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Effect of temperature on pure modes I and II fracture behavior of composite bonded joints

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ABSTRACT

The influence of the temperature on pure modes I and II fracture behavior of carbon–epoxy composite bonded joints was investigated. The joints were exposed to a specific range of temperatures during three months in order to simulate long exposure time. Three temperatures were studied: 0 °C, 25 °C (room condition) and 50 °C. The limit temperatures were defined in order to be representative of the extreme climatic conditions to which structures can be exposed in winter and summer in Portugal. Similar fracture energies were obtained at 0 °C and 25 °C under mode I loading, but an abrupt decrease was observed at 50 °C. Regarding mode II, the fracture energy was only slightly affected by temperature. A numerical study using a cohesive zone model considering trapezoidal laws was also performed to evaluate the temperature effect on the cohesive parameters. For mode I loading some influence was observed on those parameters contrasting to which happened under pure mode II whose parameters were almost unaffected in the range of temperatures studied.

1. Introduction

The adhesive bonding technique has gained importance over others joining methods like welding, bolting and riveting, owing to the process benefits. Adhesive bonding presents more uniform stress distribution on the bonded area, less stress concentrations and high fatigue resistance, thus being more efficient and having great flexibility in design.

Nowadays, adhesive joints have a wide range of applications and are exposed to extreme conditions. They have to keep their mechanical properties and their structural integrity during the operating life. In fact, the properties of bonded joints can be affected by environmental conditions during their operating life service, as it is the case of extreme temperatures or presence of moisture [1–6]. Generally, the strength of the bonded joints is influenced by temperature presenting a decreasing trend with extreme temperatures (high or low temperatures). At high service temperatures this is due to the low adhesive strength. Regarding low temperatures, the brittleness of the adhesive and the induced high thermal stresses are responsible for such behavior. In fact, the decrease of the temperature leads to an increase of the adhesive elastic modulus. On the other hand, the difference in thermal expansion of the materials composing a joint can be the most critical point of its integrity when exposed to low temperatures, since stress concentrations arise in the bonded joint [7,8]. Concerning this aspect, it is fundamental that adhesive can retain some resiliency, especially when the thermal expansion coefficients of the adhesive and the adherends are quite different.

The fracture toughness of composite materials has been studied and there are several works about that on the literature [9–14]. However, the fracture toughness of adhesively bonded joints exposed to adverse environmental conditions has been receiving minor attention from researchers. So far, there are few studies on that, especially with composite materials as adherends. Ashcroft et al. [1] studied the mode I fracture of epoxy bonded CFRP (Carbon Fiber Reinforced Polymer) joints at −50, 22 and 90 °C. They concluded that G_{Ic} increases with temperature. They also observed that temperature affects the failure mode which altered from brittle fracture at low temperatures to slip-stick phenomenon at room temperature and stable ductile fracture for elevated temperatures. Intralaminar failure mode (within the composite) at −50 °C changed to cohesive failure, i.e. within the adhesive, at 90 °C. Melcher et al. [15] investigated the fracture behavior of an adhesively bonded joint with composite (carbon-BMI) adherends at

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Table 1
Elastic properties of carbon–epoxy [19]. 1 – Longitudinal direction, 2 – transversal direction, 3 – thickness direction.

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

cryogenic temperature (−196 °C). Comparing with room temperature, G_{Ic} suffered an abrupt reduction ($\simeq$50%) at cryogenic temperatures. Regarding the fracture surface, it was observed a hackled mixed adhesive-cohesive fracture at −196 °C. Banea et al. [7,16] also studied these phenomena considering bonded joints with steel adherends. They analyzed the effect of the temperature on mode I and mode II fracture toughness on high temperature epoxy adhesive/steel bonded joints. Tests were performed at 100 °C, 150 °C and 200 °C, and results were compared with the ones obtained at room temperature. Considering mode I, they concluded that for temperatures below the adhesive's glass transition temperature T_g of the adhesive ($T_g \simeq 155$ °C), the fracture toughness is almost independent of temperature. At the extreme temperature ($T = 200\,°C > T_g$) it was observed a marked decrease of the G_{Ic} value. Regarding mode II, it was seen that G_{IIc} increases with temperature for $T < T_g$. For temperature values close to the T_g, G_{IIc} starts to decrease, while for temperatures above T_g, G_{IIc} decreases abruptly. Carlberger et al. [17] and Walander et al. [18] also analyzed the influence of temperature on fracture toughness of epoxy adhesive/steel bonded joints. Carlberger et al. [17] studied the influence of temperature on two parameters (fracture energy and peak stress) of the cohesive laws under mode I for an epoxy adhesive, DOW-Betamate XW1044-3. Tests were performed in the temperature range −40 °C to 80 °C. At lower temperatures, the fracture energy of adhesive seems to be independent of the temperature. At higher temperatures (60–80 °C), the fracture energy decreases due to the closeness the glass transition temperature ($T_g \simeq 90$ °C). Regarding peak stress, it was observed a decreasing trend with the temperature increase. Walander et al. [18] performed a similar study with a different epoxy adhesive, SP498 (SikaPower498 – $T_g \simeq 100$ °C). The considered range of temperatures was −40 °C to 80 °C. Conclusions similar to Carlberger et al. [17] were reported for mode I loading. Concerning mode II, it was settled that the fracture energy and the peak stress behave similarly, i.e., their values decrease with temperature increase.

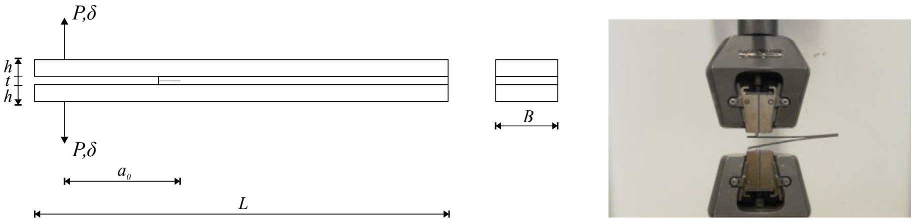
The influence of the temperature on the mode I and mode II fracture toughness of adhesively bonded joints made with carbon–epoxy laminate and structural adhesive was investigated in this work. Several Double Cantilever Beam (DCB) and End-Notched Flexure (ENF) specimens were exposed during three months at two temperatures (0 °C and 50 °C) before testing. The results of the degraded specimens were compared with the ones obtained under room conditions (25 °C). A numerical analysis was also performed to assess the temperature influence on the fracture toughness and on the parameters of the cohesive laws used to simulate accurately the fracture of adhesive bonded joints under pure mode (I and II) loading conditions.

2. Experimental work

Specimens were prepared from plates made of carbon–epoxy laminate using carbon–epoxy prepreg (SEAL® Texipreg HS 160 RM whose lamina mechanical properties are presented in Table 1). The plates were cured in a hot plate press considering $[0_{16}]$ layup. The thickness of the unidirectional layer is 0.14 mm which leads to a nominal plate thickness of 2.24 mm. The cure cycle consisted in the application of 4 bar pressure at 130 °C during 1 h. The adherends for both tests (DCB and ENF tests) were cut from the plates considering a nominal width of 3 mm. The surfaces of the adherends were treated in order to increase the adhesion and to avoid adhesive failures. The roughness of the surfaces was increased using sandpaper after which all the surfaces were cleaned with acetone. Bonding was performed at room temperature with a two part component ductile epoxy adhesive (Araldite® 2015 from Huntsman – $E = 1850$ MPa and $\nu = 0.3$ [19]). The adhesive layer thickness of 0.2 mm was assured using calibrated steel bars between the adherends during the curing process. The pre-crack was introduced by means of a razor blade which was guided at adhesive mid-thickness using calibrated bars on both sides. Metallic hinges were bonded to the upper and lower arms of the DCB specimen, permitting loading application.

Specimens were exposed at three conditions of temperature: 0 °C, 25 °C (room temperature) and 50 °C. For the 0 °C and 50 °C cases, specimens were put in containers inside the climatic chambers during three months in order to simulate a long period of exposure. These two limit temperatures (0° and 50°) were chosen in order to be representative of the extreme climatic conditions to which structures can be exposed in winter and summer in Portugal, respectively. The glass transition temperature of the adhesive provided by the manufacturer is $T_g = 75 \pm 5$ °C which means that the higher aging temperature (50 °C) is 25 °C lower than the T_g of the adhesive. For each condition 16 specimens were degraded (8 for DCB and 8 for ENF tests).

In due time, the conditioned specimens were removed from the climatic chambers and immediately tested at room temperature using a servo-hydraulic testing machine (INSTRON® 4208) equipped with a load cell of 1 kN. A loading displacement rate of 1 mm/min was applied and the load–displacement (P–δ) curve was registered during the test. A series of unconditioned specimens were also tested to compare the results obtained with the conditioned ones. Figs. 1 and 2 show schematic representations and



a) b)

Fig. 1. a) Schematic representation of the DCB specimen: $L = 150$, $h = 2.24$, $B = 3$, $t = 0.2$, $a_0 = 40$; all dimension in mm; b) photography of a DCB test.