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Fluid diffusion in cracked composite laminates – Analytical, numerical and experimental study

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ABSTRACT

Composite structural components are often subjected to service loads that cause cracks in off-axis layers, without compromising the load bearing capability of the structure. In marine or humid environments fluid ingress in the material can be accelerated by the presence of such cracks, leading to further strength degradation.

Several studies have been dealing with the effect of cracks on fluid diffusion in composites, sometimes with contradictory results. In this work the difference between cracks on the external and internal plies of the laminate has been addressed both experimentally and analytically, showing that the first ones have a strong influence on diffusivity, while the second have a negligible effect.

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1. Introduction

Multidirectional composite laminates are used in many structural applications where they are immersed in water or exposed to humid environment, like marine and offshore industry [1], aircraft industry and wind energy industry [2]. Multidirectional laminates subjected to unidirectional static or fatigue loadings, typically crack in the off-axis plies; in the case of a cross-ply laminate, cracks can appear only in the 90° plies.

Fluid diffusion in composites is an anisotropic phenomenon, for orthotropic laminates three diffusivities are necessary. These constants can be measured by weightgain measurements of immersed samples having different fiber orientation [3]. Using these diffusion constants, the water uptake of a cracked laminate can be predicted.

The experimental results available in the literature report different scenarios. In some cases, cracks have been reported to accelerate apparent diffusivity greatly [4,5], while in others negligible effect was observed [6]. In Table 1 an overview of the studies present in the literature about fluid diffusion in multidirectional pre-cracked laminates is reported along with the apparent diffusion ratio of cracked material vs. un-cracked material.

It is possible to observe a trend from the results reported in Table 1: samples with 0° layers on the outer surfaces show low diffusion increase when cracked, while samples having off-axis layers on the outer surfaces show higher diffusion increase when cracked. The cracks in the most external layers of the laminate seem to have a higher effect on diffusion than the cracks on the internal layers.

The only apparent exception is the one reported in Ref. [4], however this study dealt with satin weave layers, where cracks can appear in all layers, while in the other references unidirectional layers are studied, which contain cracks only in the off-axis plies.

Based on these considerations, in the present work [0/90/0] and [90/0/90] laminates have been mechanically loaded in the axial (0°) direction to four strain levels: $\varepsilon = 0\%$, $\varepsilon = 1\%$, $\varepsilon = 1.5\%$ and $\varepsilon = 2\%$; to verify this hypothesis. An analytical model and a finite element model, based on change of boundary conditions (BCs) in the diffusion equation due to the presence of cracks is used. The increase of weight due to the cracks filling with water is also modelled. The different behaviour of cracks on internal and external layers is caused by their discontinuous shape. This effect is explained theoretically using a mono-dimensional fluid diffusion analysis. A good agreement between the experimental results and both analytical and finite element (FE) predictions was obtained.

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List of symbols

c	Moisture content
c_i	Length of i-th crack
C_i, D_j, E_k	1-D terms of 3-D solution of diffusion equation
c_{op}	Crack opening
D_{11}, D_{22}, D_{33}	Composite anisotropic diffusion constants
D_c^1	Equivalent diffusivity inside the crack in direction 1
D_c^3	Equivalent diffusivity inside the crack in direction 3
D_{H2O}	Water diffusion constant
h	Laminate thickness
l	Representative volume element length
l_c, l_i	Length of crack and length of cracks interruption
L	Laminate length
p	Number of cracks
$m_{composite}$	Composite sample mass
$M_{eq}^{composite}$	Composite sample mass increase at equilibrium
$M_{eq}^{cracked}$	Cracked composite sample mass increase at equilibrium
m_{water}	Water mass
n	N° of plies in the laminate
$n_{90°}$	N° of 90° plies in the laminate
t	Time
w	Width
x, y, z	Cartesian coordinate system
$\rho_{composite}$	Composite density
ρ_{water}	Water density
ρ_w	Crack density

Table 1
Overview of diffusion experiments in pre-cracked composites.

Reference	Material	Layup	$D_{cracked}/D$
Suri & Perreux [5]	GF/Epoxy	$[+55/-55]_s$	2.53
Lundgren & Gudmundson [6]	GF/Epoxy	$[0_2,90]_s$	1.04
		$[0_2,90_2,0]_s$	1.03
		$[0_4,90_2]_s$	1.07
		$[(0_2,90_2)_2,0]_s$	1.04
		$[0_4,90_4,0_2]_s$	1.11
		$[0_8,90_4]_s$	1.15
Roy and Bandorawalla [4]	GF/Epoxy	$[0/90/0/90]_s$ Woven	2.23
Present study	GF/Epoxy	[0/90/0]	1.11
		[90/0/90]	1.29

2. Material and methods

2.1. Materials

A glass fiber/epoxy composite laminate has been manufactured using vaacum assisted resin transfer molding (VARTM). The matrix was Hexion Epikote™ Resin RIMR135 mixed with Epikure™ Curing Agent MGS RIMH134 with a mixing ratio of 100:30 by weight. The fibers were HiPer-tex UD glass fibers from 3B. Curing was performed at room temperature for 24 h and post-curing in a ventilated oven at 80 °C for 16 h.

The volume fraction of the laminate was obtained by matrix burnoff test, resulting in 54.2%. The density of the samples was 1.93 g/cm^3. Twenty [0/90/0] and twenty [90/0/90] tensile samples, were cut using a water-cooled diamond saw to 230 × 30 mm. Sample thickness was 2.7 mm. The material's mechanical properties have been characterized in previous studies [7]. The strain to failure of the UD laminate is 2.4% in fiber direction and 0.4% in transverse direction.

2.2. Experimental methods

Cracks were introduced into the samples by loading the coupons using an Instron 8800 tensile machine with a 100 kN loadcell under displacement control. Three values of strain were chosen to obtain different crack densities on the samples, avoiding complete failure: $\varepsilon = 1\%$, 1.5% and 2%. A set of samples for each layup was not loaded, to provide a reference for the un-cracked material diffusivity.

Fig. 1 reports the dimension of the tensile samples. From each tensile coupon, a cracked diffusion sample was obtained from the central part, far from the tabs. The samples were cut using a circular water-cooled diamond saw, resulting in dimensions: 48.5 × 30 × 2.7 mm.

Five replicates were loaded for each strain; four were conditioned after loading and one was cut, grinded, polished and analysed with an optical microscope, in order to provide more information about the crack morphology.

From the visual inspection of the samples before and after the test using translucency, Fig. 2, it was possible to measure the length of each crack, c_i. Cracks appear as horizontal lines when uniaxial load is applied, Fig. 2 (c, d, e). The matrix cracks developed only in the 90° plies. Due to the translucent nature of the epoxy the cracks could also easily be seen inside the laminate.

The weighted crack density, for a cross ply laminate, was then computed as follows [8,9]:

$$\rho_w = \frac{\sum_{i=1}^{p} c_i}{w\,L} \tag{1}$$

where c_i is the length of each crack, w the width of the laminate and L is the length of the laminate. Defining a weighted crack density allows considering that cracks do often not span over the entire thickness of the laminate. The measurements were further confirmed by the optical microscope analysis of the sample analysed with the optical microscope per each set. Crack densities obtained experimentally are reported in Fig. 3.

Fig. 4 **(a)** and **(b)** shows optical micrographs of transverse cracks in [0/90/0] and [90/0/90] laminates. Cracks extend over the entire thickness of the layer. It can be also noticed that the cracks in the [90/0/90] laminate appear thicker than the cracks in the [0/90/0] laminate. This aspect can cause a difference in the final amount of water absorbed by the material; it was therefore decided to measure crack opening by means of microscope analysis. The average crack opening, obtained from 520 measurements, was:

- 5.24 μm ± 1.82 μm in the [90/0/90] laminates,
- 2.90 μm ± 1.00 μm in the [0/90/0] laminates.

Fig. 2 indicates that most cracks seem to cross the entire width of the specimen. However, a closer inspection by microscope, Fig. 5, reveals that the wide cracks are actually an accumulation of disconnected shorter cracks. This aspect needs to be considered in the model, because the continuous cracks in the width direction give a very different diffusion behaviour that discontinuous cracks.

Samples were dried for 72 h in an oven at 40 °C and their weight was recorded daily, until stabilization. The samples were subsequently conditioned in a bath with distilled water at 60 °C ± 1 °C. This temperature provides a convenient acceleration of the test, compared to room temperature, without activating additional

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