Polymer Testing 29 (2010) 658–666

Contents lists available at ScienceDirect

Polymer Testing

journal homepage: www.elsevier.com/locate/polytest

Test Method

On the determination of delamination toughness by using multidirectional DCB specimens

X.J. Gong [a,*], A. Hurez [b], G. Verchery [a]

[a] DRIVE – Département de Recherche en Ingénierie des Véhicules pour l'Environnement, ISAT - Institut Supérieur de l'Automobile et des Transports, 49 Rue Mademoiselle Bourgeois, BP31 58027 Nevers Cédex, France
[b] IUT GMP 12 Rue de la Fonderie 71200 Le Creusot, France

ARTICLE INFO

Article history:
Received 2 March 2010
Accepted 21 April 2010

Keywords:
Polymer-matrix composites (PMCs)
Fracture toughness
Delamination
Finite element analysis (FEA)
DCB test

ABSTRACT

This work covers the problems encountered in correctly determining mode I interlaminar fracture toughness of composite materials. Pure mode I tests were performed on double cantilever beam (DCB) specimens composed by quasi-homogeneous and uncoupled multidirectional (MD) laminates using 16 or 26-ply: $[\alpha/-\alpha_2/\alpha/-\alpha/\alpha_2/-\alpha]_{\text{sym or anti-sym}}$ and $[0/\alpha/-\alpha/0_2/-\alpha/0/\alpha/0_2/\alpha/-\alpha/0]_{sym}$, with $\alpha = 0°,15°,30°,45°,90°$. A finite element analysis shows that the non-uniformity ratio $\beta=(G_{Imax}-G_{Iav.})/G_{Iav}\%$ depends not only on the parameter $D_c = D_{12}^2/(D_{11}D_{22})$, but also on the specimen geometrical ratios a/b and a/h. The condition of $Dc<0.25$ is not sufficient to assure a uniform G_I width-wise distribution. If we want to study the crack growth between any ply angles, it is difficult to find lay-ups having $\beta<10\%$. In fact, the crack initiation in MD DCB specimens usually occurred at the middle of the specimens, where G_I attained a maximum. Hence, the critical energy release rate G_{IC} has to be measured by the maximum instead of the mean of G_I.

1. Introduction

In fiber-reinforced composite laminate structures, the low interlaminar strength controlled by matrix properties may limit their application in certain cases. Failure between plies, termed delamination, is considered as a common major damage mode. Under cyclic loading, delamination can initiate from free edges or fabrication defects where there is high interlaminar stress concentration. Another well-known source of the delamination is low velocity impact. The propagation of the delamination zone can reduce the global stiffness and then lead to catastrophic structure failure. An understanding of the fracture behavior of composites becomes, therefore, of great importance in engineering design.

The characterization of the delamination resistance of composite laminates is usually based on fracture mechanics by using the critical strain energy release rate (CSERR). Herein a general loading scenario is decomposed into three elementary fracture modes: mode I + mode II + mode III. The idea is to predict crack initiation and/or crack growth by a general mixed mode criterion for a given composite system. This task remains a challenge due to the complexity of the problem. Contrary to isotropic materials, where fracture toughness is defined completely by the resistance under pure mode I loading, a composite material has to be characterized by three delamination toughness values: G_{IC}, G_{IIC}, and G_{IIIC}, corresponding to crack initiation under pure mode I, pure mode II and pure mode III loadings. In the case of mixed mode loading, the interaction of the three modes is not yet well known. Even for the pure mode I (tensile opening loading), the most dangerous fracture mode so the most important to study, the determination of delamination resistance is not as easy as it appears.

Over the last 30 years, much attention has been given to mode I delamination. The double cantilever beam (DCB) tests have been performed for the measurement of pure

* Corresponding author. Tel.: +33 3 86 71 50 15; fax: +33 3 86 71 50 01.
E-mail address: xiao-jing.gong_isat@u-bourgogne.fr (X.J. Gong).

0142-9418/$ – see front matter
doi:10.1016/j.polymertesting.2010.04.007

mode I fracture toughness. These works have led to the establishment of test method standards for mode I [1,2], which concern only mode I delamination initiation in unidirectional (UD) composites. However, as laminates widely used in industrial structures are actually multidirectional (MD), delamination initiation and propagation can occur in the interface between any fiber orientations. The questions that we have to answer are which laminate parameters affect the delamination resistance and how to predict the delamination fracture with regard to the material toughness measured on unidirectional laminates.

In order to understand the mode I delamination behavior in MD composites, DCB tests have also been performed on MD specimens since the 1980s. It is reported that the resistance to mode I delamination can vary widely as a function of laminate stacking sequence, adjacent fibre orientations and specimen geometry for certain composite systems. The results reported have shown that if a crack is initiated in $\theta_1//\theta_2$ interface with $\theta_1,\theta_2 = 0°$, 15°, 30° and 45°, the resistance heavily depended on the fracture surface morphology [3–6]. It can be invariable [7], increasing [8] or decreasing [9] with the adjacent ply angles; there was no overall tendency. Up to now, even though much more attention has been paid to this problem, there has not yet been consensus about the effect of each laminate parameter on measured G_{IC} values, nor about how to integrate these effects into the prediction of delamination in MD composites. However, the published research works give much experimental data, describe different phenomena observed and lead to some interesting debate and conclusions.

In order to identify parameters that may affect the resistance of MD composites to mode I delamination, it is interesting to examine the problems from two aspects: testing and physical. The testing approach reveals all uncertainty relative to the determination of the G_{IC} values, which can be mostly removed by the standardization of testing methods. The physical approach involves all parameters which really affect the fracture behavior of material and so have to be taken into account in mechanical structure design. Sometimes, these two aspects are so greatly dependant on one another that they will be discussed together.

1.1. Testing factors

Specimen design and data reduction method are two elements of great importance in the determination of the resistance to mode I delamination using MD DCB tests.

Concerning specimen design, firstly, the stiffness of the two arms should be the same to assure pure mode I conditions. Even in UD DCB specimens, if the crack is not located at mid-thickness, mode II contribution can reach 37% of total fracture energy [10]. Even though delamination in symmetrical MD specimens can be initiated under pure mode I, the specimen symmetry can be destroyed due to multiple cracking and/or crack shifting during the crack growth. Moreover, if crack growth is not located in its initial plane (self-similar), the well-known relationship between G_I and K_I becomes invalid. In order to avoid crack jumping in MD specimens, Robinson and Song have proposed a modified DCB specimen by introducing an artificial crack (film insert) along all of the edges [11]. It was seen that the crack jumping could be really eliminated during crack growth if the edge crack insert is wide enough.

Secondly, ideal specimens having a straight crack front must have quasi-uniform G_I width-wise distribution, or at least nearly the same distribution as UD ones. In fact, for practical purposes, data reduction models usually used for determination of G_I values give an average value and so consider the distribution of G_I across specimen width to be uniform. This is not true in the case of most DCB specimens with a straight crack front. The existence of laminate coupling terms such as D_{12}, D_{16}, D_{26}, and B_{ij} can complicate the G_I width-wise distribution and so make a valid measurement of G_{IC} difficult. The studies of Davison et al. [12–14] showed that in MD DCB specimens the value of G_I is highest at the centre and lowest at the edges. The degree of the non-uniformity can be increasing with a material non-dimensional ratio: $D_c = D_{12}^2/D_{11}D_{22}$. This ratio, defined in an analysis using classical plate theory [12], represents in fact the relative difference in DCB deflexion between the cases of plane strain and plane stress. The skewness of the G_I distribution across the specimen width was revealed to depend on another material ratio: $B_t = D_{16}/D_{11}$ [13]. Even for a laminate with vanishing Poisson's ratio, G_I varies across the beam width [15]. In addition, for a given magnitude of D_c, the higher the geometry aspect ratio a/b (crack length over width) is, the less uniform the G_I width-wise distribution becomes. It was also indicated [12,15] that the average of G_I decreases as specimens transfer from plane stress to plane strain. Consequently, low magnitude of D_c, B_t and large specimen width were recommended for specimen design.

Data reduction models proposed for determining resistance to mode I delamination are usually in closed-form for practical purposes. Each model has been developed by adopting different assumptions [1,2,10,15]. Therefore, the accuracy of G_I calculation could depend on the choice of model relative to the real case. The critical point corresponding to crack initiation is not so easy to define; and if we want to measure the R-curve corresponding to the evolution of fracture energy as the crack grows, we must know also how to measure crack length at all times. DCB test standards [1,2] propose determination of the crack initiation value G_{IC} for UD specimens by three points on the load-displacement plot: NL (deviation from linearity); 5%/Max (the offset by 5% increase in compliance or maximum load); and VIS (visual crack growth).

If these definitions are used in the case of MD DCB specimens, the NL value seems the most meaningful, since it represents the initiation of local damage around the crack tip or/and local crack growth from the straight crack front, usually in the center of the specimen where G_I attains a maximum. Concerning the 5%/Max and the VIS values, the former should correspond to 1 mm averaged crack advance for specimens with initial crack length of 50 mm [16], the latter is less meaningful. Actually, the crack front changes from a straight to curved thumbnail shaped front as the crack grows [9,11,14]. If crack extension is visual at