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Influence of bending rotations on three and four-point bend end notched flexure tests

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ABSTRACT

It has been experimentally observed that mode II critical energy release rate (G_{IIC}) values determined by four-point end notched flexure test and three-point end notched flexure test are different for the same material. At the present work correction factors related to bending rotations are introduced to explain the differences between values of G_{IIC} obtained by three point and four point end notched flexure tests. The bending angle leads to the contact zones between specimen and supports and specimen and load rollers changing in both test configurations. The present analysis has been carried out by the classical beam theory, neglecting shear effects and assuming the hypothesis of small rotated angles. Results show that the relative differences between corrected and uncorrected values of G_{IIC} are greater in the case of four-point end notched flexure than in the case of three-point end notched flexure test.

1. Introduction

One of the most important factors hindering the use of fibre-reinforced composites materials in structural applications is their inherently poor damage tolerance for delamination. The resistance of composites to delamination can be well characterized by the fracture toughness, measured as the energy dissipated per unit area of crack growth. The fracture toughness of the material can be determined as the energy release rate, *G*. Delamination in composites can occur due to tensile stresses (mode I), in-plane shear stress (mode II), and out-of-plane tearing stresses (mode III). As a result, a complete understanding of these delamination processes is needed to properly design composite structures and develop materials with improved fracture toughness characteristics [1].

Standards are currently available for the determination of critical interlaminar energy release rate in mode I (G_{Ic}) of unidirectional laminates: ISO 15024 [2] and ASTM D5528-94a [3].

However, there is still some controversy about the measurement of the mode II fracture toughness. Three-point bend end notched flexure test (3-ENF) has been widely used for the determination of the mode II delamination toughness of laminated composites. A drawback in the use of 3-ENF is that crack propagation is inherently unstable. The initial crack length must be at least 0.7 times the half span length in order to the crack propagation being stable [4,5].

An alternative configuration of mode II was proposed by Martin and Davidson [6], namely four-point bend end notched flexure test (4-ENF). In this test, the crack propagation is stable for any crack length. Then, an experimental compliance calibration can be applied for data reduction of the fracture toughness as the delamination advances and mode II resistance curve may be established.

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Nomenclature

d_0, $(2L)_0$ dimensions of the undeformed configuration
d_1, d_2, $(2L)_L$ dimensions of the deformed configuration
θ_{Aa}, θ_{Ba}, θ_{Ca}, θ_{Da} bending angles of the basic system a
θ_{Ab}, θ_{Bb}, θ_{Cb}, θ_{Db} bending angles of the basic system b
δ_{Ca}, δ_{Da} displacements of C and D points in the basic system a
δ_{Cb}, δ_{Db} displacements of C and D points in the basic system b
I second moment of area with respect to the middle plane
Q applied load
w, $2h$ width and thickness of the specimen, respectively
R radius at support and loading noses
E_f flexural modulus
η_A, η_B, η_C, η_D terms related to support and load span reduction

Shuecker and Davidson [7] observed in experimental studies that 4-ENF test produced toughnesses even 20% higher than those obtained by 3-ENF test. It was also reported that the difference between values of the critical energy released rate G_{IIc} obtained by 3-ENF and 4-ENF increases when the ratio between the inner span and the outer span increases.

Shuecker and Davidson [8], analysed by using finite element method (FEM) whether the differences in delamination toughness obtained by 3-ENF and 4-ENF test could be attributed to friction between the crack faces. It was shown that the effect of friction on G_{IIc} is greater in 4-ENF than in 3-ENF, and that this effect increases when the ratio between the inner span and the outer span in 4-ENF increases. However, it was found that frictional effects were not great enough to fully account the observed discrepancies in the values of G_{IIc}. As a result, it was postulated that the error might be due to inexact measuring techniques for determining the crack length and the compliance during the 4ENF tests.

Recent studies carried out by Sun and Davidson describe a newly developed "Direct energy balance approach" [9]. This approach is based on the original Griffith argument [10,11], with an additional term to account the energy lost due to friction. According to the authors this approach can fully recreate the perceived toughness obtained by these tests. In authors opinion it is the first complete explanation of the reasons for the observed variations in fracture toughness values obtained by 4-ENF tests with different geometries. However, numerical analysis is necessary for data reduction.

Davidson and Sun [12,13] observed that 3-ENF test provide more reliable delamination toughness results, and according to them significant work remains to be done before obtaining accurate results from 4-ENF test.

Mujika [14] analysed the effect of span variations caused by bending rotations in the calculation of flexural modulus obtained by three-point and four-point bending tests, without taking into account shear effects. The chord slope of the load–displacement curve between 0.1% and 0.3% strain values was used for modulus calculation. After corrections based on the developed analysis, the relative differences between moduli obtained by three-point and four-point bending for the same specimen were negligible.

In a similar way, the goal of the present work is to study the effects of bending rotations in 3-ENF and 4-ENF tests. Correction factors related to bending rotations have been calculated in order to explain the differences between G_{IIc} values obtained by both 3-ENF and 4-ENF tests.

The rotation of the cross sections leads to the contact zone between specimen and cylindrical supports changing in the 3-ENF test. Furthermore, in 4ENF test the contact between specimen and cylindrical loading rollers also changes.

Compliance calculation has been carried out between 0.05% and 0.25% strain values. These values are the corresponding to modulus determination according to ISO14125:1998 [15]. Otherwise, this standard specifies that for considering small displacements maximum displacement to span ratio in three-point bending must be less than 10%. This limitation is equivalent to the maximum bending angle being 0.3 rad in three-point bending [14]. This angle limitation has been considered for both 3-ENF and 4-ENF tests.

Therefore, bending rotations have been considered small quantities and second and higher order terms related to those angles have been considered negligible.

2. Energy release rate

To calculate the mode II critical energy release rate, the original Irwin's energy approach for fracture is used [16]. The energy balance for an infinitesimal crack advance is

$$\frac{\partial}{\partial a}[U - F + W] = 0 \tag{1}$$

where a is the crack length; U is the strain energy; F is the work performed by the external forces and W is the energy for crack creation. Energy release rate, G, is defined as the available energy per unit area for an increment of crack extension. If the width is w, results