$r_{ij}\left(u, v, \frac{\partial u}{\partial x}, \frac{\partial u}{\partial y}, \frac{\partial v}{\partial x}, \frac{\partial v}{\partial y}\right) = 1 - \frac{\sum_i \sum_j [F(x_i, y_j) - \overline{F}][G(x_i^*, y_j^* - \overline{G})]}{\sqrt{\sum_i \sum_j [F(x_i, y_j) - \overline{F}][G(x_i^*, y_j^* - \overline{G})]^2}} \quad (1)$$

where $F(x_i,y_j)$ is the pixel intensity in the gray scale in the point (x_i,y_j) of the reference image. $G(x_i^*, y_j^*)$ is the pixel intensity in the point (x_i^*, y_j^*) in the deformed image. The functions $\overline{F}$ and $\overline{G}$ are the average values of the intensity matrix [F] and [G], respectively [19,20]. The (x_i,y_j) and (x_i^*, y_j^*) coordinates are linked by the deformation occurred in both images. If the motion of the specimen is perpendicular to the optic axis of the camera, the relationship between coordinates can be approximated by Fourier transformation as in Eqs. (2) and (3):

$$x^* = x + u + \frac{\partial u}{\partial x}\Delta x + \frac{\partial u}{\partial y}\Delta x \quad (2)$$

$$y^* = y + v + \frac{\partial v}{\partial x}\Delta x + \frac{\partial v}{\partial y}\Delta y \quad (3)$$

where, u and v are the displacements of the ZOI center in the x and y directions. The distance from the ZOI center to the point (x,y) is defined by Δx and Δy. Then, the cross-correlation coefficient is a function of the displacements and their gradients.

ZOI depends on two parameters, the subset (S), which controls the dimension of the employed surface to follow the displacements and the step (p), which controls the space between the analyzed points during the correlation. Depending on these parameters, the image resolution (g) and spatial resolution ($S \cdot g$) can be calculated in order to obtain accurate results from the tests [25,26]. A complete description of the digital image correlation can be reviewed in references [19,20,25].

Table 1
Physical and mechanical properties for filament winding pattern at ±55°.

Composite density ρ (g/cm^3)	1.845 ± 0.03
Fiber volume fraction V_f	0.572 ± 0.02
Matrix volume fraction V_m	0.381 ± 0.01
Void content V_p	0.047 ± 0.003
Hoop elastic modulus E_h (GPa)	10.7
Axial elastic modulus E_a (GPa)	5.7
Hoop poisson ratio v_c	0.75
Axial poisson ratio v_a	0.25
In-plane shear modulus G_{ah} (GPa)	2.75
Maximum hoop strength σ_{hmax} (MPa)	70 ± 0.5
Maximum axial strength σ_{axmax} (MPa)	24 ± 0.5

3. Experimental procedure

3.1. Physical and mechanical characterization of FWC flat cells at ±55°

The first attempts to fabricate winding pattern flat specimens are carried out in order to obtain representative specimens of FWC with their unit cells. Composites are fabricated with E-glass rovings and EPOLAM 2015 resin provided by AXSON.

Pre-forms with a pattern of ±55° fiber orientation and two symmetrical plies in the thickness are fabricated by Hand Layup. Each unit cell has 15 rovings, as shown in Fig. 1, in order to reproduce similar cells for the cylinders used as in previous works [1,24]. The vacuum bagging process is implemented following the

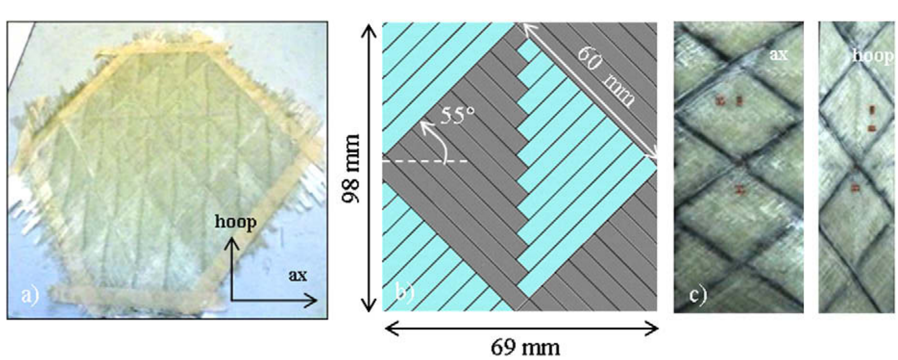

Fig. 1. FWC flat specimen (a) pre-form with filament winding pattern, (b) unit cell dimensions, (c) specimens in hoop and axial direction of the pattern.