MODELAGEM DE PROCESSOS DE DESENVOLVIMENTO DE FISSURAS EM ELEMENTOS COMPOSITOS BASEADOS NOS MODELOS “VIRTUAL CRACK CLOSURE TECHNIQUE” E “COHEZIVE ZONE MODE”**MODELLING OF CRACK DEVELOPMENT PROCESSES IN COMPOSITE ELEMENTS BASED ON VIRTUAL CRACK CLOSURE TECHNIQUE AND COHESIVE ZONE MODEL****МОДЕЛИРОВАНИЕ ПРОЦЕССОВ РАЗВИТИЯ ТРЕЩИН В КОМПОЗИТНЫХ ЭЛЕМЕНТАХ НА ОСНОВЕ МОДЕЛЕЙ VIRTUAL CRACK CLOSURE TECHNIQUE И COHESIVE ZONE MODEL**

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RESUMO

Os compósitos de fibra baseados em matrizes poliméricas são um componente essencial na criação da técnica robusta. Devido aos vários fatores, o design da engenharia aeroespacial deve consistir em materiais de alta durabilidade, resistência ao calor e ter outras propriedades qualitativas. Os problemas associados à destruição de compósitos de fibras foram relevantes em todas as etapas do desenvolvimento da tecnologia. A variedade de fibras de reforço e ligantes de polímero, bem como esquemas de reforço, permite controlar direccionalmente a resistência, rigidez, nível de temperatura operacional e outras propriedades dos materiais compósitos poliméricos. Este artigo discute o método de determinação experimental das propriedades mecânicas de materiais compósitos poliméricos à base de fibra de carbono, incluindo a determinação da tenacidade às fissuras entre camadas sob carga sob condições de rasgo, usando o método Direct Bonded Copper (DCB) e a tenacidade às fissuras sob condições de cisalhamento transversal usando o método End-notched flexural test (ENF) e resistência entre camadas. São apresentados os resultados dos testes de amostras de materiais compósitos poliméricos com reforço de carbono com diferentes densidades de superfície. Foi estabelecido que tais características como resistência entre camadas e resistência à fissuras são os parâmetros importantes e determinantes da durabilidade. Foi determinado que o esgotamento da durabilidade de camadas individuais do compósito nem sempre afeta o estado atual de tensão de toda a estrutura e às vezes é difícil de detectar experimentalmente, mas pode afetar significativamente o comportamento adicional do objeto em estudo, desde que a zona de fissura progrida. Foi estabelecida a resistência entre as camadas das amostras com valores experimentais variados. Os dados experimentais foram utilizados para identificar os parâmetros dos modelos de Crack Closure Technique (VVCCT) e Cohesive Zone Model (CZM) utilizados para descrever o desenvolvimento de fissuras nos compósitos considerados.

Palavras-chave: fibra de carbono, parâmetros de resistência as fissuras, tenacidade às fissuras, resistência entre camadas, polímero.

ABSTRACT

Fiber composites based on polymer matrices are promising structural materials that meet high requirements for strength, reliability, durability, and hardness. Therefore, composite materials are widely used as structural materials for aerospace products. The problems associated with the destruction of fiber composites

were relevant at all stages of technology development. A variety of reinforcing fibers and polymer binders, as well as reinforcement schemes, allow directional control of strength, stiffness, level of working temperatures and other properties of polymer composite materials. This article discusses a methodology for experimental determination of the mechanical properties of carbon-based fiber-reinforced polymer composite materials, including the determination of the interlayer fracture toughness under loading under separation conditions using the double-cantilever beam method (DCB) and the fracture toughness under transverse shear conditions using the ENF (End-Notched Flexure) method and interlayer strength. The test results of samples of polymer composite materials with a carbon reinforcing filler with different surface densities are presented. The experimental data were used to identify the parameters of the VCCT (Virtual Crack Closure Technique) and CZM (Cohesive Zone Model) closure models used to describe the development of cracks in the composites under consideration. It was found that the parameters determining the strength of layered composites are such characteristics as interlayer strength and crack resistance. It was found that the decrease in the strength of individual layers of the composite does not always affect the current stress state of the entire structure, which is often difficult to detect experimentally, but can significantly affect the further behavior of the object under study provided that the crack develops further.

Keywords: *carbon fiber, crack resistance parameters, fracture toughness, interlayer strength, polymer.*

АННОТАЦИЯ

Волокнистые композиты на основе полимерных матриц являются перспективными конструкционными материалами, отвечающими высоким требованиям к прочности, надежности, долговечности, твердости. Поэтому композиционные материалы нашли широкое применение в качестве конструкционных материалов для изделий аэрокосмической отрасли. Проблемы, связанные с разрушением волокнистых композитов, были актуальны на всех этапах развития технологии. Разнообразие армирующих волокон и полимерных связующих, а также схемы армирования позволяют направленно контролировать прочность, жесткость, уровень рабочих температур и другие свойства полимерных композиционных материалов. В данной статье рассмотрена методика экспериментального определения механических свойств волокнистых полимерных композиционных материалов на основе углеродных волокон, включающая определение межслоевой вязкости разрушения при нагружении в условиях отрыва по методу двухконсольной балки (DCB – Double Cantilever Beam), вязкости разрушения в условиях поперечного сдвига по методу ENF (End-Notched Flexure) и межслоевой прочности. Приведены результаты испытаний образцов полимерных композиционных материалов с углеродным армирующим наполнителем с различной поверхностной плотностью. Результаты экспериментальных данных использованы для идентификации параметров моделей закрытия виртуальной трещины VCCT (Virtual Crack Closure Technique) и когезионной зоны CZM (Cohesive Zone Model), использованных для описания развития трещин в рассматриваемых композитах. Установлено, что определяющими прочностью слоистых композитов параметрами являются такие характеристики как межслоевая прочность и трещиностойкость. Было установлено, что снижение прочности отдельных слоев композита не всегда влияет на текущее напряженное состояние всей конструкции, что зачастую трудно обнаружить экспериментально, но может существенно повлиять на дальнейшее поведение исследуемого объекта при условии дальнейшего развития трещины.

Ключевые слова: *углеродное волокно, параметры трещиностойкости, вязкость разрушения, межслойная прочность, полимер.*

1. INTRODUCTION

To create modern aerospace technology, materials with high strength, hardness, heat resistance, corrosion resistance, other characteristics and combinations of these properties are required. Fibre composites based on polymer matrices are promising structural materials since they have good specific characteristics of strength and stiffness. These materials are nowadays increasingly being used as part of aviation, space, transport, and other structures (Babaytsev and Zotov, 2019). This is

due to the requirements for weight efficiency of products, to satisfy which it is necessary to use materials with high levels of specific properties (Naghypour *et al.*, 2011; Krayushkina *et al.*, 2016; Landry and La Plante, 2012). The use of composite materials in the aviation industry significantly reduces the material consumption of structures, increases the material utilisation rate up to 90%, reduces the number of equipment, and dramatically reduces the complexity of manufacturing structures by several times reducing the quantity of parts included in them.

Nonetheless, there are many problems

specific to layered composite materials, which limit their scope (Babaytsev and Zotov, 2019). One of the main issues that arise in the design of structures made of polymer composite materials is ensuring strength under the conditions of prolonged stress and in the conditions of damage development. Notably, essential and determining strength parameters are such characteristics as interlayer strength and fracture toughness (Belnoue *et al.*, 2016; Orlov *et al.*, 2003; Nelson and O'Toole, 2019; Kyanishbayev *et al.*, 2016; Zhang *et al.*, 2019; Krayushkina *et al.*, 2019). For a more accurate assessment of strength and resource characteristics of the material, sophisticated tests are required, including tests targeted at determining the parameters of crack resistance.

To evaluate the stress-strain state of multilayered structures, we can use the final parameter of fracture mechanics can be used – the intensity of energy release – G . To find this value, the Virtual Crack Closure Technique (VCCT) method is frequently used (Liu and Islam, 2013; Krueger, 2013; Senthil *et al.*, 2013). At the same time, the use of interface elements based on CZM (Cohesive Zone Model) model (Chandra *et al.*, 2002; Skvortsov *et al.*, 2014; Cornec *et al.*, 2003; De Borst, 2003; Yang and Cox, 2005; Xie and Waas, 2006; Harper and Hallet, 2010) makes it possible to study the nucleation and development of stratification without specifying the initial defect and rearrangement of finite element mesh during its propagation. The inclusion of temperature effects was considered in (Formalev *et al.*, 2018; Bulychev and Kuznetsova, 2019; Makarenko and Kuznetsova, 2019; Hnatiuk *et al.*, 2019; Formalev and Kolesnik, 2019; Formalev *et al.*, 2019).

Therefore, resistance to interlayer fracture is a necessary condition for ensuring the solidity and operability of layered composite materials during the operation. Moreover, theoretical and experimental study of crack resistance parameters is an urgent problem of modern composite materials mechanics.

2. MATERIALS AND METHODS

The authors examined carbon-polymer composite materials with different surface densities for laying reinforcing filler: 400 g/m², 600 g/m², 800 g/m². Reinforcing filler brand Torey T800, matrix - Poly (bisphenol-A-co-epichlorohydrin) Liquid Epoxy resin (Biphend A type) The characteristics of the materials are presented in Table 1.

To study the interlayer strength, tests were performed on three-point bending samples. Tests were done according to ASTM D2344. The study of interlayer fracture toughness (fracture toughness) under loading for tear conditions under the DCB method was studied according to ASTM D 5528 on rectangular samples with preliminary delamination in the middle plane at one end (ASTM D5528, 2013). This artificial defect initiated further stratification (Chung and Blaser, 1980; Kwatra *et al.*, 2009). White paint and a scale were applied to the side face of each sample, which is required to identify the crack. The load on the sample was transmitted through hinges. Three batches of samples were tested, 10-15 pieces each. Samples were 125 mm long, 25.1 mm wide, and 3.3 – 4.5 mm thick (depending on the batch) (Figure 1).

The fracture toughness under shear conditions was determined pursuant to the ENF method according to ASTM D 7075, as in the experiments described above, on rectangular samples, at one end of which a non-adhesive insert was inserted in the middle plane during production. Three batches were tested, each containing 10 to 15 samples. The simulation of experiments on ASTM D 5528 (ASTM D5528, 2013) and ASTM D 7905 (ASTM D7905, 2013) was done using software packages Simulia ABAQUS and Ansys. The methods used were the VCCT (Virtual Crack Closure Technique) and CZM (Cohesive Zone Model). The samples were modelled as deformable three-dimensional bodies consisting of two parts of equal thickness.

The virtual crack technique (VCCT) uses the principles of linear mechanics of elastic fracture and, therefore, is suitable for tasks in which brittle crack propagation occurs along predetermined surfaces. The VCCT technique is based on the assumption that the strain energy released when a crack increases by a certain amount is the same as the energy needed to close a crack by the same value. A “surface-to-surface” contact was fixed between the two halves. The bundle formation zone was modeled using the VCCT element. To simulate tests according to ASTM D 7905, the procedure described above was also applied, except the boundary conditions (ASTM D7905, 2013). Here the sample was tested for three-point bending.

Tests on the separation and simulations using the CZM models. The Cohesive Zone Model (CZM) is based on the assumption that the ability to transfer stress between two separated faces when they are separated from each other is not

entirely lost, but instead becomes a progressive event, determined by a gradual deterioration in the rigidity of the interlayer surface. A strong point of the CZM method: a model using the CZM predicts the beginning and describes the delamination process without having to accept the assumption that there is a small supposed crack. Weak points: the need for data that can only be obtained from a complex set of experiments, as well as high sensitivity to input parameters, required fine mesh. The simulation of the experiment was carried out in a flat setting. The sample was modelled, consisting of two parts of identical thickness.

3. RESULTS AND DISCUSSION:

According to tests, it was established that the interlayer strength of the samples was 37 MPa (400 g/m²), 35 MPa (600 g/m²), 57 MPa (800 g/m²) with a variation of experimental values not more than 10%. The test results of ASTM D 5528 for determining the fracture toughness under shear conditions are shown in Figure 2 and Table 2 (ASTM D5528, 2013). Test results of ASTM D 7905 to determine fracture toughness in terms of the separation are presented in Figure 2b and Tables 3, and 4 (ASTM D7905, 2013). The calculation, according to ASTM, was done by several methods: Modified Beam Theory (MBT) Method, Compliance Calibration (CC) Method, Modified Compliance Calibration (MCC) Method.

Simulation of experiments implemented according to the methods of VCCT and CZM provides a good comparison with the experiment, but only from the beginning of the growth of the separation. It was not possible to predict further stratification growth using the applied techniques. For example, a result of the calculation by the model CZM rendered the following dependency (Figure 3).

The model of the cohesive zone is susceptible to input parameters. For solution within the framework of this model, it is essential to know the crack resistance parameters, which can only be learned from the experiment on individual samples by specific methods. This model also requires a fine mesh and thorough adjustment of the solver.

4. CONCLUSIONS:

As part of the research, an experimental and theoretical study of mechanical properties of composite materials reinforced with carbon filler

was carried out. A feature of the deformation of spatial structures made of composite materials is the possibility of the occurrence of not only cracks due to rupture of fibres and matrix material, but also the formation of delamination zones during deformation. As a result, a technique was developed for doing CRFP tests aimed at studying the interlayer strength, determining the specific work of stratification in conditions of the GIC separation using the DCB method, and under transverse shear conditions GIIC using the ENF method. An experimental base was developed; practical recommendations were arranged for further research. Samples of carbon fibre with different densities of reinforcing filler were tested.

As a result of experimental tests, it was found that the interlayer strength of the samples is 37 MPa (400 g/m²), 35 MPa (600 g/m²), 57 MPa (800 g/m²) with a variation of experimental values of not more than 10%. The experimental data were compared with models of processes of appearance and development of cracks in the finite element complexes ABAQUS and Ansys based on VCCT models, cohesive elements. Using the VCCT model, it was possible to obtain only the critical load of the start of the first crack, further stratification using this model could not be modelled, the results obtained did not correlate with experimental data at all.

The cohesion area model is susceptible to input parameters. To solve within the framework of this model, it is necessary to know the crack resistance parameters, which can only be learned from experiments on individual samples by specific methods. This model also requires a fine mesh and thorough adjustment of the solver. Within the framework of this model, it was possible to track the appearance of the first crack, and also to trace further development of the crack within the first three growth stages with an acceptable error.

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Figure 1. The test process according to ASTM D5528 (2013) and ASTM D7905 (2013)

a

b

Figure 2. a: Test results for determining fracture toughness under the separation conditions (example for samples of 600 g/m^2), b: Test results for determining of fracture toughness under conditions of shear (example for samples of 800 g/m^2)

Figure 3. Simulations of the delamination process by CZM method

Table 1. Mechanical properties of the materials used

Sample Type	E_1 [kgf / mm ²]	E_2 [kgf / mm ²]	E_3 [kgf / mm ²]		$G_{12, 13, 23}$ [kgf / mm ²]
400 g/m ²	6500	6500	800	0.3	450
600 g/m ²	7130	7130	800	0.3	450
800 g/m ²	7105	7105	800	0.3	450

Table 3. The results of tests for determining fracture toughness in conditions of the separation

Sample	MBT [kgf / mm]	MBT corrected [kgf / mm]	SS [kgf / mm]	MCC [kgf / mm]	Min [kgf / mm]	Load [kgf]
400 g/m²						
Min	0.072	0.053	0.053	0.054	0.053	7.411
Max	0.112	0.088	0.086	0.090	0.086	11.597
Middle	0.088	0.066	0.065	0.068	0.064	9.003
The coefficient of variation	16.01 %	16.37 %	15.59 %	15.35 %	15.95 %	15.80%
Standard deviation	0.014	0.011	0.010	0.010	0.010	1.422
600 g/m²						
Min	0.050	0.048	0.048	0.051	0.048	5.065
Max	0.090	0.085	0.086	0.147	0.085	7.073
Middle	0.073	0.065	0.067	0.077	0.065	6.144
The coefficient of variation	15.48 %	18.76%	16.29 %	31.09%	18.71%	10.10 %
Standard deviation	0.011	0.012	0.011	0.024	0.012	0.621
800 g/m²						
Min	0.034	0.032	0.029	0.029	0.029	5.303
Max	0.069	0.062	0.051	0.052	0.051	9.779
Middle	0.052	0.048	0.041	0.042	0.041	7.223
The coefficient of variation	20.88 %	19.60%	17.44 %	16.14 %	17.44 %	18.78%
Standard deviation	0.011	0.009	0.007	0.007	0.007	1.356

Table 4. Test results for determining fracture toughness under shear conditions

Sample label	$G_2 C$ [kgf / mm]	$G_2 C^*$ [kgf / mm]	P [kgf]	P^* [kgf]
400 g/m²				
Min	0.06	0,053	58,953	69,998
Max	0,085	0.135	71,523	111,926
Middle	0,074	0,090	65,865	80,143
The coefficient of variation	10.90%	27.11%	6.63%	14.93%
Standard deviation	0.008	0,024	4,369	11,964
600 g/m²				
Min	0,090	0.127	48,743	57,810
Max	0.137	0,203	56,515	69,632
Middle	0.109	0.161	52,890	66,096
The coefficient of variation	9.94%	13.75%	4.93%	5.29%
Standard deviation	0.011	0,022	2,606	3,497
800 g/m²				
Min	0.06	0,044	73,423	73,423
Max	0.169	0.1	114,840	103,041
Middle	0.115	0,073	96,491	86,913
The coefficient of variation	23.05%	22.19%	12.16%	9.88%
Standard deviation	0,027	0.016	11,730	8.585