

NUMERICAL AND EXPERIMENTAL ANALYSES OF THE DELAMINATION OF CROSS-PLY LAMINATES

NUMERIČNA IN EKSPERIMENTALNA ANALIZA DELAMINACIJE V KRIŽNIH PLOŠČATIH LAMINATIH

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This article focuses on a numerical and experimental investigation of the delamination of cross-ply FRP laminates. The tested samples were cut from plates [0/90/90/0] made of unidirectional carbon-epoxy prepregs in a vacuum autoclave. The experimental tests were performed on precracked double-cantilever beam samples according to ASTM standards with Mode-I loading. The load-displacement relations were recorded during the test and the crack length was measured optically with a digital camera. The corresponding numerical simulations were performed in the finite-element code MSC.Marc. The goal was to assess the critical value of the energy-release rate G , which was chosen as the interlaminar fracture toughness. The simulation used the equality between the energy-release rate and the J-integral for the elastic case.

Keywords: composite, cross-ply, beam, delamination, experiment, simulation

V delu obravnavamo numerično in eksperimentalno raziskavo delaminacije v križnih ploščatih FRP-laminatih. Preizkušanci so bili odrezani iz plošč [0/90/90/0], ki so bile izdelane v avtoklavu iz surovcev ogljikovo vlakno-epoksi. Preizkusi so bili izvršeni na vnaprej razpokanih dvojno vpetih nosilcih skladno z ASTM-standardi z obremenitvijo Mode I. Odnos obremenitev – pomik je bil ugotovljen med preskusom, dolžina razpoke pa se je merila optično z digitalno kamero. Za numerično simulacijo je bila uporabljena metoda končnih elementov s kodo MSC.Marc. Cilj je bil določiti kritično vrednost hitrosti sprostitve energije G , ki je bila opredeljena kot interlaminarna žilavost loma. V simulaciji je uporabljena enakost med hitrostjo sprostitve energije in J-integralom za primer elastičnosti.

Ključne besede: kompoziti, križna plošča, nosilec, delaminacija, eksperiment, simulacija

1 INTRODUCTION

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

In this investigation we have looked at a numerical simulation of the delamination of a laminated specimen made of unidirectional fiber-reinforced composite layers. This follows on from the work started in ¹. The aim is to design a numerical model for the simulation of crack propagation. An important parameter used in such analyses is the critical value of the energy-release rate (G_c).

The majority of studies investigating the delamination on laminated structures use either the critical value of energy-release rate G_c ²⁻⁴ or the stress-intensity

factor K_c ⁵ as the interlaminar fracture toughness. The early studies were focused mainly on the experimental procedures and analytical solutions. These were later followed by studies dealing with numerical simulations based on a finite-element analysis and introducing new, special element types for the modeling of the delamination ⁶⁻⁸.

It is known that the critical value of G_c as calculated according to the ASTM standard ⁹ does not behave as a constant. The critical value changes during the prescribed test by as much as tens of percent. Therefore, it is questionable as to which value should be chosen, for instance, for the numerical simulation.

In this work the value of G_c is assessed by experimental measurements on a Mode-I delamination specimen. The analysis was performed on a cross-ply laminate manufactured from unidirectional plies reinforced with carbon fibers in an epoxy resin. It is known ¹⁰ that in the case of linear stress-strain behavior there is equality between G and the value of the J-integral (J). Therefore, it was possible to substitute the evaluation of the decisive parameter G_c with the calculation of J_c in the numerical simulations. The numerical calculations are carried out using the finite-element method in MSC.Marc.

The difference between the experimentally and numerically obtained dependencies of force vs. displace-

ment for the critical value G_c is presented. The basic material parameters (elasticity constants) used in the simulations were identified in previous studies^{11,12}, where the damage and failure of specimens made of the same material are investigated.

2 EXPERIMENT

Firstly, an experimental assessment of the inter-laminar toughness for Mode-I delamination was carried out according to the standard ASTM D 5528-01⁹. The specimens used were rectangular strips denoted as DCB (Double Cantilever Beam) having dimensions $l \times b = (160 \times 19.7)$ mm (see **Figure 1**). Each specimen was cut out using a water jet from a 4.6-mm-thick laminated cross-ply composite plate with a lay-up $[0/90/90/0]$, whereas the middle part was 0.3 mm thick (see **Figure 2**). The plate was manufactured from 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 into the midplane of the plate (i.e., between the 90 degree plies) during manufacture (see **Figures 1 and 4**). The thickness of the foil was 11 μ m.

The experiment was performed on the Zwick/Roell Z050 testing machine. The opening force was applied using two piano hinges bonded on the lower and upper surfaces of the specimen (see **Figures 1 and 3**). During the testing process the dependence of the opening force F vs. the transverse (or load point) displacement δ was recorded (see **Figure 3**). The crack propagation with time (crack length a) was inspected optically using a digital camera (Canon EOS 400D, Sigma 105/2.8 EX DG MACRO) every 10 s (resolution approximately 20 px/mm). 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 imperfect rigidity. The delamination process had a slow and stable character up to the final rupture. The speed of the grip movement was 10 mm/min.

The major problems identified during the experiments were the inhomogeneity of the initial crack zone

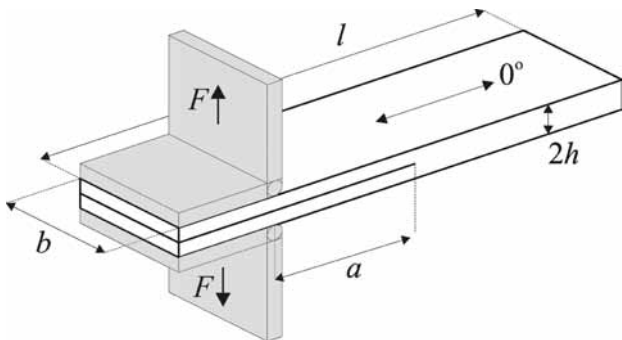


Figure 1: DCB specimen with attached piano hinges and inserted foil
Slika 1: DCB-vzorec s pritrjenim šarnirom in z vstavljeno folijo

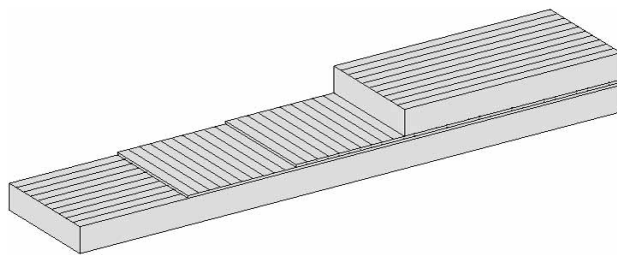


Figure 2: Material lay-up (showing the part without the foil)
Slika 2: Zlog materiala (prikazan je del brez folije)

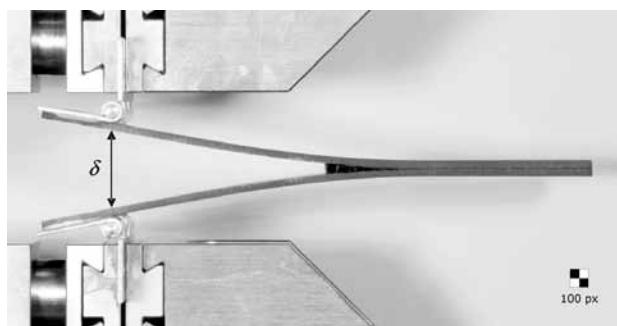


Figure 3: DCB specimen experimental setup
Slika 3: DCB-vzorec z eksperimentalno postavitvijo

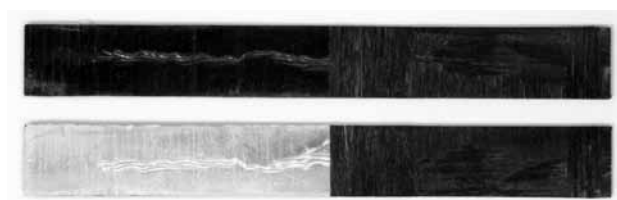


Figure 4: Crack surfaces of the fractured DCB specimen
Slika 4: Površina razpok pretrganega DCB-vzorca

(the end of the foil) and the so-called fiber bridging between the upper and lower parts of the specimen (see **Figure 5**). The bridging of fibers occurs in composite specimens within the unidirectional layers, as in this case.

3 ESTIMATION OF THE ENERGY-RELEASE RATE

The energy-release rate G is defined mathematically, in general, as

$$G = -\frac{1}{b} \frac{dU}{da} \quad (1)$$

where dU is the differential increase in the strain energy, da is the differential increase in the delamination (or crack) length, and b is the specimen width. Concerning the investigated Mode I for the DCB specimen, the corresponding energy-release rate G_I can be expressed using the Euler-Bernoulli theory of beams as^{3,13}

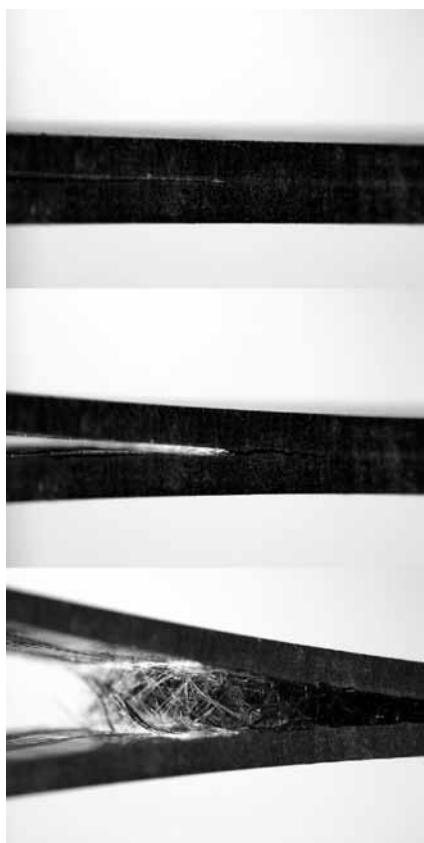


Figure 5: Sequence of photographs showing the fiber-bridging progress

Slika 5: Sekvenca posnetkov, ki prikazuje napredovanje vlaknate premostitve

$$G_I = \frac{F^2 a^2}{bEI} \quad (2)$$

where EI is the bending stiffness, i.e., the sum of the Young's moduli in the axial direction multiplied by the inertia moments for all the plies (see **Figure 1**).

There are several possible ways of calculating the strain-energy release (or eventually the interlaminar fracture toughness) according to the ASTM standard ⁹. One way is the so-called Modified Beam Theory (MBT) method. The energy-release rate in this case is calculated as

$$G_I = \frac{3F\delta}{2ba} \quad (3)$$

Since the beam is not perfectly built-in (a certain amount of rotation can occur at the crack front, i.e., where a clamped condition is assumed), a correction can be applied, which assumes that the delamination is larger by the amount $|\Delta|$. Hence, the crack length is $(a+|\Delta|)$ and the corrected energy-release rate is then given by

$$G_I = \frac{3F\delta}{2b(a+|\Delta|)} \quad (4)$$

where the value of Δ is calculated according to the procedure given in the standard ⁹ and the values

obtained for both types of specimens are shown in **Table 1**. Equation (2) can be corrected in a similar way.

4 NUMERICAL SIMULATION

The numerical simulation was performed using the finite-element method in the MSC.Marc system. In this case the analysis was solved as a plane-strain problem. The geometry was modeled using 4-node rectangular elements. The $[0/90/90/0]$ lay-up was meshed with 8/2/2/8 layers of elements in the thickness direction and 600 elements along the length. A different model was prepared for each crack length a .

The equality between the values of the energy-release rate and the J-integral in the case of the elastic analysis was used in the simulations. MSC.Marc calculates the J-integral using the DeLorenzi method ¹⁴.

The material is assumed to be homogeneous, linearly elastic, and orthotropic, and to have the following elasticity constants: longitudinal Young's modulus $E_L = 110000$ MPa, transverse modulus $E_T = 7700$ MPa, Poisson's ratio $\nu_{LT} = 0.28$ and shear modulus $G_{LT} = 4500$ MPa, which were identified previously ^{11,12}.

The critical values of the energy-release rate and the parameter Δ were calculated using (4) in order to best characterise the averaged experimental dependency in **Figure 6**. The hypothetical delamination curves for the interval $0.1 < G_{Ic} < 1.5$ kJ/m² are shown in the graph together with the optimum curve corresponding to the values displayed in **Table 1**. The reconstructed load-displacement curve from the FEA is compared with the experiment.

Table 1: Measured and calculated parameters of the DCB specimen

Initial crack length /mm	a_0	62
Crack-length correction /mm	$ \Delta $	5.12
Critical energy-release rate /(kJ/m ²)	G_{Ic}	1.373

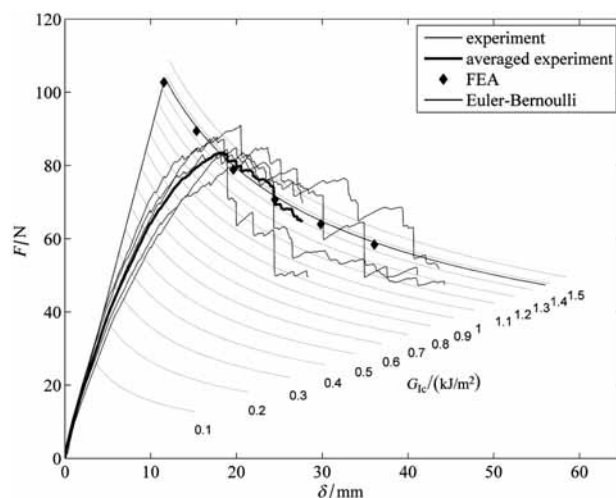


Figure 6: Load-displacement curves for the DCB specimen

Slika 6: Krivulje obremenitev – pomik za DCB-vzorec

5 CONCLUSIONS

An experimental investigation of low-speed Mode-I delamination was carried out on carbon-fiber-reinforced epoxy specimens in order to estimate the critical energy-release rate value G_{Ic} . The double-cantilever beam specimens with a cross-ply lay-up were manufactured with inserted aluminum foil serving as an initial crack. The critical energy-release-rate value was determined using the Euler-Bernoulli theory and the ASTM standard from the averaged experimental data. A numerical model was created in the FEA code MSC.Marc for the simulation of the experiment. The model took advantage of the equality between the energy-release rate and the J-integral in the case of an elastic material. The load-displacement dependency was reconstructed and compared with the experimental results. It is clear that it is possible to consider the critical energy-release rate value as the interlaminar fracture toughness in the case of the delamination of a composite with transversely oriented fibers.

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