Effect of combination of thermal and mechanical loading on delamination onset and growth of unidirectional composite materials

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Abstract—**The fatigue process in laminated composite materials includes several damage mechanisms that result in the degradation of the structure. One of the most important and critical failure modes of composite material is interlaminar damage or delamination. In this work, a finite element model has been developed in combination with the virtual crack closure technique (VCCT) to analyse the effect of temperature on the mixed-mode interlaminar fracture toughness and fatigue delamination growth rate of a carbon/epoxy material, namely IM7/8552 subjected to transient thermal and mechanical loadings that are simultaneously applied. The developed model may serve as the basis for treating different types of thermal and mechanical loading, different stacking sequences and thickness of lamina in order to build safe working conditions for composite laminates.**

Keywords—Delamination; Fracture; Composite material; Crack growth.

Introduction

Fiber reinforced composites are certainly one of the oldest and most widely used composite materials. Their study and development have largely carried out due to their vast structural potential. However, the applicability of laminated composite materials may become limited due to the frequent presence of delamination.

In the composite materials literature, delamination is generally assumed to take place at the interface between adjacent plies and rather treated as a fracture process between layers, than to consider it, more precisely, as a fracture between constituents or within one of the constituents.

In recent years, several studies have been carried out into the fracture of composites in their different stress modes under static loading, of which modes I and II have attracted more attention. A series of numerical investigations presented in literatures lead to excellent results. These methods are more suitable because of their low cost and time consuming. R. Krueger developed a finite element models using 3D shell elements which demonstrated good accordance with experimental results [1].

The calculation of delamination can be performed using cohesive elements [2, 3], which combine aspects of strength based analysis to predict the onset of damage at the interface and fracture mechanics to predict the propagation of a delamination. Initiation and propagation of delamination studied numerically with using cohesive elements and different constitutive laws lead to excellent results [4]

Over the past two decades, The criteria used to characterize the onset and growth of composite reinforced delamination under mixed-mode loading conditions are those usually established in terms of the components of the energy release rate and fracture toughness. It is assumed that the growth of delamination in composite structures starts when strain energy release rate G under service loads exceeds the fracture energy G_C. Wang et al. evaluated strain energy release rates for the damage-tolerance analysis of skin-stiffener interfaces using Finite element analysis in conjunction with the virtual-crack-closure technique (VCCT) [5, 6]. They used a wall offset to move the nodes from the reference surfaces to a coincident location on the interface between the skin and the flange.

The objective of this work is to present a method for the construction of a finite element model in combination with the virtual crack closure technique (VCCT), to analyse the effect of temperature on the fatigue delamination growth rate of a carbon/epoxy composite material, at a temperature range that is representative of in-service conditions for composites in aeronautics, and then, generate mode I and mode II components of mixed-mode fracture toughness.

I. FATIGUE DELAMINATION GROWTH MODEL

The well-known Paris law is the most commonly used method to model fatigue delamination growth. In its simplest form, the Paris law can be written as:

$$\frac{da}{dN} = A(\Delta G)^m \qquad (1)$$

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Where a is the crack length, N is the number of cycles, is the total energy release rate range, and A and m are material specific parameters which must be determined experimentally.

Following the Griffith fracture theory [7], crack extension occurs when the amount of energy required to produce unit area of fracture surface is supplied by the system. The fracture surface energy which is a so called energy release rate is equal to the derivative of potential energy with respect to crack size. In the classical fracture mechanics, energy release rate is determined experimentally from the compliance method as follows:

$$G = \frac{P^2}{2B}\frac{dC}{da} \tag{2}$$

Where a represents the crack length, B the specimen thickness, P the applied load, and C represents the compliance.

G_I and G_{II} were calculated from the crack closure method [8]. That is, G_I and G_{II} were calculated as follows:

$$G_I = \frac{F_y(v_c - v_d)}{2\delta a}\,;\quad G_{II} = \frac{F_x(u_c - u_d)}{2\delta a} \tag{3}$$

$$G_T = G_I + G_{II} \tag{4}$$

Where, δa is a crack extension size, Fx and Fy are forces in x- and y-direction. The displacements, uc (ud) and vc (vd) are the sliding and opening displacements at node “c” (node “d”) on the crack faces, respectively.

II. FINITE ELEMENT MODELING

In this study, the numerical modeling was carried out using commercial software commonly used for FEM calculations ABAQUS/CAE [13], which is an engineering tool that is used to solve various engineering problems ranging from linear to non-linear problems that are complex.

A. *Specimen and material data preparation*

The aim of this work is to determine the critical interlaminar fracture toughness mode 1 and II of Carbon-Epoxy composite material. For this purpose, the cracked-lap-shear specimen (CLS) specimen is used.

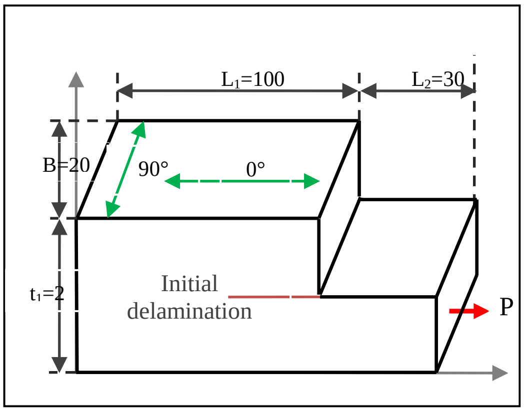

FIG. 1: SHAPE AND SIZE OF CLS SPECIMEN (DIMENSIONS IN MM)

The composite tested were Carbone/Epoxy laminates. Cracked lap shear (CLS) test specimen made of prepregs high-performance unidirectional carbon fiber reinforced epoxy Hexcel (IM7 / 8552) used for fracture tests. The volume fraction of carbon fiber in the prepreg is 60%. The material properties used are shown in Table. 1 and Table.2 , measured in a previous investigation [9], With a nominal ply thickness of 0.0626 mm, and the reference stacking sequence considered in the study is [90-0]8s.

TABLE I. IM7-8552 PLY ELASTIC PROPERTIES

Property	**Mean value**	
E_1	171.42	GPa
$E_2 = E_3$	9.08	GPa
$G_{12} = G_{13}$	5.29	GPa
G_{23}	3.98	GPa
$\nu_{12} = \nu_{13}$	0.32	
ν_{23}	0.5	

TABLE II. IM7-8552 PLY STRENGTHS

Property	**Mean value**	
X^T	2326.2	MPa
X^C	1200.1	MPa
Y^T	62.3	MPa
Y^c	200.8	MPa
S^L	92.3	MPa

For the fracture energies, a test standard exists only for matrix tension [10]. The values for tensile and compressive fiber fracture can be obtained from compact tension (CT) and compact compression (CC) tests as proposed by Pinho et al. [11]. Matrix compression fracture energy can be obtained from mode II end-notched flexure tests (ENF) and a formulation for G2 specified in [12]. According to this formulation, the value depends on the laminate stacking configuration.

In the present study the value for a strongly confined laminate is used.

TABLE III. FRACTURE ENERGIES (KJ/M²)

Property		**Mean value**
fiber tension	G_{1+}	81.5
fiber compression	G_{1-}	106.5
matrix tension	G_{2+}	0.2774
matrix compression	G_{2-}	5.62

B. *Results*

A three-dimensional finite element model of the cracked-lap-shear specimen (CLS) figure 1. with a series of vcct method has been achieved by using Abaqus finite element code in order to determine the critical interlaminar fracture toughness mode 1 and II of Carbon-Epoxy composite material.

The maximum equivalent stresses distribution was obtained and illustrated bellow

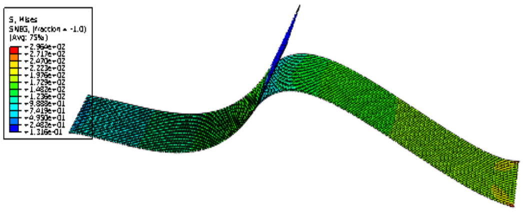

FIG. 2: EVOLUTION OF MAXIMUM STRESS VENMISES

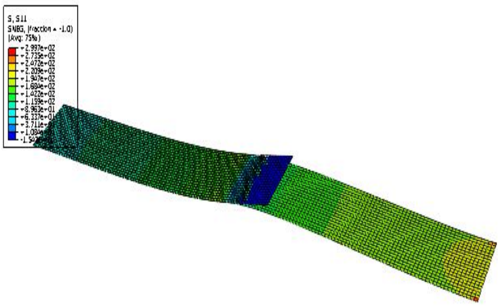

FIG. 3: EVOLUTION OF THE EQUIVALENT STRESS IN X AXIS

The mode I and mode II energy release rates, GI and GII, were calculated under a plane stress condition. The variation of GI and GII for the CLS specimen is shown in Fig.4 and Fig. 5.

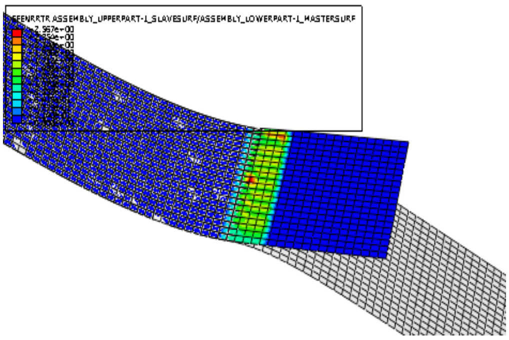

FIG. 4: MODE I ENERGIE RELEASE RATE EVOLUTION

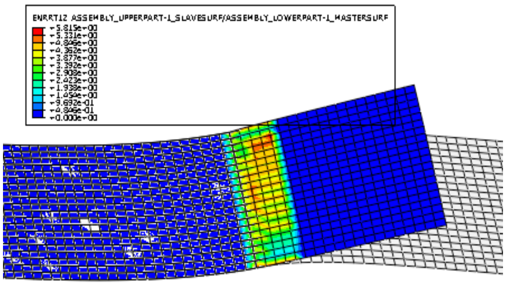

FIG. 5: MODE II ENERGIE RELASE RATE EVOLUTION

The following figure shows the variation of the energy release rate G as a function of the crack length in the specimen subjected to a constant unit load P or unit displacement d under variable temperatures.

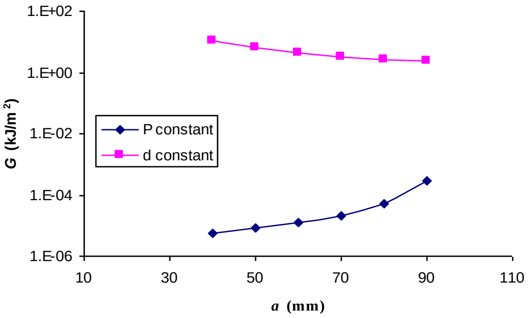

FIG. 6: ENERGY RELEASE RATE G AS A FUNCTION OF THE CRACK LENGTH

Conclusion:

Static fracture tests were conducted for unidirectional CLS specimens in order to determine the critical energy release rate of Carbone/Epoxy composite laminates. The GI GII, mode I and mode II energy release rates were calculated from finite element analysis. The nominal strain energy release rate G is evaluated, and it's concluded that the coupling of the temperature causes an effect of accelerating or retarding the growth of delamination, depending on the loading regime. It was found that a linear fracture envelope may be suitable for a CLS specimen.

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