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Analysis and evaluation of friction effects on mode II delamination testing

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ABSTRACT

In this paper the attention has been focused on the evaluation of how friction can influence Four-point End-Notched Flexure test in carbon fibre-epoxy composite materials. The starting point has been the hysteresis loop in the experimentally obtained Load versus Displacement curve due to an unloading-loading cycle. Different locations for friction have been considered. Numerical simulations have been performed by using Finite Elements and an experimental test campaign has been also carried out to validate the model and to optimize friction coefficients through the comparison with test results. The outcomes of the numerical analysis have given useful indications. Firstly, the comparison of the simulated maximum load and dissipated energy with those coming from the experimental tests has given good results.

Secondly, it has been found that the contact between pins and specimens is the most significant location for friction.

1. Introduction

Laminated composite are widely used in many industrial applications, such as aeronautical and aerospace structures, naval engineering, automotive and several other fields in which high performance and quality are required. Indeed, composite materials offer higher specific strength and stiffness than other conventional materials. It is clear that, to allow and improve the utilization of composite materials, a complete understanding of their failure mechanisms is necessary. Usually most composite parts are built in layered structures where plies are oriented in various directions; consequently, they are prone to delamination, i.e. crack that propagates between two constituent layers.

The sensitivity to delamination is one of the limits to the use of composites in lightweight load bearing structures: it is necessary to match the requirement of lightness with damage tolerance design, according also to Federal Aviation Administration requirements that argue that in case of lack of the proper knowledge of the delamination process, a no-growth approach ought to be adopted, [1].

Delamination problems can be studied by means of the fundamental results of Linear Elastic Fracture Mechanics (LEFM). The state of the art for using LEFM to calculate inter-laminar fracture toughness and delamination growth for composite materials has been outlined in the Composites Materials Handbook 17, [2]. As noted there, the American Society for Testing Materials (ASTM) developed standards for mode I (Double Cantilever Beam, DCB), [3], mixed-mode I and II (mixed-mode bending, MMB), [4], and mode II (End-Notched Flexure, ENF), [5], inter-laminar fracture toughness determination tests. The stress field at the crack tip is different for the three modes, as well as the resistance to crack propagation. Therefore, the three modes fracture properties have to be studied separately as well as their combination.

In the present work attention is given to the evaluation of mode II fracture toughness and propagation values, in order to address one of the major concerns which is a long-standing matter of debate: the influence of friction on Four-point End-Notched Flexure (4ENF) tests.

Even though the ASTM has provided a standard only for the ENF test, the 4ENF procedure, [6], is generally preferred. The reason lies on the fact that the 4ENF testing procedure allows for a wide interval of stable propagation which, on the contrary, does not occur in ENF tests where unstable propagation is likely to occur. Carlsson and Gillespie, [7], showed that for fixed load conditions crack growth in ENF tests is always unstable, while for fixed grip conditions crack growth is stable only if the influence of shear is neglected and $a/L \geq 0.7$. However, $a/L = 0.5$, is normally used [8]. In addition, as outlined in [6], the shear force is equal to zero for standard 4ENF test configurations and thus friction at delamination surfaces is reduced.

Extensive research has been undertaken in the last two decades in order to identify the main features affecting mode II inter-laminar fracture toughness of unidirectional laminated composite. However, the identification of uncertainties, as well as the development of alternative ways to increase the accuracy of both fracture toughness at initiation

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Nomenclature

a	crack length
B	specimen width
C	compliance
DCB	Double Cantilever Beam
ENF	End-Notched Flexure
ERR	Energy Release Rate
E_1, E_2, E_3	tensile moduli of elasticity
FEM	Finite Element Method
G_{12}, G_{13}, G_{23}	shear moduli
G_{II}	mode II strain Energy Release Rate
I	moment of inertia of the undelaminated beam
L	half-span length
LEFM	Linear Elastic Fracture Mechanics
MMB	Mixed-Mode Bending
P	applied load
PTFE	Poly-Tetra-Fluoro-Ethylene
t	time
u_1, u_2, u_3	boundary constrains for displacements in FEM model
δ	applied displacement.
μ_{Crack}	friction coefficient between crack faces.
μ_{PIN}	friction coefficient between pins and specimen.
μ_{PTFE}	friction coefficient between Poly-Tetra-Flouro-Ethylene parts.
ν_{12}, ν_{13}, ν_{23}	Poisson's ratios
4ENF	Four-point End-Notched Flexure

and propagation resistance (R-curve) are still under investigation. The sources of error can be gathered in four main families acting simultaneously and not independently one from each other: geometric nonlinearities, fixture compliance, crack length measurements and friction. Several attempts have been done to reduce their effects on the perceived fracture toughness.

Noteworthy is the work carried out in order to reduce the inaccuracy of crack length measurements. In fact, it is well known that the absence of a notable separation of the fracture surfaces in mode II tests makes the visual crack tip identification troublesome. However, it is worth noticing the use of optical fibres and Fibre Bragg Gratin sensors to detect the crack front in terms of strain measurements along the delamination path, [9]. Theoretical and numerical models have been proposed in order to quantify the effect of several key factors such as loading nose distance and inner span length, [10]. An extensive overview of the main variables affecting mode II delamination test is reported by Franklin and Christopher, [11]: in their paper fibre volume fraction, nose distance, inner span length, friction, measuring techniques and reduction schemes, fracture criteria effects are experimentally evaluated and discussed.

Besides the aforementioned advantages of the 4ENF test, friction is still the most problematic issue. Several works were carried out in the past decades and yet the debate is open on whether friction plays a major or minor role in 4ENF tests.

In 4ENF procedure, friction can occur in three different positions and three different coefficients are in turn defined:

i) at the delamination interface (propagation zone),
ii) at the nesting interface (initial defect),
iii) between the upper and lower sides of the specimen and the rolling pins.

Among the first to address the problem, Kageyama et al., [10], suggested that friction was the main cause of the differences in toughness resulted between ENF and 4ENF tests. Successively, they tried to quantify this effect and, assuming that dissipation occurs at the delamination interface only, the related friction coefficient was estimated to be as high as 2.1 for an inner span of 50 mm. Starting from Kageyama et al., [10], Schueker and Davison, [12], showed that, despite the fact that friction was found to have a major influence on 4ENF fracture toughness than in ENF tests, its effect was overall small if compared with other sources of error. The estimated friction coefficient was reduced with respect the one assumed in [10] and its value, found between 0.5 and 1.0, proved to be in good agreement with their experimental results. Unfortunately, in the simulations, the authors focused only on the delamination interface without taking into account the fact that the major contribution to the friction effect would come from the contact between the fixture and the specimen, as it will be shown later on in the present work.

Other research activities have been carried out in order to identify the effect of friction but most of them assume that the zone of dissipation is limited only at the crack interface, ruling out the strong contribution given by the contact between the specimen and rolling pins.

The advent of Finite Element Methods (FEM) for the simulation of composite materials behaviour and – recently – of cohesive elements has pushed forward the research on friction characterization allowing for a more precise and detailed definition of how the fractured surfaces

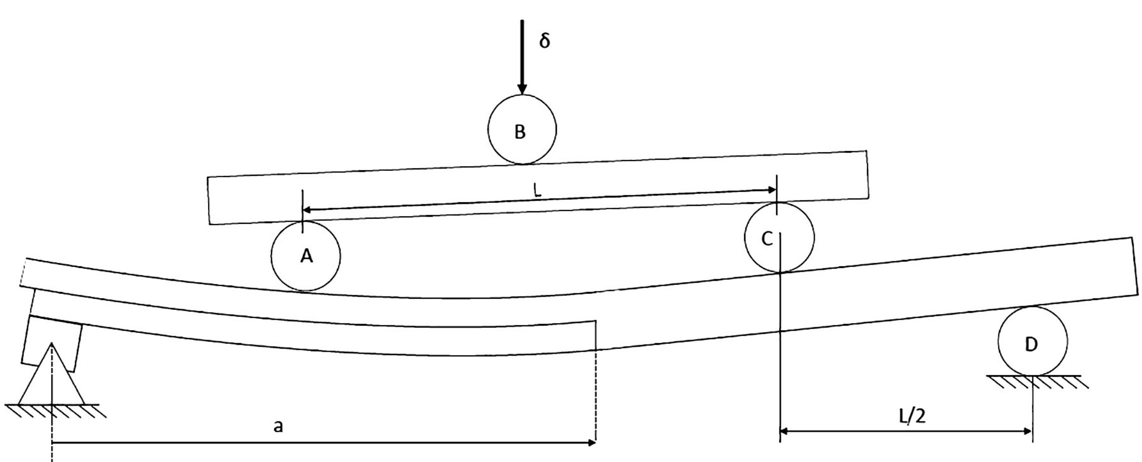

Fig. 1. Schematic of 4ENF test configuration.