Consideration of residual stress fields in stiffening ribs welding

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Abstract. The article gives information on the technique for determining the fields of residual welding stresses in the area of the welded stiffening rib. The rib is modeled by an elliptical insert. Methods of the mathematical theory of elasticity, in particular, complex potentials, are used. It is assumed that in the plate, in the absence of a reinforcing rib, a homogeneous stress state is created. The rib welding induces perturbation of the homogeneous stress field. The boundary condition on the reinforcing rib, corresponding to the absence of displacements on its boundary, can be written with complex potentials. An example of a decrease in the stress concentration factor in a plate with a circular hole under conditions of uniform tensile during the welding of the rectilinear stiffening rib is given.

1. Introduction
Welding is widely used in the manufacture of various engineering structures. The welding leads to the occurrence of residual stresses, distortions and microstructural changes in the connected elements of the structures [1–3]. The residual stress fields can significantly affect the operational characteristics and working capacity of the metal structure. For their regulation, various methods are currently used [4–11].

The effect of laser processing parameters on the welded seam using scanning electron and optical microscopes was studied in [4]. An impulse laser was used to weld sheets of an alloy of various metals (including titanium and aluminum) 1.6 mm thick. It is established that induced residual stresses lead to deformation of plates only less than 1.0 mm thick. The transverse residual stresses, present at different depths below the surface, lead to the fact that the strength of the welded specimen becomes almost equal to the strength of the base metal.

Experimental studies and thermomechanical modeling of the effect of laser welding on the residual stress and deformation of thin stainless steel sheets of the process of laser welding of stainless steel plates are considered in [5]. In particular, the accuracy and reliability of the residual stress prediction were increased by taking into account the different thermal effects in the numerical model using the adaptive grid method. X-ray diffraction was used to measure surface and internal residual stresses.

The influence of residual stresses on the growth of a fatigue crack in a welded seam was investigated in papers [6, 7].

Thus, it was shown in [6] that the residual compressive stresses on the surface resulting from the state of plane stress can lead to a slowing of the growth rate of crack fatigue on the specimen surface.

The paper [7] also showed that fatigue cracks did not occur where only compressive stresses acted. It has been established that tensile stresses have a major influence on crack growth. The study was
carried out by conducting 19 full-scale tests, which were carried out on six types of orthotropic steel decks with different structural parameters.

The influence of various methods of processing the weld seam after welding on residual stresses was studied in [8]. The influence of the material strength characteristics, residual stresses, the weld seam profile and loading conditions on the increase of the fatigue strength of engineering structures was investigated.

In [9] the effect of surface bulk defects located near the welded seam on the strength and residual life of pipelines was investigated. It is suggested when analyzing the residual stress fields to combine the results of an experimental study of the stress-strain state and analysis by the finite element method using a full-scale model. As a result, it was found that when assessing the remaining life of the pipeline, it is necessary to take into account the peculiarities of the relative position of the defect and the welded seam, as well as the features of the welded seam material.

Usage of a combination of numerical analysis and the results of experimental studies to simulate the welding process was described in [10]. The numerical analysis was carried out by the finite element method, and the experimental measurement of the temperature fields – by a thermocouple.

2. Solving method.

Stiffening ribs, which are the most common elements of various structures and intended to increase strength, reduce weight or optimize shape are mostly fixed by welding, residual stresses in a continuous structure usually do not have a significant effect on its strength.

However, the role of residual stresses increases sharply if there is a presence of a stress concentrator in the rib weld region. Along with the reduction in stress concentration due to unloading the concentrator, additional residual stresses caused by welding are added to the structure. In this context, the total stress field consists of three components: the stress concentration field, the unloading stress field near the stiffening rib and the field of residual welding stresses.

Let us consider the residual stresses caused by welding an absolutely rigid elliptical inclusion.

Let us suppose that there is a soldered absolutely rigid fixed rib in the plate. The rib is modeled by an elliptical insert having the same thickness as the plate. It does not take into account the eccentricity of the structure deformation. In addition, further calculations do not consider the stresses in the corners of the rib.

This is due to the fact that at present there is sufficient experience of design and technological developments on the use of stiffening ribs, ensuring their safe operation in real structures. Therefore, in this paper we consider residual stresses outside the rib itself, where the effects of eccentricity of deformation and the presence of corner points are smoothed out. It is assumed that in the plate, in the absence of reinforcing rib, a homogeneous stress state is created.

The stiffening rib induces perturbation of the homogeneous stress field. The boundary condition on the reinforcing rib, corresponding to the absence of displacements on its boundary, can be written with complex potentials:

$$\mu \varphi(t) - t\bar{\varphi}(t) - \psi(t) = 0,$$

where $\mu = \frac{3 - \nu}{1 + \nu}$ – the elastic constant of the plate material, connected with the Poisson’s ratio; $t$ – the complex coordinate of the point on the rib boundary; $\varphi(t)$, $\psi(t)$ – the boundary values of the potentials.

A function that conformally maps the exterior of the rib to the exterior of the unit circle has the form:

$$z = \omega(\xi) = R(\xi + m/\xi),$$
where $z = x + iy$ – the complex coordinate of the plate point outside the rib; $\xi$ – the complex variable of the domain outside the unit circle, $a = 2R(1 + m)$ – the larger rib size; $b = 2R(1 - m)$ – the smaller rib size.

The $OX$ axis is directed along a larger rib size, the $OY$ axis – along a smaller, the origin is located at the rib center. The orientation of the coordinate axes is shown in figure 1.

The residual stress field can be determined by solving the plane elasticity problem of the stress state of a plate with a circular hole of radius $R$, into which a circular flat insert is installed with a given interference $g(z)$ (where $z$ – the variable of the complex plane coinciding with the plate).

The displacement jump with sufficient accuracy for practical calculations, reflecting the stress-strain state of the structure after closing the hole, is expressed by the formula [12]:

$$\theta \Delta \theta \Delta \theta = \sin \cos \frac{2i g}{\Delta_1} + \frac{\Delta_2}{\Delta_1} \sin \theta,$$

where $\theta$ – the polar coordinate of the contour point of the unit circle; $\Delta_1$, $\Delta_2$ – the longitudinal and transverse shrinkage of the welded joint or edge displacement of the fiberglass insert when the glue hardens (determined experimentally or by special methods).

3. Numerical Results and Discussion

Figure 2 shows the results of calculating the normal stresses $\sigma_x$ in a plate with a circular hole and a rectilinear rib (the ellipse parameter is $m=1$).

The plate is stretched by a uniformly distributed load $p = 0.2\sigma_T$, directed along the rib ($\sigma_T$ – is the limit of stretching strain of the plate material). The radius of the hole is $r = 2R$, length of the rib is $l = a = 2r = 4R$.

The dashed line is the stress diagram $\sigma_x$ along the $x=0$ line, without taking into account the rib welding. Stress concentration factor is $k_T = 3$. The solid line – the stress diagram $\sigma_x$ along the $x=0$ line, taking into account the residual welding stresses of the rib welding. Stress concentration factor is $k_T = 1.59$.

4. Conclusion

Analyzing the residual stress fields in the rib welding in cases, where the weld seam received only longitudinal or only transverse shrinkage, it can be concluded that the stress field can vary
considerably both qualitatively and quantitatively with different proportions of longitudinal and transverse shrinkage.

![Image of normal stresses in a plate with a circular hole and a rectilinear rib](image)

**Figure 2.** The normal stresses in a plate with a circular hole and a rectilinear rib (the ellipse parameter is $m=1$): 1 – plate; 2 – rib.

The values of shrinkage and the ratio between them can be changed by changing the technological welding modes, electrodes, welding types. Thus, it is possible to obtain various residual welding stress fields from the welding of the stiffening rib, which, in combination with external load and stress concentration, can significantly increase the strength of structures.

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