NUMERICKÁ SIMULÁCIA DELAMINÁCIE KOMPOZITU S PODPOROU EXPERIMENTU

NUMERICAL SIMULATION OF COMPOSITE DELAMINATION WITH THE SUPPORT OF EXPERIMENT

Vladislav LAŠ, Robert ZEMČÍK, Petr MĚŠŤÁNEK[1]

Abstrakt

Článok sa zaoberá numerickým modelom pre simuláciu pomalej delaminácie kompozitu uhlíkové vlákno/epoxid. Vzorka je tvorená vrstvami orientovanými v jednom smere a je podrobená zaťaženiu Typ I. Ako kritérium pre určenie interlaminárnej lomovej pevnosti je vybratá kritická hodnota pomeru uvoľňovania energie. Táto veličina je spočítaná z experimentálne získaných závislostí medzi silou, priehybom v bode zaťaženia a dĺžkou delaminácie. Začiatočná delaminácia bola vytvorená vložením tenkej hliníkovej fólie medzi vrstvy počas procesu výroby.

Skúmajú sa dva typy vzoriek – s/bez ďalšej počiatočnej trhliny. Kritická hodnota pomeru uvoľňovania energie sa určuje využitím rôznych postupov podľa normy ASTM. Aby sa preukázal rozsah rozdielu medzi experimentálne a numericky získanými krivkami zaťaženie-deformácia, boli pri numerickej simulácii skúmaného problému použité dve limitné hodnoty. Simulácia využíva rovnosť pomeru uvoľňovania energie a *J*-integrálu v elastickej oblasti a je vykonaná pomocou metódy konečných prvkov. Dobrá zhoda medzi experimentom a simuláciou sa dosiahne iba ak považujeme kritické hodnoty pomeru uvoľňovania energie ako funkcie geometrie vzorky.

Kľúčové slová: delaminácia, experiment, pomer uvoľňovania energie, metóda konečných prvkov.

Abstract

This paper deals with the numerical model for the simulation of low-speed delamination of carbon fiber/epoxy composite. The specimen consists of unidirectional layers and is subjected to Mode I loading. The critical value of energy release rate is chosen as the interlaminar fracture toughness. This quantity is calculated from experimentally obtained dependencies between force, load point deflection, and delamination length. The initial delamination was prepared using thin aluminum foil inserted between the layers during manufacturing process.

Two types of specimens are investigated, with and without additional pre-crack. The critical value of energy release rate is determined using various approaches according to ASTM standard. Two limit values 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. Good agreement between experiment and simulation is achieved only when considering critical energy release rate values as a function of specimen geometry.

Keywords: delamination, experiment, energy release rate, finite element method.

[1] doc. Ing. Vladislav LAŠ, CSc., Ing. Róbert ZEMČÍK, Ing. Petr MĚŠŤÁNEK, Department of Mechanics, Faculty of Applied Sciences, University of West Bohemia, Plzeň, las@kme.zcu.cz,
Lektoroval: doc. Ing. Jozef BOCKO, CSc., KAMaM, SjF TU v Košiciach, jozef.bocko@tuke.sk

INTRODUCTION

Delamination is one of the most frequent failure types of composite materials which can originate due to imperfection from manufacturing process or due to static or 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 majority of works investigating the delamination on laminated structures use as the interlaminar fracture toughness the critical value of energy release rate G_{Ic} [4,5,7] or the stress intensity factor K_{Ic} [3]. The early works focused mainly on the experimental procedures and analytical solutions, 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 [2,8,9].

The presented work concerns the numerical simulation of delamination of a laminated specimen made of unidirectional fiber-reinforced composite layers. It is known that the critical value of G_{Ic} as calculated according to the ASTM standard [1] does not behave as a constant. It 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. The difference between the experimentally and numerically obtained dependencies force vs. deflection for two limit values of G_{Ic} are presented herein. The basic material parameters (elasticity constants) used in the simulations were identified in previous works [11, 12], where the damage and failure of specimens made of the same material is investigated.

EXPERIMENT

Experimental assessment of interlaminar toughness for Mode I delamination was carried out according to the standard ASTM D 5528-01 [1]. The specimens used were rectangular strips denoted as DCB (Double Cantilever Beam) having dimensions $l \times b = 154.5 \times 21$ mm (see Fig.1). 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 (see Figs. 1 and 2). 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 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 $\text{mm}\cdot\text{min}^{-1}$. The speed values in this range did not show to have major influence on the measured data.

The measurement was carried out on two types of specimens. Specimens of type A were not modified in any way (without pre-crack). The measured dependency of F vs. δ showed certain unpredictable character during the beginning of the crack propagation process for series of specimens A. This was caused by the cracking of the region at the end of the aluminum foil, where local inhomogeneities can be expected due to manufacturing process.

Therefore, to avoid this situation, specimens of type B were manually pre-cracked. This was done by clamping the specimen across its thickness approximately 5 mm away from the aluminum foil region and opening the specimen by pulling the hinges until the crack extended correspondingly. This modification proved to ensure similar cracking behavior for series of specimens.

Several measurements were performed for both types of specimens. An example of the two typical load-displacement curves obtained experimentally is displayed in Figure 3. There is an evident difference between the two curves due to the pre-cracking mentioned, the pre-cracked specimens have lower initial stiffness because of larger initial crack length, and the curve peak is much sharper in the region of propagation initiation. The values of initial crack lengths for both cases are displayed in Table 1.

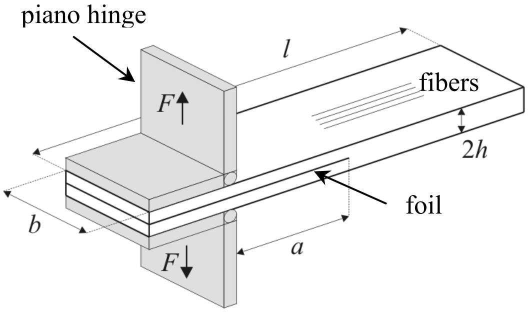

Fig.1 Specimen for Mode I delamination

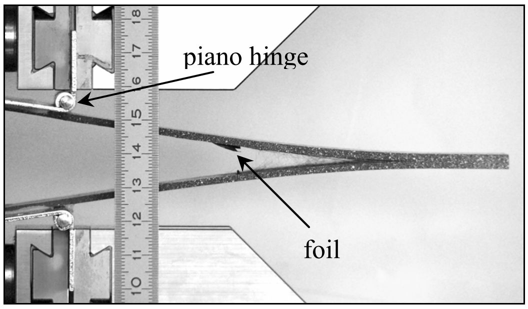

Fig.2 Experimental setup

ESTIMATION OF ENERGY RELEASE RATE

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

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

where dU is differential increase in strain energy, da is differential increase in delamination (or crack) length, and b is 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 [5, 10]

$$G_I = \frac{12F^2a^2}{b^2h^3E_{11}}, \tag{2}$$

where E_{11} is Young's modulus in the longitudinal direction (direction of fibers), and h is half of the specimen thickness (see Fig.1).

There are several possible ways of calculating the strain energy release (or eventually the interlaminar fracture toughness) according to the ASTM standard [1]. One way is so-called Modified Beam Theory (MBT) method. The energy release rate in this case is calculated as

$$G_I = \frac{3F\delta}{2ba}. \tag{3}$$

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

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

where the value of Δ is calculated according to the procedure given in the standard [1] and the values obtained for both types of specimens are shown in Table 1.

Measured and calculated parameters **Table 1**

		type A	type B
initial crack length [mm]	a_0	56.7	60.4
crack length correction [mm]	$\|\Delta\|$	10.1	7.4
minimum energy release rate [kJm^{-2}]	$G_{I\min}$	0.29	0.47
maximum energy release rate [kJm^{-2}]	$G_{I\max}$	0.66	0.68

The energy release rate values for the two types of specimens were calculated from the data shown in Fig.3 and the optically measured crack lengths. Both expressions in Eq. (3) and (4) were used to obtain the uncorrected and corrected energy release rate values in dependency on the crack length. Fig.4 shows the calculated dependencies for type A specimen and Figure 5 for the type B specimen. It can be seen that the values 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.

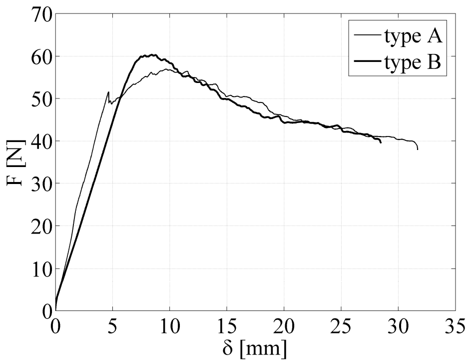

Fig.3 Typical load-displacement curves for type A and type B specimens

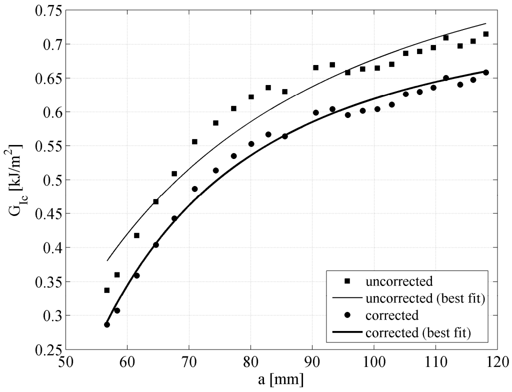

Fig.4 Energy release rate as a function of crack length on type A specimen

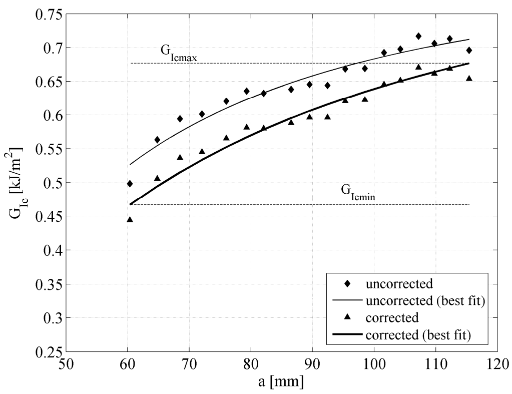

Fig.5 Energy release rate as a function of crack length on type B specimen

NUMERICAL SIMULATION

The numerical simulation was performed using finite element method in MSC.Marc system. The analysis was solved as a three-dimensional problem. The geometry was modeled using 8-node solid elements (see Fig.6). 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. The crack front is modeled here as a straight line. The equality between values of energy release rate and *J*-integral was used in the analysis.

The material is assumed to be homogeneous, linear elastic, and transversely isotropic having the following elasticity constants: longitudinal Young's modulus E_{11} = 110000 MPa, transverse moduli $E_{22} = E_{33}$ = 7700 MPa, Poisson's ratios $\nu_{12} = \nu_{13} = 0.28$, $\nu_{23} = 0.32$, shear moduli $G_{12} = G_{13}$ = 4500 MPa, and G_{23} = 2917 MPa, which were identified previously [11, 12].

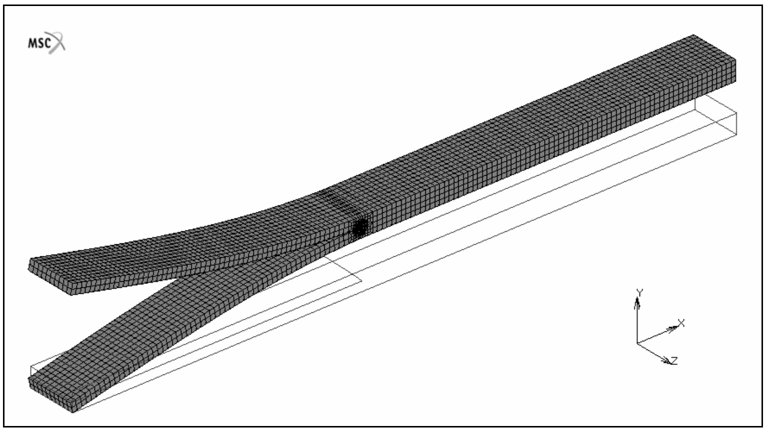

Fig.6 Deformed finite element mesh and original outlines of the 3D model

The values of *J*-integral are calculated in the MSC.Marc system using the DeLorenzi method [6]. The values of G_{Ic} approximated by the hyperbola and its limits G_{Icmin} and G_{Icmax} calculated for the pre-cracked specimen (see type B in Table 1 and Fig.5) were considered in the simulation. The reconstructed load-displacement curves are compared in Fig.7 with the corresponding curve from experiment. Is obvious that for the two constant values G_{Icmin} and G_{Icmax} the numerical simulation yields two different curves *F* vs. δ, one of which approaches the experimental data at the beginning of delamination while the latter at the moment of final rupture. Only in the case when the approximated values of G_{Ic} as a function of crack length *a* are used it is possible to obtain good agreement with experimental *F* vs. δ dependency.

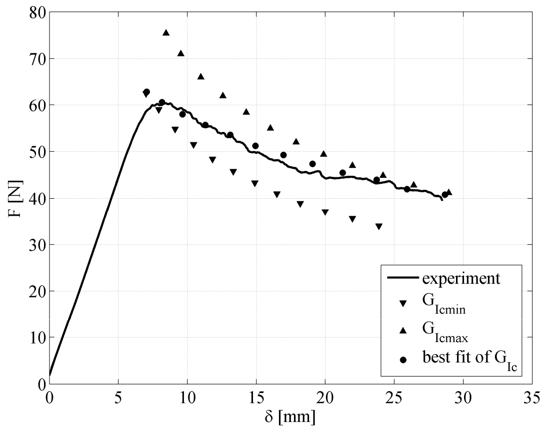

Fig.7 Comparison of load-displacement curves for constant and variable G_{Ic} values

CONCLUSIONS

An experimental investigation of low-speed Mode I delamination was carried out. The types of carbon fiber-reinforced epoxy specimens with aluminum foil serving as initial crack were studied. The critical energy release rate values G_{Ic} were determined according to ASTM standard. The ASTM standard considers the G_{Ic} to be constant, which contradicts with experimental observations. Numerical simulation of the experiment was performed using FEA and the equality between energy release rate and *J*-integral in elastic case. The load-displacement curves for two constant values of G_{Ic} were reconstructed and compared with experimental data. Numerical simulation of delamination depends strongly on the choice of G_{Ic}. It proves that the use the minimum value of G_{Ic} the model is a conservative prediction of delamination. To achieve better agreement of simulation with experiment it is necessary to consider G_{Ic} to be a function of specimen's geometry.

This work was supported by the research projects MSM 4977751303 and GA AV A200760611.

REFERENCES

[1] ASTM D5528-01: *Standard Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites*, Annual Book of ASTM Standard, 2002: 249-260.

[2] BORST R., REMMERS J. J. C.: *Computational modelling of delamination*. Composites Science and Technolgy 66, 2006: 713-722.

[3] CHOW W. T., ATLURI S. N.: *Stress intensity factors at the fracture parameters of delaminations crack growth in composite laminates*. Composites Part B. 28B, 1997: 375-384.

[4] HOJO M. et al.: *Mode I delamination fatigue properties of interlayer-toughened CF/epoxy laminates*. Composite Science and Technology 66, 2006: 665-675.

[5] KUSAKA T. et al.: *Rate dependence of Mode I fracture behaviour in carbon-fibre/epoxy composite laminates*. Composites Science and Technology 58, 1998: 591-602.

[6] MSC.Marc Volume A: *Theory and user information*, Version 2005. MSC.Software Corporation, 2004.

[7] PEREIRA A. B., MORAIS A. B.: *Mode I interlaminar fracture o carbon/epoxy multidirectional laminates*. Composites Science and Technology 64, 2004: 2261-2270.

[8] ROCHE CH. H., ACCORSI M. L.: *A new finite element for global modelling of delaminations in laminated beams*. Finite Elements in Analysis and Design 31, 1998: 165-177.

[9] SHEN F., LEE K. H., Tay T. E.: *Modeling delamination growth in laminated composites*. Composites Science and Technology 61, 2001: 1239-1251.

[10] SOHN M.-S., HU X-Z: *Comparative study of dynamic and static delamination behaviour of carbon fibre/epoxy composite laminates*. Composites 26, 1995: 849-858.

[11] ZEMČÍK R., LAŠ V.: *Identification of Composite material properties using progressive failure analysis*. In Computational mechanics 2005. University of West Bohemia, 2005: 695-700.

[12] ZEMČÍK R., LAŠ V.: *Numerical simulation of damage in fiber-reinforced composites and comparison with experiment*. In 22nd Danubia-Adria symposium on experimental methods in solid mechanics. University of Parma, 2005:174-175.