PERIÓDICO TCHÊ QUÍMICA
ARTIGO ORIGINAL

DETERMINAÇÃO EXPERIMENTAL DE CARACTERÍSTICAS DA RESISTÊNCIA À FENDILHAÇÃO E MODELAGEM TEÓRICA DE PROCESSOS DE DESENVOLVIMENTO DE FENDAS EM AMOSTRAS DE PLÁSTICO DE CARBONO SOB CONDIÇÕES DE PRODUÇÃO ADITIVA

EXPERIMENTAL FINDING OF FRACTURE TOUGHNESS CHARACTERISTICS AND THEORETICAL MODELING OF CRACK PROPAGATION PROCESSES IN CARBON FIBER SAMPLES UNDER CONDITIONS OF ADDITIVE PRODUCTION

ЭКСПЕРИМЕНТАЛЬНОЕ ОПРЕДЕЛЕНИЕ ХАРАКТЕРИСТИК ТРЕЩИНОСТОЙКОСТИ И ТЕОРЕТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ПРОЦЕССОВ РАЗВИТИЯ ТРЕЩИН В ОБРАЗЦАХ УГЛЕПЛАСТИКА В УСЛОВИЯХ АДДИТИВНОГО ПРОИЗВОДСТВА

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Received 25 May 2019; received in revised form 01 October 2019; accepted 24 October 2019

RESUMO

A urgência do problema mencionado neste artigo é que, com o desenvolvimento da tecnologia aeroespacial, a demanda por materiais de boa qualidade aumentou. Uma questão importante é garantir durabilidade em condições de cargas de longo prazo e em condições de desenvolvimento de danos. Um dos critérios que garante a resistência do material é a resistência à fendilhação. O objetivo do artigo é estudar a resistência à fendilhação entre camadas (tenacidade à fratura) sob carga em condições de separação e cisalhamento transversal, dureza entre camadas, bem como o efeito da temperatura na dureza entre camadas, propriedades mecânicas de tração. É feita uma comparação dos valores de resistência à fendilhação entre camadas GIC (separação) e GIIC (cisalhamento), bem como propriedades mecânicas de tração e dureza entre camadas de amostras de fibra de carbono. Os principais métodos para estudar esse problema foram o método de feixe curto, o método DCB, o método ENF. Os resultados dos dados experimentais foram comparados com a modelagem dos processos de aparência e desenvolvimento de fendas nos complexos de elementos finitos ABAQUS e Ansys, com base nos modelos VVCT, elementos coesivos. Foram encontrados desvios do experimento e foram tiradas conclusões de que o ponto de aplicação da carga deve ser deslocado da borda da amostra, o que reduzirá a separação inicial e aumentará a rigidez da amostra. Devido ao fato de que o modelo da zona de coesão ser muito sensível aos parâmetros de entrada, é necessário conhecer muitos parâmetros e levar em consideração um grande número de fatores. Estudos têm mostrado como usar o modelo VCCT para obter a carga crítica da germinação da primeira fenda. A técnica de pesquisa pode ser usada para novas experiências, inclusive para simular estratificação adicional com menos erros.

Palavras-chave: *material compósito polimérico, fibra de carbono, parâmetro de resistência à fendilhação entre camadas, modelagem, parâmetro de escala da teoria dos gradientes.*

ABSTRACT

The relevance of the problem stated in this article is that the development of aerospace technology increased the demand for good quality materials. An important issue is ensuring durability in conditions of long-term loads and in conditions of damage development. One of the criteria that ensure the toughness of the material is crack resistance. The aim of the work is to study the interlayer crack resistance (fracture toughness) under loading under conditions of separation and transverse shear, interlayer strength, as well as the effect of temperature on interlayer strength, mechanical tensile properties. A comparison of the values of interlayer crack resistance G_{IC} (separation) and G_{IIC} (shear) and of mechanical tensile properties and interlayer strength of

DOI: 10.52571/PTQ.v16.n33.2019.340_Periodico33_pgs_325_336.pdf

carbon fiber samples is made. The main methods for studying this problem were the short-beam method, the DCB method, the ENF method. The results of the experimental data were compared with modeling the processes of the appearance and development of cracks in the finite element complexes ABAQUS and Ansys based on the VVCT models, cohesive elements. Deviations from the experiment were found and conclusions were drawn that the point of application of the load had to be shifted from the edge of the sample, which will reduce the initial separation and increase the stiffness of the sample. Due to the fact that the cohesion zone model is very sensitive to input parameters, it is necessary to know many parameters and take into account a large number of factors. The practical importance of this work is to show how to use the VCCT model to obtain the critical load of the germination of the first crack. The research technique can be used for further experiments, including simulation further stratification with low inaccuracy.

Keywords: *polymer composite material, carbon fiber, interlayer crack resistance parameter, modeling, scale parameter of gradient theory.*

АНОТАЦИЯ

Актуальность заявленной в данной статье проблемы состоит в том, что с развитием авиакосмичной техники вырос спрос на материалы хорошего качества. Важным вопросом есть обеспечение прочности в условиях длительных нагрузок и в условиях развития повреждений. Один из критериев, который обеспечивает прочность материала, является трещиностойкость. Цель статьи заключается в исследовании межслоевой трещиностойкости (вязкости разрушения) при нагружении в условиях отрыва и поперечного сдвига, межслоевой прочности, а также влияния температуры на межслоевую прочность, механических свойств при растяжении. Приводится сравнение значений межслоевых трещиностойкостей G_{IC} (отрыв) и G_{IIC} (сдвиг), а также механических свойств при растяжении и межслоевой прочности образцов углепластиков. Основными методами к исследованию данной проблемы были метод короткой балки, метод DCB, метод ENF. Результаты экспериментальных данных были сопоставлены с моделированием процессов появления и развития трещин в конечно-элементных комплексов ABAQUS и Ansys на основе моделей VVCT, когезионных элементов. Были обнаружены отклонения от эксперимента и сделаны выводы, что точку приложения нагрузки необходимо сместить от края образца, что сократит величину изначального расслоения и увеличит жесткость образца. По причине того, что модель когезионной зоны является очень чувствительной к входным параметрам, необходимо знать множество параметров и учитывать большое количество факторов. Исследования показали, как с помощью модели VCCT получить критическую нагрузку прорастания первой трещины. Методика проведения исследования может быть использована для дальнейших опытов, в том числе для того, чтобы смоделировать дальнейшее расслоение с меньшей погрешностью.

Ключевые слова: *полимерный композиционный материал, углеродное волокно, параметр межслоевой трещиностойкости, моделирование, масштабный параметр градиентной теории.*

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1. INTRODUCTION

To create modern aerospace technology, we need materials with high strength, hardness, heat resistance, corrosion resistance, other characteristics, and the combination of these properties. Fiber composites based on polymer matrices are promising structural materials, as they have high specific characteristics of strength and rigidity. Currently, these materials are increasingly being used as part of aviation, space, transport and other structures (Kablov, 2012; Borschev and Gusev, 2014). For example, in promising aircraft products, the weight of polymer composite material in project exceeds 50%: Boeing 787 (USA) – 50%, Airbus A380 (Europe) – 30%, Airbus A 350 (Europe) – 50% (Krylov *et al.*, 2016; Savin, 2012). In a promising Russian-made aircraft of MS-21 family, a composite design of wing and tail structures was introduced (Savin, 2014). This is caused by the requirements for the weight efficiency of products, to satisfy which it is necessary to use materials with a high level of specific properties (Shejko *et al.*, 2017). The use of composite materials in the aviation industry significantly reduces material consumption of structures, increases material use rate up to 90%, reduces the number of equipment and dramatically reduces the complexity of manufacturing structures by several times reducing the number of parts included in them (Savin, 2014).

Nonetheless, there are many problems specific to layered composite materials that limit their scope of application. One of the main issues that are uncounted in the design of structures made of polymer composite materials is ensuring durability under conditions of long-term loads and conditions of damage development. In particular, such parameters as interlayer strength and crack resistance (Yakovlev *et al.*, 2014) are important and determining for strength. The importance of these characteristics is caused by the fact that cracks begin to develop in the weakest point of polymer composite material – the matrix and the interfacial zone (Figure 1).

Studies have shown that the behavior of composite materials under static and cyclic loading cannot be reliably described by classical theories. For a more accurate assessment of the durability and resource characteristics of the material, comprehensive tests are required, including tests aimed at determining the parameters of crack resistance. To assess the stress-strain state of multilayer structures, we can use the final parameter of fracture mechanics – the intensity of energy release (Finogenov and Erasov, 2003). Then, the Virtual Crack Closure Technique (VCCT) is used (Liu and Islam, 2013; Krueger, 2013; Senthil *et al.*, 2013). Now, one of the main tools for numerical solution of problems of modeling bundle growth is the finite element method (Landry and La Plante, 2012; Muñoz *et al.*, 2006).

The use of interface elements based on the CZM (Cohezive Zone Model) model (Kuznetsova *et al.*, 2015) allows us to study the initiation and development of the bundle without specifying the initial defect and rearrangement of the finite element mesh during its propagation. Theoretical and experimental study of crack resistance parameters is a relevant problem of modern mechanics of composite materials. Thus, the relevant task is to study the mechanical properties, and, in particular, the crack resistance parameters of carbon fiber based on experimental and theoretical methods (Lurie *et al.*, 2015; Lomakin *et al.*, 2017; Formalev and Kolesnik, 2017; Kolesnik *et al.*, 2015; Lomakin *et al.*, 2018; Lurie *et al.*, 2017; Bulychev *et al.*, 2018; Formalev *et al.*, 2016; Rabinsky and Turchavina, 2019; Kakhramanov *et al., 2017;* Rabinsky and Turchavina, 2018). To determine the mechanical characteristics of PCM, a number of experimental studies were carried out using standard methods: the study of shear strength by the short beam method, the study of tensile strength, the finding the specific work of delamination under tear conditions G_{IC} according to the DCB method and under transverse shear G_{IIC} according to the ENF method.

2. MATERIALS AND METHODS

Mechanical tests were performed at Instron 5969 test equipment. This machine and the set with which it is equipped to meet all that is required by the ASTM (ASTM: Active Russian Standards, 2019) standards that describe the test procedure.

2.1. Interlayer shear durability of short plates

To study the durability of short plates, the samples were tested for three-point bending. 3 batches were tested, 7 samples for each. The testing base for the first batch was 10 mm, for the second – 8.55 mm, for the third – 8.6 mm. The loading roller of the testing machine has a radius of 5 mm, and radius of supports is 2 mm. The samples were rectangular plates, the parameters of which are 15×2.44×4.95; 12×2.15×4.37; 12×2.16×4.28 respectively for the first, second and third parties (Figure 2). All the samples were measured and numbered. The geometry of the samples and the value of the base were recorded in protocol, as well as in program. Each sample was checked for defects prior to installation into the test machine. During testing, the nature of the destruction of the sample was determined using a camera with big magnification (Figure 3).

2.2. The tension tests

The tension tests were conducted according to ASTM D3039 Standard Test Method (ASTM: Active Russian Standards, 2019) for Tensile Properties of Polymer Matrix Composite Materials. The nature of the method is as follows: a tensile load is applied to the sample, the vector of which coincides with its main axis, at a constant speed until a fracture occurs, or until the stress (load) or deformation (tension) reaches the specified value (Figure 4). During the test, the load and elongation of the sample are being measured (Figure 5).

2.3. Finding the magnitude of specific work of separation in terms of separation G_{IC} according to the DCB method

Finding the magnitude of the specific work of the separation under separation conditions was performed according to ASTM D5528 (ASTM: Active Russian Standards, 2019). The specific work of separation is the limit of the ratio of change in elastic energy accumulated in the sample when it is loaded to the infinitely small increment of the area of the interlayer crack.

The method consists in testing under conditions of loading by separation of a sample with preliminary separation at its end located at the center of thickness. Tearing forces are applied to the sample through loops (Figure 6) that adhere to opposite surfaces at one end of the sample. In the time of the test, the applied force and crack length are recorded.

2.4. Finding the magnitude of the specific work of stratification under transverse shear conditions G_{IIC} according to the ENF method

The procedure of the test is described in the standard ASTM D7905 (ASTM: Active Russian Standards, 2019) (Figure 7). The nature of the method is to make the test with a constant speed of loading a three-point bend of the sample in the form of beam, at the end of which stratification is performed, located in the center of the thickness. During testing, the applied force, the displacement of the central support and the length of the crack were recorded.

3. RESULTS AND DISCUSSION:

Based on the data obtained, graphs of the dependence of the load on displacements during the interlayer shear were constructed (Figure 8). Figure 9 shows the results of tensile testing of samples. The calculation of the value of specific work of separation in terms of separation G_{IC} and under shear conditions G_{IIC} was carried out in full accordance with ASTM D5528 and D7905 (ASTM: Active Russian Standards, 2019). Based on the experimental data, the graphs were made (Figure 10, 11). The experimental data were compared with the model of the processes of appearance and development of cracks in the finite element complexes ABAQUS and Ansys based on the VVCT models and cohesive elements (Figure 12).

As a result of the numerical calculation at the first stage, the following dependences were received (Figure 13). The obtained dependencies cannot be considered reliable. The critical load deviation from the experimental is about 15%. There is also a significant discrepancy between the elasticity properties. It can be caused by many factors:

- mistakes made during experimental studies, which led to the assignment of incorrect material constants;
- inaccurate specification of the boundary conditions: during the experiment, some samples deviated from horizontal arrangement, which was caused by the asymmetric arrangement of the loops;
- inaccurate setting of the properties of CZM material: for example, Artificial Damping Coefficient can significantly affect the critical load (Figure 14) (this ratio of artificial damping is needed to stabilize the numerical solution, the smaller it is, the smaller the integration step over time), as well as critical delamination energy (Figure 15); in addition, the value of critical energy of separation in processing the results had a significant scatter, to the extent of difference in two or more times.

Another factor that affects the results is the application of loading to the sample. It can be that the loop that was used in the experiment contacted by the entire surface with the sample. Moreover, the force was applied through the loop mechanism. All this could cause redistribution of stresses in contact zone of the loop and the sample. In the process of modeling, it was supposed that this way, the point of application of the load could be shifted from the edge of the sample, which, in turn, will reduce the value of initial delamination and increase the stiffness of the sample (Figure 1-6).

4. CONCLUSIONS:

We have performed an experimental and theoretical study of the mechanical properties of composite materials reinforced with carbon filler. As a result, the testing procedure for PCM aimed at research was developed. interlayer strength, as well as the effect of temperature on interlayer strength; mechanical properties of composites materials; determining the magnitude of the specific work of delamination under separation conditions G_{IC} according to the DCB method and under transverse shear conditions G_{IIC} according to the ENF method. An experimental base was developed, practical recommendations for further studies of layered PCMs were offered. Carbon fiber samples with different densities of reinforcing filler were tested. A comparison was made of the values of parameters for interlayer crack resistance G_{IC} and G_{IIC}, and interlayer strength, mechanical tensile properties for different batches of samples.

A significant effect of temperature on the interlayer strength of layered PCMs was demonstrated. The results of the experimental data were compared with modeling of processes of appearance and development of cracks in the finite element complexes ABAQUS and Ansys based on the VVCT models, cohesive elements, and gradient theory of elasticity; the scale parameter of gradient theory of elasticity was identified. By using the VCCT model, it was possible to obtain only the critical load of the growth of the first crack, further stratification using this model could not be modeled, the results obtained did not correlate with experimental data at all.

The cohesion zone model is very sensitive to input parameters. To find solutions within the framework of this model, it is necessary to know the parameters of crack resistance, which can only be learned by experiment on special samples using certain methods. This model also requires a fine mesh and exact 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 the further development of the crack within the first three growth stages with an acceptable error.

5. ACKNOWLEDGMENTS:

The work was carried out with the financial support of the state project of the Ministry of Education and Science project code 2.9219.2017 / 8.9.

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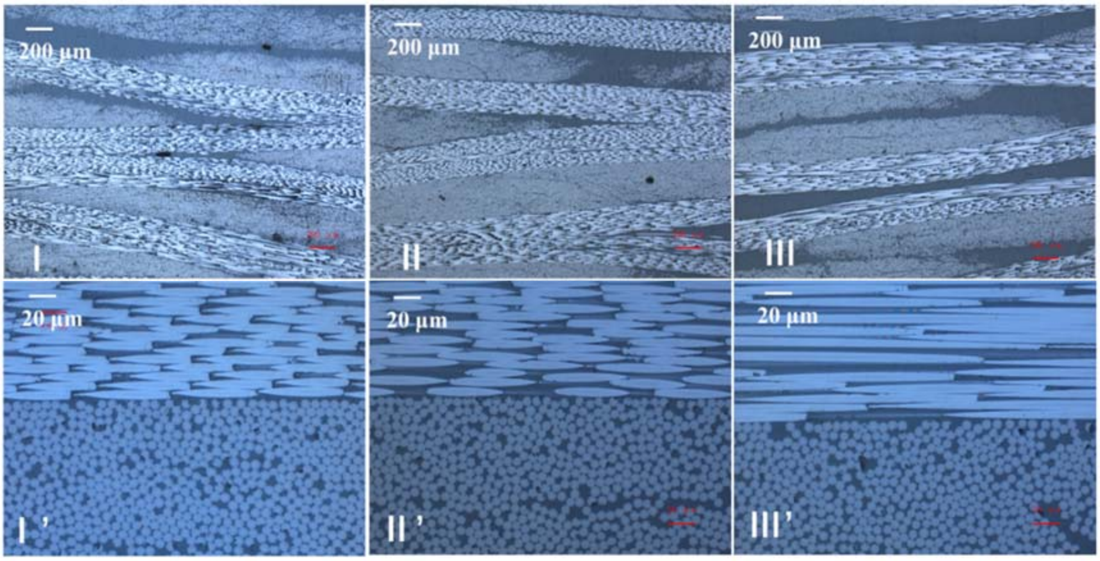

Figure 1. *The structure of polymer composite material*

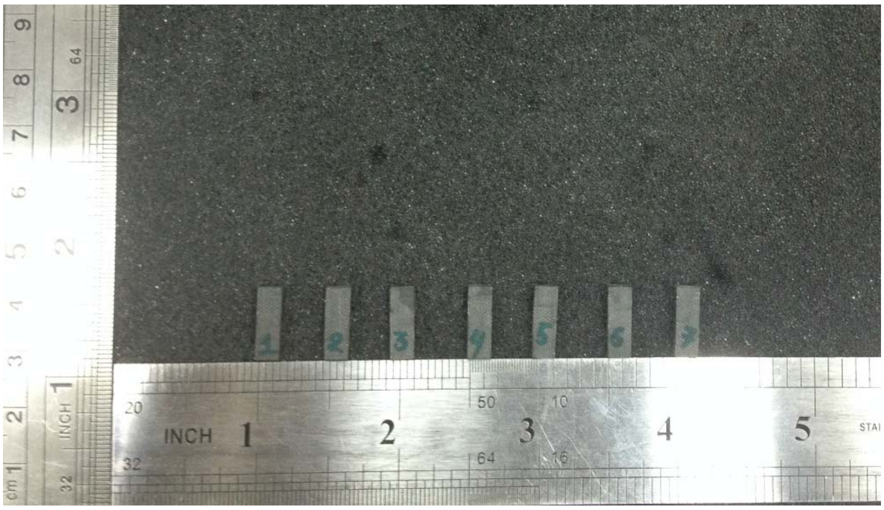

Figure 2. *Samples for studying the durability at the interlayer shear*

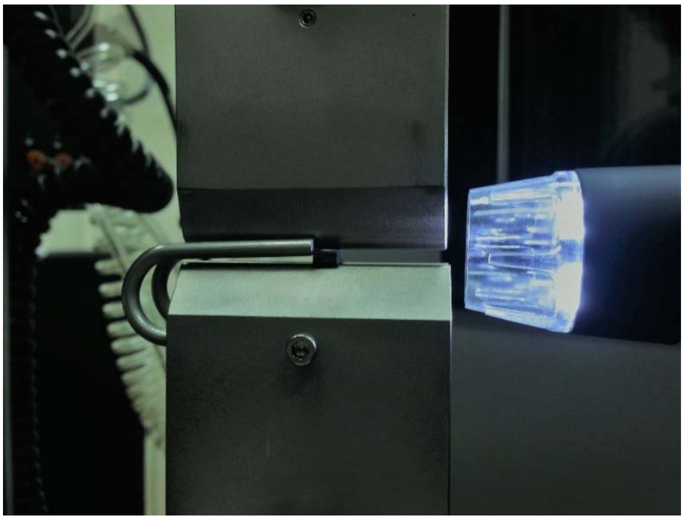

Figure 3. *View of a sample placed in the testing machine. On the right is the magnification camera*

Figure 4. *Labeled tensile test sample mounted in mechanical grips before and after the test*

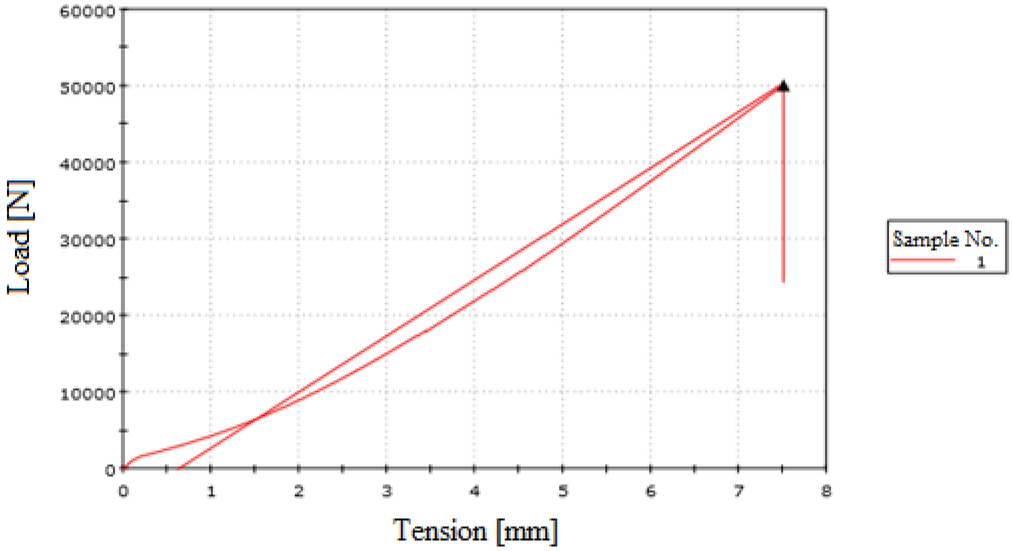

Figure 5. *Load-displacement diagram for tensile testing sample*

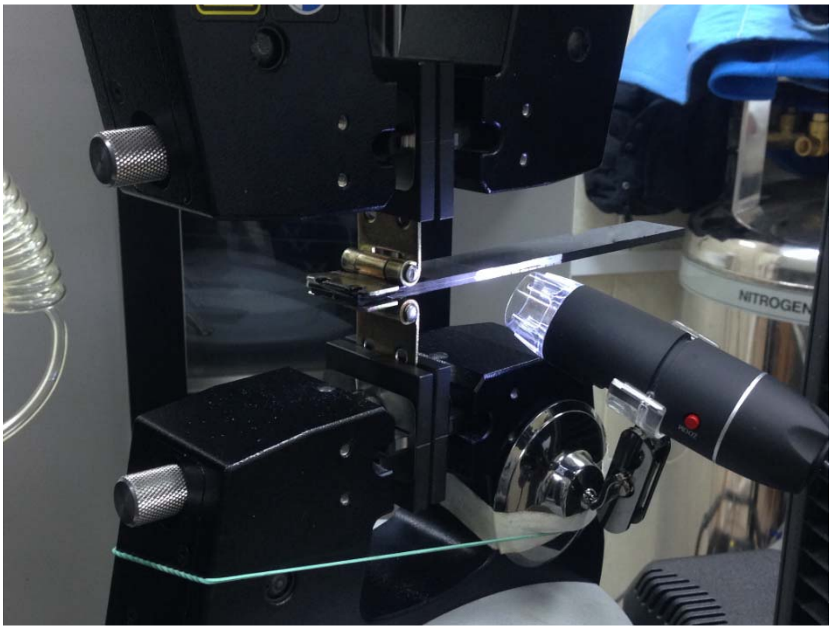

Figure 6. *Testing according to ASTM D5528 (ASTM: Active Russian Standards, 2019)*

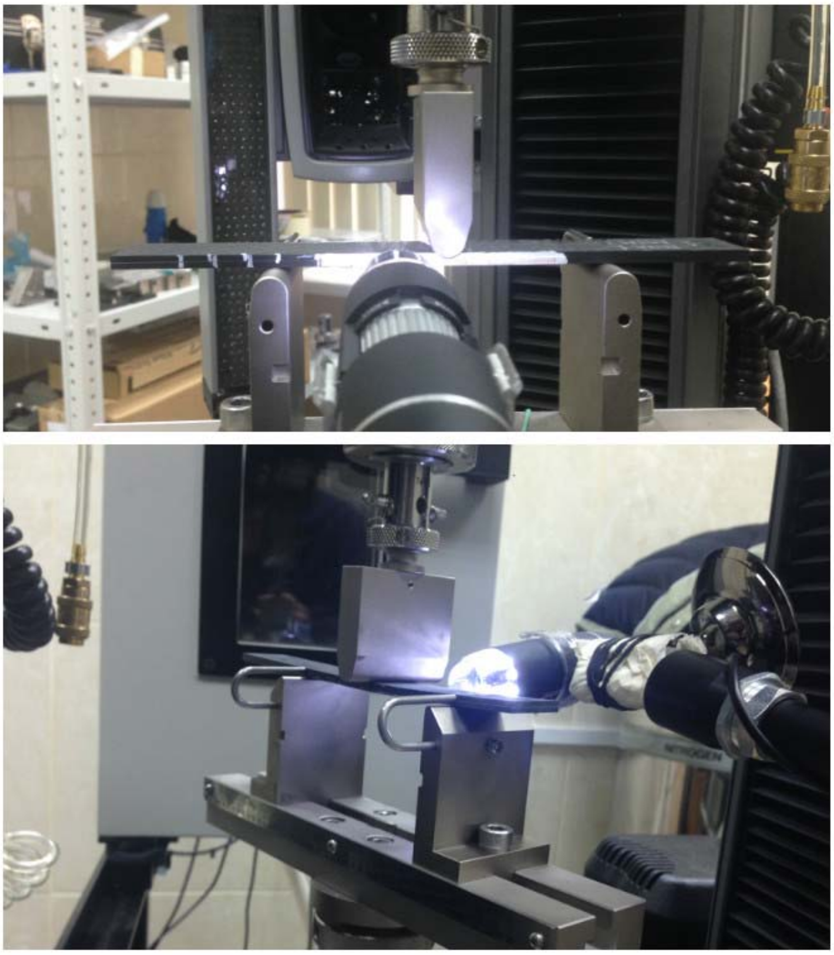

Figure 7. *Tests according to ASTM D7905*

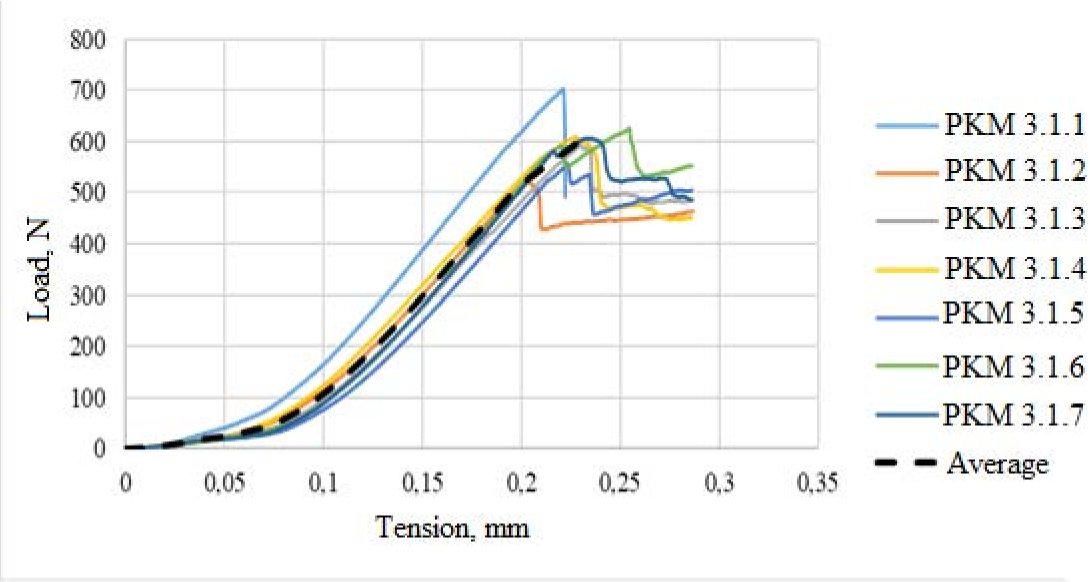

Figure 8*. The Load-displacement diagram*

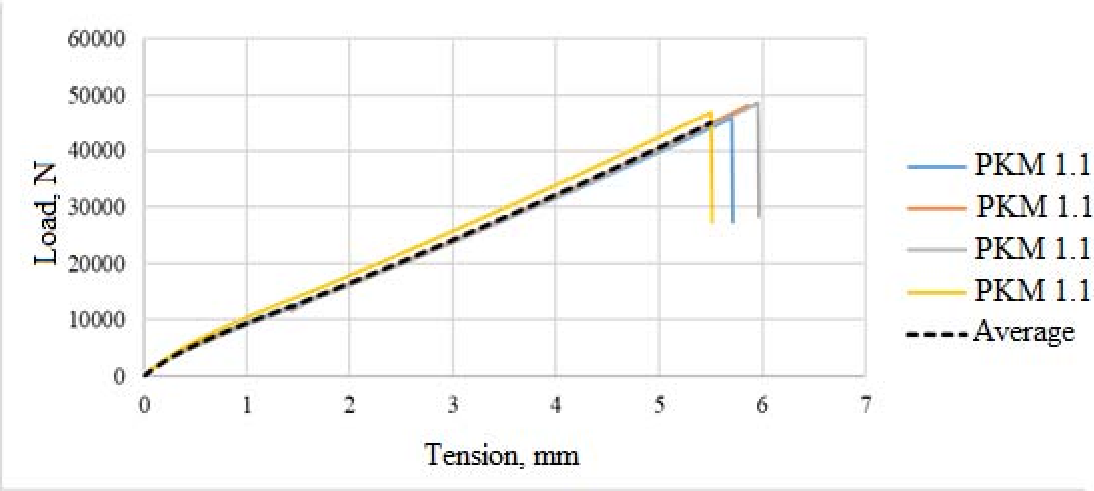

Figure 9. *Diagram of load-displacement for RMB 1.1*

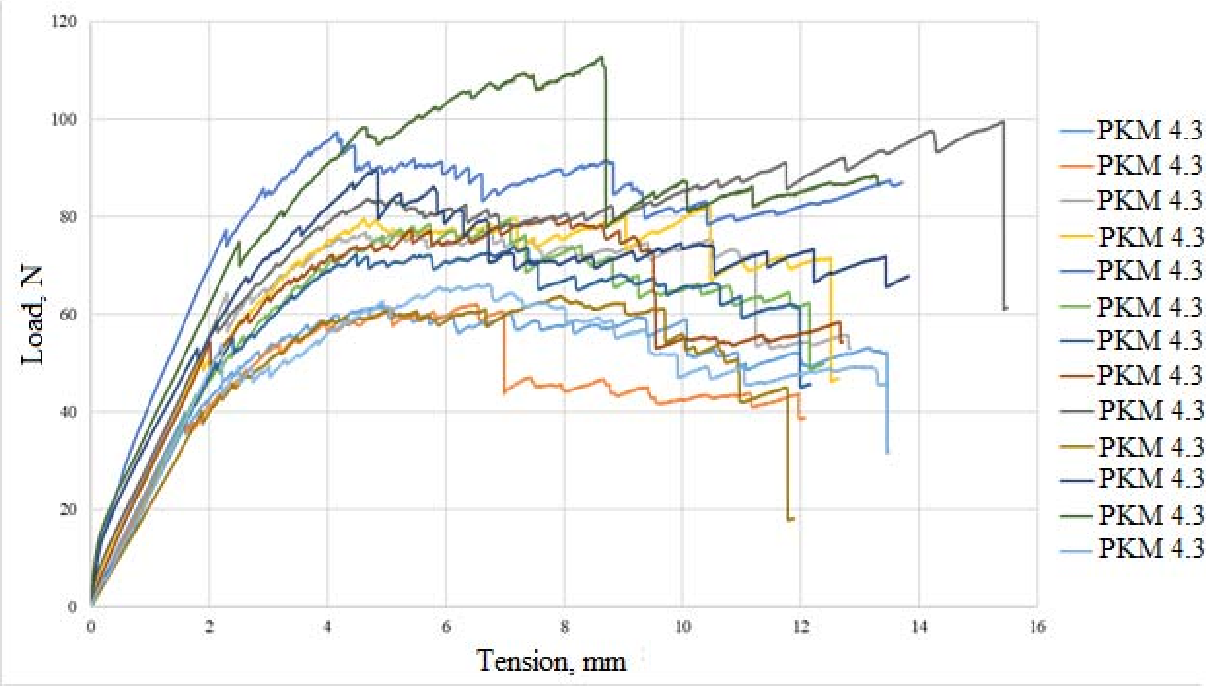

Figure 10. *The Load-displacement diagram in tests on fracture toughness by DCB method*

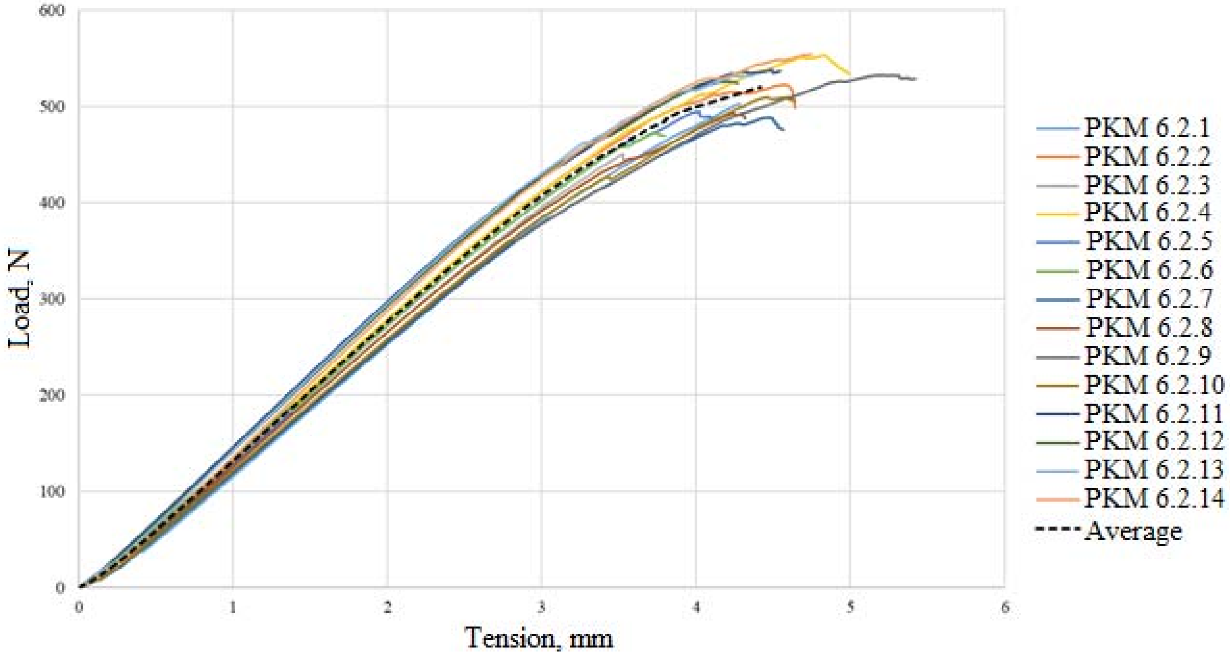

Figure 11. *The Load-displacement diagram on fracture toughness tests according to ENF*

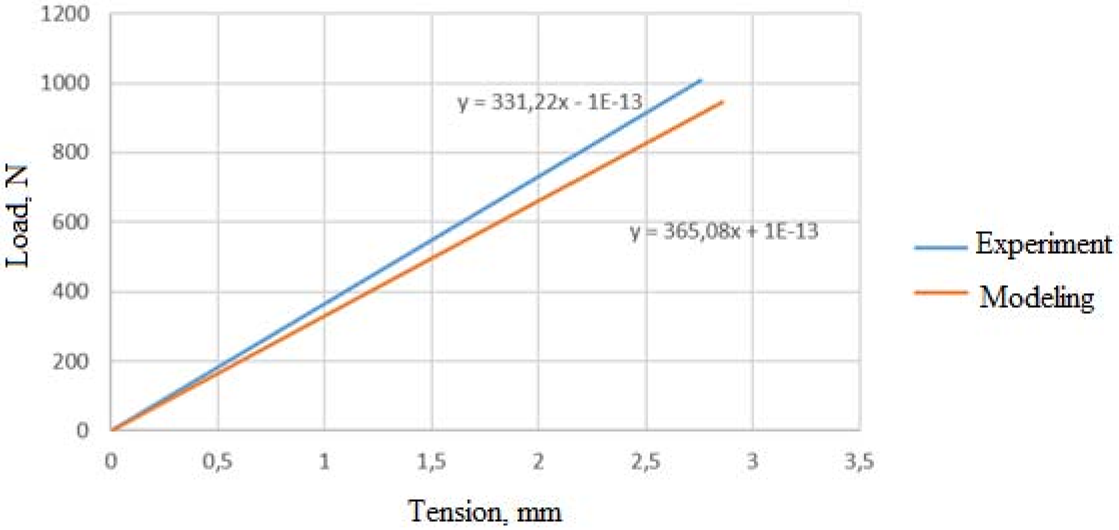

Figure 12. *Comparison of experimental and simulation results with the use of the VCCT model*

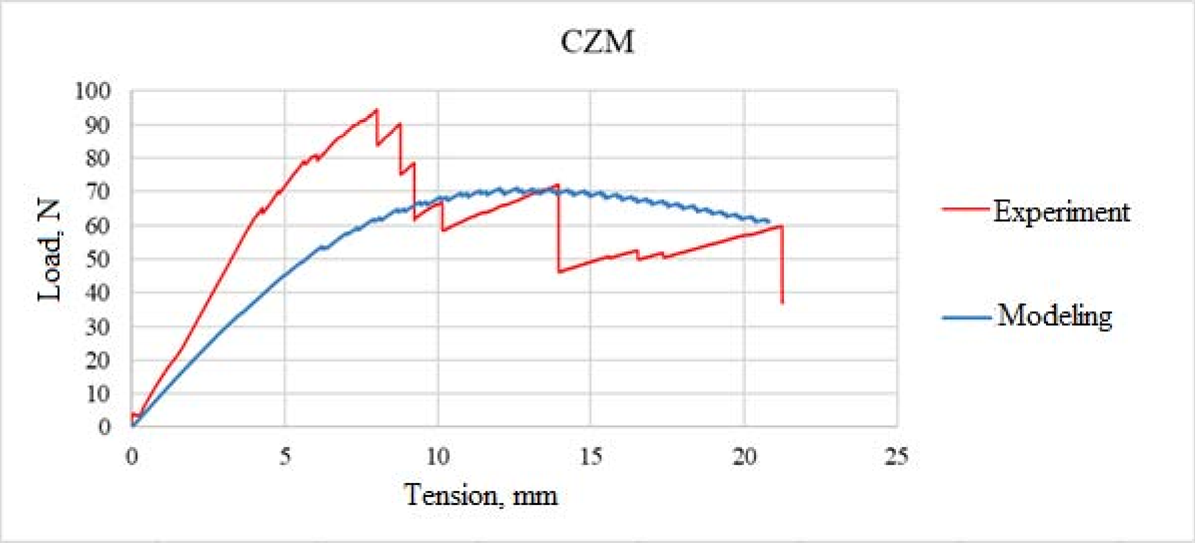

Figure 13. *Comparison of simulation and experiment data*

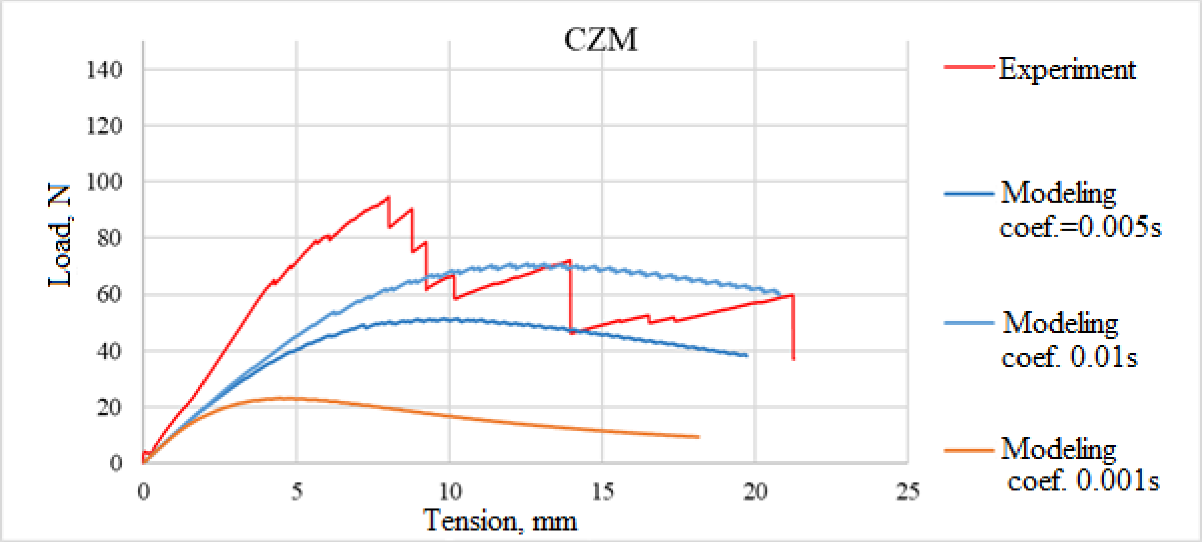

Figure 14. *Influence of damping coefficient*

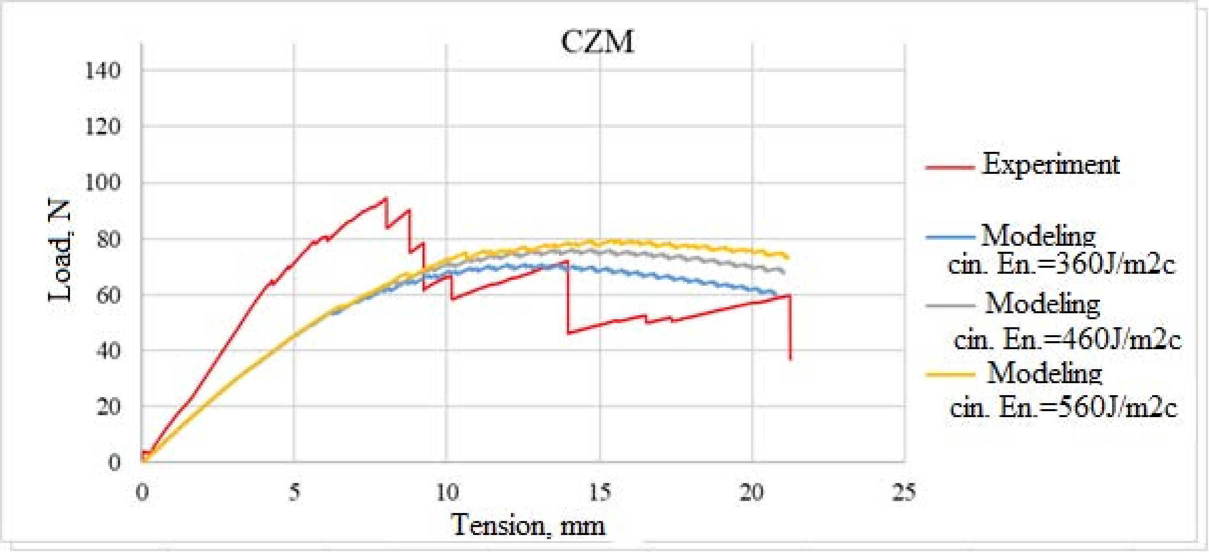

Figure 15. *The influence of critical energy of stratification*

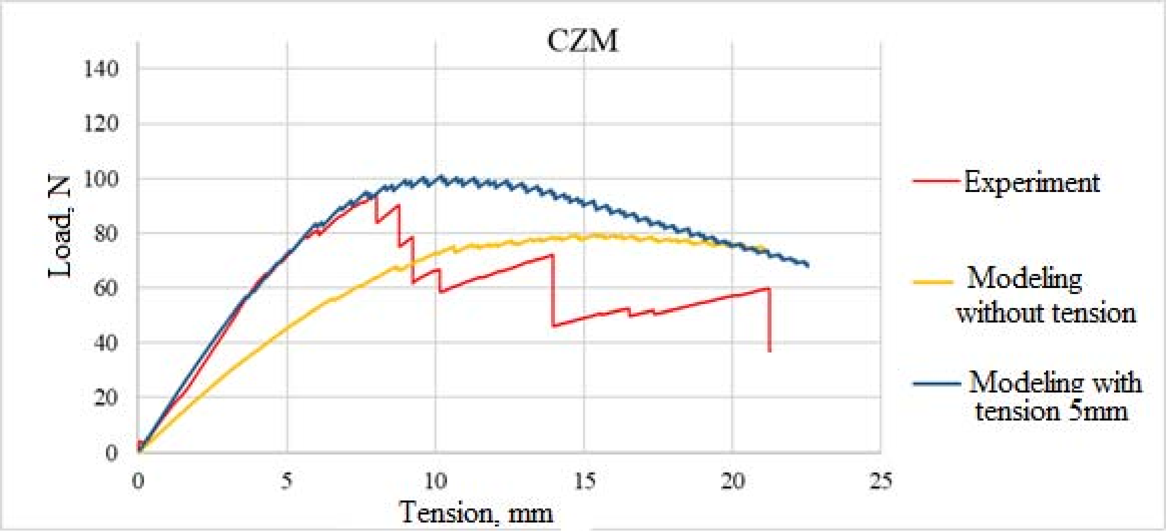

Figure 16. *Influence of point of load application*