APPLICATION OF FRACTURE MECHANICS APPROACHES FOR PERFECTION OF STRENGTH CALCULATIONS OF WELDED JOINTS AND STRUCTURE MEMBERS

V.I. MAKHNENKO

The E.O. Paton Electric Welding Institute,
Academy of Sciences of Ukraine
11 Bozhenko Str., Kiev, 252650, Ukraine

ABSTRACT

The paper deals with basic approaches used by a team of researchers headed by the author for the perfection of methods of designing and calculation of strength of welded joints and structure members operating at static or cyclic loading. The algorithm of calculation of overlap joint with a single-row spot weld is given.

KEY WORDS

Two-parameter criterion, stress intensity, stress intensity coefficient, fracture toughness, modular principle, information data banks, calculation assurance.

The continuously growing requirements to the increase of reliability and life of welded structures at reduction of their metal content, labour and energy consumption in fabrication make considerably more critical the strength calculations for welded joints and structure members.

The statistics shows that approximately 90 % of welded structure failures are due to the presence of geometric or physical heterogeneities of a design or technological nature. The accounting for the mentioned heterogeneities at the presence of complex fields of residual stresses and those from external load is a rather complicated problem for the available classical methods of calculation of welded joints and members. This fact attracted an increased interest to the new methods of calculation based on the updated achievements of the numerical methods of stress-strain state analysis, fracture mechanics, informatics, in combination with the appropriate computer service. The present paper describes the main approaches to this problem developed by the team of researchers headed by the author. These approaches envisage the computerization of all basic stages of designing typical welded joints and members, starting from the selection of rational design solutions, obtaining of necessary characteristics of weld and HAZ materials, data on value and distribution of residual stresses, i.e. from the initial information for the subsequent stages of calculation of forces (stresses), coefficients of stress intensity, evaluation of limiting states at either conditions of loading and types of fracture, optimizing typical sizes and determining quantitative characteristics of calculation assurance at pre-set variations of initial parameters.

The scheme of the developed approaches is given in Fig. 1. It is seen that the information part is presented by three data banks: "Typical welded joints and members", "Mechanical properties of welded joints" and "Residual welding stresses". It is natural that when necessary this part can be added by another information related to the strength calculation of welded joints and members.

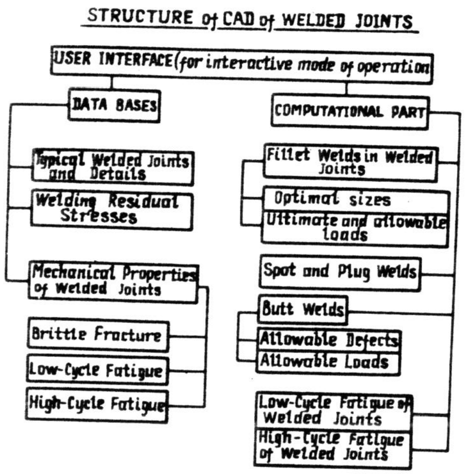

Fig. 1. Structure of the computerized system of welded joint designing.

The second part of the scheme of Fig. 1 concerns the stress calculations and contains the concrete calculation systems for such joints and members including the calculation of local characteristics of stress-strain state, determination of limiting states at static and cyclic loading, the evaluation of the calculation assurance and so on.

The third part provides the algorithms of optimization of typical sizes in welded joints and members on the basis of first two parts and corresponding optimization criteria. Since the considerable part of the typical welded joints and members included into the data bank have the design (or of technologi-

cal nature) sharp cavities of a crack-like type (Fig. 2) then the known approaches of fracture mechanics of bodies with cracks were used for evaluating the limiting states. At static loading the limiting state in the apex of the mentioned crack is determined on the basis of the two-parameter criterion, suggested by Vasilchenko, et al. (1979)

$$\left(\frac{\sigma_i^{max}}{\sigma_p}\right)^{q+1} + \left(\frac{K_{\omega\theta}^{max}}{K_{Ic}\cdot \eta}\right)^2 = 1, \qquad (1)$$

where σ_i is the intensity of nominal net stresses at the crack apex, is the characteristics of limiting state of material at tough fracture (e.g., with a certain conservativeness $\sigma_p = \sigma_в$ - is the ultimate strength of material), $K_{\omega\theta}$ is the value of coefficient of stress intensity by the theory of the generalized normal rupture determined by the relation from the work of Andreikiv (1982).

$$K_{\omega\theta} = (K_I + K_I^r)\cos^3 \omega/2 \cos^2\theta - 3(K_{II} + K_{II}^r)\sin \omega/2 \cdot$$
$$\cdot \cos^2 \omega/2 \cos 2\theta + (K_{III} + K_{III}^r)\cos \omega/2 \sin 2\theta \qquad (2)$$

where K_I, K_{II}, K_{III} are the coefficients of the stress intensity from the external load for the apex of the cavity under consideration, K_I^r, K_{II}^r, K_{III}^r is the same from the residual welding stresses.

The extreme values $K_{\omega\theta}^{max}$ correspond to the values of angles $\omega = \omega_*$ and $\theta = \theta_*$ determined from the system of equations.

$$\left.\frac{\partial K_{\omega\theta}}{\partial \omega}\right|_{\omega=\omega_*} = 0 \ , \qquad \left.\frac{\partial K_{\omega\theta}}{\partial \theta}\right|_{\theta=\theta_*} = 0 \qquad (3)$$

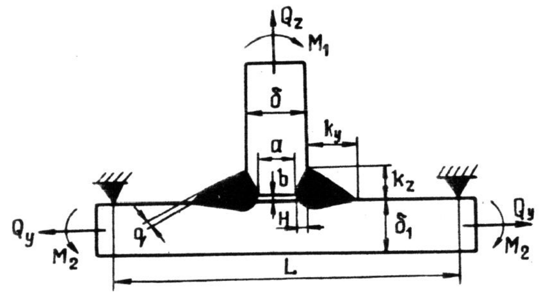

Fig. 2. Example of joint with sharp cavities.

In (1) K_{Ic} determines the material fracture toughness, η is the correction taking into account to a certain extent the fact that the cavity under consideration differs from the crack in the conditions of plane deformation. The following approximated relationships are used for $\eta \geq 1{,}0$.

$$\eta = \eta_1(r)\cdot\eta_2(h) \tag{4}$$

$$\eta_1 = 1, \text{ if } r<r_0 \qquad \eta_2 = 1, \text{ if } h>h_m = \left(\frac{K_{IC}}{\sigma_T}\right)^2 1{,}75$$
$$\eta_1=\sqrt{r/r_0}, \text{ if } r>r_0 \qquad \eta_2=\sqrt{h_m/h}, \text{ if } h<h_m. \tag{5}$$

Here, $2r$ is the width of adjacent cavity, r_0 = 0.1 mm, σ_T – yield strength of material, h is the typical geometric size. In (1) the first term characterizes the tough fracture and, therefore, does not contain the residual stresses which have time to completely relax at tough fracture long time before fracture. The value q is usually assumed equal to 1, however, at small toughness of materials the value q is equal to 3 or even 5 for increasing the role of the addend in (1). Fig. 3 gives the typical results of comparison of limiting state curves obtained by criterion (1) at different q and known CEGB two-parameter criterion, suggested by Harrison (1980).

$$\frac{K_I^{max}}{K_{IC}} - \frac{\sigma_i^{max}}{\sigma_p}\left\{\frac{8}{\pi^2}\ln\sec\left(\frac{\pi}{2}\,\frac{\sigma_i^{max}}{\sigma_p}\right)\right\}^{-1/2} = 0 \tag{6}$$

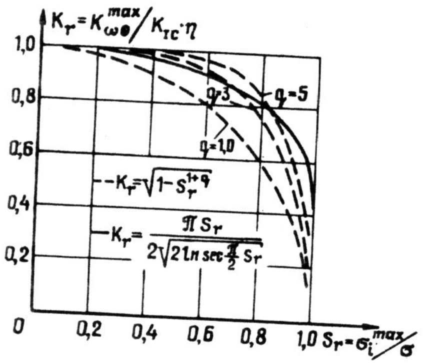

Fig. 3. Comparison of two-parameter criteria.

It follows from these data that at q = 1 criterion (1) gives more conservative estimations as compared to (6), that is, however, compensated to a certain extent by visualization and accessibility for the engineering sensing of criterion (1) plotted by sufficiently widely spread in practice the approximated principle of summing failures. It is natural, that the criterion (1) can be replaced by any other one based on ratios σ_i^{max}/σ_p and $K_{\omega\theta}^{max}/K_{IC}$, without essential changing the principal scheme of strength calculation.

At cyclic loading for joints with adjacent sharp cavities the following condition is used as criterion of the limiting state

as dissimilar joint of stainless steel (j=1) and low-carbon steel (j=2) at σ_p = 310 MPa, σ_T = 250 MPa for parent metal and σ_p = 400 MPa, σ_T = 300 MPa for HAZ, K_{IC} = 1200 N/mm$^{3/2}$, δ = 1.5 mm, R = 3.5 mm. Estimated and experimental data are correlated well.

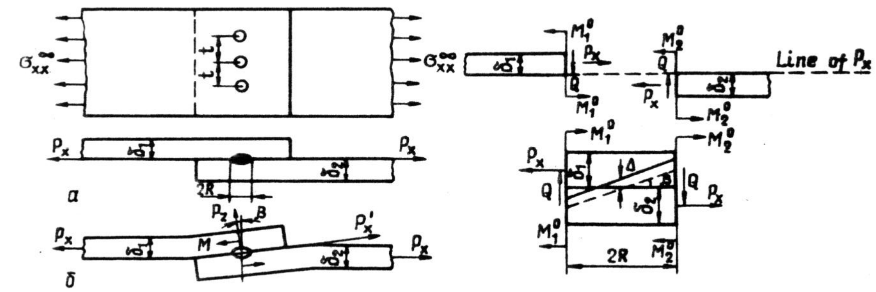

Fig. 4. Scheme of welded joint with a single-row spot weld

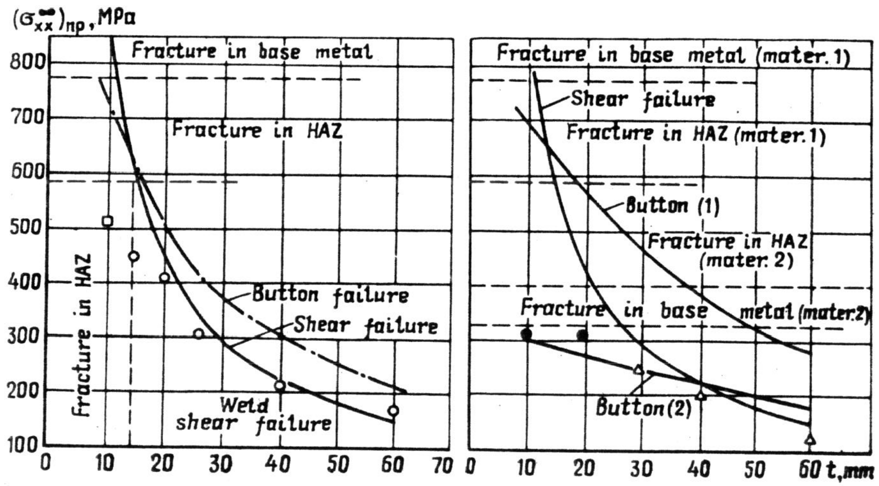

Fig. 5. Comparison of estimated and experimental data.

$$\left(\frac{\Delta K_{\omega\theta}}{1-\bar{\alpha}\, r_\sigma}\right)^{max} < \Delta K_{th} \qquad (7)$$

where $\Delta K_{\omega\theta}$ is determined by (2) depending upon the ranges of coefficients of stress intensity from external load ΔK_I, ΔK_{II}, ΔK_{III}, $r_\sigma = K^{min}_{\omega\theta} / K^{max}_{\omega\theta}$, where $K^{min}_{\omega\theta}$ and $K^{max}_{\omega\theta}$ are determined by (2) taking into account the appropriate residual stresses at corresponding values of external load and values $\omega = \omega_*$ and $\theta = \theta_*$, determined from the conditions of extremity of the right part (5), i.e.

$$\frac{\partial}{\partial\omega}\left(\frac{\Delta K_{\omega\theta}}{1-\bar{\alpha}\, r_\sigma}\right)\bigg|_{\omega=\omega_*} = 0 \; ; \; \frac{\partial}{\partial\theta}\left(\frac{\Delta K_{\omega\theta}}{1-\bar{\alpha}\, r_\sigma}\right)\bigg|_{\theta=\theta_*} = 0 \qquad (8)$$

In (6) $\bar{\alpha}$ and ΔK_{th} are the experimental characteristics of materials.

In calculations for a limited life the traditional approach is used in which the number of cycles N before fracture is determined by a sum

$$N = N_i + N_p \qquad (9)$$

where N_i is the number of cycles before fatigue crack initiation, N_p is the number of cycles of fatigue crack growth up to the critical sizes ℓ_c. For welded joints with adjacent sharp cavities of the type, given in Fig. 2, the value N_i can be neglected as compared to N_p. The experimental data for fatigue crack growth rate are used for N_p determination

$$\frac{d\ell}{dN} = f(\Delta K, K^{max}) \qquad (10)$$

depending upon the range of stress intensity coefficients K^{max} and ΔK, i.e.

$$N_p = \int_0^{\ell_c} \frac{d\ell}{f(\Delta K_{\omega\theta}, K^{max}_{\omega\theta})} \qquad (11)$$

Below, the algorithm is given, as an example, for calculation of static and cyclic strength of overlap welded joint with a single-row spot weld used in the system of designing welded joints with spot welds. Fig. 4 shows the scheme of the joint of dissimilar metals and forces acting on one welded spot of the weld. These are shear force P'_x, rupture force P_z and moments M^o_1 and M^o_2. There is an algorithm of calculation of these forces and moments, as well as the angle of rotation $\beta (M = M^o_1 + M^o_2)$.

At static loading four types of fracture, shown in Table 1, are provided. It also gives relationships for σ_i, K_I and K_{II}, used in (1) for evaluation of the limiting state. Fig. 5. shows results of calculation in comparison with experimental data from work of Ueda, et al. (1970) for evaluating limiting stresses depending upon pitch at static loading of the homogeneous joint of X18H8 stainless steel at σ_p = 775 MPa, σ_T = 425 MPa, K_{Ic} = 1200 N/mm$^{3/2}$ δ = 1.5 mm, R = 3.5 mm, as well

Table 1. Relationships for σ_i, K_I and K_{II} at four types of fractures

N	Type of fracture	Dependence for σ_i	Dependence for K_I	Dependence for K_{II}
1	Shear of spot	$\sqrt{\left(\frac{P_z}{\pi R^2}+\frac{3M}{4R^3}\right)^2+3\left(\frac{P'_x}{\pi R^2}\right)^2}$	$\frac{P_z}{2\sqrt{\pi}R^{3/2}}+\frac{3M}{2\sqrt{\pi}R^{5/2}}$	$\frac{P'_x}{2\sqrt{\pi}\, R^{3/2}}$
2	Break away of spot from first (j=1) or second (j=2) plate	$\sqrt{3\left(\frac{P_z}{2\pi R\delta_j}+\frac{M}{4R^2\delta_j}\right)^2+\left(\frac{P'_x}{t\delta_j}\right)^2}$		
3	In HAZ of first (j=1) or second (j=2) plate	$\frac{P_x}{t\delta_j}$	0	0
4	In parent metal of first (j=1) or second (j=2) plate	$\frac{P_x}{t\delta_j}\left(1+4\frac{M^o_j}{P_x\delta_j}\right)$	0	0

The same joints were also calculated for cyclic loading σ^{∞}_{xx} at r_σ = 0. By criterion (6) the limiting load $P_{x\,np.}$ was determined, at which the fatigue crack is not initiated. The corresponding comparison of calculations with experiment made by Ueda, et al. (1970) for similar and dissimilar joints is given in Fig. 6 at ΔK_{th}= 216 N/mm, and 178 N/mm, respectively. In accordance with calculations, $P_{x\,np}$ does not depend on t (dash lines in Fig. 6), while an experiment states this relationship on the base of N = 10^6 cycles at small $t<6R$ that is seldom used in practice.

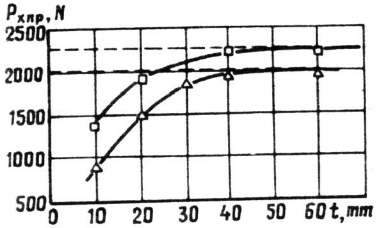

Fig. 6. Comparison of estimated and experimental data at cyclic loads.

The application of algorithm of limited fatigue (8)-(10) permits to reveal the effect of pitch t. Here, the process of crack growth is studied in two stages. At the first stage, the semi-elliptical crack is initiated from the cavity, adjacent to the spot, by using (10) and Table 1. The number of cycles N before initiating this crack is determined by typical for its size a_o = 0.2 mm [5]. At the second stage, the growth of the semi-elliptical crack occurs up to the critical size a_c, determined by the condition (1). Here,

$$(\Delta K_I)_j = \sqrt{\pi a_j}\left[\frac{\Delta P_x}{\delta_j t} f_{\sigma j} + 6\,\frac{\Delta M_j^o}{\delta_j^2 t} f_{Mj}\right]$$

$$\Delta K_{II} = \Delta K_{III} = 0$$

$$f_{\sigma i} = \frac{1{,}12 + 5\,(a/\delta)_j^4}{[1-(a/\delta)_j]\,\varphi_{oj}} \quad \text{at} \quad (a/\delta)_j < 0{,}55$$

$$f_{\sigma i} = \frac{0{,}303\,[1+3{,}03\,(a/\delta)_j]}{\varphi_{oj}\sqrt{(a/\delta)_j[1-(a/\delta)_j]^3}} \quad \text{at} \quad (a/\delta)_j > 0{,}55 \qquad (12)$$

$$f_{Mj} = \frac{0{,}7}{\varphi_{oj}\sqrt{\pi}}\sqrt{(a/\delta)_j\{[1-(a/\delta)_j]^{-3} - [1-(a/\delta)_j]^3}$$

$$\varphi_{oj} = \int_0^{\pi}\{1-(1-a_j^2/\ell_j^2)\sin^2\theta\}^{0,5}d\theta \qquad (1 \le \varphi_{oj} \le \pi/2)$$

where ℓ_j is the length of the surface crack. Fig. 7 gives the results of calculations in comparison with the experiment from [4] on life of the above-mentioned similar and dissimilar joints depending on σ_{xx}^{∞} and t. It is seen that the increase of t decreases the limiting load σ_{xx}^{∞} at the preset life N. This reduction is especially evident at small t and gradually equalizes with increase of t.

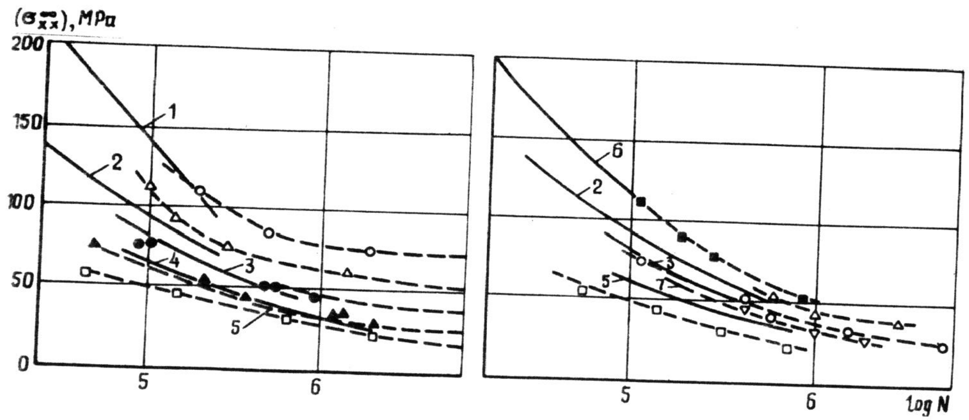

Fig. 7. Comparison of estimated and experimental data on joint life.

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