One application of the ENFR fracture test:coupon testing for wind turbine blade materials

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Abstract: - The ENFR I/II mixed-mode fracture test analyzes the interlarminar fracture in fiber reinforced composites. These materials are widely used in wind turbine blades. At the structural scale, one of the most critical failures in a blade is delamination of unidirectional laminates in the spar cap. In this paper we introduce a new methodology for mixed fracture mode analysis based on linear elastic fracture mechanics (LEFM). In order to demonstrate the consistence of the theoretical basis of the methodology, ENFR test method is applied to 10 different test conditions in specimens of one composite material typically used in wind turbine blades. Experimental results obtained for critical fracture parameters, agree with the ones obtained in pure mode fracture tests. Therefore the method can be used for wind turbine blade material characterization, at coupon testing level, as the experimental results demonstrate.

Key-Words: - wind turbine blades; delamination; fracture-mechanics; mixed-mode fracture; fracture tests

1 Introduction

Wind energy is an important resource among other clean energy sources. It is one of the most used renewable energy sources since it is less expensive than solar energy, and it has no geographical limits as hydropower has. The wind energy power instalation has grown rapidly in the recent years. In the EU, wind generation doubled over the period 2005-2010 [1]. The trends in development of new wind turbines is to design larger wind turbines, and offshore wind farms. The optimum service life for a wind turbine is about 20 years, and it is expected that repair or maintenance be minimum Therefore, minimising maintenance and repair costs has become very important issue [2]. The characteristics of the materials used in wind turbines should be: low weight, high stiffness and high resistance to fatigue. Composites materials can be tailored in order to achieve these features. The properties of the composite material used in blades are fundamental to stablish the performance of the turbine. Wind turbine rotor blades are usually made from fibre-reinforced composite subcomponents [3]. Delamination between plies is the root cause of many failures of composite material structures such as wind turbine blades. Among various failure

modes observed, the blade collapse has been caused by the delamination of unidirectional laminates in the spar cap [4]. In some wind turbines damaged by super typhoon Usagi in 2013, it was found that blade fracture and tower collapse were major structural failure of wind turbines [5]. Accumulated delamination of unidirectional composites in spar cap was one of the main causes for a 52.3m composite wind turbine blade to collapse [6,7]. Delamination can occur because of in-service loads or during the manufacturing process. Mandell et al [8] investigated the delamination in a skin-stiffener intersection of a wind turbine blade. They applied fracture mechanics for determining critical strain energy release rate in order to perform material selection. They concluded that resins which improved interlaminar toughness give greater resistance to damage. To improve the blade performance, Methods for experimental determination of material properties are valuable for improving blade performance [9]. The rotor blades studies are usually carried out from material scale (microscale) to component scale, the rotor blade. To give a better description of the materials properties testing methods and material models are important [9].

The determination of laminate properties for blade design has been widely investigated. Mechanical tests are performed on coupons and subcomponents with a representative lay-up and a processing route similar to that of the blade in question. However, the final qualification requires full-scale tests on prototype blades [10]. Giannis et al [11] carried out fracture tests on coupons of polymer composites for wind turbine blade applications. By means of mode I fracture tests the effect of the stiffness of the carbon fibers of different materials on the value of fracture toughness was assessed. By means of the four point bending test Zarouchas et al. [12] analyzed the mechanical behavior of two I-beams. The I-beam is a representation of a rescaled load carrying blade structure. The Double Cantilever Beam (DCB) test for mode I, and the End Notched Flexure (ENF) test for mode II were used by Shah and Tarfaoui, [13] for characterising bonded interfaces in order to assess zones that can fail in the structure of a wind turbine blade. Afterwards they studied experimentally a sandwich specimen used in a real wind turbine blade [14]. The energy release rates of mode I and mode II were determined. DCB test for mode I was performed, and single over leg bending test (SLB) for mode II. The failure performance of composite materials in a substructure of wind turbine blade using carbon, Kevlar and glass fibres has been also studied [15]. Wang and Soutis validate experimentally a predictive numerical model that can determine the strength of composite T-joints for wind turbine blade applications [16]. Sørensen et al. [17] studied beam type specimens made from adhesively bonded fibre-reinforced composites under steady-state mode I, mode II and mixed mode loading conditions. They proposed an analytical model for the energy release rates (ERR), which leads the determination of fracture resistance, of adhesive joints.

In this work the end notched flexure test with roller (ENFR) test method recently proposed [18-20] has been applied to the analysis of the mixed-mode I/II fracture in unidirectional composite materials used commonly in wind turbines manufacturing. The objective of this test is to obtain the critical value of the energy release rate, which gives the fracture resistance of the material. The ENFR test method is a three point bending test, where the specimen has a centered crack and a metallic roller is inserted between the two arms of the crack for promoting mixed-mode fracture. 10 different test conditions are studied with the aim of assess the applicability of the method for material characterization and to use it for wind turbine blade design at a first stage.

2 Background on delamination tests

Composite laminates are widely used in wind turbine blades. On one hand they can be tailored according to their application. On the other hand, they have low tolerance to interlaminar fracture. This means that if there is an interlaminar crack or delamination, that is to say, separation between adjacent plies, the composite material can fail leading to the collapse of the blade. The theory of linear elastic fracture mechanics (LEFM) is one of the main crack analysis methods. The energy criterion approach of Fracture Mechanics can be applied to investigate delamination growth. This approach assumes that a crack can grow if sufficient potential energy is available to overcome the surface energy of the material. The energy release rate, G, is the energy available for an increment of crack extension. The crack will grow when G reaches a critical value, GC. This critical value is the fracture toughness and it is a material property [21]. The crack can propagate in three modes as it an be seen in Fig. 1.
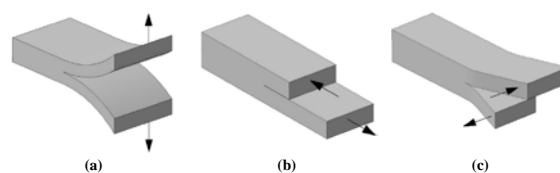

Fig. 1 Fracture modes: (a) Mode I, opening; (b) Mode II, sliding; (c) Mode III, tearing

GI, GII and GIII are the energy release rates corresponding to each mode respectively. The fracture toughness values corresponding to each mode fracture are then: GIC, GIIC and GIIIC. The delamination tests consist on a load application in beam type specimens. These specimens have an artificial crack and under load application the crack grows. During the test the applied force and the total displacement are measured. The crack length and the energy release rate can be determined by means of beam theory [22].

3 Description of the method

, The End Notched Flexure with inserted Roller (ENFR) [18,19] test configuration is applied in order to analyzing the mixed-mode I/II fracture. It is based on a three point bending test. The load is applied to a beam type specimen that has an artificial initial crack in the direction of the fibres. The three point bending test configuration is very

common in delamination tests. Sayer et al. used a three point bending test with an asymmetric beam to to study the adhesive performance between shear web and spar cap of the wind turbine rotor blade [23]. The standardized method for analyzing fracture mode II is based in a three point bending test [24].

In the ENFR test configuration, the load application gives the mode II and the opening of the crack, that is the mode I, is caused by the insertion of the roller between the two surfaces of the crack. Therefore mixed-mode I/II is obtained. The test configuration can be seen in Fig. 2, where a is the crack length, c distance of the roller position to the support and L the half span of the test. There are three possible positions of the roller: at the outer side of the crack, at the inner side, and in the vertical of the support.´
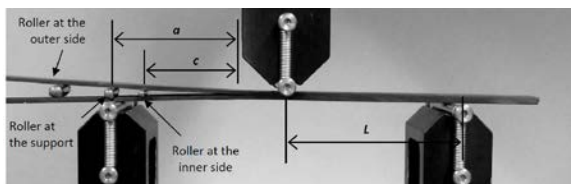

Fig. 2 Three position of the roller

The energy release rate is determined by beam theory [18], and it can be expressed as follows:

Outer side

$$G = \frac{3R^2 E h^3}{4a^4} - \frac{3PRc_o(a^2 - c_o^2)}{4a^4 b} + \frac{3P^2 c_o^2(a^2 - c_o^2)^2}{16a^4 E_f b^2 h^3} + \frac{9P^2(a - c_o)^2}{16E_f b^2 h^3}$$

Inner side

$$G = \frac{3R^2 E_f h^3}{4(a - c_i)^4} + \frac{3PRc_i}{4b(a - c_i)^2} + \frac{3P^2 c_i^2}{16E_f b^2 h^3} + \frac{9P^2 a^2}{16E_f b^2 h^3}$$

$c = 0$

$$G = \frac{3R^2 E_f h^3}{4a^4} + \frac{9P^2 a^2}{16E_f b^2 h^3}$$

$$(1)$$

The first terms correpond to GI and the second terms in other color correspond to GII, these mode partition has been validated by finite element method using the TSEP Two Step Extension Procedure [18].

When studying mixed-mode fracture the determination of a suitable failure criterion is fundamental. In pure modes, crack growth is determined by the critical energy release rate or fracture toughness of the material. Nevertheless, in I/II mixed-mode fracture, the total energy

release rate is G = GI + GII but GC ≠ GIC+ GIIC. In this work, the linear failure criterion is adopted [19] and it is expressed as follows:

$$\frac{G_I}{G_{IC}} + \frac{G_{II}}{G_{IIC}} = 1 \qquad (2)$$

Expressing the linear criterion in a different way, an equivalent energy release rate, named as Geq can be defined as [20]:

$$G_{eq} = \left(G_I G_{IIc} + G_{II} G_{Ic} \right)^{1/2}$$
$$G_{eqc} = \left(G_{Ic} G_{IIc} \right)^{1/2} \qquad (3)$$

Geqc is the critical value of the equivalent energy release rate. Thus the crack propagation condition under mixed-mode fracture in the ENFR test configuration can be expressed as:

$$G_{eq} \geq G_{eqc} \qquad (4)$$

4 Application of the ENFR method
4.1 Materials and test apparatus
T300/F593 prepregs provided by Hexcel Composites with a 55% volume-content of fibre were used to produce laminates. T300 is the carbon fiber and F593 is the epoxy matrix modified with a thermoplastic to improve fracture toughness. Unidirectional laminates of sixteen layers were manufactured. During the piling up process a Teflon film was centered introduced in order to create the initial crack. Tests were performed on an MTS-Insight 100 electromechanical testing machine equipped with a 5kN load cell, operating in a displacement controlled mode.

4.2 Test procedure
The roller is placed between the two arms of the crack, Fig. 3 (a). Then load application starts. The specimen bends, but the crack does not grow, Fig. 3 (b). During this step of the test, the relation load-displacement remains linear. When crack propagation starts, the initiation point, load displacement curve loses its linearity and there starts the experimental compliance to vary Fig. 3 (c).
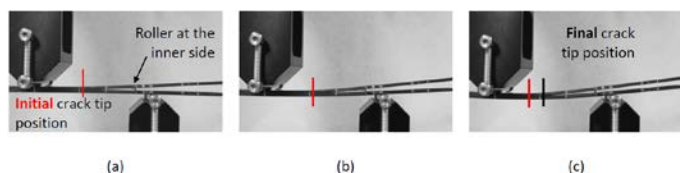
Fig. 3 Three steps of the test

With the load and displacement measured during the test, experimental compliance and the crack length are determined (boyano2) and with these data the energy release rate for each point of the test can be calculated.

4.3 Experimental test conditions

The relation between the contributions of each fracture mode is called mode-ratio and in this work is defined as GII /G. In order to get a wide range of mode ratios the initial crack length, the roller radius and the roller position can be varied. The nomenclature used in this work is: ai-Rj-ck. Being ai is the initial crack length; Rj the radius of the roller; and ck the the position of the roller. The nominal dimensions of the specimens are span 2L=120mm, width b=15mm and thickness 2h=3mm. 10 tests, with initial mode-ratio between 65%-75% with different experimental conditions were performed. All the test conditions are summarized in Table 1. Only a number will be used in the legends of the graphics for the sake of simplicity.

Table 1 Summary of experimental test conditions

ID	Nomenclature	Initial G_{II}/G (%)
1	a40-R1-c5	65
2	a42-R0.9-c8	65
3	a42-R1.5-c0	67
4	a43-R0.9-c8	67
5	a41-R1-c5	68
6	a42-R1.5-c0	68
7	a45-R1-c8	68
8	a40-R1.25-c0	71
9	a43-R1.5-c0	72
10	a46-R1.5-c0	77

4.4 Results and discussion

As it has been stated before, with the experimental compliance the crack length and the energy release rate can be determined at any point of the test. In Fig. 4 the experimental

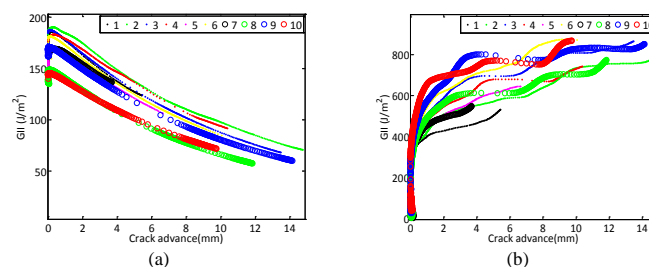values of GI and GII are represented during crack propagation.

Fig. 4 Experimetal curves (a) GI (b) GII

As it can be seen in Fig. 4, the curves corresponding to the energy release rate due to opening mode (mode I) descend slowly while the curves corresponding to sliding mode (mode II) have a initial fast rise and then they continue rising. This means that the contribution to fracture of each mode is changing during crack propagation. In other words, the mode-ratio defined as GII /G is increasing during the crack propagation.

In order to asses a mixed-mode fracture criterion, experimental values of GI and GII at different mode-ratios are needed as it is shown in Fig. 5.
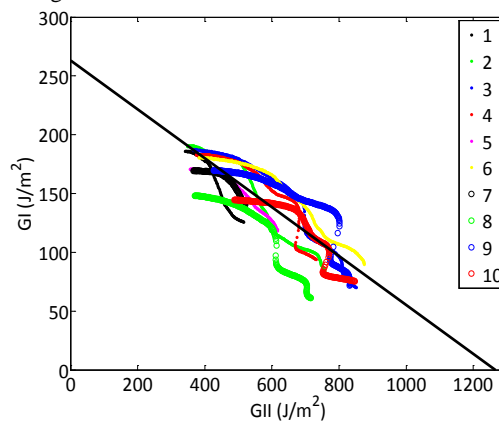

Fig. 5 GI_GII curves

Since all the curves follow a linear trend, the linear failure criterion seems to be suitable.

Results of linear fittings of the 10 case studies gives the critical strain energy release rate for each mode of fracture, and are presented in Table 2. The straight line is the representation of the linear criterion when GIC =263 (J/m2) and GIIC =1267 (J/m2). The value of the equivalent energy release rate obtained substituting those values in Eq. (3)is Geqc =550 (J/m2).

Table 2 Results of the linear fittings

Test	G_{IC} (J/m²)	G_{IIC} (J/m²)	$Geqc$ (J/m²)
1	344	798	524
2	309	1042	568
3	304	1174	598
4	298	1159	588
5	252	1241	559
6	274	1359	611
7	237	1405	577
8	265	986	511
9	278	1312	604
10	277	1179	571
All data together	263	1267	578

As it can be seen in Table 2, on the one hand the values of GIC and GIIC both agree reasonably with those obtained in the pure mode tests: GIc= 240(J/m^2) and GIIc= 1063(J/m^2) [19]. Therefore, ENFR mixed-mode tests with initial mode ratios between 65% and 75% fulfill the linear criterion, and the experimental values obtained for GIC and GIIC agree with the values obtained in the pure mode tests.

On the other hand the relative error of Geqc with respect to the value of 550 is close to 5%. Experimental values of Geq of the 10 tests studied are depicted in Fig. 6. The red line represents the value of 578 J/m2. The values tend to a plateau. That constant value is therefore the critical value of Geq, that is, Geqc. Thence, it can be considered a material property.
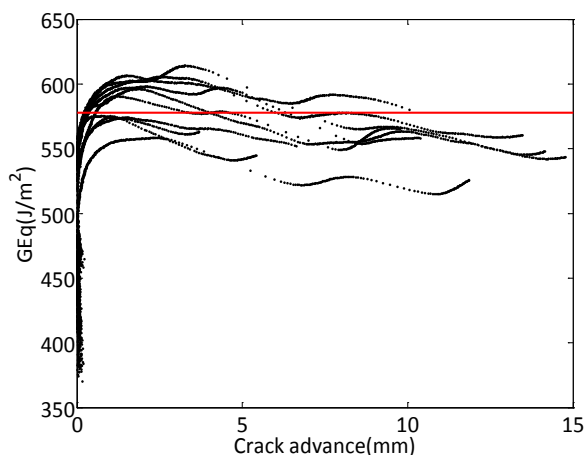
Fig. 6 Experimetal curves of Geq

5 Conclusion

Fibre-reinforced composites are materials commonly used in wind turbine blades manufacturing . The reliable characterization of materials increases the efficiency of wind turbines. Fracture damage in composite materials may reduce drastically the component endurance. A mixed mode test configuration, the End Notched Flexure test with Roller, ENFR, has been applied to 10 different mixed-mode ratios tests. Energy release rate and a recently proposed equivalent energy release rate were investigated during crack propagation. The experimental results obtained agree with the results obtained from pure mode delamination tests. If the linear failure criterion is fufilled, the proposed test configuration can be used for determining the values of GIC, GIIC and Geqc with only one mixed-mode test. Thence, it can be used for material characterization of unidirectional composite laminates of wind turbine blades at coupon testing level.

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