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Investigations on the mode I translaminar failure and determination of fracture toughness in woven-ply carbon fibers thermoplastic composites at high temperatures

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ABSTRACT

The purpose of this study is to investigate the mode I translaminar fracture energy for initiation and propagation of 5-harness satin weave carbon fabrics reinforced PolyPhenylene Sulphide (PPS) laminates subjected to tensile loadings at $T > T_g$ (glass transition temperature) when matrix toughness is significantly enhanced. Specimens with a quasi-isotropic stacking sequence and a single-edge-notch geometry are characterized by an elastic-brittle response resulting from transverse matrix cracking and fiber breakage near the notch tip. From the macroscopic response standpoint, crack initiation and propagation virtually occur at the same time corresponding to ultimate failure making therefore difficult the assessment of corresponding strain energy release rates. The values obtained for crack onset were determined by means of three different technics: (i) the Crack Tip Opening Displacement (CTOD) method based on the outer surface full-field measurements – (ii) cracking gauges bonded to the outer surface – (iii) monitoring of the Acoustic Emission (AE) activity associated with the prominent damage mechanisms (transverse matrix cracking and fibers breakage). Within the framework of Linear Elastic Fracture mechanics (LEFM), the initiation K_{I_init} and critical K_{Ic} mode I fracture toughness were calculated from the strain energy release rate G_I in the case of quasi-isotropic laminates. Through the comparison with the value calculated from semi-empirical solutions developed for isotropic materials, the capability of these methods to provide reproducible and accurate values was validated. Among the different techniques implemented in the present work, the monitoring of AE signals is particularly relevant as it provides a reliable approach to detect the crack onset at the microscopic scale.

1. Introduction

In recent years, there has been a growing interest in using thermoplastic-based (TP) composites for structural applications in aeronautics because they are characterized by very interesting mechanical properties (good impact behavior, damage tolerance, fire resistance) and processing advantages (short autoclave cycles, no particular storage conditions) [1–4]. More specifically, fracture toughness is utmost important for structural applications as it represents the material capability to resist to fracture. Thus, researchers have become greatly interested in structural failure investigation. Fracture mechanics plays now an increasingly important role not only for academic interest but also for structural design as it provides valuable data during the design process. Fracture mechanics is usually characterized by many parameters (e.g. fracture toughness) that can be obtained from different experimental techniques.

1.1. Translaminar fracture toughness measurement

In composite laminates with orthotropic or quasi-isotropic stacking sequences, transverse matrix cracking and fibers breakage (also known as translaminar failure modes) are usually the damage mechanisms occurring in the early phase of mechanical loading. A comprehensive review of techniques for the experimental characterization of the fracture toughness is given in [5], and in [6] when it comes to the translaminar failure mode of fiber-reinforced

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Nomenclature

i	(1,2,3) fracture modes
K_i	stress-intensity factors (or the fracture toughness)
K_{i_init}	initiation fracture toughness
K_{ic}	critical fracture toughness
G_i	strain energy release rate
δ	crack opening displacements
F	applied load
B	specimen thickness
h	specimen width
a	notch length
E	axial stiffness
C	compliance
F_{max}	maximum load at failure
E_x	longitudinal stiffness
σ	remote applied stress
w	specimen width
Δa	crack extension
σ_{init}	stress at crack initiation

Abbreviations

PPS	PolyPhenylene Sulphide
T_g	glass transition temperature
CTOD	Crack Tip Opening Displacement
AE	Acoustic Emission
LEFM	Linear Elastic Fracture mechanics
TP	high performance thermoplastic
FRPs	fiber-reinforced polymers
COD	Crack Opening Displacement
MAE	Modal Acoustic Emission
UD	unidirectional composites
SEN	Single Edge Notched
FWC	Finite-Width-Correction factor
DIC	Digital Image Correlation
QI	Quasi-Isotropic laminates
SENT	Single Edge Notched
PMCs	Polymer Matrix Composites
SEM	Scanning Electron Microscope

polymers (FRPs). When it comes to evaluate the mode I fracture toughness of FRPs, the translaminar fracture toughness can be estimated by means of Single-Edge-Notch structures [7–10]. However, translaminar fracture has received relatively little attention from the scientific community until now [11]. In FRPs, the fracture mechanics behavior is often studied by using the Linear Elastic Fracture Mechanics (LEFM) parameters: the critical strain energy release rate (G_{Ic}) and stress intensity factor (K_{Ic}), the J-integral, the crack opening displacement (*COD*), the J-resistance curve and R-curve analysis [12]. In fracture mechanics, the energy release rate G is one of the most fundamental parameters. It is defined as the rate of energy released by the crack growth. An important aspect of fracture resistance is that it may vary as the crack grows such that G is a function of the crack growth Δa [8]. Orthotropic and quasi-isotropic laminates are usually characterized by an elastic-brittle response. From the macroscopic response standpoint, in the case translaminar failure mode, crack initiation and propagation virtually occur at the same time corresponding to ultimate failure making therefore difficult the assessment of corresponding strain energy release rates. Indeed, once they are initiated, cracks will propagate very rapidly until ultimate failure. In the ideal case (linear elastic-brittle response), an abrupt drop in load at the moment of crack initiation occurs. Since it is difficult to precisely measure the length of the crack at the peak load (and therefore the compliance) in the polymer composites, Crack Tip Opening Displacement (CTOD) measurements and cracking gauges are often used to investigate the crack initiation and propagation, as well as to estimate the corresponding strain energy release rates [12].

1.2. Investigations on cracks initiation by Acoustic Emission techniques

To characterize damage mechanisms and investigate their evolution in FRPs, many *in situ* and non-destructive evaluation techniques have been implemented over the past 30 years. Acoustic Emission (AE) techniques are often used to detect the onset and growth of microscopic failure in composite materials [13–15], and many attempts have been made to distinguish between different types of failure [16–22]. Among the different approaches developed Modal Acoustic Emission (MAE) and peak frequency analysis of generated AE waveforms, proved to be very effective to characterize damage types as it was shown recently by Baker et al. who have studied the initiation and propagation of cracks in CFR epoxy laminates using MAE and waveform energies, coupled with peak frequency data correlated to matrix crack density in the transverse direction [23]. During mechanical loading, the degree of damage and the fracture events sequence can be extracted from an exponential damage evolution profile obtained in terms of AE counts rate and cumulative AE counts as it was shown in [24]. The point of crack initiation can also be associated with jumps in AE cumulative energy along with high decibel signals as it was successfully observed in stainless steels [25]. In order to investigate the mode I interlaminar fracture in UD glass/epoxy, a similar approach was applied to Double Cantilever Beam specimens to indicate the damage initiation from microscopic and macroscopic (delamination) standpoints by means of longitudinal and transverse strain gauges combined with an AE transducer [26]. Very recently, Ivanov et al. have demonstrated the correspondence between AE cumulative energy in the warp direction and crack appearance in the weft yarns [27]. They also conclude that the effect of transverse cracks in the matrix on the onset and growth of delamination(s) needs further investigation.

1.3. Theoretical background

Early in the sixties, Sih et al. examined the nature of the local crack-tip stress field in anisotropic bodies [28]. They proposed a method to determine the stress-intensity factors K_i which can be related to the energy release rates G_i (i = 1,2,3). As was introduced by Sih et al., the stress-intensity factors or the fracture toughness K_i represent physically the intensity of the linear-elastic stress distribution, due to the introduction of a crack into the body, surrounding a crack-tip. It is therefore assumed that small amounts of nonlinearity (e.g. plastic deformation) at the crack-tip are embedded within the field, and do not significantly disturb it [29,30]. In the case of SEN specimens, the strain energy release rate can be evaluated directly from the application of double cantilever beam method (see Fig. 1) to the mechanical tests data:

$$G_I(X,A) = -\frac{\partial \Psi}{\partial A} = \frac{12F^2a^2}{EB^2h^3} = \frac{3\delta F}{2aB} \qquad (1)$$

where δ is the crack opening displacements, F is the applied load, B is the specimen thickness, h is the specimen width, a is the notch length evolution and E is the axial stiffness. The crack opening