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ANALYSIS OF FIBER-REINFORCED ELEMENTS FROM COMPOSITE MATERIALS

The limit state of two polymer layered composite elements was studied using a numerical-analytical method, employing the finite element method during their deformation, damage, and failure. Stress intensity factors for normal separation were determined for developed complex-shaped models with initial imperfections in the form of cracks, simulating defects in the composite structure. A comparative analysis of the obtained calculated values of critical load with the experimental studies and adaptation of the developed methodology were conducted.

Keywords*: *composite material, fracture theory, finite element method, crack, stress intensity factor, limit state.

Introduction. Analytical methods of composite theory [1–3] allow to obtain accurate solutions to a limited number of problems, due to the challenges in constructing mathematical models that describe the specific features of the material structures and structural elements, as well as the dynamics of deformation during loading. Experimental methods for assessing the limit states of aerospace and mechanical engineering structures are labour-intensive and costly. The application of these methods becomes even more complicated when developing new composite materials, considering their complex structural forms, manufacturing features, and obtaining fundamentally new mechanical characteristics of strength and stiffness in individual components and the materials as a whole [4 – 8].

When conducting deformation and limit state studies using complex computational software packages and numerical methods, model-building procedures and the accuracy of the mechanical characteristics of materials, according to standardized ISO procedures, become particularly important, as these parameters define the structural element under study [9 – 10].

Numerical analysis. Numerical-analytical studies were conducted, allowing for the comparison and application of experimental data to verify the reliability of the obtained results. The calculations took into account a comprehensive set of mechanical characteristics and fracture toughness characteristics of two dispersed bidirectional polymer multilayer composite materials: epoxy fiberglass and epoxy carbon fibre, obtained from experimental studies, based on international codes, using specimens manufactured by autoclave moulding and thermo-vacuum methods.

The composite material was considered as a unified structure comprising the matrix and the reinforcing material, taking into account to the specifics of their bonding and the presence of a multilayer structure.

During the study, stress intensity factors for normal separation were determined for finite element volumetric complex-shaped models with initial imperfections in the form of cracks, simulating defects in the composite structure (see Fig. 1), using the formula derived from the asymptotic representation for displacements [11]:

$$K_1 = \frac{(2\pi)^{1/2}}{4\mathrm{R}(\Omega)} \lim_{y \to (a-0)} \left[\frac{u(y,+0) - u(y,-0)}{(a-y)^{1/2}} \right], \tag{1}$$

where $u(y,\pm 0)$ – projection of the crack surface displacement onto the x-axis;

a – crack length;

$(a - y)$ – distance from the crack tip to the point, where the crack surface displacement is determined;

$\mathrm{R}(\Omega)$ – the real part of the complex expression Ω.

For epoxy fiberglass, in expression (1), the value of the real part of the complex expression $\mathrm{R}(\Omega)$ = 1,007, for epoxy carbon fibre $\mathrm{R}(\Omega)$ = 2,216.

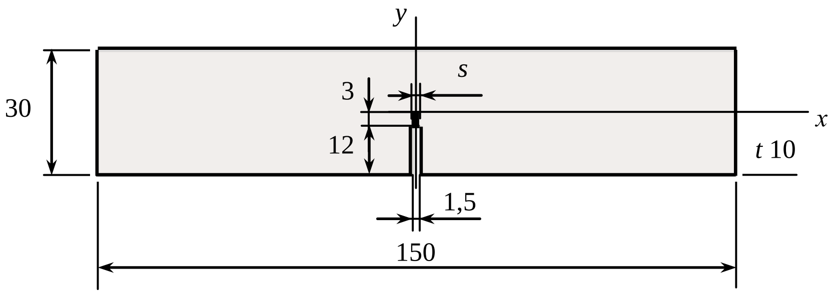

Fig. 1. Geometric diagram of the thin specimen (mm).

The values of the displacement projections $u(y,\pm 0)$ onto the x-axis at points near the crack tip in expression (1) were determined by solving the stress-strain state (SSS) problem using the finite element method. The pre-failure state of the material was modelled by introducing variations in the crack length a_i and its opening width δ_i, with automatic generation of the finite element mesh and subsequent recording of the obtained displacement values u at selected points around the crack tip (Fig. 2).

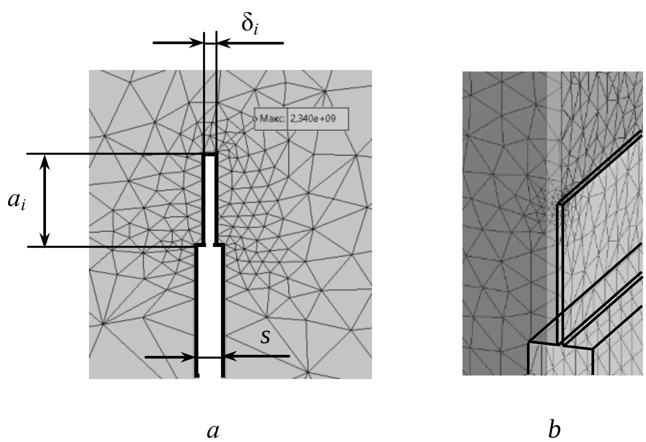

Fig. 2. Finite element model with automatic mesh generation:
a – in the analysed cross-section;
b – in the vicinity of the crack tip.

The limit state assessment of composite materials was conducted based on the combination of modern strength criteria, the theory of mechanics of deformable solids in an orthotropic medium, and fracture mechanics methods. The developed model was adapted for investigating the limit state of elements of layered shell structures, including structures with subcritical defects.

The numerical parameters of the stress-strain and limit states of elements under deformation, damage, and failure were studied. The limit state of the composite was assessed based on the results of numerical and graphical analysis through the joint solution of an equation:

$$g_i(x) - p_i(x) = 0, \qquad (2)$$

which was used to determine the critical values of external load and the corresponding crack length at which element failure occurs, where $g_i(x)$ describes the stress state in an element without a crack; $p_i(x)$ – represents the limit equilibrium state of a body with a crack [12].

The normal stresses σ_x distribution pattern and the graphs of the functions $g_i(y)$ for the cross-section along the symmetry axis of the epoxy fiberglass element are shown in Fig. 3 for two types of models with the finite element mesh was created:

- *type A* – on a solid body by dividing it into a specified number of layers (*1*);
- *type B* – on a body in the form of a multilayer shell with defined surfaces (*2*).

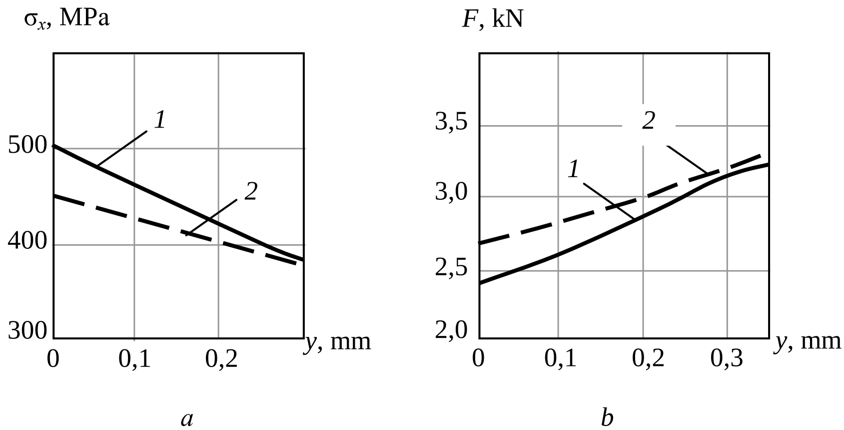

Fig. 3. Normal stresses σ_x distribution pattern (*a*) and graphs of the functions $g_i(y)$ (*b*) in the cross-section of the epoxy fiberglass element: *1* – for the finite element mesh *type A*; *2* – for the finite element mesh *type B*.

The pre-failure state of the composite was modelled by introducing variations in the possible crack length *a* and its opening width δ = 0,02 mm. The stress intensity factor distribution diagrams for normal separation K_1 of the fiberglass element, calculated using formula (2) for two types of the finite element mesh models, as well as the graphs of the functions $p_i(y)$ for the cross-section along the symmetry axis, are shown in Fig. 4.

The SSS of the epoxy carbon fibre element was analysed at the critical cross-section along the symmetry axis of the sample under a load of F = 3 kN and with an additional crack width of s = 0,1 mm. The normal stress intensity σ_x distribution pattern near the crack tip is shown in Fig. 5.

A comparative analysis of the studied composite elements modeled with the finite element mesh *types A* and *B*, under failure load and critical crack length, is presented in Table 1 and shown in Fig. 6.

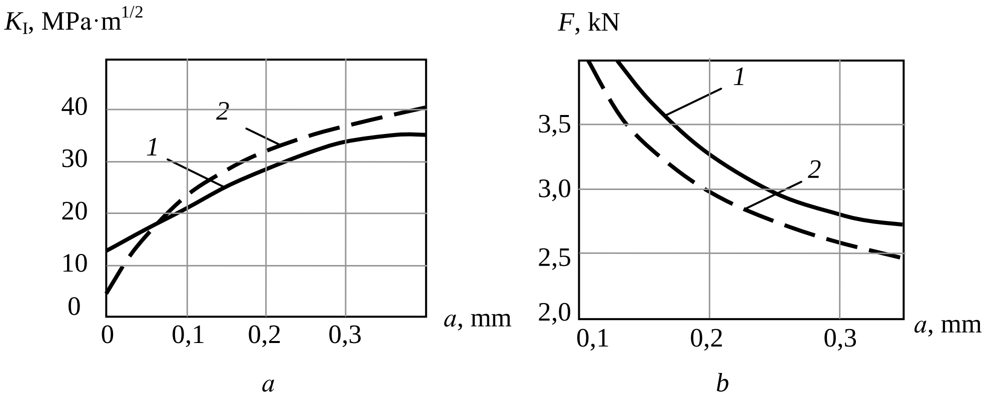

Fig. 4. The stress intensity factor distribution pattern
for normal separation K_1 (*a*) and graphs of the functions $p_i(y)$ (*b*)
in the cross-section of the epoxy fiberglass element:
1 – for the finite element mesh *type A*; *2* – for the finite element mesh *type B*.

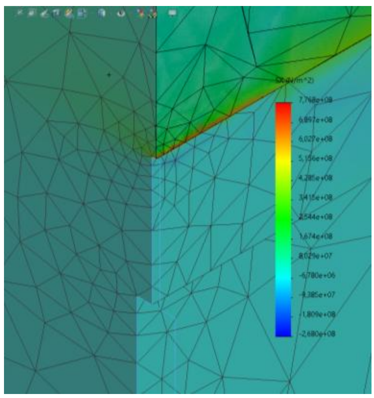

Fig. 5. Stress intensity σ_x distribution isofields near the crack tip

Table 1

Comparative analysis of the obtained results

Material	Finite element mesh type	Parameters	Computational analysis	Experimental data	Discrepancies, %
Bidirectional epoxy fiberglass	*A*	F_{cr}, kN	2,987	3,04	1,7
		a_{cr}, mm	0,249	-	-
	B	F_{cr}, kN	2,988	3,04	1,7
		a_{cr}, mm	0,198	-	-
Bidirectional epoxy carbon fiber	*A*	F_{cr}, kN	4,847	5,13	5,5
		a_{cr}, mm	0,022	-	-

The discrepancies in critical forces between the two finite element mesh types for fiberglass do not exceed 0,3%. The obtained values of the critical load are also confirmed by experimental data, with discrepancies not exceeding 1,7% for fiberglass and 5,.5% for carbon fibre. These results suggest that it is more appropriate to use the finite element mesh type *B* for the given problems in the future, as it allows for adjustment of fibre orientation at an arbitrary angle α, as well as number of layers and their thickness, based on the specified characteristics of each composite layer. Moreover, compared to *type A*, *type B* involves significantly fewer nodes and finite elements, enabling the analysis of more complex design models with the same computational resource usage.

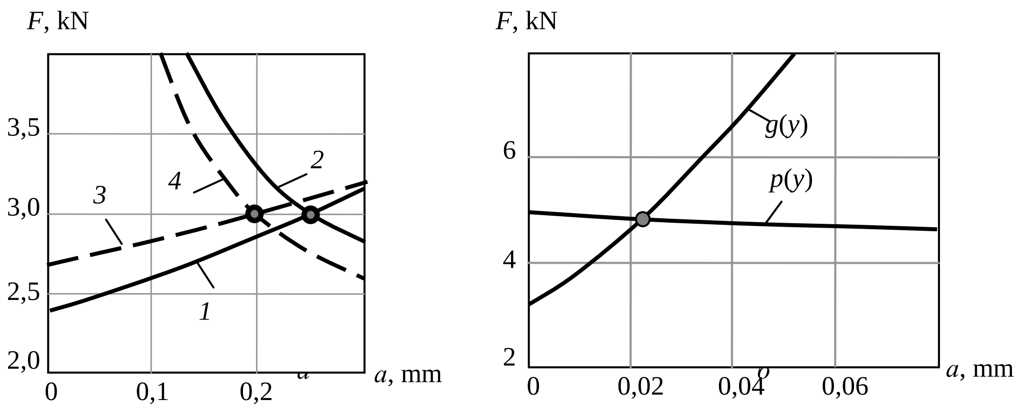

Fig. 6. Limit state analysis of fiberglass (*a*) and carbon fiber (*b*) elements:
1 and *2* – graphs of the functions $g_i(y)$ and $p_i(y)$, respectively, for the finite element mesh *type A*;
3 and *4* – graphs of the functions $g_i(y)$ and $p_i(y)$, respectively, for the finite element mesh *type B*.

Conclusions

1. Three-dimensional numerical models of complex-shaped elements made of bidirectional polymer fibre-reinforced multilayer fiberglass and carbon fibre composites were studied, using physical and mechanical characteristics obtained through experimental studies conducted according to international standardized procedures.

2. The limit state numerical parameters of three-dimensional finite element models under deformation, damage, and failure were analyzed.

3. Computational analysis of the studied finite element models, as the finite element meshes on a solid body divided into a specified number of layers (*type A*) and as the finite element meshes on a body in the form of a multilayer shell with a defined surfaces (*type B*), showed good results convergence within 1 %.

4. The obtained results of the numerical studies for elements under applied loads were compared with the processed experimental data: discrepancies did not exceed 1,7% – for fiberglass and 5,5 % – for carbon fibre composites.

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АНАЛІЗ ВОЛОКОННО-ЗМІЦНЕНИХ ЕЛЕМЕНТІВ ІЗ КОМПОЗИЦІЙНИХ МАТЕРІАЛІВ

Досліджено граничний стан двох полімерних шаруватих композиційних елементів чисельно-аналітичним способом із використанням метода скінченних елементів при їх деформуванні, пошкодженні та руйнуванні. Визначено коефіцієнти інтенсивності напружень нормального відриву для розроблених моделей складної форми з початковими недосконалостями у вигляді тріщин, що моделюють порушення структури композиту. Виконано порівняльний аналіз отриманих розрахункових величин критичного навантаження з експериментальними дослідженнями та адаптацію розробленої методики.

Ключові слова: композиційний матеріал, теорія руйнування, метод скінченних елементів, тріщина, коефіцієнт інтенсивності напружень, граничний стан.

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