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Mode I fracture characterization of a hybrid cork and carbon–epoxy laminate

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ABSTRACT

In this work fracture characterization under mode I loading of a hybrid laminate composed by a unidirectional carbon–epoxy composite and cork was performed using the Double Cantilever Beam test. An equivalent crack length procedure based on specimen compliance and Timoshenko beam theory applied to the composed beam was adopted to evaluate the fracture energy. The procedure revealed to be quite effective and it was validated numerically by means of finite element analysis including cohesive zone modelling. The analysis of the experimental results has shown that an increase of 32% of mode I toughness relative to monolithic carbon–epoxy laminate was obtained, which proves that hybridization using cork results in a quite effective procedure to increase interlaminar toughness of composite laminates.

1. Introduction

It is widely known [1–4] that laminate composite materials are prone to suffer delaminations i.e., interlaminar damage at interfaces between layers, namely when submitted to transverse loading, as is the case of low velocity impact. In fact, mechanical properties of these materials can be drastically reduced in presence of delamination that may develop specially between adjacent plies with different orientation. Delamination is caused by the failure of the thin resin layer that exists between two different oriented plies and can be considered as very dangerous since it is not easily detectable. This kind of failure occurs predominantly at interfaces between different oriented layers and is motivated by the mismatch bending of those adjacent interfaces.

Epoxy resins are widely used in composite systems. They are generally characterized by lack of toughness thus leading to brittle failure at interfaces. Several methods have been proposed to increase interlaminar toughness of laminated composites: fiber and matrix toughening, interface toughening, hybridizing and through-the-thickness reinforcements. A combination of tougher resin systems along with higher strength fibers increases the composite interlaminar strength [5,6]. Another strategy consists of including tougher adhesive layers at critical interfaces of laminates [7–11]. This concept is known as “interleafing” and has been found to increase considerably the impact resistance. A different solution is the hybridization which consists of adding tough materials, such as high strain-to-failure fibers, e.g. S-Glass, Kevlar or Spectra, to the host composites [12–14]. Delamination resistance can also be improved by means of reinforcing the interface, such as through-thickness stitching, z-pinning or weaving [15–17], although the associated in-plane properties, such as stiffness, can be significantly compromised.

In general these solutions are not easy to implement and contribute to increase the final cost of the material. In this work a hybrid carbon–epoxy and cork laminate is considered. The main goal is to assess the eventual benefit in terms of interlaminar toughness resulting from the introduction of a cork layer between layers of carbon–epoxy laminate. Cork is the bark of an Oak tree that is periodically extracted from the tree. This natural material is continuously regenerate after harvesting, thus constituting a renewable material. It has a low density, possesses high thermal and acoustic insulation properties, low thermal conductivity and fire resistance, low stiffness, low strength and large compressive strains, which may lead to a more energy absorbing sandwich composite. Reis and Silva [18] performed shear and bending tests on sandwich of carbon–epoxy faces and cork-based cores in order to compare the mechanical behavior with classical core materials used in sandwiches as is the case of Rohacell and honeycomb. They concluded that the application of cork-based agglomerates as a core material for sandwich components of lightweight structures can be advantageous relatively to classical core materials. Castro et al.

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[19] performed static bending tests, in order to characterize the mechanical strength of different types of cork agglomerates, and evaluated the ability to withstand dynamic loads, from a set of impact tests using carbon–cork sandwich specimens. Cork agglomerates consisting of cork granules and epoxy resin were fabricated in order to obtain a better overall specific strength. Cork–epoxy agglomerates presented a considerably good core shear stress limit, better than other core materials, reducing the crack propagation region. Moreover, cork-based sandwiches presented considerably higher load values than those obtained for other type of high performance core materials, excellent recovery capacity and a high energy absorption capacity with minimum damage occurrence.

The study presented herein focus on mode I fracture characterization of a carbon–epoxy and cork laminate using the Double Cantilever Beam (DCB) test. An equivalent crack length data reduction scheme for composed beams was developed and applied to experimental load–displacement curves to assess fracture toughness under mode I loading. The method was validated numerically by means of the finite element analysis involving cohesive zone modelling.

2. Experimental work

Specimens were prepared from hybrid plates made of carbon–epoxy (C–E) laminate and cork considering [0_8, cork, 0_8] layup. The plates were manufactured in a hot plate press considering the same cure cycle used for monolithic carbon–epoxy laminates which consists in the application of a 4 bar pressure at 130 °C during 1 h. Excellent adhesion between composite and cork was obtained, namely by means of the "anchorage" phenomenon of the epoxy adhesive through the pores of the cork layer. The thickness of the unidirectional carbon–epoxy (SEAL TEXIPREG HS 160 RM from SEAL®, Legnano, Italy – Table 1) layer is 0.14 mm and the cork one (CORECORK NL20 from Amorim Cork Composites, Portugal – Table 2) is 0.8 mm which leads to a nominal plate thickness of 3.0 mm approximately. The pre-crack was introduced by means of a thin Teflon® film (thickness of 25 μm) at one interface between cork and composite. Seven DCB tests (nominal width B = 20 mm and length L = 150 mm – Fig. 1) were prepared considering two different initial crack lengths (a_0 = 43 and a_0 = 48 mm) to assess an eventual influence of this parameter on the measured fracture energy.

Tests were performed at room temperature using a servo-hydraulic testing machine (INSTRON® 4208) equipped with a load cell of 1 kN (Fig. 2). A loading displacement rate of 2 mm/min was applied and the load–displacement (P–δ) curve was registered during the test. Although some marks had been previously drawn at the specimens' edge it was concluded that accurate measurement of the crack length in the course of the test was not feasible (Fig. 3). To overcome this drawback a data reduction scheme based on crack equivalent concept was developed in the next section.

3. Data reduction scheme

Classical data reduction schemes used to evaluate toughness in the DCB tests are based on crack length monitoring during the test. However, this procedure is susceptible to remarkable reading errors depending on the material to be characterized. Alternatively, an equivalent crack length procedure based on Timoshenko beam theory and specimen compliance can be used.

Assuming that the crack grows at the mid-thickness of the cork layer (i.e., at the specimen mid-plane) the compliance due to bending (C_b) is

$$C_b = \frac{P}{\delta_b} = \frac{2a^3}{3D_m} \tag{1}$$

where D_m is the equivalent bending stiffness of each specimen arm given by (Fig. 4)

$$D_m = E_l B\left(\frac{h_l^3}{12} + h_l d_l^2\right) + E_c B\left(\frac{h_c^3}{12} + h_c d_c^2\right) \tag{2}$$

where E_l and E_c are the Young moduli of the C–E laminate (longitudinal) and cork, respectively. The distances between the neutral axes of each material and the global neutral axis in each arm are (Fig. 5)

$$d_l = \frac{E_c h_c (h_l + h_c)}{2(E_l h_l + E_c h_c)}; d_c = \frac{h_l + h_c}{2} - d_l \tag{3}$$

The compliance shear component requires the definition of shear stress profile along thickness for a bi-material composed beam [20]

$$\tau_{xy} = \frac{V}{D_m B}\int_A E_i y dA \tag{4}$$

being V the transverse load and E_i and A_i the longitudinal elastic modulus and section area of each material (C–E laminate and cork), respectively. Considering Fig. 5 the following equations are obtained for the stress profile along thickness of each specimen arm, where three regions were considered: C–E laminate above the neutral axis (l_s), C–E laminate below the neutral axis (l_i) and cork (c).

$$\tau_{l_s} = \frac{V}{D_m}\int_y^{\frac{h_l}{2}+d_l} yE_l dy;\ 0 \leqslant y \leqslant \frac{h_l}{2} + d_l$$

$$\tau_{l_i} = \frac{V}{D_m}\left[\int_y^{-d_c+\frac{h_c}{2}} yE_l dy + \int_{-d_c+\frac{h_c}{2}}^{-d_c-\frac{h_c}{2}} yE_c dy\right];\quad -d_c + \frac{h_c}{2} \leqslant y \leqslant 0 \tag{5}$$

$$\tau_c = \frac{V}{D_m}\int_y^{-\left(d_c+\frac{h_c}{2}\right)} yE_c dy;\ -\frac{h_c}{2} - d_c \leqslant y \leqslant -d_c + \frac{h_c}{2}$$

This procedure guarantees shear stress continuity at the interface between the two materials, which can be verified using $y = -d_c + \frac{h_c}{2}$ in the second and third Eq. (5). The strain energy of the specimen due to shear effects is

$$U_{shear} = 2\int_0^a \int_{-\left(d_c+\frac{h_c}{2}\right)}^{-d_c+\frac{h_c}{2}} \frac{\tau_c^2}{2G_{xy(c)}} Bdxdy + 2\int_0^a \int_{-d_c+\frac{h_c}{2}}^{0} \frac{\tau_{l_i}^2}{2G_{xy(l)}} Bdxdy + 2\int_0^a \int_0^{\frac{h_l}{2}+d_l} \frac{\tau_{l_s}^2}{2G_{xy(l)}} Bdxdy \tag{6}$$

being $G_{xy(c)}$ and $G_{xy(l)}$ the shear moduli of cork and C–E laminate, respectively. Combining Eqs. (5) and (6) the shear strain energy of the specimen is

$$U_{shear} = \frac{BV^2 a}{4D_m^2} C_1 \tag{7}$$

Table 1
Elastic properties of unidirectional carbon–epoxy laminate [2].

E_1 = 109 GPa	ν_{12} = 0.342	G_{12} = 4315 MPa
E_2 = 8819 MPa	ν_{13} = 0.342	G_{13} = 4315 MPa
E_3 = 8819 MPa	ν_{23} = 0.342	G_{23} = 3200 MPa

Table 2
Mechanical properties of cork.

ρ (kg/m^3)	E (MPa)	G (MPa)	σ_u (MPa)	τ_u (MPa)
200	6.0	5.9	0.7	0.9