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Calculating a damage parameter and bridging stress from G_{IC} delamination tests on fibre composites

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Abstract

In this paper, a number of experimental round-robin data sets obtained using the mode I double cantilever beam (DCB) specimen to evaluate G_{IC} for fibre composite laminates have been reanalysed with a view to determining additional parameters to describe microcracking and damage in the composite arm, and the bridging stresses at the crack tip. The additional parameters are derived using the length correction term deduced from corrected beam theory. However, the reanalysis of the round-robin data revealed significant variations in this length correction term. It is argued here that these variations originate from errors in the measurement of crack length which can be either random or systematic. An alternative analysis scheme is proposed from which the crack lengths are calculated using the measured compliance and a pre-determined flexural modulus value. Such an approach yields considerable insight into the accuracy of the test method.

Keywords: A. Polymer matrix composites (PMCs); B. Fracture toughness; B. Modelling; C. Delamination; Fibre bridging

1. Introduction

The international standard for the determination of the mode I delamination resistance of unidirectional fibre reinforced polymer composites, ISO 15024 [1], was published in 2001 and followed numerous round-robin test programmes initiated by the various relevant technical working committees in Europe, USA and Japan [2–4]. A large quantity of data was collected using the double cantilever beam (DCB) test specimen for both glass fibre and carbon fibre reinforcement, and also for various polymer matrices including epoxy, toughened epoxy, PMMA and PEEK. Also, a number of analysis schemes for the determination of G_{IC} were developed or adapted, including a corrected beam theory analysis [5] and also various forms of compliance calibration analysis. Of these schemes, the corrected beam theory approach has been, perhaps, the most popular and the advantages of such a scheme have been that both stable and unstable crack length data may be analysed and also the analysis scheme provides a valuable cross-check by determining the flexural modulus of the arms of the laminate which, as expected, is shown to be independent of delamination length [5]. Another potential advantage is that the crack length correction term, Δ, derived by the scheme may be used to determine additional parameters to describe microcracking, damage and the bridging stresses at the crack tip in the composite [6]. However, these additional schemes require accurate and repeatable values of the correction term, Δ, to be known and of course in previous studies the accuracy of this correction term was of only secondary importance.

In the DCB test, the load, P, the displacement, δ, and the crack length, a, are determined simultaneously during crack growth and the compliance, C, (where $C = \delta/P$) is determined as a function of a. The delamination resistance, G_{IC} is found from

$$G_{IC} = \frac{P^2}{2b} \cdot \frac{dC}{da}, \quad (1)$$

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where b is the width of the specimen. The corrected beam theory analysis corrects simple bending for the effects of transverse shear and for deformation beyond the crack tip [7]. This is achieved by the addition of the correction, Δ, to the measured crack length [1]

$$\frac{C}{N} = \frac{8}{E_1 b h^3} \cdot (a + \Delta)^3, \tag{2}$$

where E_1 is the flexural modulus and h the thickness of one arm of the DCB specimen, and N is a finite displacement correction to account for load-block effects. Eq. (2) is usually recast in the form

$$\left(\frac{C}{N}\right)^{1/3} = \left(\frac{8}{E_1 b h^3}\right)^{1/3} \cdot (a + \Delta) \tag{3}$$

and the corrected beam theory progresses by plotting the value of $(C/N)^{1/3}$ versus the measured crack length a. Such data is usually highly linear and the average value of E_1 for a specimen is determined from the slope, and the average value of Δ from the intercept with the negative a axis. (The convention followed is that a negative a axis intercept yields a positive value of Δ and vice versa). A feature of uncorrected beam theory had been that E_1 was observed to increase with crack length when calculated on a point-by-point basis which was not a physically reasonable result. Corrected beam theory on the other hand, when employed on a point-by-point basis, i.e., by

$$E_1 = \frac{8N(a + \Delta)^3}{Cbh^3} \tag{4}$$

resulted in constant values of E_1 with increasing crack length for a given specimen. However, some inconsistencies were noticed with the analysis scheme during round-robin testing. Firstly, whilst the value of E_1 was usually shown to be independent of crack length, it was frequently higher than the independently measured value from a three point bend test. The test protocol [8] developed by the European technical working committee ESIS TC4 acknowledged this and warned that the value of E_1 derived from the DCB test should not be quoted as the flexural modulus of the laminate (*ESIS TC4 is the European Structural Integrity Society, Technical Committee on Polymers, Composites and Adhesives*). However, no limits were placed on how much higher the value from the above fitting procedure could be above the known value. The effect was attributed to fibre bridging, where unbroken fibres straddle the opened crack surfaces. Secondly, variations in the value of Δ from specimen to specimen were observed and occasionally, in extreme examples, a negative value of Δ resulted from an intercept at a positive crack length value via the corrected beam theory approach. This caused some concern, but as these variations appeared to have little or no effect on the values of G_{IC} determined via

$$G_{IC} = \frac{3P\delta}{2b(a + \Delta)} \cdot \frac{F}{N}, \tag{5}$$

where F is a large displacement correction, then these variations were accepted. However, the extreme situation, where a negative value of Δ was determined, was deemed unacceptable so a minimum value of zero was specified such that if Δ was negative, then $\Delta = 0$ would be used. The ESIS TC4 protocol [8] and the ISO standard [1] both make this recommendation however, the latter makes no mention of E_1 values. It was observed in some of the original work on carbon-epoxy and APC 2 materials [5] however, that while E_1 was usually close to the known value, Δ was often higher than the elastic value and this was attributed to damage reducing the lateral stiffness.

In the present work, we re-visit a number of the round-robins conducted by the ESIS TC4 working committee and analyse the variations in E_1 and Δ deduced by the corrected beam theory with a view to rationalising the observations and determining whether the values of Δ obtained may be used reliably to characterise bridging stresses and damage.

2. ESIS TC4 Round-robin data

2.1. Introduction

ESIS TC4 has completed about a dozen round-robins on delamination testing in modes I, II and mixed-mode I/II since its formation in 1986 and a summary of these activities may be found in [9]. Some of the more recent activities have concentrated on delamination in non-unidirectional laminates, e.g. $[0/90]_{6S}$ symmetric laminates [10] and on z-pinned reinforced laminates [11]. The work during the development of ISO 15024 included round-robins on carbon-fibre epoxy, carbon-fibre toughened epoxy, glass-fibre epoxy and glass-fibre PMMA. A number of sets of data are now presented from these activities and the general characteristics of the data will be identified. The data presented are sometimes from multiple laboratories, and sometimes from single laboratories. For some of the data sets the amount of fibre bridging has been quantified. The corrected beam theory analysis has been employed to determine average values of E_1 and Δ via Eq. (3) and G_{IC} via Eq. (5). The value of E_1 from independent 3-point bend tests is always also given. Elastic values of Δ have been deduced via [12]:

$$\left(\frac{\Delta}{h}\right)^2 = \frac{1}{10}\left(\frac{E_1}{\mu} - 2\nu\right) + 0.24\sqrt{\frac{E_1}{E_2}}, \tag{6}$$

where E_2 and μ are the transverse and shear moduli of the composite, respectively, and ν is Poisson's ratio.