Assessment of the bearing capacity of welded joints for an arbitrary character of failure

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Abstract. In this paper, we propose one of the approaches to assess the load-bearing capacity of metal structures for an arbitrary type of failure based on the use of interpolation-type criteria based on the principle of boundary interpolation. This approach allows for the standardization of defects taking into account their location, sharpness at the top, as well as the properties of the base metal or welded joints. The use of the calculated ratios that have been experimentally confirmed during the testing of welded joints with surface defects allows us to estimate the range of their admissible sizes that do not lead to a decrease in operating loads acting on welded metal structures during their operation, proceeding from ensuring the required level of allowable stresses. This range of permissible defect sizes is determined by a number of parameters characterizing the type of defect, the mechanical properties of the weld metal, the type, stiffness and concentration of the stressed state, the thickness of the metal structures, the operating conditions (temperature T), and the accepted safety factor.

The standardization of defects in welded metal structures, as a rule, is based on the methods of calculating their load-bearing capacity, taking into account the alleged failure mechanism during operation. In this case, the procedure for determining the permissible defect sizes is carried out proceeding from the realization of the case, which is the most unfavorable from the point of view of loss of the bearing capacity, corresponding to the minimum level of destructive stresses [1-3]. This approach to the standardization of defects contributes to a significant increase in the amount of repair work, which leads to an increase in the cost and timing of manufacturing or repair.

Recently, when assessing the load-carrying capacity of metal structures, widely used methods of calculation based on the application of interpolation-type criteria based on the principle of boundary interpolation. In accordance with this approach, the solution for intermediate states is represented in the form of interpolation relations between known boundary interpolations corresponding to two alternative mechanisms of fracture: brittle and viscous. The use of this approach allows, in our opinion, to carry out the rationing of

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defects taking into account their location, sharpness at the top of the defects, as well as the properties of the base metal or welded joints.

At the heart of the proposed solution is one of the criteria of the interpolation type [4], taking into account the mixed nature of the destruction of metal structures during their operation

$$\left(\frac{\Lambda_i}{\Lambda_\rho}\right)^s + \left(\frac{K_I}{K_{IC}(\rho)}\right)^{2s} \leq 1, \quad (1)$$

where s is the interpolation parameter (as a rule, $s = 2$); $K_{IC}^*(\rho)$ is the critical stress intensity factor (the fracture toughness of the structural metal or welded joint); K_I is the stress intensity factor, which can be represented in the following form [5]

$$K_I = \sigma_{nom} \sqrt{\frac{\pi}{2} l} \cdot f_K \cdot f_M \cdot f_{III} \cdot f_\rho, \quad (2)$$

where σ_{nom} the nominal stresses in the wall of the metal structure; l - size (depth) of the defect in the thickness direction of the metal structure t ; f_K - correction for the thickness of the metal wall ($f_K = \sqrt{\sec\left(\frac{\pi l}{2t}\right)}$ - Federsen's amendment [5]); f_M - correction for the location of the defect ($f_M = 1.12$ - for the surface defect, $f_M = 1$ - for the internal defect, [5]) (Figure 1).

Fig. 1. Fragment of a welded joint with an internal concentrator of finite radius (a) and surface non-fusion at the fusion boundary (b): (T) is the base metal; (M) - welded seam.

f_{III} - correction for plasticity, taking into account the features of the formation of the plastic zone in the vicinity of the top of the defect.

For homogeneous welded joints in accordance with the approach [3], the correction f_{III} can be obtained on the basis of the calculation scheme shown in Figure 2.

$$f_{III} = \left[\frac{\cos^2 \theta}{1 - \cos \theta} + \frac{1}{4} \left(\frac{1}{\cos \theta} - \cos 2\theta \right) \right]^{-\frac{1}{4}}, \quad (3)$$

where θ is the slope angle of the wedge-shaped plasticity zone in the vicinity of the vertex of the defect (for the case of plane deformation $\theta = \pm \frac{\pi}{4}$, $f_{III} = 0.84$).

Fig. 2. Calculation scheme for the account of the plastic zone in the vicinity of the vertex of the defect

The correction for the sharpness of the defect f_p in determining the stress intensity factor K_I was obtained on the basis of an adjustment of the Griffiths solution by taking into account the dependence of the size of the unloading zone above and below the defect on the radius value in the vicinity of its vertex [3]

$$f_p = \left[1 - \frac{(\pi - 2)(2 - \sqrt{2})}{\pi} \frac{2\rho}{l} - \frac{(\pi - 1) - (\pi - 2)(2 - \sqrt{2})}{\pi} \left(\frac{2\rho}{l} \right)^2 \right]^{1/4}. \quad (4)$$

For crack-like defects such as faulty fusion, undercuts, with an internal concentrator of finite radius and the like $f_p \approx 1$.

The critical stress intensity factor K_{IC} , also depends on the sharpness at the vertex of the defect and for the case under consideration can be determined taking into account the following relation [3]

$$K_{IC}(p) = K_{IC} \cdot F_p, \quad (5)$$

where F_p is the correction for the sharpness of the defect in determining K_{IC}

$$\begin{cases} F_p = \sqrt{\rho/\rho_0}; \quad \rho_0 = 0,08r_p; r_p = \frac{1}{6\pi} \left(\frac{K_{IC}}{\beta\sigma_0} \right)^2; \quad \text{at } \rho > \rho_0 \\ F_p = 1, \quad \text{at } \rho \leq \rho_0 \end{cases} \quad (6)$$

The parameters in the left parenthesis of relation (1), Δi and Δp , describe the boundary of the interpolation range corresponding to the viscous destruction of the compounds in question with a concentrator (defect).

The value of Δi , characterizing the level of accumulated damage in the vicinity of the vertex of the concentrator, was determined in accordance with [3,5], taking into account the effect of stress concentration in the vicinity of the vertex of the defect [6]

$$A_i = 0,278 \frac{K_1^2 K_\sigma^2}{\sigma_T E \rho}, \quad (7)$$

where K_σ is the stress concentration coefficient in the vicinity of the vertex of the defect of finite radius [7].

$$K_\sigma = 1 + 2\sqrt{\frac{1}{2\rho}} \quad (8)$$

The value of Λ_ρ , which characterizes the limiting stock of ductility of the metal of the construction or welded joint, was determined on the basis of the results of [8], according to this paper, the plasticity diagram can be represented as an exponential function $\Lambda_\rho = \Lambda_0 e^{-\alpha \Pi f(v_\sigma)}$ (where Λ_0 is the plasticity margin for pure shear, that is, for $\Pi = 0$). In accordance with this, a relation was obtained that allows for the parameters of the

approximated curve of material deformation $\sigma_i = \sigma_T \left(E \frac{\varepsilon_i}{\sigma_T} \right)^m$: m (index of hardening of the material), E and σ_T (modulus of elasticity and yield stress) and parameters Π and v_σ , determining the scheme and nature of the loading, to estimate the stock of ductility of the metal

$$\Lambda_\rho = \frac{2m}{1-m} e^{-\frac{\Pi}{2\pi} f(m, \frac{E}{\sigma_T}, v_\sigma)}, \quad (9)$$

where

$$f(m, \frac{E}{\sigma_T}, v_\sigma) = \ln \left(\frac{m}{10\pi} \frac{E}{\sigma_T} [1 + \pi - \arccos(\frac{v_\sigma}{3})]^{-2} \right). \quad (10)$$

The index of hardening of the material m that enters into this relation (10) can be determined from the known value of the limiting uniform strain ε_ρ [9]

$$\varepsilon_\rho = \ln \left(\frac{1}{1-\psi} \right). \quad (11)$$

Where ψ is the relative narrowing of the material .

$$m = \frac{\varepsilon_\rho}{2}. \quad (12)$$

The value of Π , which determines the rigidity of the stress state in the most loaded part of the structure, depends on a number of factors [3]. In particular, in the vicinity of the vertex of a crack-like defect, under the conditions of plane deformation $\Pi = 4.14$. Value v_σ - an indicator of the form of the stress state in the pre-destruction zone (for the case of

plane deformation, which is realized in the vicinity of the vertex of the concentrator, $v_{\sigma} = 0$).

In accordance with the interpolation approach, based on the ratio (1), we can estimate the level of nominal stresses σ_{HOM} in the wall of the metal structure weakened by the defect

$$\tilde{\sigma} = \frac{\sigma_{HOM}}{\sigma_T} \leq \frac{3,2}{f_m} \sqrt{\frac{\rho/t \left[\frac{\cos(\pi l / 2t)}{l/t} \right]}{\frac{K_{\sigma}^2}{\Lambda_p} \cdot \frac{\sigma_T}{E} + 0,015}} \tag{13}$$

Figure 3 shows the curve $\sigma_{HOM}/\sigma_T = f(l/t)$, constructed taking into account the relations (2) - (12), characterizing the load-carrying capacity of welded joints made of steel BCт.3пс (analogue: USA A570-36; Germany RSt37-2) (thickness $t=20$ mm by mechanized welding in shielding gas (CO2) medium by a filler wire Cв-08Г2С (analogue BÖHLER, Austria EML5; LINCOLN, USA Lincolnweld L50 SUPRA MID) diameter 2 mm.

Fig. 3. Comparison of calculated and experimental data on the evaluation of the strength of welded joints with surface defects from steel BCт.3пс:
 — the relation (12), ● - experiment at – T = 213K.

Experimental data obtained during testing of welded flat samples with a surface defect located in the central plane of the welded seam are also presented here. The defect was applied mechanically (the radius at the vertex $\rho = 0.1 \dots 0.14$ mm, the depth of the defect $l=1\dots8$ mm ($l/t=0,05\dots0,4$). Tests of the samples were carried out at a temperature of $T=213K$ ($T= -60^{\circ}C$). The strength characteristics of the weld metal at the test temperature were respectively $\sigma_B=400$ MPa and $\sigma_T =300$ MPa.

As can be seen, the use of interpolation-type criteria in assessing the bearing capacity of welded joints with a defect provides an acceptable convergence of the calculated and experimental values of the strength of welded joints with a surface defect.

The resulting relation (12) allows us to estimate the range of permissible defect sizes $[0; (l/t)_0]$, which do not lead to a decrease in the operational loads acting on welded metal structures during their operation, based on ensuring the required level of permissible stresses $[\sigma] = \sigma_T / n$ (where n is the safety factor for the yield strength, $n = 1.3 \dots 1.6$). For example, for the welded joints of steel VS.sub.3p.s under the conditions of operation of metal structures ($T = -600$ C.) and the level of permissible stresses $[\sigma] = 0,66\sigma_T$ ($n=1,5$), the range of permissible sizes of surface defects $[0; (l/t)_0]$ with a radius at the vertex (0.1 ... 0.14 mm) is in the interval $[0; 0,1]$ (see Figure 3).

Mathematically allowable range of defect sizes for the case under consideration can be represented by the following relation

$$0 \leq \left(\frac{l}{t}\right)_0 \leq 10 \frac{\Lambda_p}{f_M} \frac{E}{\sigma_T} \frac{\rho}{t} \frac{n^2}{K_\sigma^2}. \quad (14)$$

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