EXPERIMENTAL CHARACTERIZATION AND COHESIVE LAWS FOR DELAMINATION OF OFF-AXIS GFRP LAMINATES

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ABSTRACT

This work experimentally characterizes mixed mode delamination in glass fibre reinforced polymer laminates taking into account the influence of the off-axis angle between the lamina orientation and the crack growth direction on the fracture properties. Thus, providing a cohesive law that enables analysis of 3D models in which mixed mode crack growth within laminates having anisotropic fracture properties takes place.

1 INTRODUCTION

In recent years cohesive zone modelling approaches have become popular for the prediction of onset and growth of delamination in laminated composite structures. Despite that cohesive zone modelling is becoming available in commercial finite element software, there are still many challenges to be addressed in order to improve the reliability, generality and spread the applicability of the method.

Current state-of-the-art cohesive zone models for delamination in laminates can handle mixed mode loading conditions by applying a mixed mode interaction criterion, such as the Benzeggagh-Kenane criterion [4] or the power law criterion [5], which is readily available in commercial finite element programs like Abaqus and ANSYS. These models may prove sufficient for 2D delamination simulation where the crack is predetermined to grow in a certain direction within the laminate. However, for 3D delamination simulation current cohesive zone models are insufficient since they lack the ability to describe how the fracture properties may vary according to the crack front orientation, and thus apply isotropic fracture properties in the delamination plane. In order to handle these dependencies a framework has to be developed which involves the following parts:

1. Experimental characterization of mixed mode fracture properties in delamination of laminates taking into account the off-axis angle between the lamina orientation and the crack growth direction.
2. Development of a mixed mode cohesive law that accounts for the off-axis angle.
3. Development of a new cohesive zone finite element formulation that is based on the new off-axis mixed mode cohesive law and thus able to relate between different relative orientations between interface materials and crack front.

The current work mainly considers part 1, which deals with experimental characterization of mixed mode fracture toughness in delamination of GFRP laminates having different off-axis angles between the lamina orientation and the crack growth direction.

For that purpose a modified and improved test fixture of that proposed by [1] has been developed. The test fixture can produce uneven moments on DCB specimens based on a pure tensile loading input from a standard tensile testing machine. The fracture toughness in different configurations is evaluated by computing the J-integral from the applied moments.

2 CURRENT STATE-OF-THE-ART COHEZIVE ZONE MODELS

In order to understand the limitations of current cohesive zone models and their numerical formulation in finite elements a state-of-the-art cohesive zone model based on [2,3] is described.

3.1 Cohesive interface kinematics

A cohesive crack and potential crack path are modelled as a traversing surface of discontinuity in displacements through the continuum body, which divides it into two parts. In the deformed configuration, the separation of the two parts of the deformed body is described in a local Cartesian coordinate system, ($\mathbf{e}^1$, $\mathbf{e}^2$, $\mathbf{e}^3$) located on the middle surface, $\bar{S}$, see Figure 1.

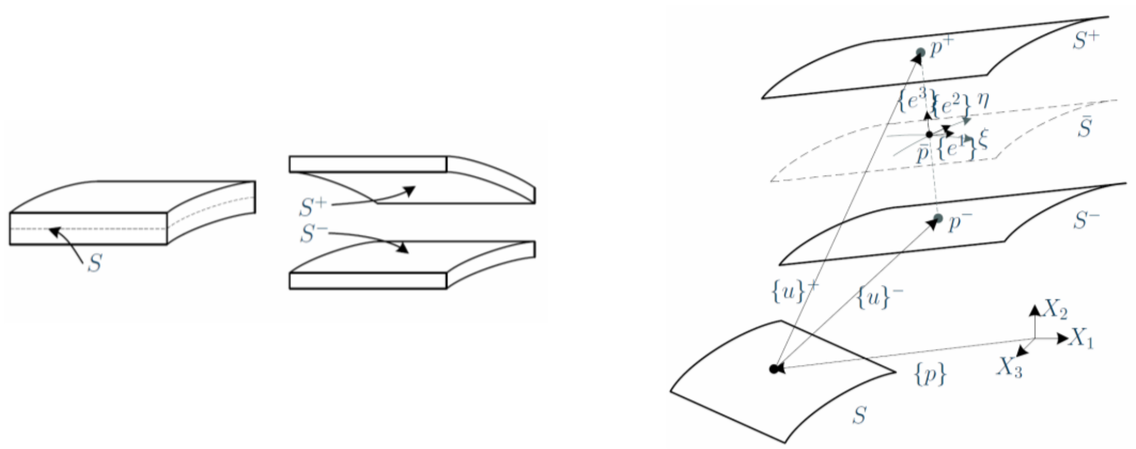

Figure 1: Left: Undeformed cohesive interface defined by the traversing surface *S*. Right: Description of the middle surface $\bar{S}$ in the deformed configuration.

The middle surface in the deformed configuration is defined as the average distance between initially coinciding points at the upper and lower surfaces of the undeformed body and is in the global Cartesian coordinate system defined as $\{\bar{x}\} = \{p\} + \frac{1}{2}(\{u\}^+ + \{u\}^-)$. The separation of points at the interface in the global Cartesian coordinate systems is given by $(\{u\}^+ - \{u\}^-)$ and is coordinate transformed to the local coordinate system ($\mathbf{e}^1$, $\mathbf{e}^2$, $\mathbf{e}^3$) located on the middle surface defining the different mode openings by $\{\Delta\} = [\Theta](\{u\}^+ - \{u\}^-)$.

The crack separations in the local coordinate system on the deformed mid-surface are defined by three opening modes in Figure 2. To describe mixed-mode behaviour it is common to reduce the three basic opening modes to two, i.e. a mode I opening and a shearing mode which is a combination of mode II and III, i.e. $\Delta_S = \sqrt{\Delta_1^2 + \Delta_2^2}$. The latter is done since no information about the crack front location is included in the kinematic description in Figure 1, and thus it is not possible to distinguish between mode II and III.

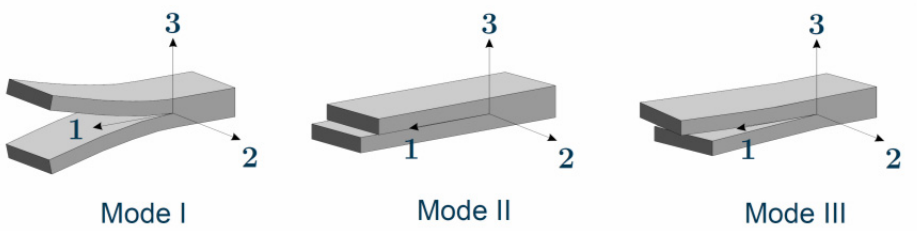

Figure 2: Basic opening modes.

3.2 Cohesive constitutive interface behavior

A typical model for the cohesive interface behaviour is the bilinear law shown in Figure 3, which relates tractions and separations for a given mode mixity depending on the value of the scalar damage parameter d. τ^0 is the onset traction of damage, Δ^0 is the corresponding onset opening, Δ^f is the opening at which full damage is reached, and Δ^t is the threshold opening for further damage development at the current damage state. The input parameters τ^0 and G_c are material parameters, which are dependent on the opening mode mixity and together with the penalty stiffness E, control the shape of the constitutive law.

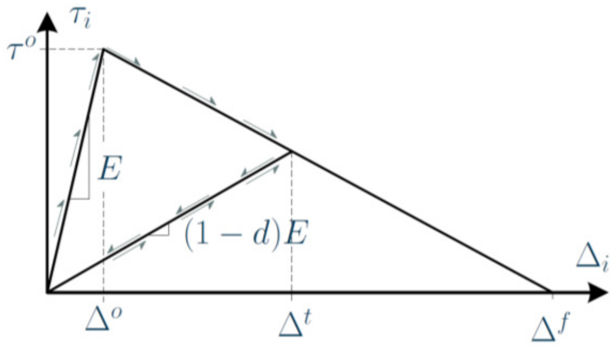

Figure 3: A bilinear constitutive law of the cohesive interface for a given mode mixity.

In case of mixed mode damage a mixed mode interaction criterion, such as the Benzeggagh-Kenane criterion [4] or the power law criterion [5] can be used to predict mixed mode crack propagation. These mixed mode damage models basically interpolates between the cohesive constitutive law from pure mode I and shearing depending on a mixed mode ratio parameter.

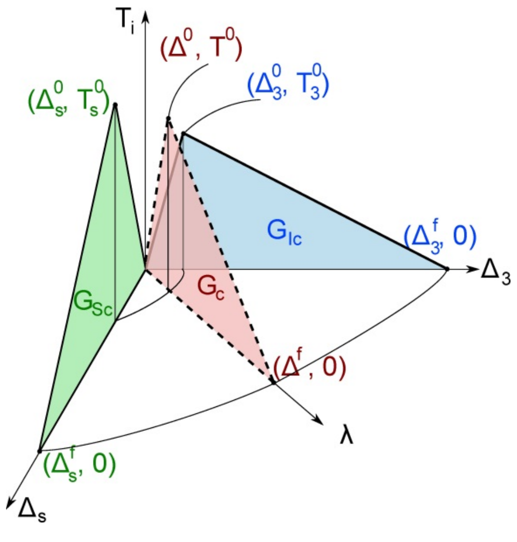

Figure 4: Mixed mode bilinear constitutive law by using the Benzeggagh-Kenane interaction criterion.

The input parameters for a mixed mode damage model are the onset tractions Δ^0 and the fracture toughnesses G_c for mode I and shearing, respectively, together with the penalty stiffness.

3.3 Limitation in current cohesive zone models

In order to describe 3D delamination crack growth in laminate composites the current state-of-the-art models as just briefly reviewed suffer several limitations. Currently the fracture toughness properties for mode I and shearing used in mixed mode cohesive laws assumes same fracture toughness independent of crack growth direction. Evidently, this means that isotropic fracture properties are assumed in the delamination plane since crack front orientation is not included in either the kinematic description or in the constitutive model of the interface.

3 PURE MOMENT LOADED TEST TOOL FOR MIXED MODE FRACTURE

To characterize the fracture properties in different off-axis laminate configurations a special purpose test tool has been developed and manufactured, see Figure 5. The concept of the test tool is based on the principle from [1] where a string pulley system can introduce pure uneven bending moments on a double cantilever beam specimen. The developed test tool is designed such that unwanted effects from large displacements and rotations are minimized and thus improved compared to the original setup by [1]. This is realized by redesigning the entire topology of the string pulley system, the roller support of the specimen, and also the orientation and attachment of the moment loading arms. It ensures that a pure moment can be enforced to the specimen even in conditions involving large displacements and rotations and effectively means that the test tool is much more compact size wise and may be used to test compliant and thin DCB specimens. Furthermore, the test tool has been designed such that it can be mounted and actuated by standard tensile testing machines, thus using the actuation and high quality data acquisition system already available.

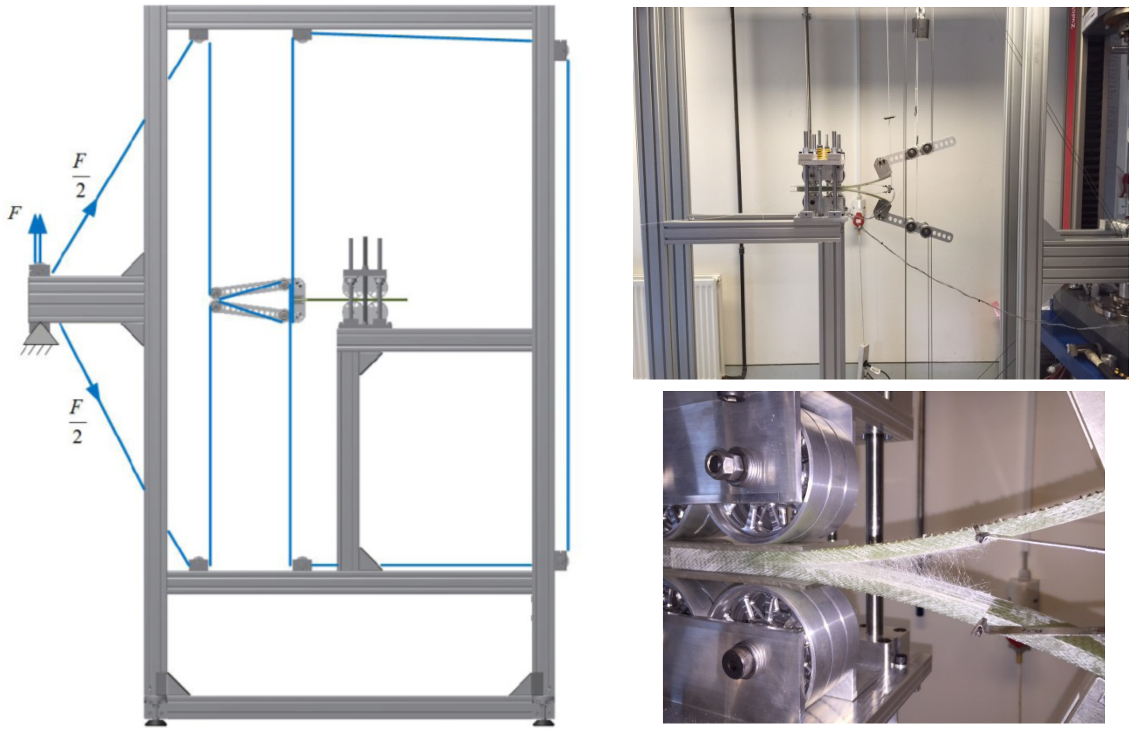

Figure 5: Developed test tool for pure moment loaded mixed mode fracture characterization.

During fracture testing the applied moment is recorded together with the crack end-opening displacement. Using solutions based on the J-integral approach the fracture resistance and possible R-curve behavior can be derived. Secondly, if cohesive law of the interface is wanted it may be derived by differentiation of the fracture resistance curve with respect to the crack end-opening displacement measured throughout the experiment.

4 DESCRIPTION OF TESTED OFF-AXIS LAMINATES

Double cantilever GFRP beam specimens produced by the VARTM process are used to characterize the fracture properties of different off-axis configurations. The specimens are made from dry unidirectional fiber mats supported in an epoxy resin. The base material is unidirectional biax

(0°,90º) 800g/m^2 glass fiber mat from Lintex and epoxy infusion resin INF-114 and slow infusion hardener INF-212 from Pro-set. A single unidirectional glass fiber mat of 200g/m^2 is introduced in a single layer on one side of the predefined crack plane in the DCB specimen. The fiber angle in this particular layer is varied in the different DCB configurations in order to characterize the effect of the off-axis angle on the fracture properties. This is illustrated in Figure 6.

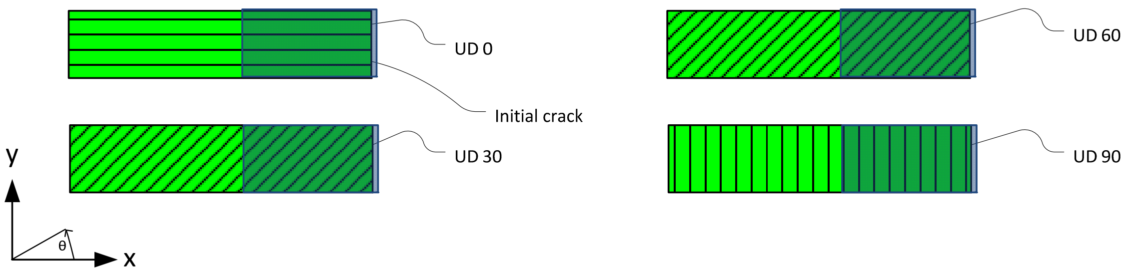

Figure 6: Definition of double cantilever GFRP specimens and off-axis angle defining the orientation of the single unidirectional layer varied throughout the test.

The layup definitions of the DCB specimen are [(90,0)@Biax$_6$,PTFE film,θ@UD,(0,90)@Biax$_6$]. The 0.13µm PTFE film defines the predefined crack tip in one end of the DCB specimens. The fiber angle θ of the single UD layer is the only parameter varied in the different DCB configurations. The biax layers are placed such that the 0° UD ply in the biax surrounds the crack plane and avoids the crack to propagate to a different interface.

The DCB specimens are not perfectly symmetric considering the layup definition. Asymmetry between the DCB arms might results in different mode mixity than expected and laminate coupling effects in the DCB arm embedded with the off-axis UD layer might introduce uneven tractions and opening displacements in the transverse width direction of the specimen resulting in an angled crack front. However, considering that only a single thin UD layer introduces this asymmetry this is considered negligible with respect to the fracture properties. This assumption has been supported by considering the individual laminate coupling terms, the neglected terms in the J-integral evaluation when performing a 2D simplification of the DCB specimen, and finally by a numerical assessment where J-integral evaluation based on Bernoulli-Euler beam theory is compared with 3D finite element prediction of the energy release rate by using the finite crack extension method.

5 DISCUSSION AND CONCLUSION

Experimental testing is currently been carried out, thus results will be presented and discussed at ICCM20 in Copenhagen.

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