COMPUTER SYSTEM FOR CALCULATION OF WELDED JOINTS WITH FILLET WELDS

T.G. RYABCHUK

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

ABSTRACT

The paper describes the main calculation approaches used in the developed computer system of strength analysis of the welded joints with fillet welds. The degree of validity of the calculated data on ultimate load is shown on separate modules in comparison with the experimental results, algorithms for optimization of dimensions and assessment of the assurance of fillet weld calculation are presented.

KEYWORDS

Fillet welds, limiting state, static load, cyclic load, optimum dimensions, calculation assurance.

Use of computers in the design of welded joints and components is one of the most complicated fields of engineering activity computerization in welding production. This complexity is attributed to the need to coordinate the design results with the codes in force, which, in turn, incorporate the state-of-the-art.

In this connection the designers of the welded joints are faced with an urgent task of developing and trying out the new approaches based on the capabilities which have been essentially broadened by mass computerization.

Over the last years the E.O.Paton Electric Welding Institute has been conducting an active search in this field.

Since the welded joints with fillet welds are the most widely accepted ones, attention was first of all directed to the elaboration of the calculation system for such joints.

The system enables to solve a whole range of tasks, such as:
- finding the optimum dimensions of fillet welds,
- calculation of ultimate and admissible loads,

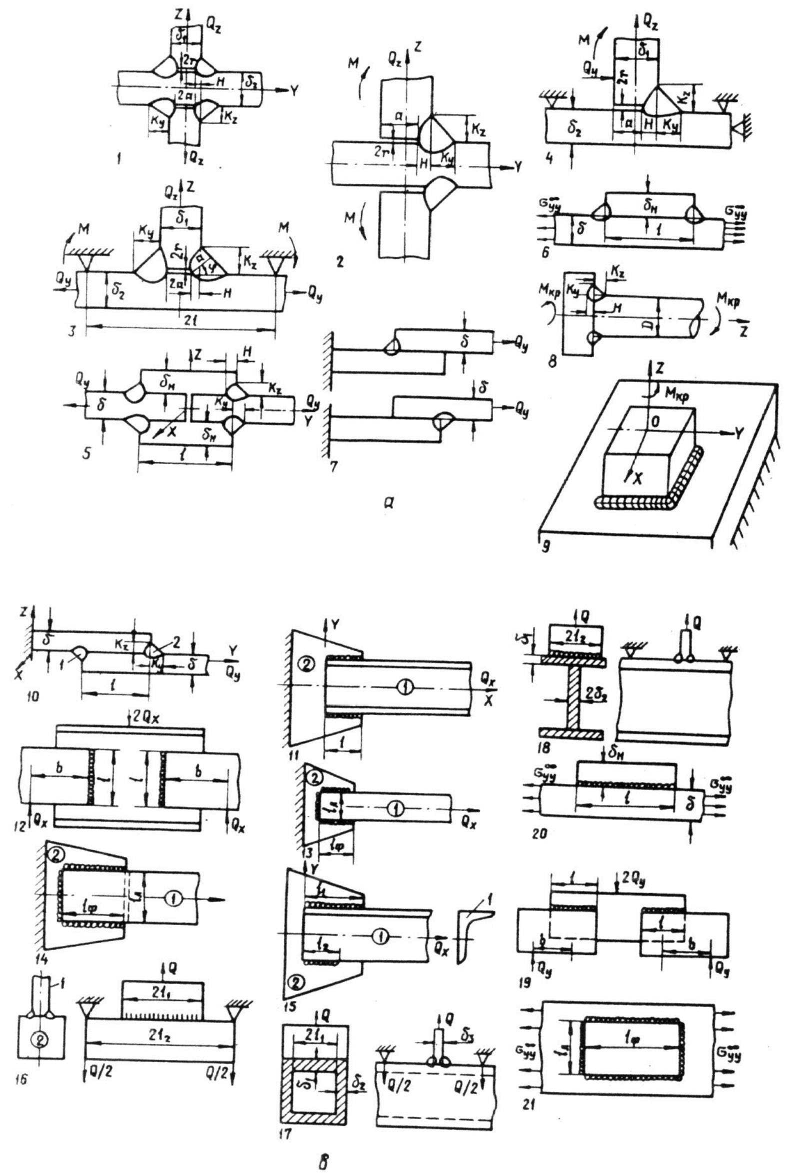

Fig. 1. Scheme of welded joints with fillets, corresponding to the main modules of the system: a - statically determinate, b - statically indeterminate.

- determination of margin factors,
- assessment of the calculation assurance.

All the above-mentioned tasks are solved under various kinds of loading, i.e. at static and cyclic loads.

The system is based on a modular principle, depending on the welded joint type (Fig. 1). Each module provides for the user work in the dialog mode, explaining to the user which initial data are required, what and how can be derived. When solving the task of optimization of the fillet weld dimensions the main calculation algorithm provides the sought forms and dimensions of a weld, each cross-section of which at approximately the same time passes into the limiting state determined by a certain criterion equation

$$f\ (x_1,\ x_2,\ \ldots\ldots,\ y_1,\ y_2 \ldots n_1,\ n_2,\ \ldots\ t) = 0 \qquad (1)$$

where x_1, x_2, ... are characteristics of the stresses-strained state; y_1, y_2, ... are characteristics of material resistance to deformation (fracture), n_1, n_2, ... are safety factors; t is time.

The concrete form of (1) depends on the mathematical model of the limiting state; in the system for the cases of static (one-time) loading the dependence from the works of E.Morozov (1973) and G.Vasilchenko (1979) is used as (1):

$$\left(\frac{\sigma_i}{\sigma_p} n_B\right)^2 + \left(\frac{K^{max}_{\omega\theta}}{K_{Ic}\ \eta} n_x\right)^2 = 1 \qquad (2)$$

where σ_i is stress intensity; σ_p is material resistance to tough fracture (either σ_B - ultimate strength, or σ_t - long-term strength with a given number of hours..., respectively); $K_{\omega\theta}$ = K ($K_I + K_I^r$, $K_{II} + K_{II}^r$, $K_{III} + K_{III}^r$) is stress intensity factor by the hypothesis of generalized normal tear (A.Andreikiv,1982) under the effect of external load and of the residual welding stresses at the tip of lack-of-fusion (adjacent cavity); K_{Ic} is fracture toughness of the material of the weld or heat-affected zone under the appropriate service conditions; η is correction factor allowing for severity of the weld zone loading and size of the blunting at the adjacent cavity (V.Makhnenko et al., 1984); n_B and n_x are the appropriate coefficients of assurance in case of the tough and brittle fracture.

If the welded joint is subjected to alternating loads, then besides the criterion equation (2) at σ_i and $K^{max}_{\omega\theta}$ corresponding to the maximum load, the following additional condition is used:

$$K^{max}_{\omega\theta_{max}} - K^{max}_{\omega\theta_{min}} \leqslant \frac{\Delta K_{th}}{n_{u}} (1 - \bar{\alpha} R) \qquad (3)$$

where $K^{max}_{\omega\theta_{max}}$ corresponds to the value of stress intensity factor at the tip of the adjacent cavity under the maximum load;

$K^{max}_{\omega\theta max}$ is the same at the minimum load; ΔK_{th} is threshold value of the range of stress intensity factor for the metal of the weld (heat-affected zone) with the cycle asymmetry factor R = 0; α is a certain property of the material equal approximately to 0.50...0.85; n_u is safety factor.

The use of the equations (2), (3) requires, first of all, the ability to calculate the σ_i, $K^{max}_{\omega\theta max}$ and $K^{max}_{\omega\theta min}$ values in the fillet weld cross-section. On the whole, it is a cumbersome task. Therefore, it is recommended to use for these purposes the approximation methods based on the approximation of exact solutions derived in the main-frame computers or by experimental measurements. Each calculation module consists of several submodules, as it is shown at Fig. 2.

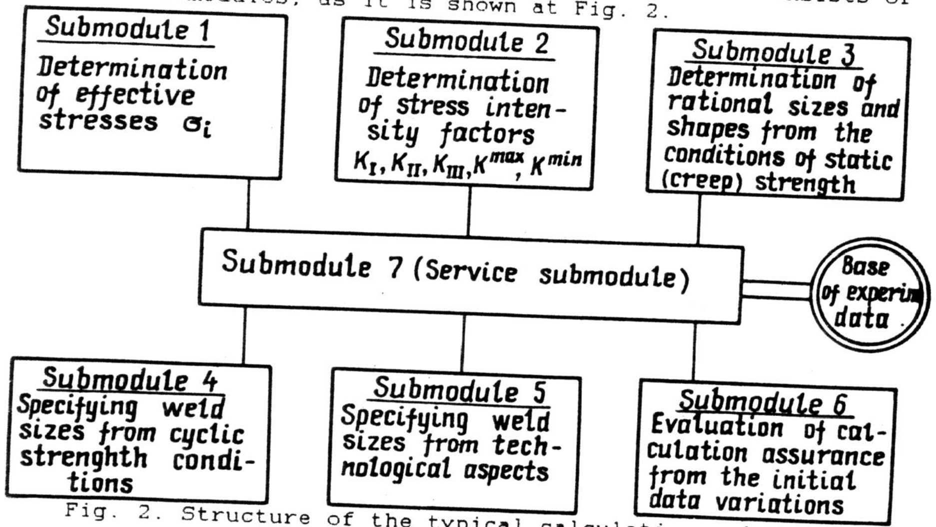

Fig. 2. Structure of the typical calculation module

One of them (#1) calculates σ_i by an approximate dependence. The assumption of static equivalence of the simplest stress distributions along the fillet weld cross-section length (Fig. 3) and of external load in the states close to the limiting ones is used, it allowing to apply the following dependence:

$$\sigma_i(\varphi)=\sqrt{\left(\frac{P}{h}+\frac{4M}{ch^2}\right)^2+3\left(\frac{V^2}{h^2}+\frac{T^2}{h^2}\right)} \qquad (4)$$

where P, V, T and M are forces and moments induced in the cross-section φ = const by external load, respectively; c is a certain coefficient varying within 1.5 > C > 1.

Dependences for P, V, T, M in each concrete calculation module are determined by the joint geometry and external load.

The submodule #2 calculates the stress intensity factors

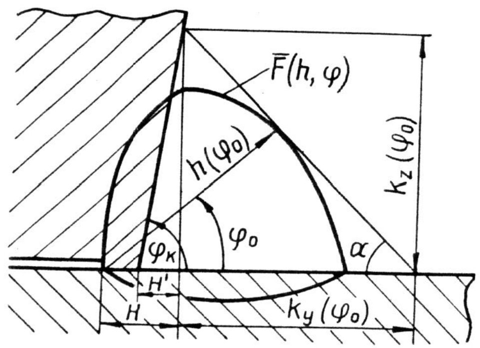

Fig. 3. Ideal profile of the fillet weld $\bar{F}(h,\varphi)$ and its approximation by triangular cross-section

$(K_I + K_I^r)$, $(K_{II} + K_{II}^r)$, $(K_{III} + K_{III}^r)$ on the basis of approximate dependences, where K_I^r, K_{II}^r and K_{III}^r are factors of intensity of stresses from residual stresses specific for the given geometry and load. The $K^{max}_{\omega\theta max}$ and $K^{max}_{\omega\theta min}$ values are determined by $K_I + K_I^r$, $K_{II} + K_{II}^r$, $K_{III} + K_{III}^r$. Here, the following dependences from (A.Andreikiv, 1982) are used:

$$K^{max}_{\omega\theta} = ((K_I + K_I^r)\cos\frac{\omega}{2} - 3(K_{II} + K_{II}^r)\sin\frac{\omega}{2})\cos^2\frac{\omega}{2}\cos^2\theta + (K_{III} + K_{III}^r)\cos\frac{\omega}{2}\sin 2\theta \qquad (5)$$

at $\omega = \omega_*$, $\theta = \theta_*$, determined by the following conditions

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

The submodule #3 realizing the static loading conditions (2), determines an ideal form and dimensions of the fillet weld as a certain function $F(y,z)=\bar{F}(h,\varphi)=0$ (Fig. 2), usually derived in a tabular form. The following approximate dependence is usually used for the correction factor η in (2):

$$\eta = \eta_1(h)\cdot\eta_2(r),$$

$$\eta_1(h)=1, \text{ if } h>h_m=m\left(\frac{K_{IC}}{\sigma_T}\right)^2; \qquad \eta_2(r)=1 \text{ if } r<r_0 \qquad (6)$$

$$\eta_1(h)=\sqrt{\frac{h_m}{h}} \text{ if } h<h_m \quad ; \qquad \eta_2(r)=\sqrt{\frac{r}{r_0}} \text{ if } r>r_0$$

where m = 1.0...2.5; $r_0 \approx$ 0.1 mm; r is blunting radius in the adjacent cavity, approximately equal to half of the gap.

Since in the majority of cases the $\bar{F}(h,\varphi) = 0$ curve is difficult to implement from the viewpoint of technology and is not always ideal in the transition zones at φ = 0 and $\varphi = \varphi_*$ (Fig. 2), the submodule #3 approximates the $\bar{F}(h,\varphi) = 0$ curve by conventional shapes, for instance, a circumscribed triangle with appropriate legs K_y and K_z. Since a considerable part of the $\bar{F}(h,\varphi) = 0$ curve (by the φ parameter) is convex, the circumscribed triangle is defined by the tangent to the $\bar{F}(h,\varphi)$ curve in a certain point $\varphi = \varphi_0$ and appropriate legs $K_y(\varphi_0)$ and $K_z(\varphi_0)$ from the intersection of this curve with the surfaces of the components being welded. The appropriate angle α (φ_0) is given by the expression

$$ctg\,\alpha = \frac{h(\varphi_0)\sin\varphi_0 - h'(\varphi_0)\cos\varphi_0}{h(\varphi_0)\cos\varphi_0 + h'(\varphi_0)\sin\varphi_0} \qquad (7)$$

The optimum value of φ_0 is assumed to be such a value in the $0 < \varphi < \varphi_k$ region, at which the cross-section of the deposited metal

$$F_\Delta = \frac{1}{2}(K_y + H')\cdot K_z$$

would be minimum. Here, H' is the penetration depth.

The submodule #4 precises the dimensions of the K_y and K_z legs from the cyclic loading conditions by the equation (3).

The submodule #5 contains limitations on the fillet weld dimensions for technological reasons, i.e. prevention of hot and cold cracks.

If the experimental data are representative enough, their processing enables to derive not only the average values of σ_p, K_{IC}, ΔK_{th}, σ_T, but also their variation range for the given class of materials, i.e. expectation and coefficients of variation of these values. The availability of such data enables to better substantiate the specification of margin factors n_B, n_x, n_u in each concrete case. For these purposes the system has a submodule # 6 for assessment of the calculation reliability, which permits to take into account the variation of load, geometrical dimensions and mechanical properties.

Accordingly, the lack of detailed information results in broadening the intervals of initial data variation and to the increase of margin factors proceeding from the conditions of guaranteeing the required reliability of calculation. This case also illustrates a great flexibility of the described calculation system for the welded joints with fillet welds.

Let us consider an example of calculation of an optimum cross-section of fillet welds for a symmetrical cruciform joint (Fig. 4). Here, the stress intensity and stress intensity factors were given by the following dependences:

$$\sigma_i = \frac{Q_z}{2h(\varphi)}\sqrt{1+2\sin^2\varphi}\,,\quad K_I = \frac{Q_z}{W}\sqrt{\frac{\pi a}{\cos \pi a/W}}\,, \qquad (8)$$
$$W = S + 0{,}66 K_y$$

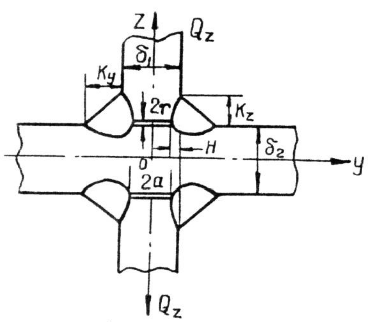

Fig. 4. A two-sided cruciform joint.

The material of the weld is an aluminium alloy with the following properties σ_B = 320 MPa, σ_T = 180 MPa, K_{Ic} = 1000 N/mm$^{3/2}$. For the cruciform joint the specified values are Q_z = 3000 N/mm, S = 15 mm, 2a = 8 mm, H = 3.5 mm, H = 0 mm. The optimum dimensions of legs K_y and K_z were determined with the specified assurance of calculation by load and appropriate variation of initial parameters. For simplicity it was assumed that the coefficient of variation ω is the same for all the parameters used (σ_B, σ_T, K_{Ic}, S, a, H, h). The variations with ω = 0.05, 0.1 and 0.15 were considered. The corresponding results are tabulated in Table 1, which depending on the ω_n and P_n value gives the optimum dimensions K_y and K_z of the deposited material area $F_\Delta(\omega)$, respectively, and of $F_\Delta(\omega)$ / $F_\Delta(0{,}05)$ ratio with constant P_a, as well as the n_a value equal to the ratio of ultimate load to the specified one, i.e. safety margin.

Table 1. Effect of variation of initial data and of the assurance of calculation on the optimum dimensions of fillet welds

P_a	ω	K_y, mm	K_z, mm	$F_\Delta(\omega)$, mm^2	$F_\Delta(\omega)/F_\Delta(0{,}05)$
	0.05	4.39	12.76	27.8	1.0
0.90	0.10	7.23	14.12	51.0	1.8
	0.15	9.02	17.62	79.5	2.82
	0.05	5.65	16.31	46.1	1.0
0.99	0.10	10.09	19.72	99.4	2.16
	0.15	13.67	26.70	182.5	3.96

The analysis of the data in this Table shows that for the cruciform joint (statically determinate system) improvement of the calculation assurance P_a from 0.9 up to 0.99 increases the volume of the deposit approximately by 1.5 - 2.2 times. Here, this increase is the greater, the more pronounced is the variation of the initial ω data.

Given further are the results of using separate modules of the system for determination, in combination with the experimental data, of the limiting state of various welded joints with fillets.

It was necessary to assess the degree of validity of the calculation results derived using the developed system and since a common approach is used for all modules, certain conclusions can also be drawn about the value of the system as a whole.

As an example of calculation of the ultimate load let us consider the determination of the ultimate load for transverse fillet welds of a butt joint with symmetrical cover plates (Fig.5). The static loading by the tensile and compressive force is considered. The geometrical dimensions are indicated in Table 2. The following dependences were used:

$$P = Q_y/2 \sin\varphi;\ V = Q_y/2 \cos\varphi;\quad M = -Q_y h/4 \cdot \sin\varphi$$

$$K_I = \frac{0{,}5369}{\sqrt{h}}\left(P + 8{,}0625\frac{M}{h}\right) \geq 0;\ K_{II} = \frac{0{,}5369}{\sqrt{h}}V;\ T = K_{III} = 0 \qquad (9)$$

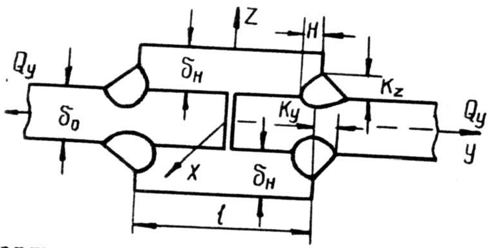

Fig. 5. Transverse fillet welds of a butt joint with cover plates

The ultimate load was considered for joints on CT3 steel at the temperature of - 196 °C, when the metal of the weld and HAZ undergoes brittle fracture. The following values were taken: K_{IC} = 500...700 N/mm$^{3/2}$, $\sigma_p \approx$ 800 MPa, H = 0.

The results of calculation of ultimate loads Q_y and certain

Table 2. Comparison of design and experimental loads under static loading of a butt joint with two symmetrical cover plates

# vers	δ_H, mm	δ_0, mm	K_y, mm	K_z, mm	Ultimate load, N/mm tension calc.	tension exper.	compression calc.	compression exper.	Admis. load
1	10	10	4.28	5.85	3113 4380	4050 500	-1264 -1780	-	1350
2	10	10	5	5	3274 4610	4600 500	-1227 -1728	-	1577
3	10	10	5.85	4.28	3398 4784	5100 500	-1174 -1653	-	1350
4	20	20	8.5	11.7	4398 6194		-1787 -2517	1900+ 200-	2700
5	20	20	10	10	4631 6521		-1734 -2444	2040+ 200+	3154
6	20	20	11.7	8.5	4803 6764		-1659 -2336	2120+ 200-	2700

appropriate experimental data are given in Table 2. The Table also shows the values of admissible loads according to SNiP standards. It can be seen that the considered joint under the mentioned conditions has a much higher ultimate load in tension, than in compression. It is connected with the fact that in tension, from the expression (9), the values of K_I = 0, since the decisive role is played by the negative (bringing together the crack edges) moment M. It can also be seen that with the same weld cross-section area the ultimate load to a certain extent depends on the ratio of the legs K_y/K_z.

The use of recommendations from SNiP for such a joint is obviously inadmissible for the compressive loads Q_y. The calculation results correlate rather well with the experimental data.

CONCLUSION

The prospects of a broad application of personal computers in the engineering practice open up new possibilities for improving the methods of welded joint design when designing welded structures. The development of automated calculation systems which combine the modern approaches of fracture mechanics and the numeric methods of calculation is quite effective for these purposes.

REFERENCES

Andrejkiv A.E.(1982) Spatial problems of the crack theory. Naukova Dumka. Kiev. 345 p.

Makhnenko V.I., Yushchenko K.A., Pochinok V.E. (1984) Calculation of the bearing capacity of welds with incomplete penetration. Avtomat. svarka. N8. P.1 - 6.

Morozov E.M., Sapunov V.T. (1973) On calculation of fracture diagrams. Prikladnaja mehanika i technicheskaya fizika. N2. P.172-176.

SNiP 11-23-81 standard. Construction codes and regulations. Design codes. Steel structures. In action since 01.01.82. Strojizdat. Moscow. 1982. 93 p.

Vasilchenko G.S., Morozov E.M., Shur D.M. (1979) Evaluation of the bearing capacity of crack components of welded structures. In: IIW Colloquium on Pract. Appls. Fracture Mechs. Bratislava. P.52-59.