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OPTIMAL ARRANGEMENT OF A PERIODIC AND DOUBLE-PERIODIC SYSTEM OF RIGID REINFORCING ELEMENTS IN COMPOSITES*

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The strength of fibrous composite plates is dependent to a significant degree on the geometry of fiber placement, i.e., on the sequence of their arrangement and orientation. To select the optimum reinforcement geometry for these composites from positions of linear fracture mechanics, it is necessary to have at one's disposal data on the local stress-strain state near reinforcing elements of the fiber-inclusion type. Consideration of the interaction between fibers, which provides for accurate computed data for the design of fibrous composites, is also required. In this connection, problems involving the elastic equilibrium of plates with inclusions that are ordered into certain systems, for example, with their periodic and double-periodic arrangement, are of special interest in the theory of the failure of composite materials.

Up till now, solutions of periodic and double-periodic problems in crack-notch theory alone have been presented most completely in the scientific literature [1-3]. An investigation of the periodic problem was recently conducted by Berezhnitskii and Stashchuk for rigid linear inclusions [4].

The present study addresses similar problems for the periodic and double-periodic systems of linear fibers of infinite stiffness, which are contained in an elastic homogeneous isotropic matrix. Analytical equations for computing the stress intensity factors near these structural stress raisers that interact with one another are presented, and their optimal orientations, which give rise to minimum stress intensity factors, determined.

Each discrete fiber of a composite plate is modeled by a thin nondeformable filament of finite length. In this case, it is assumed that the matrix in which the fibers exist is a continuous medium, which ensures an ideal bond between the fibers and the matrix material. It is also assumed that the shear modulus of the fibers exceeds that of the matrix by a factor of 100 and more; this corresponds to a composite reinforced with fibers of infinite stiffness.

To state and solve the problems considered in the study, the plane of the composite is combined with the plane of an xOy Cartesian coordinate system with respect to which the orientation and arrangement of fibers in the composite, which are ordered into a periodic or double-periodic system, are prescribed. Stress and rotations are absent in this plane at infinity; in this case, boundary conditions of the problems are given at the ends of the fibers in the composite.

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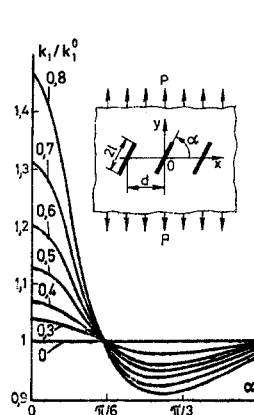


Fig. 1

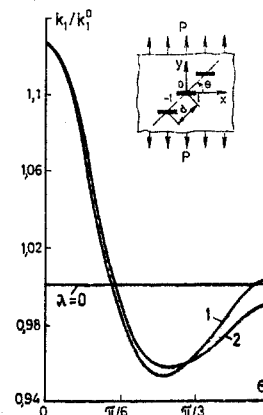


Fig. 2

Fig. 1. Relationships between ratio k_1/k_1^0 and angle of fiber orientation α in case of plane stressed state. $\mu = 0.3$. Figures near curves denote values of λ .

Fig. 2. Variation of k_1/k_1^0 ratio for system of parallel adjacent fibers with centers on single straight line due to angle $\pi/2 - \theta$ of orientation of this line to loading system: 1) plane strain; 2) plane stressed state.

Periodic Fiber-Inclusion System in an Elastic Plane. Let us examine a periodic system of linear rigid inclusions of length $2l$ with centers on the real Ox axis and with equal angles of incline to it ($\alpha_k = \alpha$, Fig. 1). The distance between neighboring defects d is constant.

Similar displacement jumps

$$2G \frac{d}{dt_n} (u_n^\pm + iv_n^\pm) = f'(t_n) \pm g'(t_n); \quad |t_n| < l \quad (1)$$

are given for the contours of fibers of infinite stiffness by virtue of periodicity, while the stress jumps

$$\sigma_n^\pm - i\tau_n^\pm = p(t_n) \pm q(t_n); \quad |t_n| < l \quad (2)$$

are unknown functions. The plus and minus signs correspond to the upper and lower ends of the inclusions, t_n are points on the n -th contour of the inclusion, and G is the shear modulus of the composite's matrix material. Introducing the designations

$$\{G(\rho^*, t_n), F(\rho^*, t_n)\} = \begin{cases} \{-2q(t_n), -2p(t_n)\}, \rho^* = -1; \\ \{2g'(t_n), 2f'(t_n)\}, \rho^* = \kappa, \end{cases} \quad (3)$$

where $\kappa = 3 - 4\mu$ for plane strain, $\kappa = (3 - \mu)/(1 + \mu)$ in the case of a generalized plane stressed state, and μ is Poisson's ratio, we arrive at a single integral equation in terms of the unknown function $G(\rho, t)$

$$\int_{-l}^l [G(\rho, t) K(t-x, \rho^*) + \overline{G(\rho, t)} L(t-x)] dt = 0.5\pi i (\rho - \rho^*) F(\rho^*, x); \quad |x| < l, \quad (4)$$

the kernels of which, according to [4, 5], assume the form

$$K(x, \rho^*) = \frac{\pi\rho^*}{2d} \left(e^{i\alpha} \operatorname{ctg} \frac{\pi x e^{i\alpha}}{d} + e^{-i\alpha} \operatorname{ctg} \frac{\pi x e^{-i\alpha}}{d} \right);$$

$$L(x) = \frac{\pi}{2d} (e^{-i\alpha} - e^{-3i\alpha}) \left(\operatorname{ctg} \frac{\pi x e^{-i\alpha}}{d} - \frac{\pi x e^{-i\alpha}}{d} \operatorname{cosec}^2 \frac{\pi x e^{-i\alpha}}{d} \right),$$

by satisfying boundary conditions (1) and (2) in a manner similar to that in [1, 2, 4, 5]. For a composite reinforced with fibers of infinite stiffness, the parameters $\rho^*(\rho)$ correspondingly assume the value $\kappa(-1)$. If we set $\rho^* = -1$ and $\rho = \kappa$, we obtain an integral equation of the periodic problem for cracks.

The solution of Eq. (4) should satisfy the condition

$$\int_{-l}^l G(\rho, t) dt = 0,$$

which ensures the well-defined character of displacements on circumventing the contours of the defects. For large distances between fiber centers, the unknown function $G(\rho, t)$ was found by the asymptotic method [1, 2, 4, 5] as a series in terms of the parameter $\lambda = 2l/d$, which characterizes the relative distance between the fibers of the composite. Terms of order λ^6 were taken into account.

If the solution of Eq. (4) is found, we can use the equations

$$k_1^\pm - ik_2^\pm = \mp i\rho^*(\rho - \rho^*)^{-1} \lim_{x \rightarrow \pm l} \sqrt{(l^2 - x^2)/l} G(\rho, x); \quad (5)$$

$$M = \rho^*(\rho^* - \rho)^{-1} \operatorname{Re} \left\{ \int_{-l}^l [G(\rho, x)/\rho^* + \overline{G(\rho, x)}] dx \right\}; \quad M(\varepsilon) = 0 \quad (6)$$

to calculate the stress intensity factors [6], principal moments, and deflection angles ε for the fibers. Here, "+" refers to the right, and "-" to the left tip of the fiber. The stress intensity factors and deflection angles of the fibers were computed in accordance with the above-described method. The calculations were performed for uniaxial tensioning of the composite plate by forces of intensity p , which were applied at infinity.

Relationships between the quantity k_1/k_1^0 (k_1^0 is the stress intensity factor for the same oriented isolated fiber [5]) and the angle α of rigid-fiber orientation relative to the distribution line of their centers for $\mu = 0.3$ and for a plane stressed state are presented in Fig. 1. It is found that interaction between fibers of the same orientation at an angle α to the Ox axis gives rise to a reduction in strength as compared with the strength of a plate with a single fiber, if $0 \leq \alpha \leq \pi/6$. A certain hardening of the plate, i.e., a reduction in the intensity factor k_1 , occurs when $\pi/6 \leq \alpha \leq \pi/2$. The mutual effect of linear fibers is minimal when $\alpha = \pi/6$ and $\alpha = \pi/2$. Antisymmetric stress components characterized by the quantity k_2 can be neglected. The deflection angles for the given disposition of defects are virtually the same as those for a single fiber. The variation of the quantity k_1/k_1^0 for the plane deformation and plane stressed state of a composite ($\lambda = 0.5$ and $\mu = 0.3$) with a system of parallel adjacent fibers with centers along the axis directed at an angle θ to the Ox axis is shown in Fig. 2.

Fibers arranged along a single straight line result in maximum values of the stress intensity factor k_1 as compared with k_1^0 for an isolated fiber in the matrix. Minimum values of k_1/k_1^0 are attained when this line is oriented at an angle $\theta = \pi/4$ to the line of the plate's tensioning. The mutual effect of parallel adjacent rigid fibers with centers on a single straight line is minimal when $\theta = \pi/6$ and $\theta = \pi/2$.

Investigation of the effect of Poisson's ratio on the local stressed state in the vicinity of linear fibers, which are arranged in periodic order, indicated that it exerts a minor influence on the magnitude of the stress intensity factors. The effect of Poisson's ratio is most apparent as the fibers are drawn together.

To compute the stress-strain state of a composition reinforced with a system of colinear ($\alpha = 0$) fibers and subjected to biaxial tension by mutually perpendicular forces p and q (the force p is directed at an angle φ to the Ox axis), the precise analytical expressions are derived for the stress intensity factors and deflection angles

$$k_1^\pm = 0.25p[(1 - \rho^*)(1 + \eta_0) - 2(1 - \eta_0)\cos 2\varphi] \sqrt{\frac{d}{\pi} \operatorname{tg} \frac{\pi l}{d}};$$

$$k_2^\pm = 0; \quad \varepsilon = 0.25p(1 - \eta_0)\sin 2\varphi/G.$$

In the case of a system of parallel inclusions—fibers, these analytical approximate expressions for the quantities k_1 , k_2 , and the deflection angle ε are derived on the basis of the approximate closed solution of the integral equation (4):

$$k_1^\pm = 0.25p[(1 - \rho^*)(1 + \eta_0) - 2(1 - \eta_0)\cos 2\varphi] \sqrt{\frac{2\rho^*l}{\pi(1 - \rho^*)\lambda} \operatorname{tg} \frac{\pi(1 - \rho^*)\lambda}{2\rho^*}}; \quad k_2^\pm = 0. \quad (7)$$

Computations performed from Eqs. (7) indicated that interaction between rigid parallel fibers arranged in a periodic system can be neglected when $\lambda \leq 0.33$.

Double Periodic System of Fibers of Infinite Stiffness in an Isotropic Matrix. Let an elastic unrestrained plane contain a double-periodic system of fibers. In the parallelogram of periods with the basic periods ω_1 and ω_2 ($\operatorname{Im} \omega_1 = 0$, $\operatorname{Im} (\omega_2/\omega_1) > 0$), there are N fibers with the contours L_k ($k = 1, 2, 3, \dots$) related to the

local systems of coordinates $x_k O_k y_k$, which have origins at the points $z_k^0 = x_k^0 + iy_k^0$ of the principal coordinate system xOy . In this case, the boundary conditions are given by type (1) and (2) relationships in which the jumps and the sum of the stresses and displacements correspond to the $q_n(t_n)$ and $p_n(t_n)$ and $g_n(t_n)$ and $f_n(t_n)$ functions, respectively; here, the discontinuity in the displacements $g_n(t_n)$ at the ends of the fibers is equal to zero. Let us also assume that the principal force vector in the projections X_n and Y_n on the Ox and Oy axes is known separately for each fiber-inclusion; in this case, the vector of the total forces acting on all contours of the linear fibers is equal to zero.

Using the designations of (3) and satisfying boundary conditions (1) and (2), we obtain a system of singular integral equations of the problem of the stress-strain state of a composite plate with fibers ordered in a double-periodic manner by the method developed in [1, 2, 5]:

$$\sum_{h=1}^N \int_{L_h} [K_{nh}(t_h, t'_n; \rho^*_{nh}, \rho^*_{nh}) Q_h(t_h; \rho^*_{nh}, \rho_h) dt_h + L_{nh}(t_h, t'_n) \overline{Q_h(t_h; \rho^*_{nh}, \rho_h)} d\bar{t}_h + M_{nh}(t_h, t'_n) G_h(\rho^*_{nh}, t_h) dt_h] = \pi F_n(\rho^*_{nh}, t'_n); \quad t'_n \in L_n, \quad n=1, 2, 3, \dots, N, \quad (8)$$

where

$$K_{nh}(t_h, t'_n; \rho^*_{nh}, \rho^*_{nh}) = \frac{e^{i\alpha_k}}{i} \left\{ \rho^*_{nh} [\zeta(T_h - T'_n) - A_1 \bar{T}_h - A_2 T_h] + e^{-2i\alpha_n} \frac{d\bar{T}'_n}{dt_n} \times \right. \\ \times [\rho^*_{nh} \zeta(T_h - T'_n) + \bar{A}_1 T_h + \bar{A}_2 \bar{T}_h] \left. \right\}; \quad L_{nh}(t_h, t'_n) = \frac{e^{-i\alpha_k}}{i} \left\{ \overline{\zeta(T_h - T'_n)} - \bar{A}_1 T_h - \right. \\ \left. - \bar{A}_2 \bar{T}_h + e^{-2i\alpha_n} \frac{d\bar{T}'_n}{dt_n} [\mathfrak{I}_1(T_h - T'_n) - (T_h - T'_n) \mathfrak{I}(T_h - T'_n) - \bar{A}_2 T_h - A_3 \bar{T}_h] \right\}; \\ M_{nh}(t_h, t'_n) = i e^{i(\alpha_k - 2\alpha_n)} \zeta(T_h - T'_n) \frac{d\bar{T}'_n}{dt_n}; \\ Q_h(t_h; \rho^*_{nh}, \rho_h) = \frac{G_h(\rho_h, t_h) - G_h(\rho^*_{nh}, t_h)}{\rho_h - \rho^*_{nh}}; \quad T_h = t_h e^{i\alpha_k} + z_k^0;$$

$$T'_n = t'_n e^{i\alpha_n} + z_n^0; \quad A_1 = 2\pi i/D; \quad D = \bar{\omega}_1 \omega_2 - \omega_1 \bar{\omega}_2; \quad A_2 = (\delta_2 \bar{\omega}_1 - \delta_1 \bar{\omega}_2)/D; \\ A_3 = (\gamma_2 \bar{\omega}_1 - \gamma_1 \bar{\omega}_2)/D; \\ \delta_r = 2\zeta\left(\frac{\omega_r}{2}\right); \quad \gamma_r = 2\mathfrak{I}_1\left(\frac{\omega_r}{2}\right) - \bar{\omega}_r \mathfrak{I}\left(\frac{\omega_r}{2}\right); \quad r=1, 2;$$

α_k is the angle of incline of the k -th fiber to the Ox axis, $\zeta(z)$ is a Weierstrass zeta function, $\mathfrak{I}(z)$ is a Weierstrass elliptical function, and $\mathfrak{I}_1(z)$ is a special meromorphic function [1, 5].

The solution of system of equations (8) should satisfy the condition of well-defined displacements of the form

$$\int_{-l_n}^{l_n} Q_n(t; \rho^*_{nh}, \rho_n) dt = \frac{i(X_n + iY_n)}{\alpha + 1} e^{-i\alpha_n}; \quad n=1, 2, 3, \dots, N. \quad (9)$$

Let there be a single fiber of length $2l$ at the vertex of the period parallelogram. The centers of the fibers are located at the vertices of the period parallelograms, i.e., at the points $P_{mn} = m\omega_1 + n\omega_2$ ($m, n = 0, \pm 1, \pm 2, \pm 3, \dots$) with the principal periods ω_1 and ω_2 ($\text{Im } \omega_1 = 0, \text{Im } (\omega_1/\omega_2) > 0$). As an example, let us consider the point P_{00} to be the center of the local coordinate system (x_1, y_1) , and position the fiber so that it is directed at an angle α to the Ox_1 axis.

On the basis of system of singular integral equations (8), we obtain a single equation for the problem

$$\int_{-1}^1 [K(\xi - \eta, \rho^*) G(\rho, \xi) + L(\xi - \eta) \overline{G(\rho, \xi)}] d\xi = \pi(\rho - \rho^*) F(\rho^*, \eta); \quad |\eta| < 1$$

in terms of the unknown function $G(\rho, \xi)$ in which

$$K(\tau, \rho^*) = \frac{\lambda \rho^*}{2} [e^{i\alpha} \zeta(\lambda \tau e^{i\alpha}) + e^{-i\alpha} \bar{\zeta}(\lambda \tau e^{-i\alpha})] + \rho^* a_1 \lambda^2 \tau; \quad L(\tau) = \frac{\lambda}{2} [e^{-i\alpha} \bar{\zeta} \times \\ \times (\lambda \tau e^{-i\alpha}) - \lambda \tau e^{-2i\alpha} \mathfrak{I}(\lambda \tau e^{-i\alpha}) + e^{-3i\alpha} \mathfrak{I}_1(\lambda \tau e^{-i\alpha})] + b_1 \lambda^2 \tau; \quad \tau = \xi - \eta; \quad \lambda = 2l/\omega_1; \\ a_1 = \frac{\omega_1}{8\rho^*} \left[\frac{\pi(1 - \rho^* - e^{-2i\alpha} + \rho^* e^{2i\alpha})}{\text{Im } \omega_2} + \bar{\delta}_1 e^{-2i\alpha} - \rho^* \delta_1 e^{2i\alpha} \right];$$

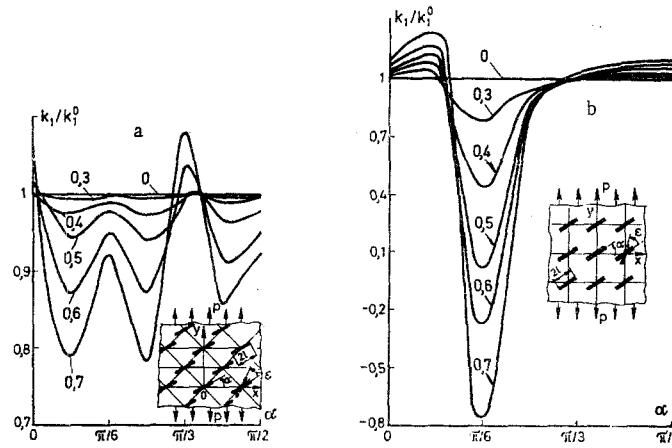


Fig. 3. Relationships between k_1/k_1^0 ratio and fiber-orientation angle α in plane stressed state for triangular (a) and square (b) period grids.

$$b_1 = \frac{\omega_1}{4} e^{-2i\alpha} \left[\frac{\pi(1 - \cos 2\alpha)}{\text{Im } \omega_2} - \bar{\delta}_1 + \frac{\bar{\delta}_1 - \bar{\gamma}_1}{2} e^{-2i\alpha} \right];$$

$$t_1 = x_1 = l\xi; \quad t'_1 = \omega(\eta); \quad G(\rho, \xi) = G(\rho, t)l; \quad F(\rho^*, \eta) = F(\rho^*, t)l.$$

Using supplemental equations (9), the singular equation can be solved by the asymptotic method [1, 5] in terms of the parameter λ , which was introduced earlier, considering that the distance between the centers of the fibers is large.

After determining the unknown function $G(\rho, \xi)$ by the asymptotic method, we can derive explicit expressions for the stress intensity factors k_1 and k_2 and the deflection angles ε of the fibers in the form

$$k_{1\pm} = f_1(l, p, \lambda, \alpha, \varepsilon); \quad k_{2\pm} = f_2(l, p, \lambda, \alpha, \varepsilon); \quad \varepsilon = f_3(l, p, \lambda, \alpha) \quad (10)$$

on the basis of Eqs. (5) and (6).

In the case of a double-periodic system of rigid linear inclusions, stress intensity factors were computed from type (10) equations for the schemes presented in Fig. 3. The computations were performed for different values of the relative distance λ between the centers of defects for a plane stressed state and $\mu = 0.3$.

For the uniaxial tensioning of a plate at infinity, a reduction in the stress intensity factor occurs, as can be seen from Fig. 3a, for all values of $\lambda \in [0, 1]$ in the range of variation $\pi/48 < \alpha < 5\pi/48$ for the case of a triangular period grid as compared with a single isolated fiber, i.e., it hardens. Optimal orientations of rigid inclusions are observed for $\alpha = \pi/12$; $\alpha = \pi/4$; $\alpha = 5\pi/12$. Computations of the antisymmetric component k_2 indicated that it differs little from k_2^0 for an isolated in-plane inclusion. The stress intensity factor k_2^0 can therefore be used for strength computations. Note that a similar problem (see the diagram in Fig. 3a) was also examined for uniform shear by forces τ applied to a plate at infinity, the latter having a double-periodic system of fibers positioned at the vertices of periodically repeating triangles. It is found that under this loading situation, the stress-strain state of the composition for the period grid under consideration differs little from a similar loading for a single isolated fiber, since the maximum deviation of k_1 from k_1^0 when $\lambda \in [0, 0.7]$ is not more than $0.9 \cdot 10^{-3}$; the stress intensity factor in this case is the same as that for a single isolated inclusion in an elastic plane.

With the plate under uniaxial tension, it hardens for all $0 \leq \lambda \leq 0.7$ for the case of a square period grid as compared with a single isolated fiber for a fiber orientation $\pi/9 < \alpha < \pi/4$.

In this case, optimal orientations are observed for $\alpha = \pi/6$. As in the case of a triangular period grid, the coefficient k_2 differs little from k_2^0 for an isolated inclusion in an elastic plane.

It follows from calculations of the stress intensity factors obtained for the case of a plate reinforced in a similar manner (square grid) and subjected to uniform shear at infinity that an increase in the parameter λ when $\alpha = \pi/12$, $\pi/4$, and $5\pi/12$ gives rise to a loss of plate strength.

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CERTAIN MECHANICAL PROPERTIES OF CARBON-FIBER-REINFORCED PLASTIC BASED ON AN ALL-FABRIC REINFORCING CAGE

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Recent studies directed toward elimination of deficiencies in composite materials with traditional reinforcing schemes have resulted in the creation of materials with various patterns of three-dimensional reinforcement [1]. Use of this class of composites in design components requires more complete study of their mechanical properties. The present paper, which is a continuation of our work [2], is therefore devoted to examination of certain elastic and strength properties of a composite based on fabrics with various schemes of three-dimensional weaving. The paper also evaluates the possibility of computing the deformation properties of the components, their volumetric content, and the geometry of fiber arrangement in the composite.

A model carbon-fiber-reinforced plastic fabricated from a phenol binder and a filler in the form of an all-fabric reinforcing cage of carbon filaments consisting of singular low-modulus grade "Ural-N-24" fibers served as the test material. A structural diagram of the reinforcement is shown in Fig. 1. As is apparent from the figure, the material under consideration has a regular structure; this makes it possible to separate a certain repeating three-dimensional element having the shape of a parallelepiped.

Uniaxial-tension, torsion, and double-shear tests were conducted on specimens having the shape of two-sided blades, rods of rectangular section, and bars, respectively. The blades and rods were cut from plates in two mutually orthogonal directions - along the weft filaments (along the y axis), and along the root (along the z axis). The carbon-fiber-reinforced-plastic plates were fabricated by the method of impregnation in a vacuum under pressure in special die-casting molds. The thickness of the plates ($h = 18$ mm) was equal to the height of the reinforcing cage along the x axis.

The carbon-fiber-reinforced-plastic specimens were examined experimentally in tension ($\dot{\sigma} = 5$ MPa/sec = const) and torsion ($\dot{\nu} = 0.003$ rad/sec) at room temperature on a programmed testing machine, and in shear under similar conditions on a ZD-40 machine.

The overall reinforcement factor ($\mu_{\Sigma} = 0.27$) of the composition under investigation was determined by weighing the specimens and measuring their volumes. The amount of reinforcement in different directions was

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