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EXPERIMENTAL AND NUMERICAL ANALYSIS OF DELAMINATION OF COMPOSITE MATERIAL

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Abstract: *This paper deals with the numerical and experimental investigation of low-speed delamination of carbon fiber/epoxy composite. The composite specimens consist of unidirectional layers and they are subjected to Mode I and Mode II loadings. The critical value of energy release rate* G_{Ic} *is chosen as the interlaminar fracture toughness. This quantity was calculated from experimentally obtained dependencies between force, load point deflection, and delamination length according to ASTM standard. The initial delamination was prepared using thin aluminum foil inserted between the layers during manufacturing process. Two limit values of* G_{Ic} *are used in numerical simulation of the problem investigated in order to show the discrepancy range between the experimentally and numerically obtained load-displacement curves. The simulation is taking advantage of the equality of energy release rate and J-integral in the elastic case, and it is carried out using finite element method. The experimental investigation is further extended with the optical grating method which allows the determination of surface displacements and deformations of the tested specimen.*

Keywords: *composite material, delamination, stereometric optical measurement, finite elements*

1. Introduction

One of the damage mechanisms in laminates is the origin and propagation of failure or crack between individual layers, so-called delamination. This phenomenon must be considered in the design of a laminated structure. Delamination can be caused by imperfections during manufacturing process or due to static and dynamic loads. The existence of delamination in composite material degrades its stiffness and in certain cases it can degrade the stability to critical level. The dangerous factor is the delamination propagation which is influenced by geometric parameters, material characteristics and loading type. There can be both types of propagation – slow and stable as well as fast and unstable.

The presented work concerns the numerical simulation of delamination of a laminated specimen made of unidirectional fiber-reinforced composite layers and follows the work started in [8]. The aim is to design a model for the numerical simulation of the crack propagation. An important parameter used in such analysis is the critical value of the energy release rate (G_c). The energy release rate G, also known as the crack driving force, is mathematically defined as

$$G = -\frac{1}{b}\frac{dU}{da}\ , \tag{1}$$

where U is the strain energy, a is the crack length and b is specimen width.

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The majority of works investigating the delamination on laminated structures use either the critical value of energy release rate G_c [6, 7 and 10] or the stress intensity factor K_c [4] as the inter-laminar fracture toughness. The early works were focused mainly on the experimental procedures and analytical solutions. These were later followed by works dealing with numerical simulations with the use of finite element analysis and introducing new special element types for the modeling of delamination [3, 12 and 13].

It is known that the critical value of G_c as calculated according to the ASTM standard [1] does not behave as a constant. The critical value changes during the prescribed test as much as by tens of percent. Therefore, it is a question which value should be chosen for, for instance, the numerical simulation.

2. Specimen testing

Recently, an experimental assessment of interlaminar toughness for Mode I delamination was carried out [8] according to the standard ASTM D 5528-01 [1]. The specimens used were rectangular strips denoted as DCB (Double Cantilever Beam). Each specimen was cut using water jet from a 4 mm thick laminated unidirectional composite plate. The plate was manufactured from 20 epoxy prepregs reinforced with continuous Toray T600SC carbon fibers using autoclave technology. A non-adhesive aluminum foil, which served as the initial crack, was inserted in one half of the plate's midplane during manufacture. The thickness of the foil was 11 μm.

The experiment was performed on the Zwick/Roell BTC-FR50 testing machine. The opening force was applied using two piano hinges bonded on the lower and upper specimen surfaces [8] During the testing process the dependence of the opening force F vs. transverse (or load point) displacement δ was recorded. The crack propagation in time (crack length a) was measured optically using a digital still camera. The optical measurement also served as a verification of the transverse displacement values, which might differ, in general, from the grip movement as recorded by the testing machine due to its unknown internal stiffness. The delamination process was having slow and stable character up to the final rupture. The speed of the grip movement was chosen in the range between 1 and 5 mm·min^{-1}. The speed values in this range did not show to have major influence on the measured data.

Further experiments were performed on specimens having slightly altered geometry. These were so-called Mixed Mode Flexure (MMF) specimens subjected to three-point bending having dimensions $l \times b = 154.5 \times 21$ mm (see Figure 1). The specimen is therefore subjected to a combination of Mode I and II. The lower part of each specimen was shortened using milling machine, so that the contact with the support was on the midsurface. The scheme of the test is shown in Figures 1 and 2.

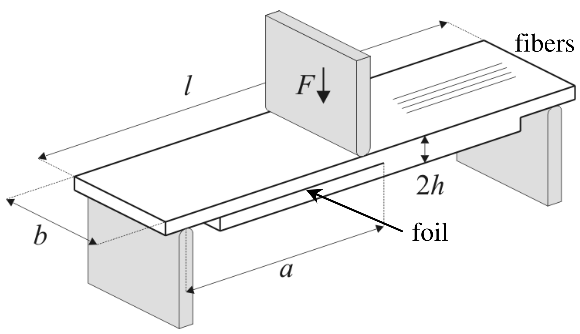

Figure 1 MMF specimen (Mode I and II).

Figure 2 MMF experimental setup.

The energy release rate values for the pre-cracked DCB specimens were calculated from the measured data [8] and the optically measured crack lengths according to ASTM standard [1]. Figure 3 shows the calculated dependencies of for selected specimen. It can be seen that the values are not constant as predicted by the theory. They tend to converge to some specific value, thus, a best fit by hyperbolic function is plotted for each set of data to emphasize this phenomenon.

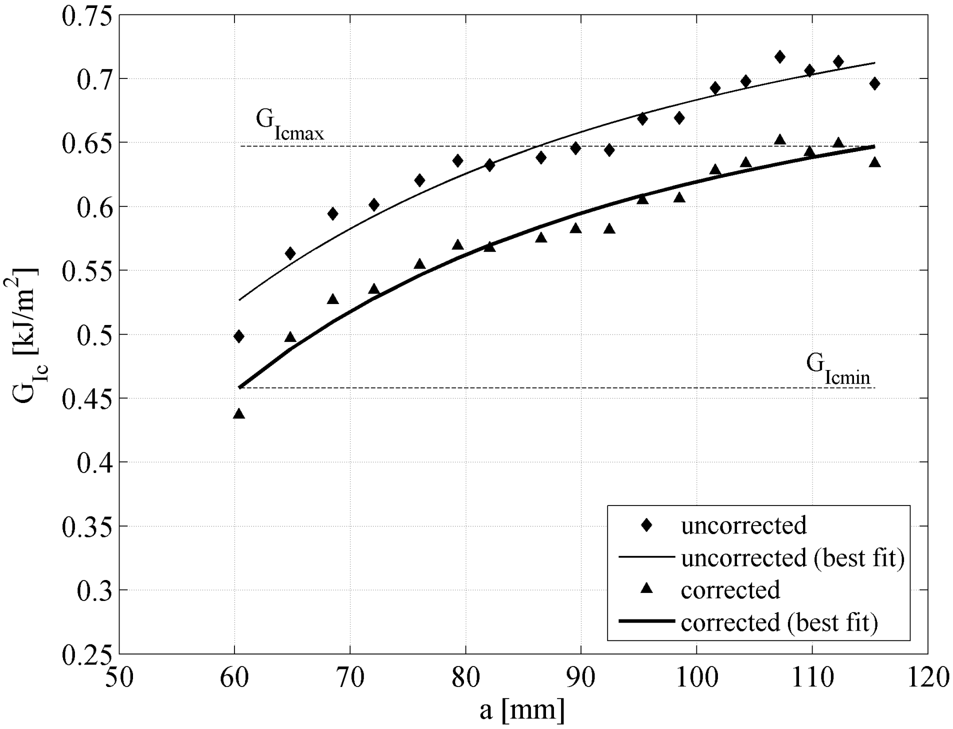

Figure 3 Energy release rate as a function of crack length measured on DCB specimen

3. Optical measurement

The actual deformation of the specimens was measured on the surface of the specimen by optical grating method. The deformation of the specimen's surface was measured by recording the displacements of the optical marks and captured in such a way that the 3D coordinates are connected with picture coordinates. During the experiment, the grating structure related to different deformation states of the specimen was recorded by two CCD cameras, with a resolution of 1024×768 points and 256 gray levels. Several stages of deformation are recorded by displacement of random grating attached to the specimen surface.

Mutual independent image coordinates and also the number of equations is bigger than a number of unknowns in over-determined mathematical triangulation model. The equation system is solved by the bundle adjustment method by applying suitable digital processing algorithms of the ARAMIS GOM measuring system [5]. In general, mathematical model is based on well known space intersection for calculation of corresponding object point $P(X,Y,Z)$ if the position of the two cameras and two homologous image points $p_1(x_1,y_1)$ and $p_2(x_2,y_2)$ are known [11]. The constants are calculated through a calibration procedure as is shown in references [2] and [14].

Positions of each homologous point pairs for each image can be calculated by a calculation of all three 2D displacements between images of deformed and reference undeformed state.

Since these homologous points represent the same object point in two loaded stages, it's coordinates in 3D space can be calculated via back projection.

Results in Fig. 2 combined from ARAMIS and the testing machine for the three-point bend specimens with inserted foil show the critical force at origin of the delamination. Further increase of force shows lower slope as stable crack propagation.

Object grating method, in contrast to standard measurement methods, provides view to strain field. The other advantage of object grating method is easy and accurate determination of initiation of stable crack propagation. Since the deformation on the surface facet at the vicinity of the crack tip is observed and measured, one can expect that this technique will be the future for accurate experimental fracture testing of composite materials in order to ensure structure integrity of components.

3. Numerical simulation

The numerical simulation was performed using finite element method (FEM) in MSC.Marc system. Herein, the analysis was solved as a plane strain problem. The geometry was modeled using 4-node square elements. The region with bonded hinges was assumed to be absolutely rigid and therefore not considered in the model. The critical area around the crack front was meshed with collapsed elements. Different finite element mesh was prepared for each calculated case with certain crack length a.

The equality between values of energy release rate and J-integral in the case of elastic analysis was used in the simulations. The MSC.Marc code can calculate the J-integral using the DeLorenzi method [9]. Two limit values $G_{Ic\mathrm{min}}$ and $G_{Ic\mathrm{max}}$ calculated for the pre-cracked specimen (see Table 1 and Figure 3) were considered in the simulation of MMF specimen.

The material is assumed to be homogeneous, linear elastic, and transversely isotropic having the following elasticity constants: longitudinal Young's modulus E_L = 110 GPa, transverse modulus E_T = 7.7 GPa, Poisson's ratio ν_{LT} 0.28, G_{LT} = 0.32, which were identified previously [15, 16].

The reconstructed load-displacement data are compared in Figure 4 with the corresponding curves obtained from experiment. It is clearly seen that the MMF model is not very sensitive to the value of G_c when comparing the slopes of the load-displacement curves. However, it plays important role as the parameter which triggers the delamination, in other words, where the slope of the curves begins to change.

The comparison of displacement results calculated in FEM and those obtained from Aramis system is shown in Figures 5 and 6. Note that the color data from the two systems could not be fully equalized. The overall comparison shows good agreement between both experimental methods and the simulation.

Table 1 Calculated limit values of G_{Ic} used in FEM simulations.

minimum energy release rate [kJm^{-2}]	$G_{Ic\mathrm{min}}$	0.4579
maximum energy release rate [kJm^{-2}]	$G_{Ic\mathrm{max}}$	0.6468

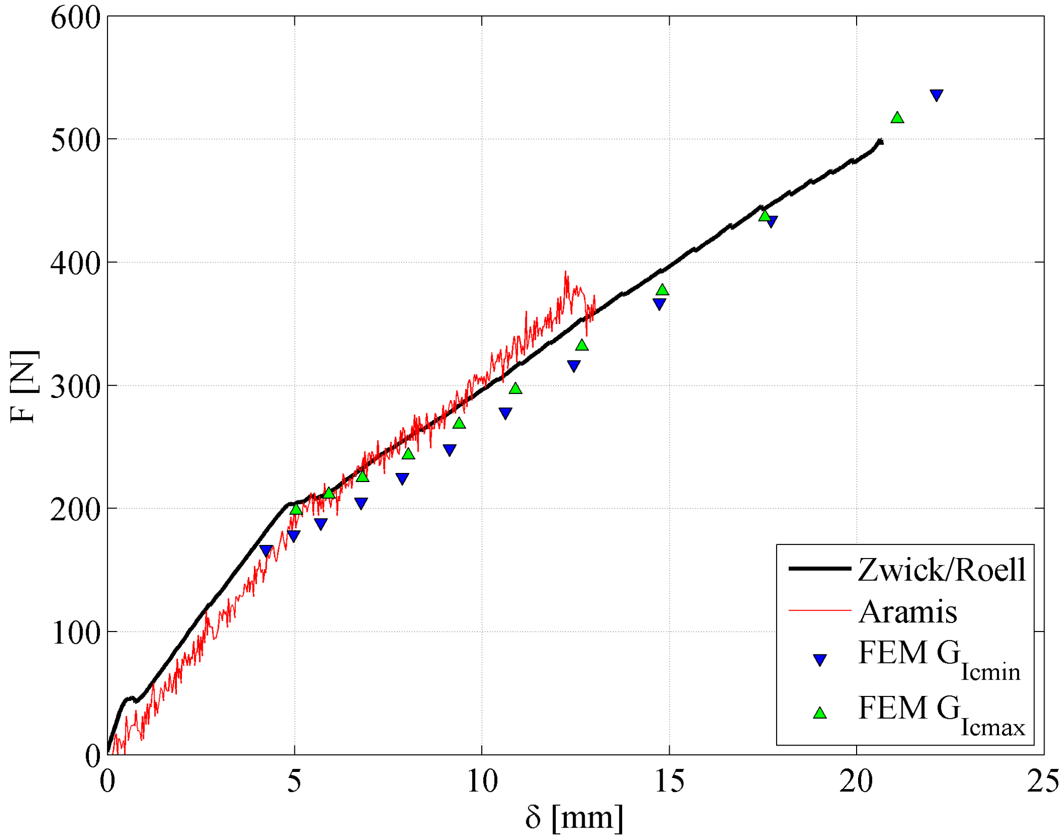

Figure 4 Load-displacement curves for MMF specimen.

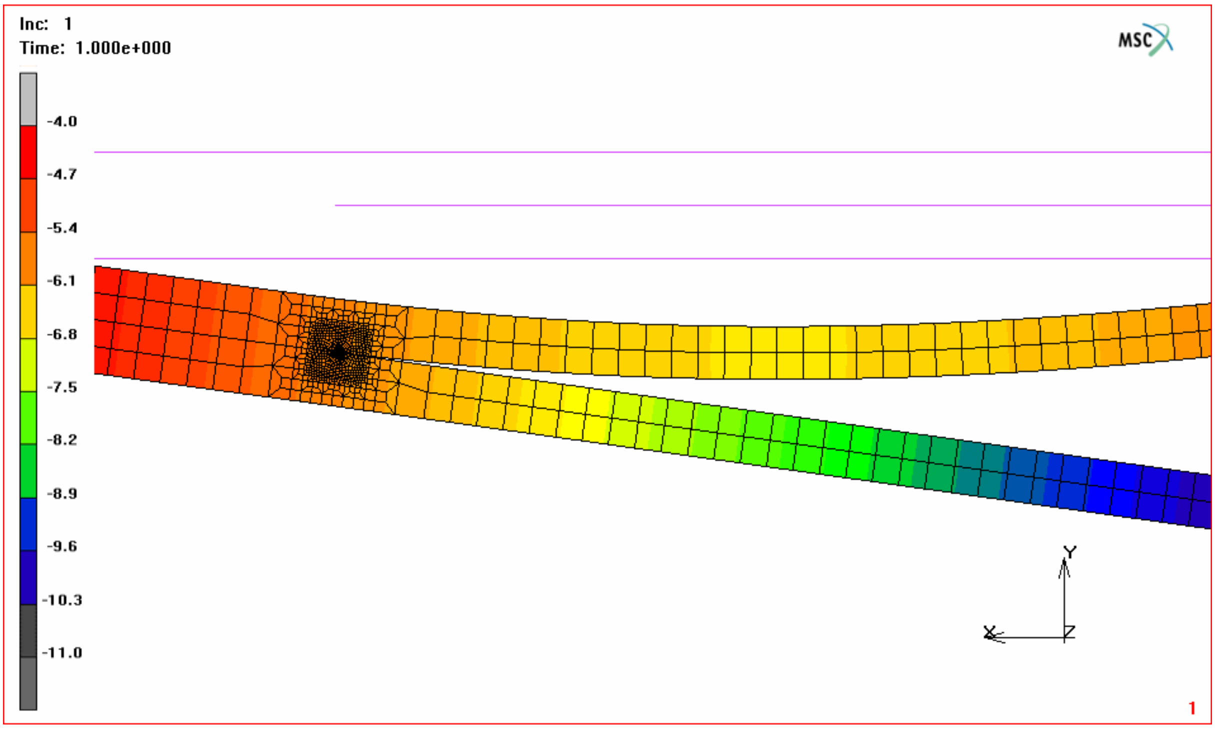

Figure 5 FEM results from MSC.Marc showing contours of vertical displacement.

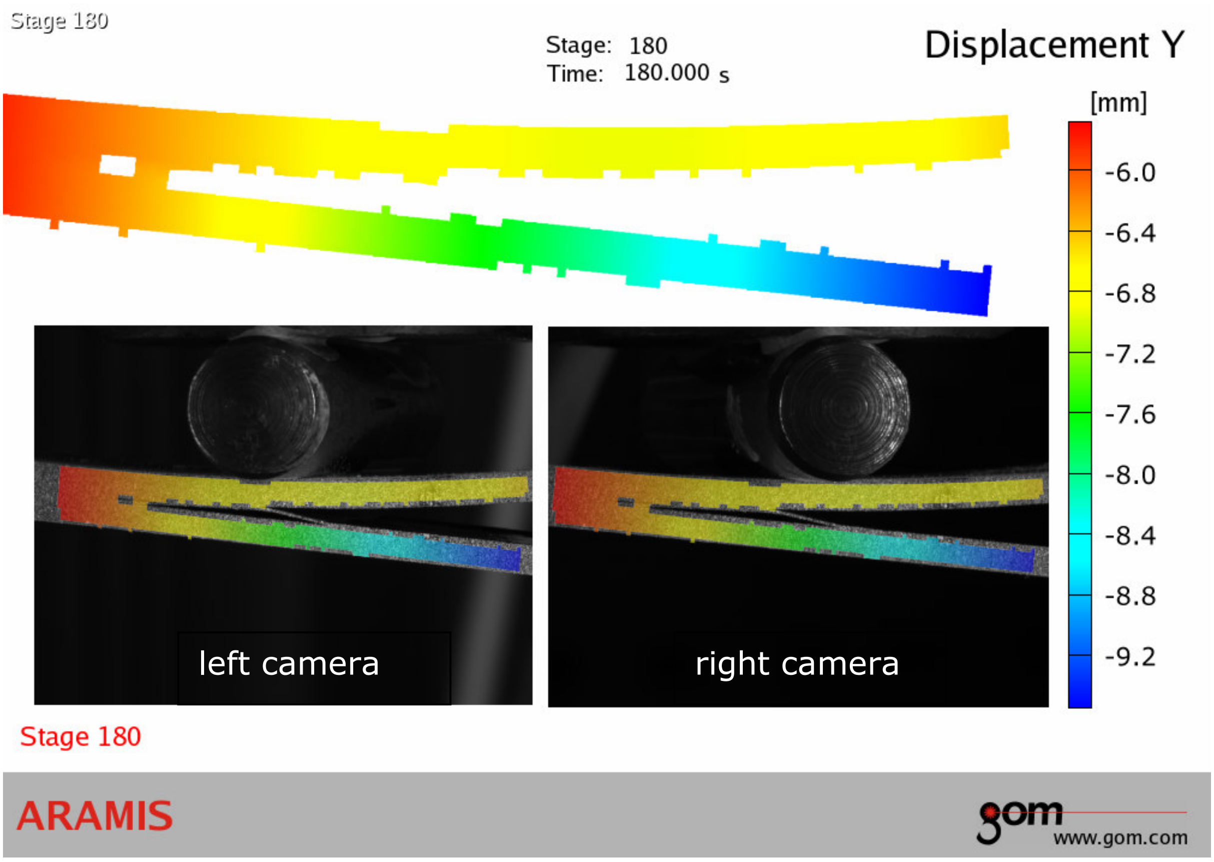

Figure 6 Results from Aramis showing contours of vertical displacement.

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