

---

---

METHODS OF STUDY  
OF PROPERTIES OF MATERIALS

---

---

## Use of Experimentally Determined Parameters of the Cohesive Zone in the Numerical Evaluation of the Resistance to Delamination of Polymer Composites Materials

P. G. Babayevsky<sup>a, \*</sup>, N. V. Salienko<sup>a, \*\*</sup>, and G. V. Novikov<sup>a, \*\*\*</sup>

<sup>a</sup>*Moscow Aviation Institute (National Research University MAI), Moscow, 121552 Russia*

\**e-mail: gena@mati.ru*

\*\**e-mail: intdep@mati.ru*

\*\*\**e-mail: ngv92@mail.ru*

Received August 10, 2018; revised September 12, 2018; accepted September 13, 2018

**Abstract**—The technique of cohesive zones makes it possible to evaluate the stability of the material, both at the beginning of the crack propagation and to the appearance and development of defects in the places of stress concentration. The ability to reliably determine the parameters of fracture of polymer composite materials and to predict the behavior of structural elements from them under loading is an urgent task for the aerospace industry. It is proposed to use the length of the cohesive zone in the finite-element 3D model for mode I of interfacial delamination of the carbon fiber composite laminates in the form of a double cantilever beam (DCB). The length of the cohesive zone is calculated from the experimentally determined parameters such as the local interlayer cohesive strength of the material and the critical strain energy release rate. The determined length of the cohesive zone is used in the model to select the minimum number of finite elements at their optimum size, which ensures a higher accuracy of calculations of the main parameters of fracture toughness of carbon fiber composite laminates. As a result of the research, the main parameters of crack resistance are determined and the optimal length of the interface elements is chosen. The obtained model accurately describes the process of crack growth along the entire length of the cohesive zone, and the results of its application correlate well with the results of the experiments.

**Keywords:** carbon fiber composite laminates, double cantilever beam (DCB), parameters of the cohesive zone, experimental techniques, finite element 3D model of delamination DCB

**DOI:** 10.1134/S2075113319050022

### INTRODUCTION

Rational employment of the structures made from laminate polymer composite materials based on high-quality thermosetting and thermoplastic matrices and reinforcing elements, in particular, carbon fabrics, tapes, or tow, is one of the essential approaches to improve contemporary aerospace equipment. Carbon fiber (CF) composite laminates possess evident advantages as compared to conventional types of structural materials according to density and specific stiffness and strength, as well as corrosion resistance and others along with control of anisotropy of their structure and properties. One of the main drawbacks of these materials is low interlaminar strength and crack resistance, which results in the loss of the cohesive bond between the layers of the material owing to formation and propagation of defects in the polymer matrix and interfaces (cracks, delaminations and splitting at the points of stress concentration) upon exposure to residual (internal) stresses, external loads, and environmental factors (moisture and temperature

cycling) both in the fabrication of structural elements and in their operation. It is evident that it is necessary to correctly evaluate and predict the parameters of the resistance to propagation of existing and initiation of new interlaminar defects in order to provide reliability of structural elements of aircraft made of CF composite laminates.

Linear elastic fracture mechanics (LEFM), which allows one to measure energy and power global load parameters on a crack at its specified location, configuration, and type of loading, is the most effective approach to evaluate the resistance of brittle and pseudo-brittle structural materials to the propagation of existing defects (cracks). Critical values of these parameters characterize the resistance of the material to initiation of crack growth, that is, its crack resistance [1].

LEFM methods lay the foundation of analytical calculations and experimental methods for the determination of the parameters of interlaminar crack resistance of CF composite laminates, in particular,

energy parameter  $G_{IC}$  (the critical strain energy release rate) at normal delamination of opposite surfaces of crack as the most dangerous type of loading (mode I) using a simple configuration of the specimen in the form of double cantilever beam (DCB) with edge crack. However, analytical evaluation of crack resistance and prediction of crack propagation conditions within LEFM is difficult or impossible at a complex configuration of the structures and defect. In addition, LEFM methods and parameters, which evaluate the resistance of an existing crack to onset (initiation) of critical propagation, cannot determine the conditions of formation and propagation of crack at the points of stress concentration, when there are no free surfaces.

The aim of this work is to determine the length of the cohesion zone using numerical simulation and experimental local properties of the CF composite laminate specimens in the form of DCB and employ the obtained cohesion zone to determine the optimal size and the number of interface elements (IEs), which increase the accuracy of evaluation of the conditions of generation and propagation of interlaminar crack at acceptable computational capacity in 3D numerical modeling.

#### NUMERICAL MODELING OF INITIATION AND PROPAGATION OF CRACKS

At present, numerical methods of modeling of initiation and propagation of cracks are developed and widely used; in particular, the finite element method (FEM) is one of the principal approaches to numerical solution of diverse problems of mechanics of materials and structures using the ANSYS and ABAQUS application software packages [2–4]. The virtual crack closure technique (VCCT) and decohesion method also known as the model of cohesion zone (MCZ) are the most widespread. The VCCT method evaluates the conditions of initiation of propagation of an existing crack at composite stress after achievement of critical value of the general criterion, which considers the crack resistance parameters at all loading modes on crack edges, namely, extension (mode I) and in-plane (mode II) and anti-plane shear (mode III) [2–4]. The MCZ is a simpler and more effective method to evaluate interlaminar crack resistance of such materials as CF composite laminates based on cured polymer matrices. In the MCZ method, physical (micromechanical) models are implanted, which were developed within the LEFM and analytically describe irreversible processes of elastoplastic strain (in the Dugdale model) and brittle or pseudo-brittle prefracture (in the Barenblatt model) in a local zone in front of the crack edge, whose propagation precedes initiation of crack propagation and eliminates stress singularity at its tip [5, 6]. The local process zone was referred to as the cohesive zone (CZ) by Barenblatt, the main dimensional parameters of which as material constants are length ( $l_{cz}$ ) and maximum separation ( $\delta_{max}$ ),

which are analytically derived from the following equations:

$$l_{cz} = \frac{\pi E G_{IC}}{8 \sigma_{IC}^2}, \quad (1)$$

$$\delta_{max} = \frac{G_{IC}}{\sigma_{IC}}, \quad (2)$$

where  $E$  is the elastic modulus, GPa;  $\sigma_{IC}$  is the cohesion strength (in the Barenblatt model) or the yield strength (in the Dugdale model), MPa; and  $G_{IC}$  is the critical strain energy release rate upon propagation of this zone, J/m<sup>2</sup>.

The model of cohesive zone implanted in the FEM considers the cohesive zone as the zone of effect of restraining (cohesion) coupling forces in front of the crack edge (Fig. 1a) or at any different point of stress concentration, while its behavior is described by the specified traction-separation law (TSL);  $\sigma(\delta)$  is the relationship of local stress  $\sigma$  and strain  $\delta$  (separation of the CZ). The TSL depends on the loading type and the mechanism of local prefracture of the material in the physical CZ and can have different forms (exponential, bilinear, trapezoidal, and others) [2–4, 7, 8]. Owing to the difficulty of direct experimental determination of the TSL and its parameters, the form of TSL at numerical simulation of crack resistance of brittle and pseudo-brittle materials in the MCZ is specified as derived from general considerations of the material and the formation and propagation of cracks in it and the possibilities of application the software package used in the FEM. In mode I delamination, the TSL corresponds to the diagram of local extension of material  $\sigma_f(\delta)$ . In the case of pseudo-brittle prefracture, Barenblatt suggested the exponential law (Fig. 1b) [5], which is most often used during numerical simulation with the ANSYS application software package along with bilinear law [7, 8].

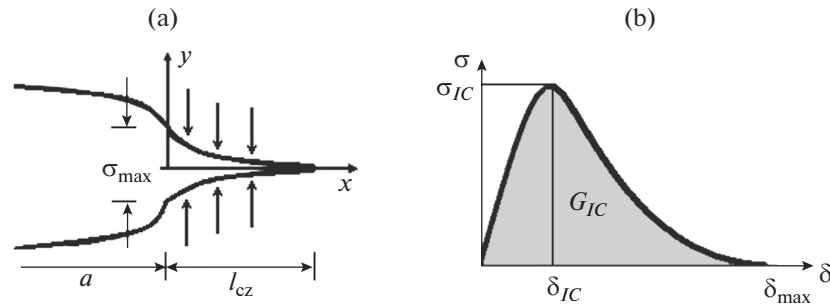
The total area under the TSL curve  $\sigma_f(\delta)$  corresponds to the critical strain energy release rate within the scope of the global LEFM and is determined by the following equation:

$$G_{IC} = \int_0^{\delta_{max}} \sigma(\delta) d\delta, \quad (3)$$

where  $\delta_{max}$  is the limiting strain or maximum separation of the CZ.

On the contrary, the derivative of the crack resistance parameter with respect to the separation of the CZ determines the diagram of its failure  $\sigma(\delta)$ , that is, the TSL [2–4, 7, 8], which is determined using following equation:

$$\sigma(\delta) = \frac{dG_{IC}}{d\delta}. \quad (4)$$



**Fig. 1.** (a) General view of crack in brittle body with cohesive zone for mode I delamination:  $a$  is the length of crack,  $l_{cz}$  is length of cohesive zone, and  $\delta_{max}$  is the maximum separation of cohesive zone; (b) exponential type of traction-separation law:  $\sigma_{IC}$  is the local cohesive strength of the material;  $G_{IC}$  is the critical strain energy release rate (crack resistance of material), and  $\delta_{IC}$  is the separation of the cohesive zone at maximum traction (local deformation of the material at fracture).

In this case, local deformation of material  $\delta_{IC}$  at limiting load  $\sigma_{IC}$  is determined by following relation (Fig. 1b):

$$\delta_{IC} = \frac{kG_{IC}}{\sigma_{IC}}, \quad (5)$$

where  $k$  is the coefficient depending on the TSL:  $k = 1/2$  in the case of the bilinear law, while  $k = 1/e$  in the case of the exponential law;  $e = 2.71$  is the base of the natural logarithm.

Thus, using of the MCZ implanted in the FEM allows one to evaluate the crack resistance of material according to Eq. (3) at the known TSL, while the dependence of the crack resistance parameter on the separation of the cohesion zone and the local strength of the material provides calculation of the TSL by Eq. (4) and its parameter  $\delta_{IC}$  according to Eq. (5) at various configurations of images and loading modes [4, 6–8].

Choice of the length and the number of special finite (interface) elements (IEs), which are located in the model (numerical) CZ in front of the crack front or at the stress concentration zone on a descending part of the TSL, is an important factor, which determines the performance and reasonability of modeling of initiation and propagation of crack (accuracy of calculations at minimum computational capacity) during implantation of the MCZ into numerical models of the FEM. To obtain reliable numerical results using the MCZ, stresses in the CZ should be exactly represented by finite element spatial discretization (finite element network) in this zone; i.e., the FE network should be sufficiently small to arrange the necessary number of IEs along the CZ. However, in the case of larger structures, a small network results in a drastic increase in computational capacity and, accordingly, necessary computational resources. Optimization of the network should be based on exact knowledge of the real length of the physical CZ and the minimum number of IEs arranged in the numerical CZ.

At present, there is no general opinion on the necessary minimum number of IEs to model delamination of CF composite laminates [3, 4, 7, 8]. It is agreed that at least two IEs should be used and the following equation is employed for the calculation of the optimal number of IEs in the CZ ( $N_e$ ):

$$N_e = \frac{l_{cz}}{l_e}, \quad (6)$$

where  $l_{cz}$  is the real length of the cohesion zone and  $l_e$  is the optimal length of IEs.

To determine  $l_{cz}$ , Eq. (1) can be used and  $l_e$  is chosen from the condition  $N_e > 2$ . At present, no general technique is developed because of the differences in the TSL and settings that control the solution of the MCZ; the investigations on the evaluation of the minimum number of IEs determining the specified accuracy of calculations at minimum computational capacity are necessary in each particular case.

#### EXPERIMENTAL DETERMINATION OF PARAMETERS AND FINITE ELEMENT MODELING OF COHESIVE ZONE OF CF COMPOSITE LAMINATE

The object of experimental studies is orthotropic carbon fiber composite based on carbon fabric of URAL T-1-22A brand and model epoxy binder (equimolar mixture of ED-20 epoxy resin and diaminodiphenylmethane curing agent) with the ratio of reinforcing fabric to binder of 60 : 40%. To determine the critical strain energy release rate  $G_{IC}$ , carbon fiber composite plates with the size of  $200 \times 180 \times 4$  mm made from ten fabric layers were pressed and, then, successively packed into a mold, impregnated with binder, and pressed under the pressure of 0.8 MPa, maintaining the plate at 100 and 160°C for 2 h at each temperature. To form the specified interlaminar crack (defect), a fluoroplastic film 10  $\mu$ m in thickness and 50 mm in width was packed in the specimens after packing and impregnation of the fabric layer with

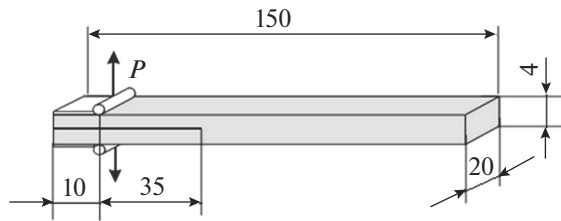


Fig. 2. Schematic of double cantilever beam (DCB) specimen for  $G_{IC}$  tests.

binder from face side in the middle of package by thickness (between fifth and sixth layers). After pressing, test specimens  $150 \times 20 \times 4$  mm in size were cut from the carbon fiber composite plate.

After removal of the embedded film and formation of the initial crack tip with wedge, the exact initial crack length was determined using an Axio Imager.Z2m microscope (Carl Zeiss). Aluminum corners were glued on the both sides of the specimens on the side of the crack, using which the specimens were gripped in a tensile machine, while the free part of the specimen remained in the free state. In Fig. 2, the schematic of the DCB specimen for tests to determine the critical strain energy release rate  $G_{IC}$  is given.

The applied force  $P$  and the crack separation  $\Delta$  were recorded at tests according to the displacement of tensile testing grips to obtain the curve in force–crack separation coordinates. The length of propagating crack  $a$  was visually determined. The critical strain energy release rate  $G_{IC}$  was determined according to the maximum load corresponding to the onset of critical crack propagation with consideration of its initial length and dimensional parameters of DCB specimen using the following formula:

$$G_{IC} = \frac{12P_c^2 a^2}{Eb^2 h^3}, \quad (7)$$

where  $P_c$  is the critical load, N;  $a$  is the crack separation length, mm;  $b$  is the width of the specimen, mm; and  $h$  is the half-thickness of the specimen, mm.

During preparation of the specimens for experimental determination of the cohesion strength of the material  $\sigma_{IC}$ , plates with the size of  $80 \times 50 \times 4$  mm made from ten layers of orthotropic epoxy carbon fiber composite with the interlayer between the fifth and sixth layers of CF composite laminate of continuous fluoroplastic film  $10 \mu\text{m}$  in thickness with the square ( $10 \times 10$  mm) cut in the middle, which simulates the local cohesion zone upon mode I delamination, were pressed. The CF composite laminate plates were pressed strictly following the conditions which are analogous to pressing of plates for the determination of  $G_{IC}$ . The specimens of  $70 \times 40 \times 4$  mm were cut from the central part of the plates. Aluminum corners were glued to the specimens to mount them in tensile testing grips.

Tensile tests were carried out at the rate of cross-head movement of the tensile machine of 1 mm/min by recording the fracture diagram in force–displacement coordinates. To eliminate tangential (shear) stresses and provide a uniform failure in the coupling zone, the specimen was carefully balanced in the horizontal plane. Failure of the specimen occurred at the point of maximum load  $P_{\max}$ . The failure surfaces are given in Fig. 3. The normal local cohesion strength was calculated using the following equation:

$$\sigma_{IC} = \frac{P_{\max}}{S}, \quad (8)$$

where  $S$  is the area of the failure zone,  $\text{m}^2$ .

The experimental mean value of  $\sigma_{IC}$  of seven CF composite laminate test specimens was 10.7 MPa. The root-mean-square error obtained from the results of cohesion strength tests was less than  $\pm 0.48$  MPa. This indicates high reproducibility of this parameter in

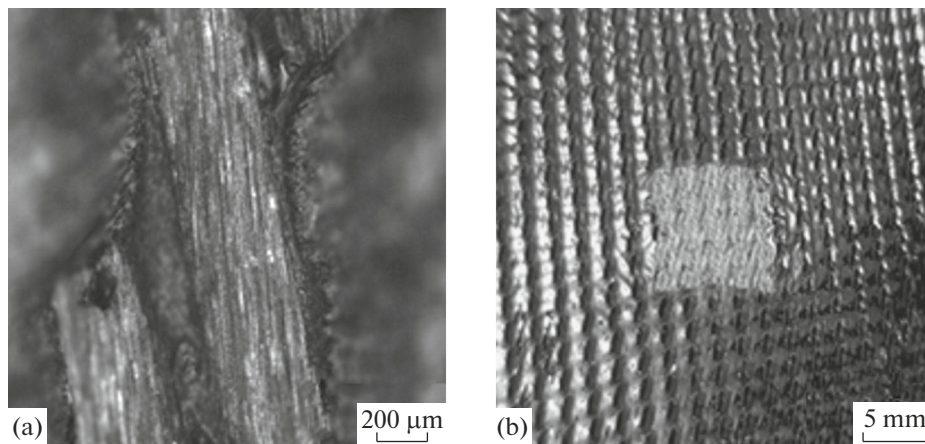


Fig. 3. Image: (a) the surface of fracture of the test zone, (b) the layers of plate after the tensile failure of local coupling zone.

seven CF composite laminate plates, which were prepared at strict fulfillment of pressing parameters.

The ultimate strain at  $P_{\max}$  corresponding to separation of crack  $\delta_{IC}$  at  $\sigma_{IC}$  on the TSL curve given in Fig. 1b is 0.0072 mm.

The values of  $G_{IC}$  (210 J/m<sup>2</sup>) and  $\sigma_{IC}$  (10.7 MPa), as well as transverse elastic modulus  $E$ , which was previously determined and was 5 GPa, were used for the calculation of the length of the cohesion zone  $l_{cz}$  corresponding to 3.6 mm.

To generate the 3D model of DCB specimen from epoxy CF composite laminate for mode I delamination 150 mm in length, 20 mm in width, and 4 mm in thickness at the specified length of initial crack of 45 mm (Fig. 2) with the exponential TSL, two types of finite elements, namely, Solid 185 and Inter 205, were chosen in the preprocessor library using the ANSYS application software package. The exponential TSL was specified from the program line of the ANSYS interface and necessary experimental parameters were added, namely, maximum cohesion strength  $\sigma_{IC}$  ( $C_1 = 10.7$  MPa) and local deformation of separation at maximum traction  $\delta_{IC}$  ( $C_2 = 0.0072$  mm), as well as corresponding intrinsic values for epoxy CF composite filaments [4, 8], such as Young's modulus ( $E_{11} = 128$  GPa,  $E_{22} = 5$  GPa, and  $E_{33} = 5$  GPa), Poisson coefficients ( $\nu_{12} = 0.24$ ,  $\nu_{13} = 0.24$ , and  $\nu_{23} = 0.33$ ), and shear moduli ( $G_{11} = 5.2$  GPa,  $G_{12} = 5.2$  GPa, and  $G_{13} = 3.08$  GPa). Then, the interaction between internal surfaces of DCB and the cohesion zone between them are specified using program tools and a regular network is formed by splitting the model into finite elements. Then, the loading and direction of motion of DCB components are specified and the parameters of calculation in the processor of the program are tuned. Virtual delamination of the specimen occurs upon modeling and the results of calculations are analyzed in the postprocessor of the program complex. The calculated dependence of loading on the crack separation is plotted in Fig. 4, curves 1–4.

Fractional values of the number of elements along the cohesion zone were obtained from Eq. (6). The length of the cohesion zone  $l_{cz}$  determined in this work for the material under study was 3.6 mm. Therefore, it is necessary to use more than one element (1.8) to split the interlaminar interface by this length using interface finite elements that are 2 mm in size. Consequently, full coverage of this zone by 0.5-mm elements requires more than seven elements (7.2), and so on. Comparison of the curves of the loading on crack edges versus its separation for the DCB specimen obtained by numerical modeling using various sizes of IEs and, accordingly, their different number along the CZ (Fig. 4, curves 1–4) with the experimental dependence (Fig. 4, curve 5) shows that the most reliable results in modeling of DCB delamination were obtained in the case of IE size of 0.9 mm and their number in the numerical

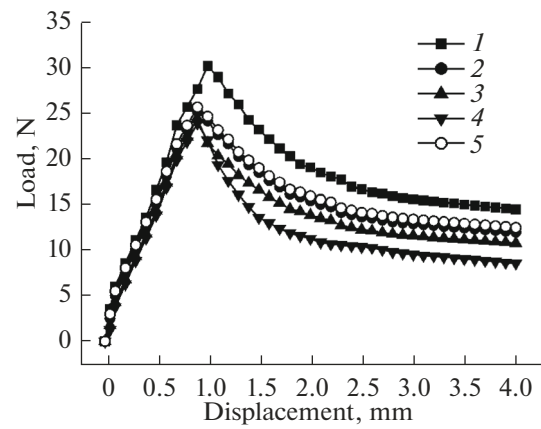


Fig. 4. Dependence of load on the edges of crack on their displacement during crack opening in the DCB. Calculated from 3D model using different size interface elements on the entire length of the cohesive zone: (1) 2 mm and 1.8; (2) 0.9 mm and 4; (3) 0.5 mm and 7.2; (4) 0.1 mm and 36, respectively; (5) the experimentally obtained dependence.

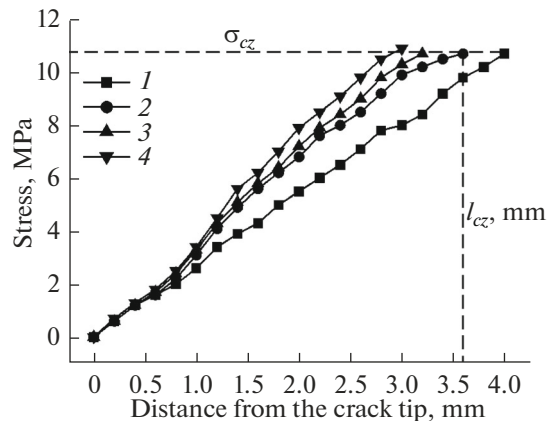


Fig. 5. Distribution of stresses along the length of the numerical cohesive zone from the tip of the crack at different length of cohesive elements, mm: (1) 2; (2) 0.9; (3) 0.5; (4) 0.1.

CZ equal to 4. When using IEs that are less than 0.9 mm in length, their number in the CZ drastically increases along with the capacity and time of calculations and this does not lead to an increase in the accuracy of modeling. The dependences obtained using IEs that are more than 0.9 mm in length significantly exceed the experimental data.

The distribution of stresses along the numerical cohesion zone from the crack tip at different length of cohesion elements is given in Fig. 5. Using of 0.9-mm cohesion elements also gives the value which is the closest to the experimental  $\sigma_{IC}$ .

Thus, a total of four 0.9-mm IEs are sufficient for the evaluation of the load resulting in the onset of crack propagation with the accuracy of 95% in the developed 3D model of DCB specimen made from

carbon fiber composite laminate and the experimental length of physical CZ  $l_{cz}$  equal to 3.6 mm.

Application of this approach for the analysis of structures involves the determination of specific parameters of composite materials using relatively simple techniques, adjustment of IEs using the obtained parameters for each particular material, and arrangement of elements along the interface of monolayers in the bulk construction. The IE sizes are sufficiently small to fill the most geometrically complex sections of the design. This allows one to study the bulk construction possessing geometry of any complexity from the viewpoint of initiation and growth of cracks. Reliability of the results is provided by the perfection of the geometrical model of object and the use of the optimal number of IEs with real averaged characteristics of a particular polymer composite for the generation of the finite element network. The states and changes in the geometry and structure of the virtual model of the construction can be analyzed many times until the necessary quality of the construction is achieved.

### CONCLUSIONS

The results of experimental and numerical studies allow us to state practical implementation of the traction-separation law in the models of failure of laminar CF composite laminates caused by initiation and propagation of a crack.

The proposed approach to use the experimental parameters of the cohesion zone with the specified exponential TSL of the behavior of material in a finite element 3D model made it possible to determine the load corresponding to onset of delamination, which took the value of 25 N in this case.

Analysis of the results of modeling at the length of finite cohesion element of 0.9 mm has shown that the

model accurately describes crack propagation along the cohesion zone corresponding to 3.6 mm.

The results of numerical simulation agree well with the experimental results, and the measurement error of the load resulting in initiation of crack propagation is less than 5% after optimization of the number of finite elements along the cohesion zone to four.

### REFERENCES

1. Babaevsky, P.G. and Kulik, S.G., *Treshchinostoičnost' otverzhdennykh polimernykh kompozitsii* (Crack Resistance of Solidified Polymer Compositions), Moscow: Khimiya, 1991.
2. Hillerborg, A., Modéer, M., and Petersson, P.-E., Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements, *Cem. Concr. Res.*, 1976, vol. 6, no. 6, pp. 773–781. [https://doi.org/10.1016/0008-8846\(76\)90007-7](https://doi.org/10.1016/0008-8846(76)90007-7)
3. Turon, A., Davila, C.G., Camanho, P.P., and Costa, J., An engineering solution for mesh size effects in the simulation of delamination using cohesive zone models, *Eng. Fract. Mech.*, 2007, vol. 74, no. 10, pp. 1665–1682.
4. Harper, P. and Hallett, S.R., Cohesive zone length in numerical simulations of composite delamination, *Eng. Fract. Mech.*, 2008, vol. 75, no. 16, pp. 4774–4792. <https://doi.org/10.1016/j.engfracmech.2008.06.004>
5. Barenblatt, G.I., The mathematical theory of equilibrium cracks in brittle fracture, *Adv. Appl. Mech.*, 1962, vol. 7, pp. 55–129.
6. Dugdale, D.S., Yielding of steel sheets containing slits, *J. Mech. Phys. Solids*, 1960, vol. 8, no. 2, pp. 100–108.
7. Xu, X. and Needleman, A., Numerical simulations of fast crack growth in brittle solids, *J. Mech. Phys. Solids*, 1994, vol. 42, pp. 1397–1434.
8. Moslemi, M. and Khoshrovan, M. Cohesive zone parameters selection for mode-I prediction of interfacial delamination, *J. Mech. Eng.*, 2015, vol. 61, no. 9, pp. 507–516.

*Translated by A. Muravev*