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RESEARCH ARTICLE

INTERACTION OF THE BICIAL-PERIODIC SYSTEM AND RIGHT LINEAR BREAKOUT CRACKS IN A COMPOSITE DURING A LONGITUDINAL SHIFT

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ABSTRACT

An antiregular deformation is considered for an in-equal elastic material consisting of an infinite system of parallel identical circular fiber cylinders covered with a homogeneous cylindrical film uniformly covering the surface of each fiber and a binding medium weakened by a doubly periodic system of rectilinear cracks. The boundaries of the destruction of the composite are determined, which occur by the detachment of the fiber from the matrix, at the fiber-matrix interface. By varying the rigidity of the fiber with respect to the stiffness of the binder medium, the degree of viscosity of the composite as a whole can be controlled. The viscosity fracture equations for the stress intensity factor of a fibrous composite are obtained as a function of the nature of internal structural defects. A mathematical description is given of the strength of the composite both in detachment and in share. As a result, the stress-strain state of the fiber composite weakened by periodic linear cracks is determined.

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INTRODUCTION

Let a doubly periodic lattice with circular holes have a radius λ ($\lambda < 1$)and centers at the points:

$P_{mn} = m\omega_1 + n\omega_2;\ (m, n = 0, \pm 1, \pm 2, \dots\dots);\ \omega_1 = 2;\ \omega_2 = \omega_1 \cdot he^{i\alpha};\ h > 0;\ Im\omega_2 > 0;$

Circular holes of the grating are filled with washers (fibers) of isotropic elastic material whose surface is uniformly covered with a homogeneous cylindrical film.The shores of the cracks are free from external forces (fig. 1). In the lattice, the mean loads $\tau_y = \tau_y^\infty$, $\tau_x = 0$(shear at infinity) take place. Because of the symmetry of the boundary conditions and the geometry of the region S occupied by the binding medium, the stresses are doubly periodic functions with the main periods ω_1 and ω_2. The matrix is assigned the role of a protective coating, protecting fibers from mechanical damage and oxidation. In addition, the matrix should provide strength and rigidity of the system under the action of a tensile or compressive load in a direction perpendicular to the reinforcing elements. If the tensile load is directed along the axis of the fibers arranged parallel to each other, then in order to obtain a hardening effect, the ultimate elongation of the matrix should not lead to fiber breakage.In the case of ideal contact at the boundaries of the coating fiber ω_{mn} and the coating-binder S_{mn} (where the indices $m, n = 0, \pm 1, \pm 2, \dots$ determine the conditions on the contour of the mn th fiber, the coordinates of which are P_{mn}), the displacementsand the voltages are equal to each other . Representing the stress and displacement through the analytic function $f(z)$, the boundary conditions will be written [1] in the form:

$$\left(1 + \frac{\mu_b}{\mu_t}\right) f_b(\tau_1) + \left(1 - \frac{\mu_b}{\mu_t}\right) \overline{f_b(\tau_1)} = 2 f_t(\tau_1) \quad (1)$$

$$\left(1 + \frac{\mu_t}{\mu_s}\right) f_t(\tau) + \left(1 - \frac{\mu_t}{\mu_s}\right) \overline{f_t(\tau)} = 2 f_s(\tau) \quad (2)$$

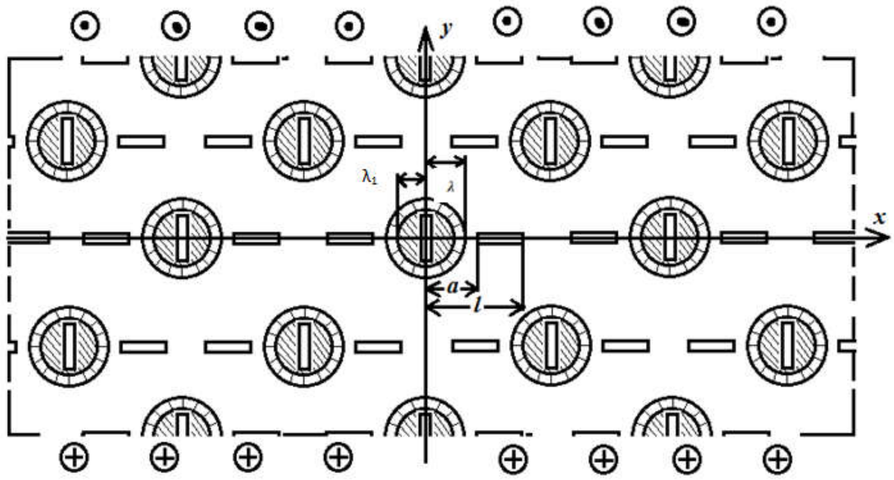

Fig. 1. The lattice scheme is weakened by a doubly periodic system of rectilinear cracks

$$f_s'(t)-\overline{f'(t)}=0 \tag{3}$$

$$f_b'(t)-\overline{f_b'(t)}=0,$$

In which

$$\tau=\lambda e^{i\theta}+m\omega_1+n\omega_2;\ m,n=0,\pm1,\pm2,\ldots\tau_1=(\lambda-h)e^{i\theta}+m\omega_1+n\omega_2$$

$t-$ affix of the points of the shores of the cracks, $h-$ thickness of the coating, the value relating to the coating, the fiber and the binder, are subsequently marked respectively by the indices $t,\ b$ and$s$.

We write the solution of the boundary value problem in the form:

$$f_s(z)=f_1(z)+f_2(z)$$
$$f_b(z)=f_{1b}(z)+f_{2b}(z) \tag{4}$$

$$f_{1b}(z)=\sum_{k=0}^{\infty}a_{2k}\frac{z^{2k+1}}{2k+1};\ f_t(z)\sum_{k=-\infty}^{\infty}b_{2k}z^{2k+1}$$

$$f_1'(z)=\tau_y^{\infty}+\sum_{k=0}^{\infty}\propto_{2k+2}\frac{\lambda^{2k+2}\gamma^{(2k)}(z)}{(2к+1)!}+B$$

$$f_2'(z)=\frac{1}{\pi i}\int_L g(t)\xi(t-z)dt+A \tag{5}$$

$$f_{2b}(z)=\frac{1}{\pi i}\int_{-l}^{l}\frac{g(t)dt}{t-z},$$

Where the integrals in (5) are taken along the line $L=\{[-l,-a]+[a,l]\},\gamma(z)$ и $\xi(z)$ andweierstrass functions [2], $g(t)$ is an unknown function, A is a constant.The strength of the boundary can be either higher or lower than the strength of the matrix. Part of the properties of composite materials is determined by the strength of the interface to peel (transverse strength, compressive strength, viscosity), part of the strength of the boundary to shear (longitudinal tensile strength of the composite reinforced with short fibres, critical fibre length, etc.).To the relations (3)–(5) we need to add an additional condition, which results from the physical meaning of the problem

$$\int_{-l}^{-a}g(t)dt=0;\ \int_a^l g(t)dt=0;\ \int_{-l}^{l}g(t)dt=0 \tag{6}$$

The condition of constancy of the principal vector of all forces acting on an arc joining two congruent points in S, taking into account (6) and properties of the functions $\gamma\ (z)$ and $\xi\ (z)$ at congruent points, leads to the relation

$$J_m\left[A\omega_1+i\delta_j b-\alpha_2\lambda^2\delta_j\right]=0;\ (j=1{,}2)$$

$$b=-\frac{1}{\pi}\int_L tg(t)dt$$

The unknown function g (t) and constants a_{2k}, b_{2k}, α_{2k}must be determined from the boundary conditions (1)–(2).To compose equations for the coefficients α_{2k} in the function $f_1'(z)$we represent the boundary condition (1) in the form

$$\left(1+\frac{\mu_b}{\mu_t}\right)f_{1b}(\tau_1)+\left(1-\frac{\mu_b}{\mu_t}\right)\overline{f_{1b}(\tau_1)}=2f_1(\tau_1)+if_2^*(\theta), \quad (7)$$

Where is

$$if_z^*(\theta)=-\left(1+\frac{\mu_b}{\mu_t}\right)f_{zb}(\tau_1)-\left(1-\frac{\mu_b}{\mu_t}\right)f_{zb}(\tau_1) \quad (8)$$

$$\left(1+\frac{\mu_t}{\mu_s}\right)f_t(\tau)+\left(1-\frac{\mu_t}{\mu_s}\right)\overline{f_t(\tau)}=2[f_1(\tau)+if_z(\theta)], \quad (9)$$

Where

$$if_2(\theta)=f_2(\tau) \quad (10)$$

Relatively, $if_2^*(\theta)$and $if_z(\theta)$we assume that it decomposes $|\lambda| = \tau$ into a Fourier series. By virtue of symmetry, this series has the form:

$$if_2^*(\theta)=\sum_{k=-\infty}^{\infty}B_{zk}e^{zki\theta}\ ;\ ReB_{2k}=0; \quad (11)$$

$$if_2(\theta)=\sum_{k=-\infty}^{\infty}C_{2k}e^{2ki\theta};\ ReC_{2k}=0;$$

$$B_{2k}=\frac{1}{2\pi}\int_0^{2\pi} i\,f_2^*(\theta)e^{-2ki\theta}d\theta$$

$$C_{2k}=\frac{1}{2\pi}\int_0^{2\pi} i\,f_z(\theta)e^{-2ki\theta}d\theta;\ (k=0,\pm1,\pm2,\dots\dots)$$

Substituting here the rotation (8) and (10) with allowance for (5) and changing the order of integration, after calculating the integrals by means of the theory of residues, we find

$$B_{2k}=-\frac{1}{\pi i}\int_{-l}^{l}g\,(t)f_{zk}^*(t) \quad (12)$$

$$f_0^*(t)=-\frac{1}{t};f_{2k}^*(t)=\left(1-\frac{\mu_b}{\mu_t}\right)\frac{\lambda^{2k}}{(2k)!\,t^{2k}}+\left(1++\frac{\mu_b}{\mu_t}\right)\frac{\lambda^{2k}}{(2k)!\,t^{2k}}$$

$$f_{-2k}(t)=-\left(1-\frac{\mu_b}{\mu_t}\right)\frac{\lambda^{2k}}{2t^{2k+1}}$$

$$c_{2k}=\frac{1}{\pi i}\int_L\ f_{2k}\,(t)g(t)dt \quad (13)$$

$$f_{2k}(t)=\frac{\lambda^{2k}}{(2k)!}\xi^{(2k)}(t);\ (k=0,\pm1,\pm2,\dots.)$$

Substituting expansions in Laurent series for $f_b(z)$, $f_t(z)$, $f_1(z)$ into boundary conditions, and instead of $f_2(z)$, $f_{2b}(z)$is the Fourier series On $|\tau| = \lambda$ and comparing the coefficients for the same powers of $exp(i\theta)$, we obtain an infinite system of linear algebraic controls:

$$b_{2k}=\left(1+\frac{\mu_b}{\mu_t}\right)\frac{a_{2k}}{2(2k+1)!}-\frac{B_{2k}}{2(\lambda-h)^{2k+1}}$$

$$b_{-2k-2}=\left(1-\frac{\mu_b}{\mu_t}\right)\overline{a_{2k}}\frac{(\lambda-h)^{4k+2}}{(2k+1)}-\frac{B_{-2k-2}}{2(\lambda-h)^{-2k-2}}$$

$$\frac{a_0}{4}[g_1+f^2h_1]=\tau_y^{\infty}+A+C_0+\sum_{k=1}^{\infty}\propto_{2k+2}\lambda^{2k+2}A_{0,k}+\frac{B_0}{2\lambda_*} \quad (14)$$

$$\frac{\overline{a_0}}{4}[h_2f^2+g^2]=-\propto_2$$

$$\frac{\overline{a_{2k}}}{4}\lambda^{2k}[g_2+f^{4k+2}h_2]=-\propto_{2k+2}$$

$$\frac{a_{2k}}{4}[g_1+f^{4k+2}h_1]=\lambda\alpha_2A_{k,0}+\sum_{P=1}^{\infty}\propto_{2p+1}\lambda^{2p+2}+\frac{C_{2k}}{\lambda_{2k}}+\frac{B_{2k}}{2\lambda_*^{2k+1}}$$

Where

$$g_1=\left(1+\frac{\mu_b}{\mu_t}\right)\left(1+\frac{\mu_t}{\mu_s}\right);\ g_2=\left(1+\frac{\mu_b}{\mu_t}\right)\left(1-\frac{\mu_t}{\mu_s}\right)$$

$$h_1=\left(1-\frac{\mu_t}{\mu_s}\right)\left(1-\frac{\mu_b}{\mu_t}\right);\ h_2=\left(1+\frac{\mu_t}{\mu_s}\right)\left(1-\frac{\mu_b}{\mu_t}\right)$$

$$A_{P,k}=\frac{(2P+2k+1)!\,g^*_{p+k+1}}{(2P)!\,(2k+1)!\,2^{2p+2k+z}}\ ;\ A_{0,0}=0;\ \lambda_*=\lambda-h$$

$$g^*_{p+k+1}=\sum_{mn}{}' \frac{1}{T^{2p+2k+2}};\ T=\frac{1}{2}P_{mn};\ f=\frac{\lambda-h}{\lambda}$$

Depending on the type of bond and the strength of the boundary, the destruction of the composite can occur in different ways. If the crack propagating in the composite crosses the fibers, then the fracture toughness increases the more, the more the fibers peel off from the matrix. In this case, a weak bond at the fiber-matrix interface is preferred to increase the fracture toughness. When the crack propagates parallel to the fibers, it is preferable to have a strong bond at the fiber-matrix interface, which helps to prevent disruption along the interface.Requiring that the functions (3) satisfy the boundary condition on the edge of the cut L, we obtain a singular integral equation with respect to $g\ (x)$

$$\frac{1}{\pi}\int_L g(t)\xi(t-z)dt-Im[A+f_1'(x)]=0 \text{ на } L \qquad (15)$$

$$\frac{1}{\pi}\int_{-l}^{l}\frac{g(t)dt}{t-x}-Im[f_{1b}'(x)]=0 \qquad (16)$$

The system (14) together with the singular equation (15) and (16) are the basic equations of the problem allowing to determine $g\ (x)$ and the coefficients $a_{2k}, b_{2k}, \alpha_{2k}$. Recall that the system (14) contains the coefficients C_{2k}, B_{2k} and that depend on the desired function $g\ (x)$. The system (14) and equation (15) and (16) proved to be connected must be solved jointly.Knowing the functions $f_s(z)$, $f_b(z)$, $f_t(z)$ we can find the stress–strain state of the plate. Changing the ratio of the stiffness of the fiber to the stiffness of the binding medium, one can obtain all the options, starting with the free-running from the forces of the circular hole and ending with the absolutely hard fibers. The viscosity of a composite reinforced with fiber oriented in several directions of the reinforcing fiber depends mainly on those fibers that are located across the crack and whose destruction is necessary for further propagation of the crack.Using the expansion of the function $\xi\ (z)$, taking into account $g\ (x)\ =-g\ (-x)$ and applying the change of variables, the control (15) and (16) lead to the standard form

$$\frac{1}{\pi}\int_{-1}^{1}\frac{P(\tau)d\tau}{\tau-\eta}+\frac{1}{\pi}\int_{-1}^{1}P\ (\tau)B(\eta,r)d\tau-\dot{I}m[A+f_1'(\eta)]=0 \qquad (17)$$

$$\frac{1}{\pi}\int_{-1}^{1}\frac{P(\tau)d\tau}{\tau-\eta}-\dot{I}m\ f_{1b}'(\eta)=0 \qquad (18)$$

There

$$P(\tau)=g(t);\ B(\eta,\tau)=\frac{1-\lambda_1^2}{2}\sum_{j=0}^{\infty}g_{j+1}\left(\frac{l}{2}\right)^{2j+2}U^jA_j$$

$$A_j=\left\{(2j+1)+\frac{(2j+1)(2j)(2j-1)}{1\cdot2\cdot3}\left(\frac{U}{U_0}\right)+\cdots+\left(\frac{U}{U_0}\right)^j\right\}$$

$$U=\frac{1-\lambda_1^2}{2}(\tau+1)+\lambda_1^2;\ U_0=\frac{1-\lambda_1^2}{2}(\eta+1)+\lambda_1^2;\ \lambda_1=\frac{a}{l}$$

$x = \eta_0 l;\ t = \eta l;\ \eta_0^2 = U;\ \eta^2 = U;\ (j = 1, 2, \dots.)$

We represent the solution of (17) and (18) in the form:

$$P(\eta) = \frac{P_0(\eta)}{\sqrt{1-\eta^2}} \tag{19}$$

The function $P_0(\eta)$ is replaced by the interpolation Lagrange polenomial constructed from the Chebishev nodes. Using quadrature formulas

$$\frac{1}{2\pi}\int_{-1}^{1}\frac{P(\tau)d\tau}{\tau-\eta} = \frac{1}{n\, sin\theta}\sum_{\nu=1}^{n} P_\nu^0 \sum_{m=0}^{n-1} cos\, m\theta_\nu * \sin m\theta;$$

$$\frac{1}{2\pi}\int_{-1}^{1} P(\tau)B(\eta,\tau) = \frac{1}{2n}\sum_{\nu=1}^{n} P_\nu^0 B(\eta,\tau_\nu);\ \tau_\nu = \eta_\nu \tag{20}$$

$$C_{2k} = -\frac{1-\lambda^2}{2}\frac{1}{2n}\sum_{\nu=1}^{n} P_\nu^0 f_{2k}^*(\tau_\nu) \tag{21}$$

$$B_{2k} = -\frac{1-\lambda_1^2}{2}\frac{1}{2n}\sum_{\nu}^{n} P_\nu^0 f_{2k}^*(\tau_\nu)$$

There

$$f_{2k}^{**}(\tau) = f_{2k}^{**}(\xi^2);\ \xi f_{2k}^*(\xi^2) = l f_{2k}(t);$$

$$f_{2k}^{**}(\tau) = f_{2k}^{**}(\xi^2);\ \xi_{2k}^{**}(\xi^2) = l f_{2k}^*(t)$$

(20), (21) formulasmake it possible to replace the basic equations (17) and (18) by an infinite system of linear algebraic equations with approximate values $g\,(t)$ of the required function at the node points, as well as the coefficients $\alpha_{2k} = \alpha_{2k}' + \alpha_{2k}''$. In this case, successively eliminating the constants a_{2k}in the relations (14) and defining the real parts from imaginary ones, we obtain two systems of equations with respect to α_{2k}' andα_{2k}''.

$$\sum_{\nu=1}^{n} a\, m_\nu P_\nu^0 - \frac{1}{2}[A + f_1'(\zeta_m)] = 0; \tag{22}$$

$$\sum_{\nu=1}^{n} b_{mn} P_\nu^0 - \frac{1}{2} Im\, f_{1b}'(\zeta_m) = 0. \tag{23}$$

There

$$a_{m\nu} = \frac{1}{2n}\left[\frac{1}{sin\,\theta_m} ctg\frac{\theta_m + (-1)^{|m-\nu|}\theta_\nu}{2} + B(\eta_m,\tau_\nu)\right];\ \tau_m = \eta_m$$

$$b_{m\nu} = \frac{1}{2n}\left[\frac{1}{\sin\theta_m} ctg\frac{\theta_m + (-1)^{|m-\nu|}\theta_\nu}{2}\right]$$

To system (22) - (23) it is necessary to add an additional condition, which in the discrete form has the form

$$\sum_{\nu=1}^{n}\frac{P_\nu^0}{\sqrt{\frac{1}{2}(1-\lambda_1^2)(\tau_\nu+1)+\lambda_1^2}} = 0 \tag{24}$$

System (21) - (24) is connected (closed) by infinite systems (14), in which the relation (21) is substituted for C_{2K}andB_{2K}.The three systems noted completely determine the solution of the problem. After finding the values of P_ν^0, the stress intensity factor $K_{III}$is determined on the basis of relations (15), (18), (19), (21):

$$K_{III}^a = \sqrt{\frac{\pi l(1-\lambda_1^2)}{\lambda_1}}\frac{1}{2n}\sum_{\nu=1}^{n}(-1)^{\nu+n} P_\nu^0\, tg\frac{\theta_\nu}{2}$$

$$K_{III}^l = \sqrt{\pi l(1-\lambda_1^2)}\frac{1}{2n}\sum_{\nu=1}^{n}(-1)^{\nu} P_\nu^o \frac{\theta_\nu}{2}$$

$$K_{III}^{-a} = \sqrt{\pi l}\,\frac{1}{n}\sum_{k=1}^{n}(-1)^{k+n}P_k^0\,tg\,\frac{\theta_k}{2}$$

$$K_{III}^{-l} = \sqrt{\pi l}\frac{1}{n}\sum_{k=1}^{n}(-1)^{k}P_k^0 ctg\frac{\theta_k}{2}$$

One of the most important characteristics of the structural material is its resistance to crack propagation or fracture toughness. In any material there are always internal defects (pores, cracks, etc.), which under the action of relatively small stresses can increase and lead to destruction. The reliability of the structure depends on how well the material resists the spread of cracks.

Analysis of the solution: For numerical calculations, the case of the hole arrangement at the vertices of the triangular$\omega_1 = 2, \omega_2 = 2e^{\frac{1}{3}i\pi}$and square $\omega_1 = 2, \omega_2 = 2i$of the lattice was taken. The calculations were performed on an IBM computer using the Matlab program. It was assumed that $n = 10$ and $n = 20$, which corresponds to a partition of the interval into 10 and 20 Chebyshev nodes, respectively. The resulting systems were solved by the Gauss method with the choice of the main element. Based on the results obtained in Fig. Figures 2, 3, and 4 show graphs of the dependence of the critical load (limit load) $\tau^* = \tau_y^{\infty}\sqrt{\omega_1}/K_{III\,c}$ for both crack vertices on the crack length$l_* = l - a$for some

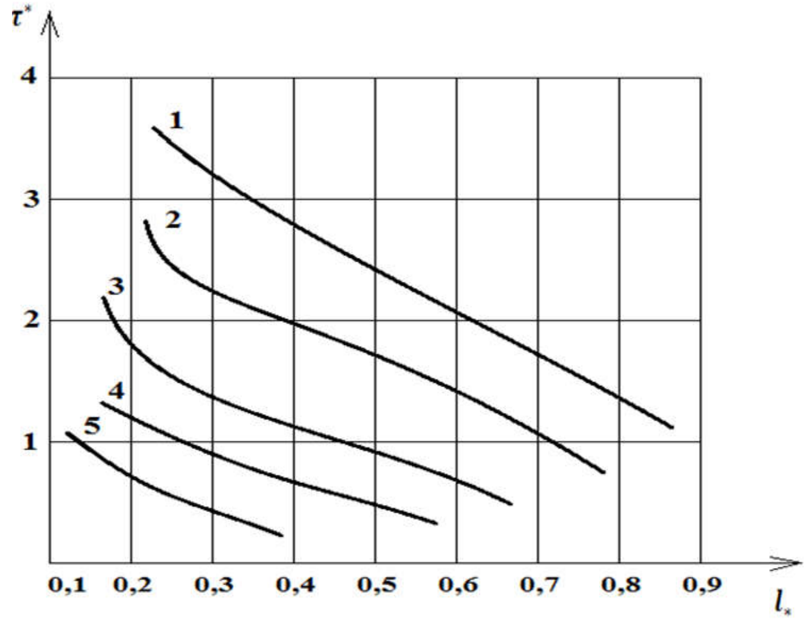

Fig. 2. Dependence of the ultimate load on the crack length

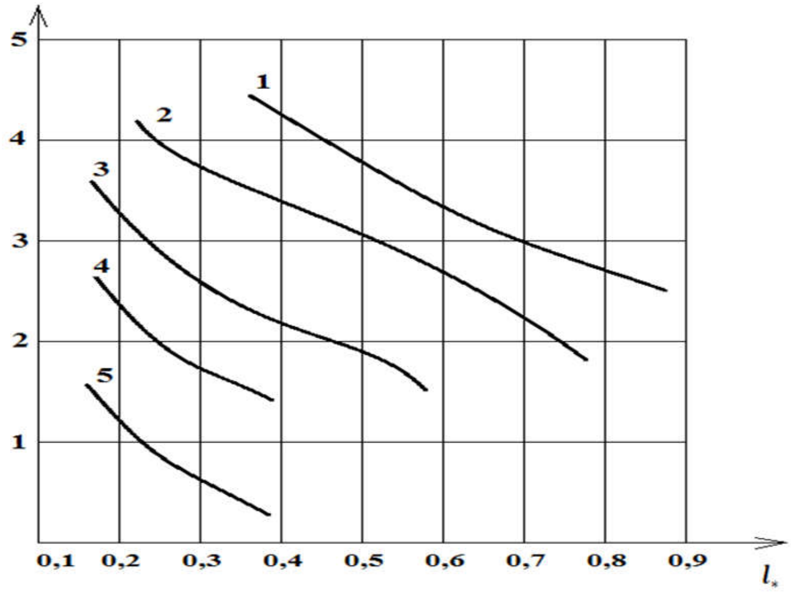

Fig. 3. Dependence of the ultimate load on the crack length

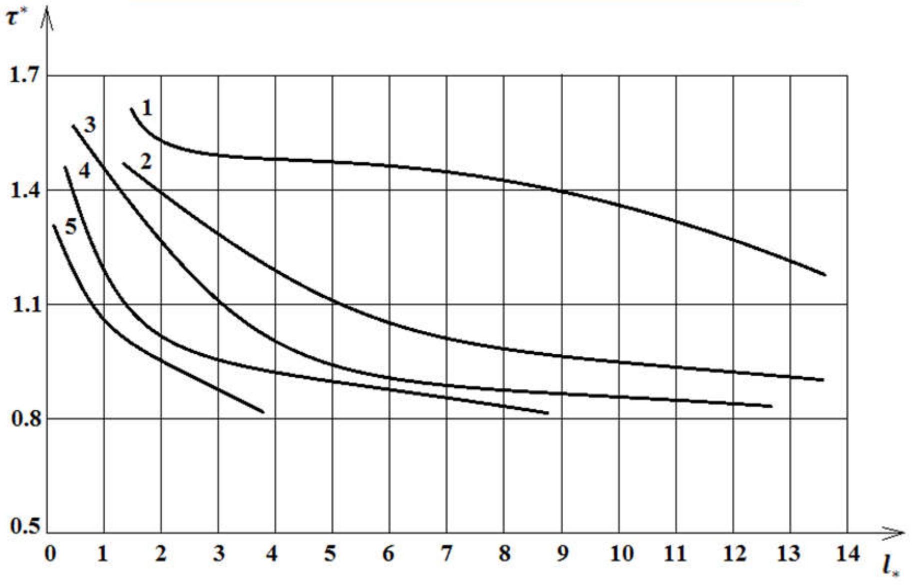

Fig. 4. Dependence of the ultimate load on the crack length

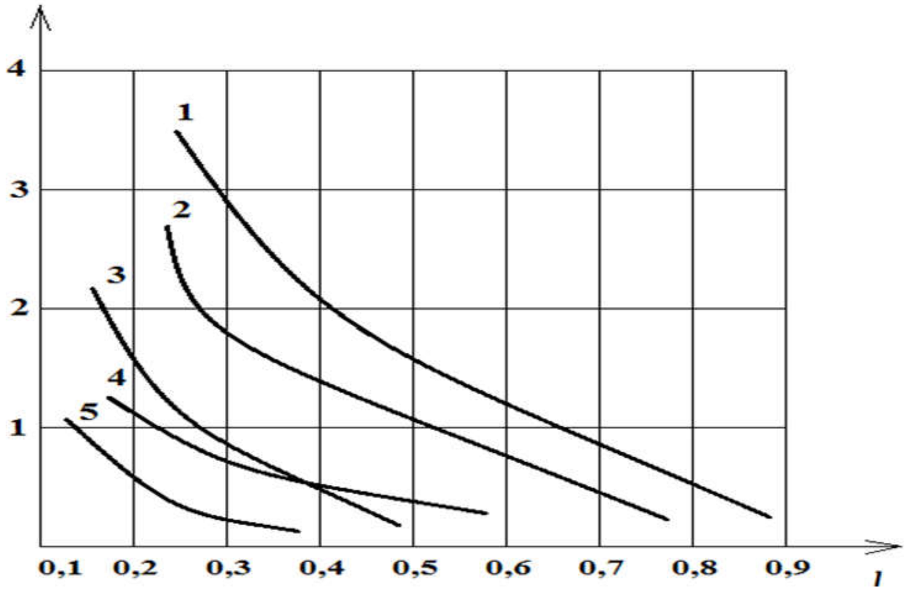

Fig. 5. Dependence of the ultimate load on the crack length

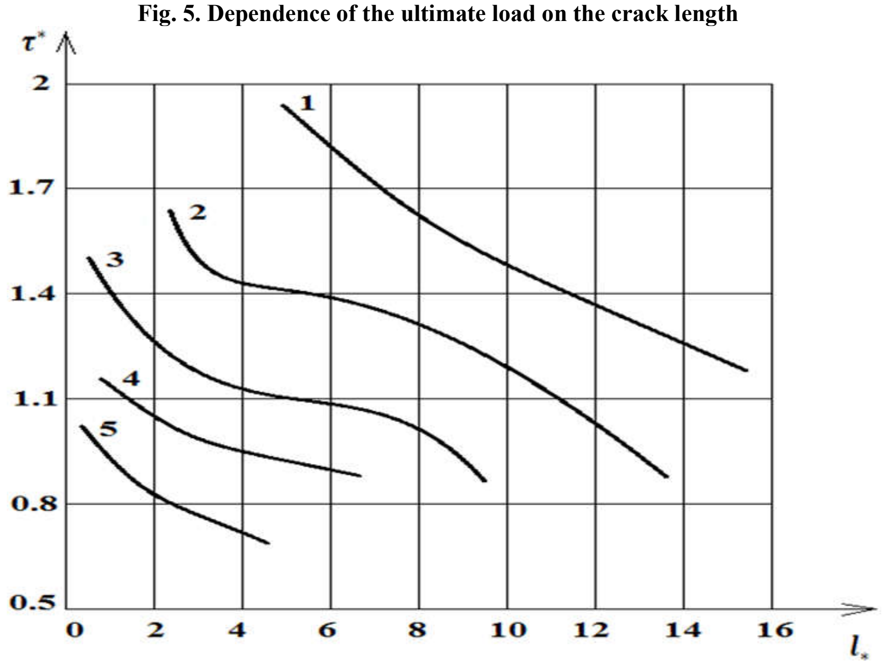

Fig. 5. Dependence of the ultimate load on the crack length

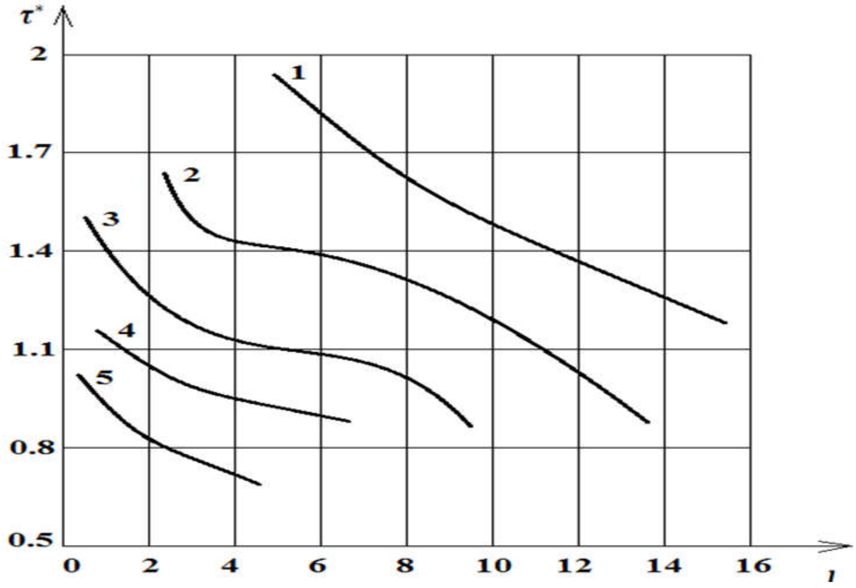

Fig. 6. Dependence of the ultimate load on the crack length

values of the hole radius $\lambda = 0.2; 0.3; 0.4; 0.5; 0.6$ (curves 1-5). In Fig. 5, 6 and 7 an analogous dependence is shown for a square lattice.The case when cracks are present only in inclusion is considered. In Fig. 8 for the square lattice, the results of calculations of the critical load (limit load).$\tau^* = \tau_y^{\infty}\sqrt{\omega_1}/K_{III\,c}$are presented for the values of the hole radius, depending on the crack length $l = ((\lambda - l))/l = 0.2; 0.3, 0.4, 0.5, 0.6$ (curves 1-5). In Fig. 9 an analogous dependence is shown for a triangular lattice.The calculations were carried out for the following values of the elastic parameters$\frac{\mu_b}{\mu_s} = 25, \frac{\mu_b}{\mu_t} = 50$.

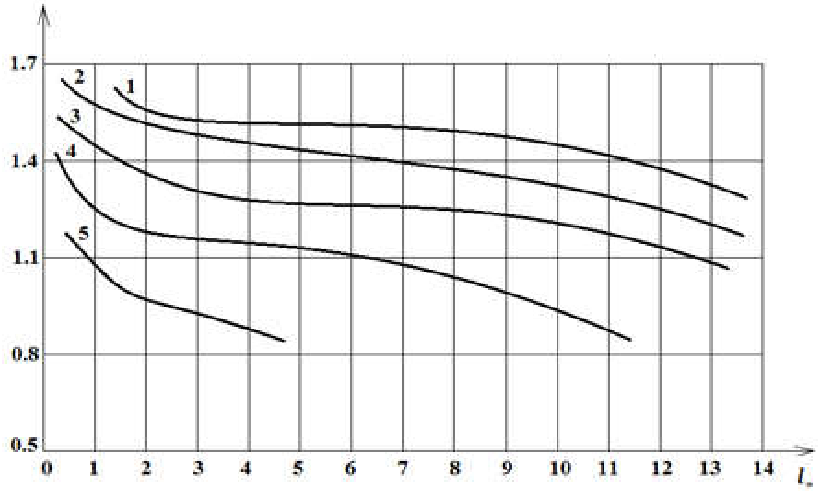

Fig. 7. Dependence of the ultimate load on the crack length

l_*

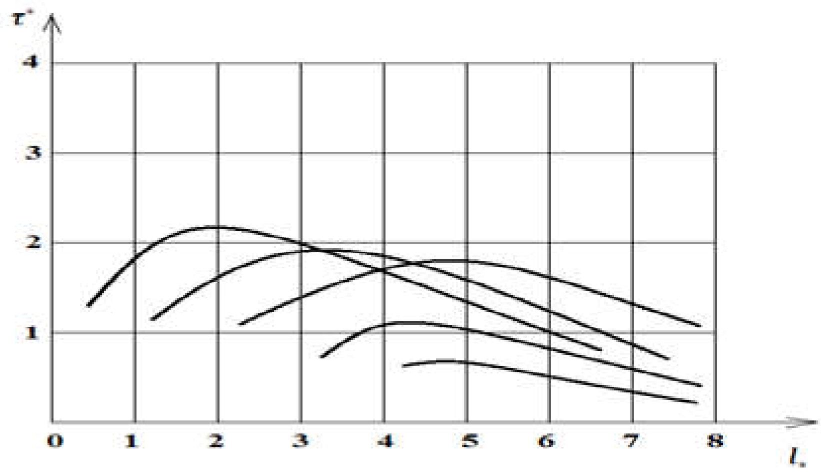

Fig. 8. Dependence of the ultimate load on the crack length

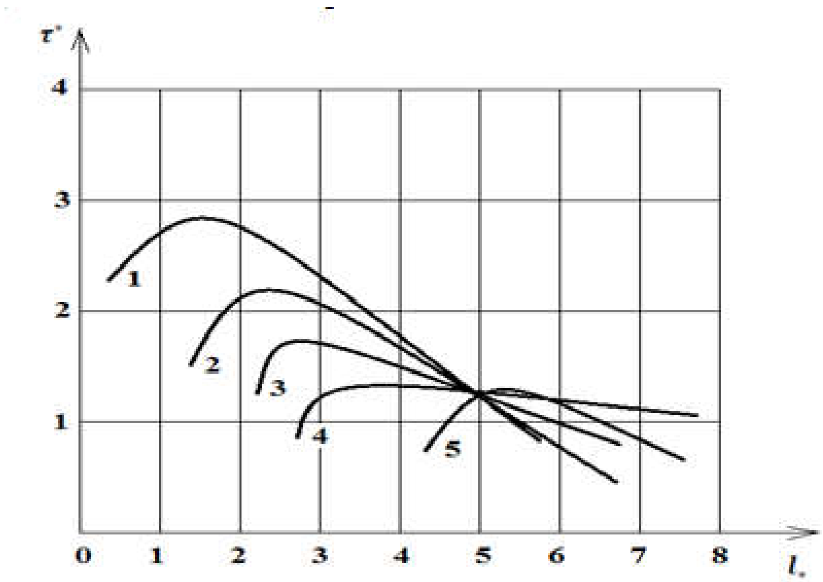

Fig. 9. Dependence of the ultimate load on the crack length

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