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Analytical and numerical approach of an End Notched Flexure test configuration with an inserted roller for promoting mixed mode I/II

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ABSTRACT

A test configuration for studying mixed-mode is analyzed analytically and numerically. It is based on the End Notched Flexure test, inserting a roller in the cracked part in order to promote mixed mode I/II. The analytical approach includes the calculation of the force exerted by the roller, the midpoint displacement, the compliance of the test, and the relative displacement of both arms of the crack. Moreover, the energy release rate is determined based on the complementary strain energy. With respect to numerical analysis, the two-step extension procedure is used for determining energy release rates in mode I and mode II. Comparison between analytical and numerical results has been carried out in order to check the suitability of the test method.

1. Introduction

Interlaminar fracture is one of the most common failure modes in composite materials. As delamination in composites is often a mixed-mode fracture, it is important that the composite toughness be measured at different mode mixtures [1–4]. Using fracture mechanics to characterize the onset and growth of delamination has become a generally accepted practice. According to Griffith–Irwin linear elastic fracture mechanics, the crack initiation and propagation is governed by the critical strain energy release rate G [5,6].

A standardized method for characterization of the mixed-mode I–II fracture toughness was introduced in 2001 [6], named mixed mode bending test (MMB). The fixture proposed in the standard ASTM D6671 [6] is a modified version of that originally proposed by Reeder and Crews [3,7]. Chen et al. [8] carried out a modification on the MMB test rig for making it easier to calculate G, avoiding to introduce the weight of the lever. Blanco et al. [9] proposed a solution for determining the distance of the lever arm in the MMB test with better accuracy. Tenchev and Falzon [10], presented an analytical solution for the MMB problem, when the crack has propagated beyond the middle of the beam.

For the MMB test the ratio between mode I and mode II, named mixed-mode ratio, remains constant. In the mixed-mode end load split test (MMELS) the mode mix depends on the crack extension. This test is a modified version

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Nomenclature

a, a_I, Δa	crack length, corrected crack length and crack increment, respectively
c_o, c_i	distances from the support to the position of the roller when it is at the outer side and at the inner side of the support, respectively
b, $2h$	width and thickness of the specimen, respectively
d_{interf}	distance from the support to the edge of the specimen, when there is interference
A_1, A_2, A_0	surface areas of the upper and lower arms in the cracked zone, and of the whole section in the uncracked zone, respectively
C	compliance of the test
E_f	flexural modulus
E_L, E_T, G_{LT}, ν_{LT}	longitudinal, transverse, in-plane shear elastic moduli and Poisson ratio, respectively
F_{x1i}, F_{y1i}, u_{1i}, v_{1i}	forces at the crack tip and horizontal and vertical displacements of the released nodes, respectively
G_I, G_{II}, G	mode I, mode II and total energy release rates, respectively
I_1, I_2, I_0	second moments of area with respect to the middle plane of the upper and lower arms in the cracked zone, and of the whole section in the uncracked zone, respectively
M_1, M_2, Q_1, Q_2	bending moments and shear forces in the cracked zone
M_I, M_{II}, Q_I, Q_{II}	bending moments and shear forces in the crack tip due to mode I, and mode II, respectively
L	half span of the test
P	applied load
R	roller radius
W, U, U^*	work done by external forces, strain energy and complementary strain energy, respectively
Y	force exerted by the roller
δ	displacement of the load application point of the specimen
δ_{rel}	relative displacement between the upper and lower arms in the cracked zone
P_0, δ_0	initial load and initial displacement, respectively
ADCB	asymmetric double-cantilever beam
ELS	end load split test
MMELS	mixed-mode end load split test

of the end load split test (ELS), where the interlaminar crack in a beam-type specimen is forced to propagate under mixed-mode and has been analyzed by different researchers. The studies of Hashemi et al. [11] and Kinloch et al. [4] are based on the beam theory formulated by Williams [12]. They proposed a series of analytical expressions for the characterization of the test. Blanco et al. [13] demonstrated that beam theory is capable of modelling MMELS test when the crack is centred in the thickness.

Other test and specimen configurations have been proposed in order to analyze the mixed mode I/II fracture. The asymmetric double-cantilever beam (ADCB), where the crack plane is out of the laminate midplane, generating a mixed mode load state at the crack tip. Mangalgiri et al. [14] were the first to apply the ADCB test. The European Structural Integrity Society (ESIS) TC4 group studied it in the 1990s. [15]. Ducept et al. [16] carried out experiments on ADCB glass fibre reinforced epoxy composite samples and compared results with analytical and numerical ones. Bennati et al. [17,18] developed an enhanced beam theory model for the ADCB test based on the experimental work developed by Ducept et al. ADCB configuration has been analyzed by other authors [19–21].

Szekrényes proposed three different specimens for analyzing mixed mode I/II: Two prestressed specimens, one based on the End-Notched Flexure (ENF) specimen [22], and other based on the ELS specimen [23]. The main characteristic of these methods is that the mode I is provided by the insertion of a steel roller at the delamination plane. The third proposal, developed by Szekrényes and Uj [24], was the over-leg bending specimen, which is a modification of the single-leg bending specimen, where the load is introduced eccentrically.

Kolluri et al. [25] introduced a new miniature setup capable of applying a mixed mode bending load to a bilayer delamination sample with a pre-crack. In this set up a microscope is necessary to observe the delamination.

Bonhomme et al. [26] proposed the two-step extension procedure (TSEP) as an alternative to the virtual crack closure technique (VCCT), which allows to determine G. Mollón et al. [27], compared experimental results of G obtained by ADCB and reduced by an analytical method based on a modified beam theory with numerical results obtained by the TSEP. They found a good agreement among all the studied methods.

The aim of this study is to present a novel analytical model for a mixed-mode I/II interlaminar fracture test configuration for unidirectional composites. It is similar to ENF, but the specimen has an inserted roller for promoting mixed mode. This configuration was proposed by Szekrényes [22] for the particular position in which the roller is above the support. In the present work, the configuration is generalized for any position of the roller. Numerical analysis is also carried out by FEM applying the TSEP.