INVESTIGATION OF THE FATIGUE OF STEEL IN THE PRESENCE OF BIHARMONIC LOADING

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With certain assumptions the loading conditions of the parts of a number of structures during service can be represented as a biharmonic or polyharmonic process with constant or slowly varying amplitudes of the components. Examples are elements of aircraft and ship structures, motors, and power plants, where the frequencies of the main process of loading and periodic vibration are substantially different.

According to the literature data, with a two-frequency loading cycle (Fig. 1) the service life is shorter than with a one-frequency cycle with amplitude $\sigma_l$. The life drops more intensely than when one of the components is replaced by a static component equal to the amplitude of this component [1, 2].

Figures 2 and 3 present the results of comparative cantilever bend tests with rotation of specimens of steel 45 of 8 mm diameter with a stress raiser at the same total loads $\sigma_l = \sigma_u = 25 \text{ kg/mm}^2$, same ratio of the amplitudes of the components $q = \sigma_l/\sigma_u = 0.5$, but at different ratios of the frequencies $f = n_u/n_l$. Statistical analysis of the results shows that the life changes monotonically in a wide range of ratios of the frequencies.

The regularities of the drop of life as a function of the parameter of the form of the cycle $q$ and quantity $\sigma_l$ at a frequency ratio $f > 10$ are still inadequately explained quantitatively, although it is precisely this region of $f$ that is of greatest interest in connection with an evaluation of service life.

In this article we will consider the results of fatigue tests of flat 8 x 18 mm specimens made of steels St. 4 and 09G2 in the presence of two-frequency loading with a frequency ratio $f = 16.5$, which approximately corresponds to the ratio of the frequencies of vibratory and wave loads for the hull of ships [3].

The fatigue curves are plotted for one- and two-frequency bending (Fig. 4). For a two-frequency load the parameter of each curve was the amplitude of stress of the lower frequency: below the fatigue limit, near the fatigue limit, and near the yield point. The addition of loads was carried out as the addition of deflections, and the sum of the stresses $\sigma_l + \sigma_u$ was taken as the nominal stress.

The stresses calculated thus should be regarded as fictitious, owing to the presence of plastic deformations of the surface layers of the specimen being bent. The ratio of stresses $\sigma_l/\sigma_u$ is also taken as the nominal value, since on adding the loads in the plastic region this ratio varies in conformity with the plastic deformation curve.

The fatigue curves in plane cantilever bend tests in the case $\sigma_l = \text{const}$ and $\sigma_u = \text{var}$ represent a pencil of rays, the focus of which is located in the service-life region of $0.6-1.2 \times 10^5$ cycles with respect to the lower frequency. This is because with a two-frequency load the absolute change of life are small in the low-cycle region.

We see from Fig. 5 that the dependence of the exponent of the slope angle of the fatigue curve $m$ in logarithmic coordinates on

the parameter $\sigma_1$ in the first approximation can be considered linear. The exponent of the slope angle of the fatigue curve for two-frequency loading can be expressed by the equation

$$m' = m - c\sigma_1.$$  

(1)

The fatigue curve for a two-frequency bending load has the form

$$N(\sigma_\phi, \sigma_1) = N_\phi \left(\frac{\sigma_1}{\sigma_\phi}\right)^{m - c\sigma_1},$$

(2)

where $N_\phi$ and $\sigma_\phi$ are the coordinates of a point at which the family of fatigue curves intersects; $c$ is a constant; according to the experimental data for two types of specimens and two grades of steel $c = 0.2 - 0.3 \text{ mm}^2/\text{kg}$. The expression obtained permits determining the life at different ratios of amplitudes $\sigma_1$ and $\sigma_\phi$ of bending stresses, including values at which tests were not conducted. Such an estimate is approximate, since the interval in which the values of the parameters $N_\phi$, $\sigma_\phi$, and $c$ are located is rather wide.

In view of the known complexity of interpreting the results of cyclic bend tests in the region of elastoplastic deformations, especially with loading over complex trajectories, we carried out tension-compression tests of the same specimens under rigid deformation conditions. During the course of testing each specimen the range of deformations of the upper frequency component $\varepsilon_\phi$ and the range of total deformation $\varepsilon_t$ were kept constant. The tests were carried out in the region $\varepsilon_t = 0.04 - 0.5\%$ at $f = 16.5$. The main fatigue curve for the one-frequency loading cycle (Fig. 6) is described by the equation

$$\varepsilon^{3.31} N = 173.$$  

(3)

Of interest is the calculated estimate of the life in the presence of a two-frequency load in terms of the parameters of the one-frequency fatigue curve. This can be accomplished on the basis of formal considerations following from the hypothesis of a linear accumulation of damage.

We express the average relative damage per cycle with one-frequency loading by the relation

$$d = \frac{1}{N} = \frac{\varepsilon^n}{C},$$

(4)

where $\varepsilon$ is the total deformation; $N$ is the life; $C$ and $m$ are parameters of the fatigue curve. With a complex form of the cycle the effect of accumulation of damage can be ascribed to the ranges of deformation of each of the components, the range of their sum, or some other combination of $\varepsilon_\phi$ and $\varepsilon_t$. The relative