ISSN 1392 - 1207. MECHANIKA. 2010. Nr.2(82)

Influence of ply orientation on mode I interlaminar fracture toughness of woven carbon and glass composites

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1. Introduction

The problems of toughness of steels, metal alloys, plastics and composite, and strain mechanics that are tackled show up during extreme loads. Various tests predicting behavior of materials and structures [1-3] were performed trying to manage the mechanical characteristics of materials and the best of them in developing innovative mechanical systems and technologies. Therefore investigation of the most widely used composite materials is relevant.

Because composite laminates are high performance structural materials, there is a need of accurate evaluation of the interlaminar fracture toughness for optimal design and material selection of composite structures. Various test methods were developed to measure critical strain energy release rate G_{Ic}: the double cantilever beam test (DCB), is used for Mode I, the 3 point end notch flexure test (3 ENF) or the 4 point end notch flexure test (4 ENF) is used for Mode II and the mixed-mode bending test (MMB) is used for mixed-mode I/II [4-7]. The specimen usually contains an implanted delamination in the form of a nonadhesive insert and is used for unidirectional fiber reinforced composites. However, the most practical applications involve woven reinforced and cross-ply multidirectional laminates where delaminations occur between the plies of different orientations. Therefore, it is essential to characterize the delamination resistance G_{Ic} with various stacking sequence along the interface for the development of more accurate design methods. Several studies were already performed on the mode I and mode II fracture of multidirectional laminates [8, 9] and the majority of those results were affected by intraply damage and crack jumping to another interface.

The aim of this paper is to study the effects of ply orientation on the interlaminar fracture behavior of mode I in woven carbon and glass composites. For defining the exact instant of crack initiation the nonlinearity (NL), 5% offset or maximum force criteria were used.

2. Double cantilever beam (DCB) test details

The specimens of woven carbon and glass composites were used in DCB tests to determine critical strain energy release rate G_c. Mode I (DCB) test were performed on twill woven carbon/epoxy and glass/epoxy composite systems. The specimens (width 25 mm, length 150 mm) were made in an enterprise “Sportinė Aviacija” (Fig. 1). The matrix of laminar composite was reinforced with glass 92 125 and carbon 98 131 fibre 2/2 twill woven fabrics. Tenax HTA type filaments were used in carbon fibre fabrics. Epoxy/hardener system L285/287 was used to manufacture laminar composites. The initial fracture was made by inserting aluminium foil of 30 μm thickness into the middle of the sample edge. Under the critical load applied this crack propagates into the specimens’ delamination plane. To determine the influence of reinforced angles of the layers between inserts on critical strain energy release rate G_{Ic}, the layer reinforced angles in four specimens (I-IV) groups of woven carbon and glass composites were arranged as follows:

I - $[(0_2/90)_3/0_2//(0_2/90)_3/0_2]$,
II - $[(0_2/90)_3/0_2//90/(0_2/90)_3/0_2]$,
III - $[(0_2/90)_3/0_2/+45//-45/(0_2/90)_3/0_2]$,
IV - $[(0_2/90)_3/0_2//+45/(0_2/90)_3/0_2]$.

With such layout of the layer reinforcement angles the extreme influence of the elasticity bonds on the G_c should be reduced because they generate asymmetrical delamination front. Such sequence of ply layout was chosen to meet the obligatory condition, i.e., to avoid great shifts in the layer of plastic deformations and damages. Delamination spread in middle part of the sample marked with a symbol „//“ in parallel direction to the adjacent layers. The layer reinforcement angles in the middle part of the specimen are 0//0, 0//90, + 45//− 45 and 0//+ 45.

Cantilever made from aluminum alloy was glued to the specimens with the cold-welding type adhesive during DCB test. The pull force of cantilever of aluminium foil-absent was 3 kN, i.e., 30 times exceeding the required proper adhesion. For better visual observation of the crack front propagation the measure was drawn on the white background on the specimen side beginning from the end of aluminum foil (Fig. 1).

Tests were made in the Centre for Strength and Fracture Mechanics of Kaunas University of Technology using the universal tension and compression test bench produced by Swiss company “Amsler” (the greatest load 50 kN). DCB test was made in accordance with standard ASTM D5528 [5] crack is opened by tearing in the woven carbon and glass composite specimens. During this test the specimen was loaded by tension in the direction perpendicular to middle plane of the specimen while the force was distributed in cantilevers (Fig. 2).

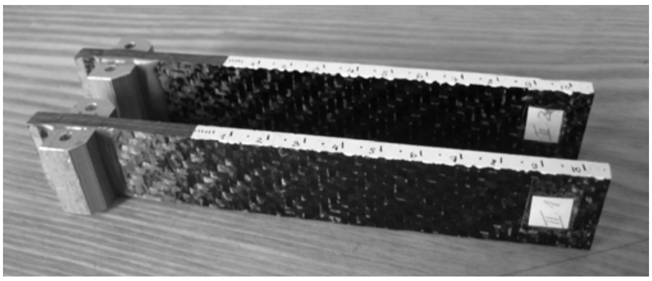

Fig. 1 Specimens used in DCB test

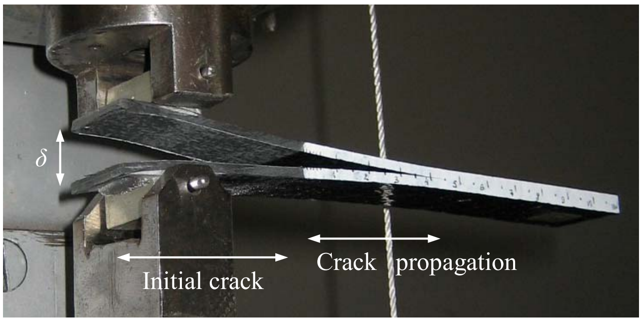

Fig. 2 DCB test. Carbon/epoxy specimen

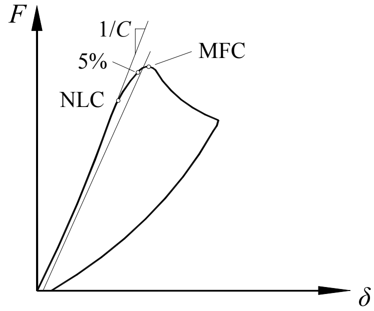

Fig. 3 Alternative criteria of fracture initiation [10]

Delamination developed in accordance with the mode I crack in the middle plane of the specimen. Crack opening displacement δ_I – the crack opening height was measured during the experiment. Crack length a was visually determined during the test. The push was from 0.5 to 1.0 mm/min. Because stable crack increase ($dG/da < 0$) was observed in the course of DCB test, the unloading was done at the beginning of the test at 2.0 and 3.0 mm, and later increments of 5.0 mm.

In conformity with the tests results the critical values of force F_c, displacement δ_c, crack length a_c and compliance C were defined. Alternative nonlinearity (NL) and 5% offset from the initial curve rise or the maximum force (MF) criteria [8, 9] were used in practice to estimate the inter-laminar critical strain energy release rate to precisely determine the fracture initiation (Fig. 3). NL characterized the crack advance at the moment when the force-displacement curve diverged from the linearity.

Because DCB test was used to determine the mode I fracture toughness G_c may be found from the force and deflection data by compliance calibration using the fundamental Eq. (1)

$$G_c = \frac{F^2}{2}\frac{dC}{dA} = \frac{F^2}{2b}\frac{dC}{da} \qquad (1)$$

where b is the specimens width.

A compliance calibration is therefore required and this can be performed using one of two modified beam theory expressions

$$G_{I_c} = \frac{3F_I\delta}{2b\left(a + |\Delta_I|\right)} \qquad (2)$$

where Δ_I is the correction to the crack length to take account of imperfectly clamped beam boundary condition, and is defined as the intercept on the x axis of a plot of cube root of compliance (δ/F) versus crack length. For Berry method the compliance as a function of crack length may be obtained for each specimen from the slope of its load versus deflection data. The method of least squares can be used to obtain the coefficients k and n from $C = ka^n$ into equation

$$G_{I_c} = \frac{nF_I\delta}{2ba} \qquad (3)$$

where F_I and δ are the load and deflection, respectively, at the onset of crack advance.

When the load-displacement curves for the cracked specimens exhibit a linear elastic response, the change in total energy in the body due to crack extension from a to $(a + \Delta a)$ is simply the area A between the loading and unloading curves. Thus G_{Ic} is given by

$$G_{I_c} = \frac{\Delta A}{b\Delta a} = \frac{1}{2b}\frac{F_1\delta_2 - F_2\delta_1}{\Delta a}. \qquad (4)$$

where δ_1 and δ_2 - displacement, estimated respectively by loading and unloading cracked specimens.

3. Influence of ply orientation on fracture toughness

Relationships of the force F and crack opening displacement δ_I of the specimen with initial crack were obtained during the test (Fig. 4 and Fig. 5).

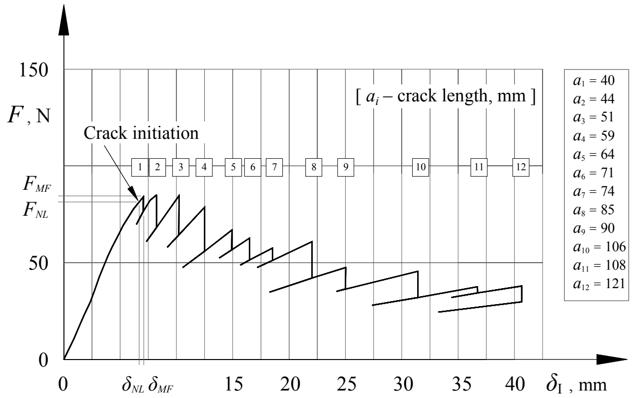

Fig. 4 Carbon/epoxy 2DCB specimen. Relationship of the force and crack opening displacement

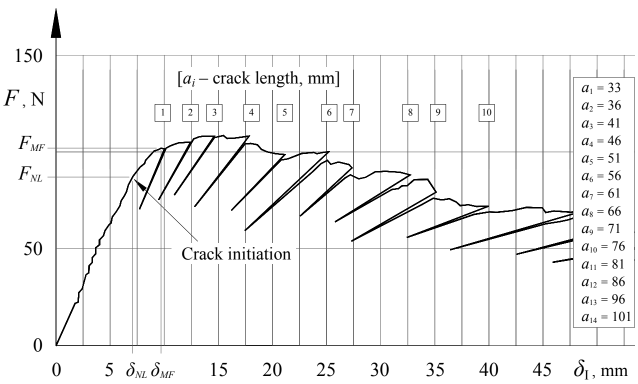

Fig. 5 Glass/epoxy 2DCB specimen. Relationship of the force and crack opening displacement

The investigation results showed that in the case of carbon/epoxy specimen when compared with glass/epoxy, the smaller offset of the relationship of load force displacement and crack opening displacement from the linearity was determined. In glass/epoxy composite relationship nonlinearity from 10 to 20 times greater could be visually observed.

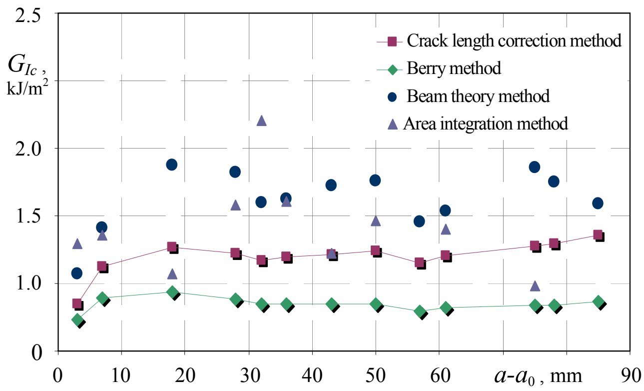

Fig. 6 Relationships of G_{Ic} and crack increase during crack opening. Reinforcement angles in carbon/epoxy specimen delamination planes: 0//90

The increase of load force value at the beginning of fracture in glass/epoxy specimens had an influence on the sharp increase of critical strain energy release rate. This determined the formation of great plastic zone in the crack tip depending on the type of reinforced material. Unstable crack propagation was noticed in carbon/epoxy specimen during the experiment due to the influence of brittle fabric of carbon fibre on the crack propagation in the epoxy resin. This consistent pattern was reflected in the nature of relationships between F and δ (see the vertical apexes in Fig. 4).

Test results were processed on the basis of Eqs. 2 - 4 using the crack length correction and Berry methods, estimating the compliance C and beam theory (F, a) and area integration methods. The crack length a was determined visually after each unloading of the specimen until its general predetermined value was reached. G_{Ic} is required for crack propagation for some particular value a_i expressed by the area limited with load-offset curve excluding elastic energy, and estimated as the beam compliance C (mm/N).

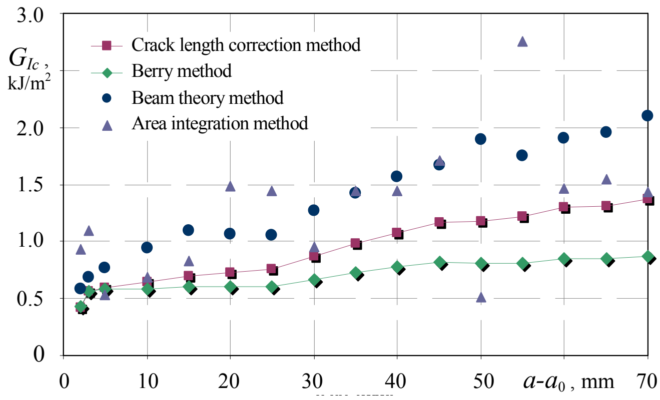

Fig. 7 Relationships of G_{Ic} and crack increase during crack opening. Reinforcement angles in glass/epoxy specimen delamination planes: 0//90

But in glass/epoxy specimen during crack propagation the significant increase of G_{Ic} was obtained as the result of the initial delamination branching into additional layer of the specimen delamination plane. The increase of the values of G_{Ic} during crack propagation was set in most of glass/epoxy specimen. It was specified that when the layers were reinforced at the angles + 45//− 45 in the delamination plane, the crack was branching into the adjacent 0//+ 45 layers after the area a - a_0 = 30 - 40 mm was reached. When the reinforced angles of the layers in delamination plane were arranged as 0//0 and 0//90, the increase of G_{Ic} was noticed when the value a-a_0 reached 30 mm length.

During crack opening, the values G_{Ic} were calculated at the points of crack initiation, i.e., NL and MF. The values of critical strain energy release rate during crack initiation were determined with the help of initial crack length. Analogous variation in amplitude response of the G_{Ic} of carbon/epoxy and glass/epoxy specimens was obtained using the method of crack length correction and Berry method.

Figs. 6 and 7 show the results of G_{Ic} of delamination in the middle plane of carbon/epoxy and glass/epoxy specimen at the angle of 0//90 by using maximum force criteria. The values of G_{Ic}, defined by the nonlinearity criterion to values of G_{Ic}, defined by maximum force criteria were compared. In the case of carbon/epoxy the nature of relationships of G_{Ic} and crack growth for all four groups of the reinforced angles in the middle plane during crack propagation remained constant.

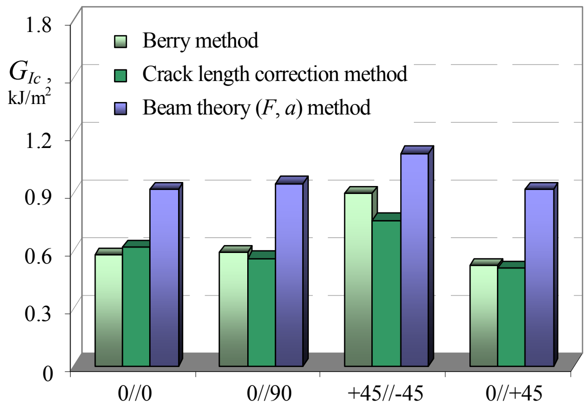

Fig. 8 DCB experiment. Glass/epoxy specimens when NL criterion was used for G_{Ic}

The application of area integration method resulted in significant variation of estimated values. Beam theory method used in case of glass/epoxy specimens showed the variation of relationships analogous to the crack length correction and Berry method. But the values determined with the help of nonlinearity and maximum force criteria in Beam theory method significantly exceeded the values of G_{Ic} obtained with more conservative methods (Figs. 8 − 11).

On the basis of nonlinearity criterion in Berry method, the following G_{Ic} values of mode I and mode II were obtained for glass/epoxy specimen types: G_{Ic} = 0.577 kJ/m^2 [0//0] and G_{Ic} = 0.591 kJ/m^2 [0//90].

DCB test defined the relationships of the critical strain energy release rate of composite materials and crack increase describing the character of the crack propagation and $G_{Ic\text{-}prop}$ values (Table). The values of G_{Ic} in carbon/epoxy and glass/epoxy specimens were calculated. They were estimated in relation to the reinforced angles of the layers in the delamination plane and the calculation methods of the crack initiation and crack propagation in various change areas (NL and MF).

In carbon/epoxy specimens when the angles 0//0 were used to reinforce layers in delamination plane and using the method of crack length correction the values of G_{Ic} in the delaminating area were 0.28 - 0.42 kJ/m^2 and using Berry method the values were 0.20 - 0.23 kJ/m^2. G_{Ic} values in the maximum force (MF) area were 0.32 and 0.23 kJ/m^2, approximately.

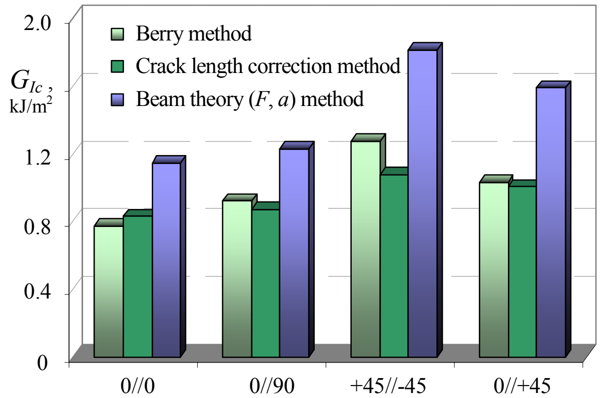

Fig. 9 DCB experiment. Glass/epoxy specimens when MF criterion was used for G_{Ic}

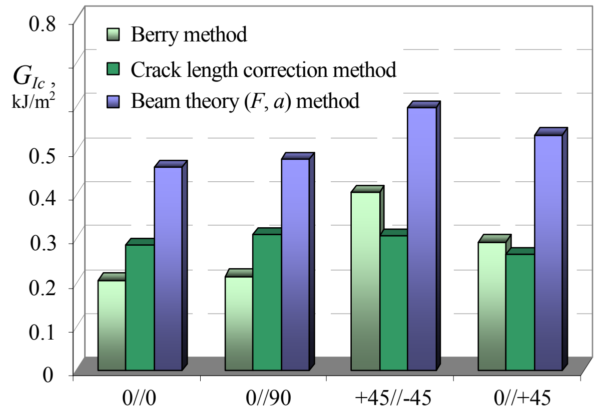

Fig. 10 DCB experiment. Carbon/epoxy specimens when NL criterion was used for G_{Ic}

When G_{Ic} values of the specimen were estimated at the maximum force equal to [0//0] using the crack length correction method, the critical strain energy release rate values of glass/epoxy specimens were 0.83 and 0.77 kJ/m^2

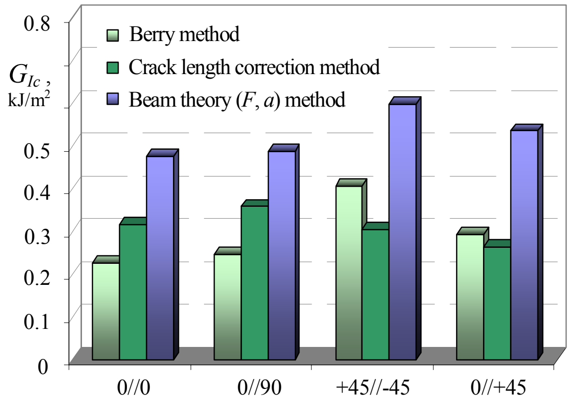

Fig. 11 DCB experiment. Carbon/epoxy specimens when MF criterion was used for G_{Ic}

when Berry method was used. G_{Ic} values of the carbon/epoxy specimen changed by 33% in the initiation-propagation area of maximum force when the crack correction method was used, and by 1.3% when Berry method was used, thus this made significantly smaller part if compared with the change of the G_{Ic} values of the polymer composites reinforced with glass fibre fabric.

For glass/epoxy specimens 52 % change was determined in the first instance, and 18 % variation was defined in the second instance. The estimated significant increase of the G_{Ic} determines the greater than actual values in many specimen types, especially mode I [0//0]. But the most conservative Berry method was chosen for the more precise values of the G_{Ic}. Table and Fig. 12 demonstrated the values of compliance C (mm/N) and coefficient n used in this method.

Figs. 13 and 14 demonstrated the relationships of G_{Ic} values of the carbon/epoxy and glass/epoxy specimen groups of modes I – IV on the angles that reinforced the layers in the delamination plane using Berry method.

The values of G_{Ic} of the critical strain energy release rate of glass/epoxy specimens by 2.8, 2.76, 1.78 and 2.21 times are greater if compared with the G_{Ic} values of carbon/epoxy specimens using NL criterion at the corresponding angles of layer reinforcement in delamination area: 0//0, 0//90, 0//+ 45 ir + 45//− 45. The more significant variation of specimens was obtained for MF criterion, i.e., 3.96, 5.01, 2.37 and 2.06 times, respectively. This showed greater resistance of glass/epoxy specimens to delamination when the crack was opened by tearing (mode I) and especially, in the case of mode II [0//90] and mode I [0//0] specimen groups at NL and MF load.

Table

Critical strain energy release rate employing Berry method

Composite system	Interlayer	MFC		NLC		$G_{Ic\text{-}prop.}$, kJ/m^2
		C, mm/N	$G_{Ic\text{-}init.}$, kJ/m^2	C, mm/N	$G_{Ic\text{-}init.}$, kJ/m^2	
Glass/epoxy 92 125// L285/287	0//0	0.100	0.774	0.094	0.577	0.911
	0//90	0.091	0.919	0.075	0.591	1.178
	0//+ 45	0.085	1.030	0.074	0.721	1.130
	+ 45//− 45	0.070	1.274	0.068	0.895	1.554
Carbon/epoxy 98 131// L285/287	0//0	0.085	0.227	0.079	0.205	0.230
	0//90	0.069	0.247	0.061	0.214	0.355
	0//+ 45	0.070	0.292	0.070	0.292	0.477
	+ 45//− 45	0.037	0.405	0.037	0.405	0.754

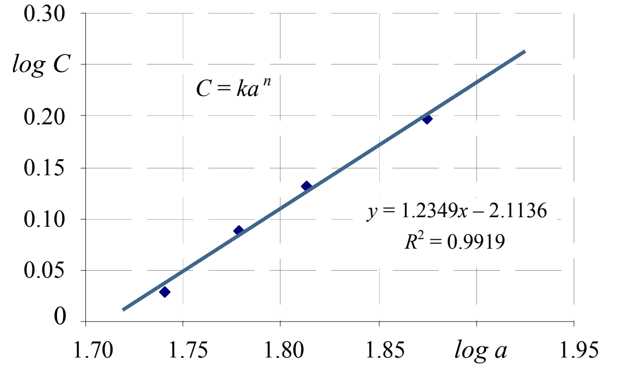

Fig. 12 Carbon/epoxy DCB specimen. The logarithmic relationship between the compliance and the crack length. Angles 0//0 of layer reinforcement in delamination plane

G_{Ic} values of carbon/epoxy and glass/epoxy specimen were the greatest in the interlayer of + 45//− 45. It has been determined that the variation of the angle θ in the sequence of 0º, 45º and 90º in the delamination plane of layer reinforcement, the equivalent change of the G_{Ic} in the glass/epoxy specimens was obtained when the difference of the crack length was 20 - 30 mm.

But this consistent pattern could not be used with carbon/epoxy specimens. Great result variation was obtained during the trail in carbon/epoxy specimen due to unstable crack propagation ($dG/da > 0,\ a_0 < L/\sqrt[3]{3}$). Thus the estimation of more precise G_{Ic} values was impossible to determine.

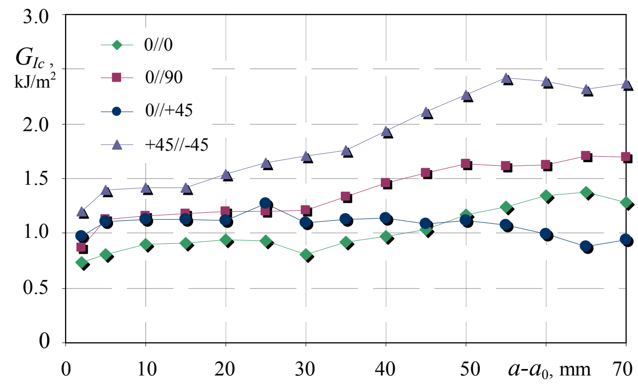

Fig. 13 The influnce of reinforced angles of glass/epoxy layers in delamination plane on the G_{Ic}

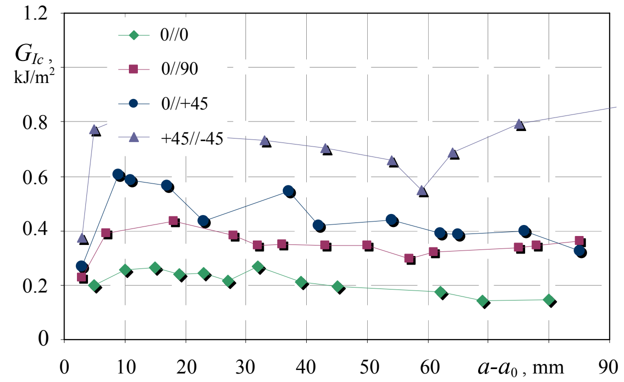

Fig. 14 The influence of reinforced angles of carbon/epoxy layers in delamination plane on the G_{Ic}

After the layer reinforcement angles in the delamination plane were arranged in + 45//− 45 the extremely great variation from 0.91 to 0.54 J of G_{Ic} values was obtained. If compared with the values of critical strain energy release rate obtained at the angle 0//0 arrangement that varied in the range from 0.3 to 0.13 J, the variation was by 2.5 to 4 times greater. With such result variation in the crack propagation area, it was appropriate to determine G_{Ic} values in the zone of initial fracture where the actual delamination in the sample interlayer started.

3. Conclusions

In order to determine the influence of angles used to reinforce the layers between inserts on the critical strain energy release rate, the quasi-stationary test analysis was used to open the crack by tearing the woven carbon and glass composites. In accordance with the test results with carbon/epoxy composites from 10 to 20 times less deflection from linearity was defined for the relationships between load force and the crack opening displacement. The increase of the load force value in glass/epoxy specimens at the fracture initiation has significant influence to the increase of G_{Ic} that determined the formation on the great plastic zone on the crack tip determined by the type of reinforcement material.

When nonlinearity criterion was used the value of G_{Ic} of glass/epoxy specimen was by 2.8, 2.76, 1.78 and 2.21 times greater if compared with G_{Ic} values of carbon/epoxy specimen of the corresponding angles of layer reinforcement in delamination area: 0//0, 0//90, 0//+ 45 and + 45//− 45. This showed greater resistance of glass/epoxy specimens to delamination when the crack opened by tearing.

It was determined that G_{Ic} in glass/epoxy significantly increased when the crack branching in the delamination plane occurred. The variation of critical strain energy release rate was obtained in crack propagation area due to unstable crack propagation in carbon plastics; thus this energy in the crack propagation area should be defined in the initial crack zone.

The values of critical strain energy release rate determined with area integration method showed great variation of results. For this reason the conservative Berry method (mode I) and nonlinearity criterion were chosen for the result estimation. NL criterion made it possible to predict the increase of the damages in the microlevel.

After the estimation of the influence of the angles used to reinforce the layers on G_{Ic} the conclusion was made that the reinforcement at the angles of 0//0 and especially 90//0 was the most dangerous. Thus in the structures the layers should be reinforced at the angles of 0//+45 because G_{Ic} was by 1.4 times greater if compared with the instance of 0//0 angles.

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ANGLIAPLASTIKIO IR STIKLAPLASTIKIO SLUOKSNIŲ ARMAVIMO KAMPŲ ĮTAKA IRIMO TARPSLUOKSNYJE TĄSUMUI ATPLĖŠIANT

R e z i u m ė

Straipsnyje pristatomas angliaplastikio ir stiklaplastikio sluoksnių armavimo kampų įtakos irimo tarpsluoksnyje tąsumui atplėšiant tyrimas. Atliktas dvigubos gembinės sijos iš anglies ir stiklo pluošto audiniu armuoto plastiko eksperimentas, plyšį atveriant. Pasirinkti sluoksnių armavimo bandinių su pradiniu plyšiu viduryje kampai 0//0, 0//90, + 45//− 45 ir 0//+ 45. Tiksliai nustatant plyšio atsiradimą taikyti netiesiškumo ir 5% nuokrypio ar didžiausios jėgos kriterijai. Rezultatams įvertinti pasirinktas konservatyvus Berry metodas bei netiesiškumo kriterijus, leidžiantis nustatyti mikrolygmenyje atsirandančių pažeidimų didėjimą. Įvertinus sluoksnių armavimo kampų įtaką kritinei irimo energijai, nustatyta, kad sluoksnių atsisluoksniavimo plokštumoje pavojingiausias yra armavimas 0//0 (taip pat ir 90//0) kampais. Todėl konstrukcijose sluoksnius siūloma armuoti kampais 0//+45, kuriems esant kritinė irimo energija būna iki 1.4 karto didesnė nei esant 0//0 kampui.

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INFLUENCE OF PLY ORIENTATION ON MODE I INTERLAMINAR FRACTURE TOUGHNESS OF WOVEN CARBON AND GLASS COMPOSITES

S u m m a r y

The paper presents the study of the influence of ply orientation on mode I interlaminar fracture toughness of woven carbon and glass composites. Double cantilever beam test of mode I as performed on twill woven carbon/epoxy and E-glass/epoxy composite systems. Specimen stacking sequences with initial delamination at the angles of 0//0, 0//90, + 45//− 45 and 0//+ 45 were used. To define the exact instant of crack initiation the criteria of nonlinearity (NL) and 5% offset or maximum force criteria were used. The conservative Berry method and nonlinearity criterion that enable to determine the increase of the damages in microlevel were chosen for the result estimation. The evaluation of the influence of the layer reinforcement angles on G_{Ic} disclosed that the reinforcement of the layers in the delamination plane at the angles of 0//0 and especially 90//0 was the most dangerous. Thus in the structures the layers should be reinforced at the angles of 0//+45 because G_{Ic} was by 1.4 times greater if compared with the instance of 0//0 angles.

Н. Кершене, А. Жилюкас, А. Кершис

ВЛИЯНИЕ УГЛОВ АРМИРОВАНИЯ НА ВЯЗКОСТЬ РАЗРУШЕНИЯ В ПРОСЛОЕ УГЛЕПЛАСТИКА И СТЕКЛОПЛАСТИКА В СЛУЧАЕ ОТРЫВА

Р е з ю м е

В работе представлено исследование влияния углов армирования на вязкость разрушения в прослое углепластика и стеклопластика при отрыве. Проведен тест двойной консольной балки из тканью армированноого углепластика и стеклопластика. Выбрана последовательность углов армирования при наличии начальной трещины 0//0, 0//90, + 45//− 45 и 0//+ 45. Для точной установки возникновения трещины применены критерии непрямолинейности и отклонения на 5% или наибольшей силы. При оценке результатов выбраны метод Берри и критерий непрямолинейности, позволяющий установить рост в микроуровне появляющихся повреждений. Оценив влияние углов армирования слоев на критическую энергию разрушения, установлено, что в площади расслоения армирование углом 0//0 (также и 90//0) являются наиболее опасным. Поэтому в конструкциях рекомендуется армирование углами 0//+45, при которых уровень критической энергии разрушения в 1.4 раза больше, чем в случае угла 0//0.

Received February 03, 2010
Accepted April 15, 2010