

INFLUENCE OF RESIDUAL STRESSES ON THE STRESS INTENSITY FACTORS FOR A SURFACE CRACK IN THE RAIL HEAD

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The stressed state of a rail damaged with crack is studied by the method of singular integral equations in the presence of longitudinal residual stresses. The values of the stress intensity factors are obtained for different angles of orientation of the crack and friction coefficients in the case of rolling contact.

Keywords: railroad rails, residual stresses, crack, singular integral equations, stress intensity factors.

Residual stresses formed in railroad rails after their manufacturing and in the process of operation may substantially affect their contact-fatigue fracture. The character of distribution of stresses in the rails was studied in numerous works (see, e.g., [1–5]). The diagrams of distribution of longitudinal residual stresses over the height of the rail along its axis of symmetry observed after manufacturing and in the process of operation are somewhat different (Fig. 1). In the first case, the stresses formed near the running surface of the rail, are tensile and attain the maximum value ~ 200 MPa. At the same time, in the process of operation, local plastic strains appear in the subsurface layer down to a depth of 2.5 mm, which leads to mechanical hardening in this part of the rail head. As a result, the residual stresses are redistributed in this region, become compressive, and remain maximum near the surface.

Therefore, for a rail operating under the conditions of contact rolling fatigue in the presence of stresses of this kind, the surface cracks propagating in the railhead prove to be especially dangerous. It should be emphasized that, at present, in 30% cases, the replacement of rails on European railroads is caused just by the presence of contact-fatigue defects in their heads [6]. However, the influence of residual stresses on the stressed state near cracks of this sort is studied insufficiently. In the present work, we continue our previous investigations [7, 8] and solve this problem by the method of singular integral equations in the two-dimensional statement [9].

Statement of the Problem

Instead of a railroad rail damaged by a surface cracklike defect, we consider an elastic half plane containing an edge rectilinear cut (crack) in the two-dimensional statement. The half plane is referred to a coordinate system xOy whose Ox -axis coincides with the edge of the half plane and the origin O coincides with the crack mouth. The crack is referred to a local coordinate system $x_1O_1y_1$ (Fig. 2). The contact pressure exerted upon the rail by a wheel is modeled by the repeated translational motion of Hertzian contact forces along the boundary of the half plane (in the right–left direction):

$$s(x) = -(1 + if)p(x) = -\frac{p_0(1 + if)\sqrt{a^2 - (x - x_0)^2}}{a}, \quad |x - x_0| \leq a,$$

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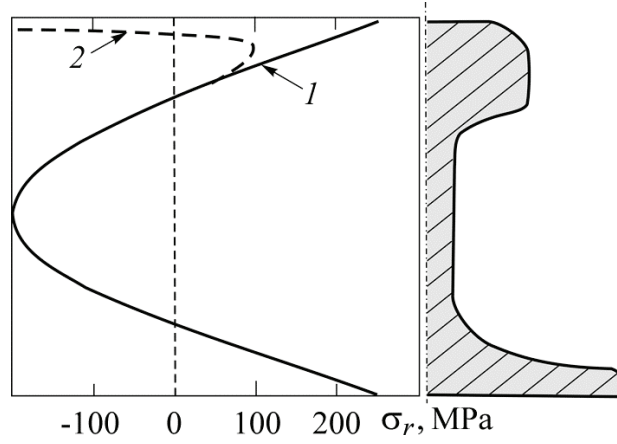


Fig 1. Typical distributions of longitudinal residual stresses σ_r in a rail: (1) after manufacturing, (2) in the process of operation [3].

where f is the coefficient of contact friction. The longitudinal residual stresses are modeled by uniform uniaxial tension-compression forces σ_r applied at infinity. The location of the contact zone relative to the crack mouth is determined by the parameter $\lambda = x_0/l$, the relative crack length by the parameter $\varepsilon = l/a$, and its orientation by the angle β .

The boundary conditions of the posed problem on the boundary of the half plane and at infinity take the form

$$\sigma_y(x, 0) - i\tau_{xy}(x, 0) = \begin{cases} s(x), & |x - x_0| \leq a, \\ 0, & |x - x_0| > a, \end{cases} \quad (1)$$

$$\sigma_x^\infty = \sigma_r, \quad (2)$$

where $\sigma_r > 0$ if the residual stresses are tensile or $\sigma_r < 0$ if they are compressive.

For some locations of the Hertzian contact load (some λ), with regard for the action of residual stresses, the crack lips may be in contact. In what follows, we consider the case of their smooth contact. By L' we denote the collection of the zones of crack opening. Thus, the boundary conditions of the problem on the crack lips have the form

$$N^\pm(x_1) = 0, \quad x_1 \in L', \quad (3)$$

$$T^\pm(x_1) = 0, \quad x_1 \in L, \quad (4)$$

$$u_n^+(x_1) - u_n^-(x_1) = 0, \quad x_1 \in L \setminus L', \quad (5)$$

where L is the crack contour relative to a local coordinate system $x_1O_1y_1$, N and T are the normal and tangential stresses acting on the crack lips, and u_n is the normal component of the vector of displacements of the crack lips.

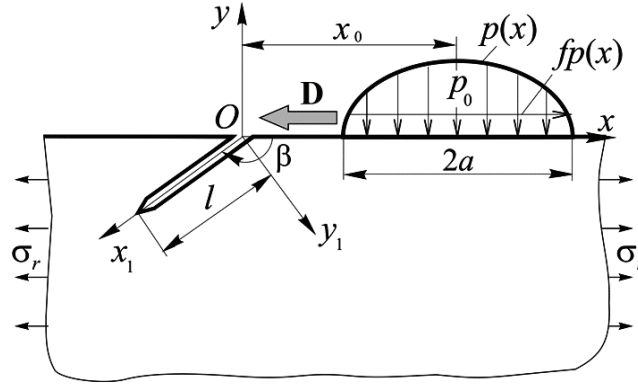


Fig. 2. Geometry and force scheme of the problem; **D** is the direction of motion of the contact load.

Satisfying the boundary conditions of problem (1)–(5) by using the Kolosov–Muskhelishvili complex potentials, we arrive at a system of singular integral equations, which can be represented in the operator form as follows:

$$\operatorname{Re} D(x_1) = \pi \operatorname{Re} P(x_1), \quad x_1 \in L', \quad (6)$$

$$\operatorname{Im} D(x_1) = \pi \operatorname{Im} P(x_1), \quad x_1 \in L, \quad (7)$$

where the function

$$D(x_1) = I\{L'\} g_1'(x_1) + I\{L\} g_2'(x_1)$$

and the operator $I\{L\}$ is given by the formula

$$I\{L\}\varphi(t) = \int_L \left[R(t, \tau)\varphi(\tau) d\tau + S(t, \tau)\overline{\varphi(\tau)} d\bar{\tau} \right].$$

On the right-hand side of system (6), (7), we have

$$P(x_1) = \frac{P_0}{\pi} \left\{ \operatorname{Re} \left[(1 + if)c(x_1) \right] - \left[(1 - if) \frac{\overline{c(x_1)}}{la(x_1)} \operatorname{Im} (\epsilon x_1 e^{-i\beta}) - if \overline{c(x_1)} \right] e^{2i\beta} \right\} - \frac{\sigma_r (1 - e^{2i\beta})}{2},$$

where

$$a(x_1) = \sqrt{1 - b^2(x_1)}, \quad b(x_1) = \epsilon x_1 e^{-i\beta} - \lambda, \quad c(x_1) = a(x_1) - ib(x_1)$$

and the kernels $R(t, \tau)$ and $S(t, \tau)$ are presented in [10]. The required functions $g_1'(\tau)$ and $g_2'(\tau)$ characterize, respectively, the derivatives of the jumps of normal and tangential displacements on the crack lips.

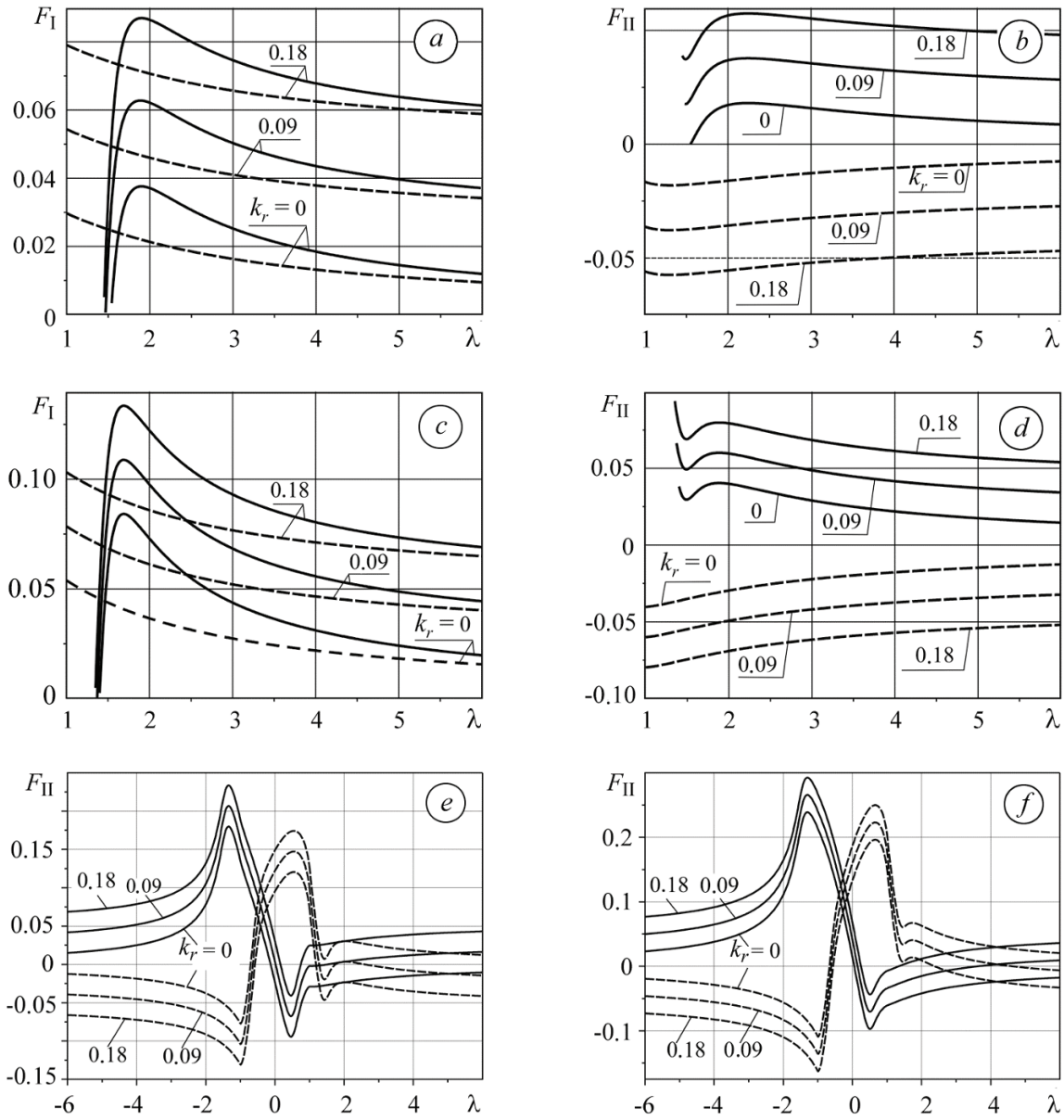


Fig. 3. Dependences of the dimensionless SIF $F_{I,II} = K_{I,II}/(p_0\sqrt{\pi a})$ for the edge rectilinear crack of relative length $\varepsilon = 0.5$ on the location of the contact load λ : $f = 0.25$ (a, b, e) and $f = 0.40$ (c, d, f). The solid lines correspond to $\beta = 25^\circ$ and the dashed lines to $\beta = 155^\circ$.

The system of equations (6), (7) is solved numerically by the Gauss–Chebyshev method of mechanical quadratures. Its solution is used to determine the stress intensity factors (SIF) according to the well-known relation from [9].

Numerical Results

The values of normalized SIF for the given direction of motion of the contact load (see Fig. 2) are obtained

for a gently sloping crack (with angles of orientation $\beta = 25^\circ$ and 155°) of relative length $\varepsilon = 0.5$ and the following friction coefficients in the case of rolling contact: $f = 0.25$ and 0.40 . The ratio of the maximum values of contact pressure p_0 and forces σ_r is described by the parameter $k_r = |\sigma_r|/p_0$. Thus, under a contact pressure $p_0 = 1100$ MPa, we have $k_r \approx 0.09$ for $\sigma_r = \pm 100$ MPa and $k_r \approx 0.18$ for $\sigma_r = \pm 200$ MPa. For comparison, we also present the data obtained in the absence of residual stresses, i.e., for $k_r \approx 0$.

In the presence of tensile residual stresses ($\sigma_r > 0$), we consider the range of the parameter λ in which the crack is open ($\lambda > 0$). As expected, these stresses increase the stress intensity factors (Figs. 3a–d). Clearly, the higher the residual stresses (and the parameter k_r), the higher the SIF. In addition, the increase in the friction coefficient in the case of rolling contact also increases the values of the SIF. It is of interest that the maximum values of the coefficient F_I are attained when the wheel is located near the crack mouth. Note that, for the acute angle of orientation β , this happens earlier than for the blunt angle (Figs. 3a and c).

In the presence of compressive residual stresses ($\sigma_r < 0$), on the basis of the accumulated numerical results, it is shown that the crack is completely close and $F_I = 0$ for the given set of operating parameters. It is also revealed (see Figs. 3e and f) that the SIF F_{II} are maximum when the wheel is located near the crack mouth: for the acute orientation angle $\beta = 25^\circ$ (when it approaches the mouth) and for the blunt angle $\beta = 155^\circ$ (when it leaves the mouth). Moreover, the higher the residual stresses, the higher the SIF F_{II} . On the other hand, as expected, the SIF increase with the friction coefficient f .

CONCLUSIONS

The analysis of the diagram of longitudinal residual stresses in the cross section of the rail enable us to detect a dangerous zone of crack initiation, namely, the subsurface layer of the rail head. This layer is characterized by the formation either of the maximum tensile residual stresses (after manufacturing of the rail) or of the maximum compressive stresses (in the process of its operation).

In the presence of tensile residual stresses, in view of the direction of motion of the contact load (from the right to the left), the surface gently sloping crack is open when the wheel approaches the crack mouth. Moreover, the stress intensity factors K_I attain their maximum value when the wheel is located near the mouth. In addition, the presence of tensile residual stresses noticeably increases the values of the SIF K_I and K_{II} . At the same time, if the crack is located in the region of compressive residual stresses, it is completely close and $K_I = 0$ for the analyzed set of operating parameters. However, as far as the SIF K_{II} are concerned, they also increase with the level of residual stresses, as in the previous case.

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