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Development of a Method for the Assessment of Stresses in Welded Structures.

Part 1. Conventional Methods

Abstract: Various machinery parts or welded structure elements are characterised by significant cross-sectional changes along their length, leading to locally increased or accumulated stresses. The concentration of stresses is often of vital importance when determining structural stresses and strains, affects the service life of elements exposed to cyclic loads as well as influences the initiation and propagation of fatigue cracks. The article is an overview of works concerning conventional methods enabling the determination of maximum local stresses present in the stress concentration area triggered by the geometrical shape of welded joints.

Keywords: welded joints, weld geometry, stress condition, concentration of stresses, computational methods

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The design of welded structures involves the adoption of input quantities excluding their premature fatigue failure and taking into consideration the economic aspects connected with the making of such structures. To satisfy these conflicting requirements it is necessary to precisely identify the fatigue service life at the early design stage and, when doing so, allow for the concentration of stresses determined by the geometry of welds. The stress concentration effect on the fatigue service life and crack resistance was addressed in many works. The problem concerning the determination of maximum stresses in relation to the shape of an element has remained a significant problem for over 50 years now.

The traditional method used when determining maximum stresses during plastic strains involves the multiplication of nominal stresses by the theoretical stress concentration factor (SCF) used as the quantitative evaluation of stress accumulation. The recent decades have seen the development of both traditional and new approaches aimed to determine the SCF as well as the development of methods enabling the identification of maximum stresses without calculating the SCF.

It is known that when preset external force factors affect a structural element containing a weld, the SCF does not depend on material properties but on the type of a concentrator, its sharpness and relative dimensions. It should also be noted that the concentration of stresses is limited to a specific area. Traditionally, the nature of stress distribution on the concentration zone was determined using two methods.

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The first (theoretical) method involved elasticity theory methods [1], conformal representation [2, 3], the Kolosov-Muskhelishvili stress potentials [4], numerical methods [5, 6] etc. [7-10]. The SCF values obtained on the basis of results of works [1-10] varied significantly. For instance, computational dependences in work [5] provided minimum SCF values restricted within the range of 1.26 to 2.38 in relation to various steel grades and welding methods. In relation to the same steel grades and welding methods, the formulas presented in work [4] provided SCF values restricted within the range of 2.04 to 6.90. Other works provided intermediate, also varying results.

The second approach consisted in the use of experimental testing methods, including extensometric measurements [11], varnish coats [12, 13], photoelasticity, and, in particular, the polarisation-optical method [14-18]. It should be noted that according to the results of the above-named works, regardless of the experimental nature of the methods, the values of stress concentration factor are characterised by a significant scatter. For instance, in works [14, 15] the obtained values of stress concentration factor were restricted within the range of 1.2 to 1.3, whereas in works [16, 17] of 2.5 to 3.0. In work [18], the intermediate values of SCF were obtained. In work [19], the above-named scatter was explained by differences of the contour of modelled specimens. Works [1-10, 12-18] were concerned with butt welded joins. Analogous tests also involved welded joints with fillet welds. Using the theoretical approach based on numerical solutions of elasticity theory problems, in works [20-24] expressions enabling the identification of the stress concentration factor in T-joints were obtained. The similarity of methods used in the above-named works determined the convergence of results. The solution involved the use of the conformal representation method in two stages. The first stage involved the performance of the conformal representation of the area under consideration, whereas the second stage involved the determination of stress in relation to preset boundary conditions. The obtained values of SCF amounted to 3.15..3.35 in relation to the bending of the web. In terms of overlap joints with fillet welds parallel to the direction of forces (FWPL), determined using the FEM, in work [26] the stress concentration factor values amounted to 1.7..3.8. In relation to the same welded joints, in work [13] the value of SCF determined using the polarisation-optical method amounted to 1.8..3.2. In relation to the above-named joints, similar SCF ranges were obtained using the formula recommended by handbook [9]. Crosswire joints and overlap joints with fillet welds perpendicular to the direction of forces (FWPr) were characterised by higher stress concentration. For instance, according to work [18], the value of SCF can reach 5.7, yet according to the results of work [14] concerning overlap joints with FWPr not more than 4.0. Work [24] proposed that T-joint-related dependences be used as the basis for calculating the SCF for crosswire joints and overlap joints with FWPr. It was proposed that taking into consideration additional concentration triggered by lines of forces transferred by fillet welds (e.g. additional bending stresses in presence of only FWPr) should involve the use of the correction function depending on the thickness of plates, gap width and the leg of the weld.

In spite of various results, methodologies [1-10, 12-26] and other methodologies were recognised as reliable. Some of these methodologies were referred to on handbooks [9, 27-29] and in national standards. For instance, the SCF-related computational dependences according to wok [4] were recommended in relation to calculations of critical welded structures of nuclear power plants (Standards of Strength Calculations for Fixtures and Pipelines of Nuclear Plant Power Equipment PNAE-G-002-86) [30]. The results of work [21] have become, to some extent, a standard in relation to structures of hulls and deep-well equipment. The dependences, as in [4, 21] have the following form:

$$\alpha_\sigma = 1 + A \cdot \rho^{-n} \quad n = 0,3 \div 0,67 \qquad (1),$$

where α_σ – theoretical SCF, ρ – toe radius, depending on the welding technology and welded material, being a random variable with high variance; A – parameter of welded joint macrogeometry, determined by dimensions present at the design stage and external force factors.

Most publications of the period [1-10, 12-26] refer to dependences enabling the determination of SCF, usually without evaluating their accuracy and recommending application scopes. For this reason, the overcoming of differences concerning SCF-related calculation results obtained using various methods remained an important issue. To solve the above-named problem, the authors of work [31] formulated recommendations obtained on the basis of computational and experimental methodologies applied. Using the statistical study concerned with recommendations in works [2, 4, 5, 23, 29, 32-41] and related to specific values of parameters characterising the weld shape, the zone of "reliable recommendations" in relation to provided formulas was identified. Work [31] was concerned with the butt welded joint having one-sided excess weld metal and subjected to tensile strength as well as T-joints and crosswire joints subjected to tensile strength or bending moment. It should be noted that out of 15 works analysed by the authors, only work [38] makes it possible to calculate the stress concentration factor in relation to the joint effect of tensile strength and bending moment.

In addition, it should be noted that formulas related to butt joints discussed in publication [31] enable the obtainment of reliable results in relation to radius ρ and excess weld metal height g up to metal thickness S amounting to 0.01..0.1 and 0.05..025 respectively. The highest applicability scope was that of the Stakanov-Kostylev-Rybin formula (ρ/S = 0.01..0/6; g/S = 0.01..1.0) [42], yet in relation to welded joints of thin-walled elements the ρ/S ratio was 0.7 [43] and that of g/S – 1.7 [44].

The analysis presented in work [45] demonstrated that among formulas determining the SCF and presented in publication [31], the formulas to become the most commonly used were those presented in works [40, 46, 47].

A characteristic approach to determining the SCF as the function of weld shape factor φ identified as excess weld metal width e – excess weld metal g ratio was described in works [48-50], where, based on work by H. Neuber [51], the above-named factor was used instead of side angle θ being its analogue.

The authors of work [48] distinguish between two types of stress concentrators. The concentrators of the first type are connected with the specific structure, whereas those of the second type with the geometry of the weld. The maximum stress in the zone of concentrators of the second type was determined in relation to geometrical parameters of the weld. However, both in work [48] and [51] (by H. Neuber), the above-named maximum stress depends on the excess weld metal width e–toe radius ρ ratio, yet the excess weld metal height g is not taken into consideration as it determines φ, which is characteristic of works by German authors of that time. In cases of short radiuses, the authors move away from the use of shape factor φ and determine side angle θ by describing the convexity using the circular segment.

In work [49], the stress concentration factor is referred to as the shape numeral and is determined in relation to two weld shape factors: the first φ (according to work [48]) and the second ψ are determined as the excess weld metal width e – penetration depth ratio. The empirical dependence of both weld shape factors on welding parameters (arc voltage, welding current and welding rate) was determined. In the above-presented manner it was presented that the stress concentration factor indirectly (through shape factors and toe radius) depends on welding process parameters. In addition, the empirical dependence of toughness on weld shape factors, and, consequently, on the stress concentration factor, was determined.

Work [50] presents an experimentally determined correlation between the service life of the welded joint on the weld shape factor so that when the excess weld metal width is constant, the fatigue service life limit depends either on the weld shape factor or on the weld height. As a result, the dependences of the weld shape factor and of toughness on arc voltage were obtained.

The authors of work [52], when solving a problem analogous to that presented in work [31], investigated the stress concentration factor using the finite element method (FEM). The analysis of 316 numerical experiments involving the use of the least squares method enabled the obtainment of approximating dependences (2) in relation to the axial tension of a butt welded joint (Fig. 1a)

$$\alpha_\sigma = 1 + \frac{0{,}57}{\left[\rho\left(\frac{1}{s}+\frac{1{,}2}{e}+\frac{0{,}4}{g}\right)\right]^{0{,}63}} \cdot \frac{1-exp\left\{-2{,}4\left[\frac{s\cdot e}{2g(s+1{,}1e)}\right]^{0{,}4}\cdot\theta\right\}}{1-exp\left\{-2{,}4\left[\frac{s\cdot e}{2g(s+1{,}1e)}\right]^{0{,}4}\cdot\frac{\pi}{2}\right\}} \quad (2)$$

The axial tension of T-shaped (Fig. 1b) and crosswire (Fig. 1c) welded involved the solving of 50 problems (in each case), leading to the empirical determination of dependences in relation to T-joins (3)

$$\alpha_\sigma = 1+0{,}494\left\{\frac{(sin\theta)^{0{,}83}}{\left[\rho\left(\frac{1}{s}+\frac{0{,}96}{k}+\frac{0{,}076}{k\cdot tg\theta}\right)\right]^{0{,}55}} + \frac{1}{\left[\rho\left(\frac{1}{s}+\frac{0{,}96}{k+s/2}+\frac{0{,}076}{H}\right)\right]^{0{,}55}} - \frac{1}{\left[\rho\left(\frac{1}{s}+\frac{0{,}96}{k}+\frac{0{,}076}{H}\right)\right]^{0{,}55}}\right\} \quad (3)$$

and crosswire joints (4)

$$\alpha_\sigma = 1+0{,}32\left\{\frac{(sin\theta)^{0{,}49}}{\left[\rho\left(\frac{1}{s}+\frac{0{,}64}{k}+\frac{0{,}005}{k\cdot tg\theta}\right)\right]^{0{,}58}} + \frac{1}{\left[\rho\left(\frac{1}{s}+\frac{0{,}64}{k+s/2}+\frac{0{,}005}{H}\right)\right]^{0{,}58}} - \frac{1}{\left[\rho\left(\frac{1}{s}+\frac{0{,}64}{k}+\frac{0{,}005}{H}\right)\right]^{0{,}58}}\right\} \quad (4)$$

The designations adopted in formulas (2)-(4) were consistent with standard GOST 5264-80 "*Manual arc welding. Welding joints. Main types, design elements and dimensions*"

The above-named work also discussed the creation of related curves and the determination of dimensions of finite elements ensuring high stress gradient determination accuracy

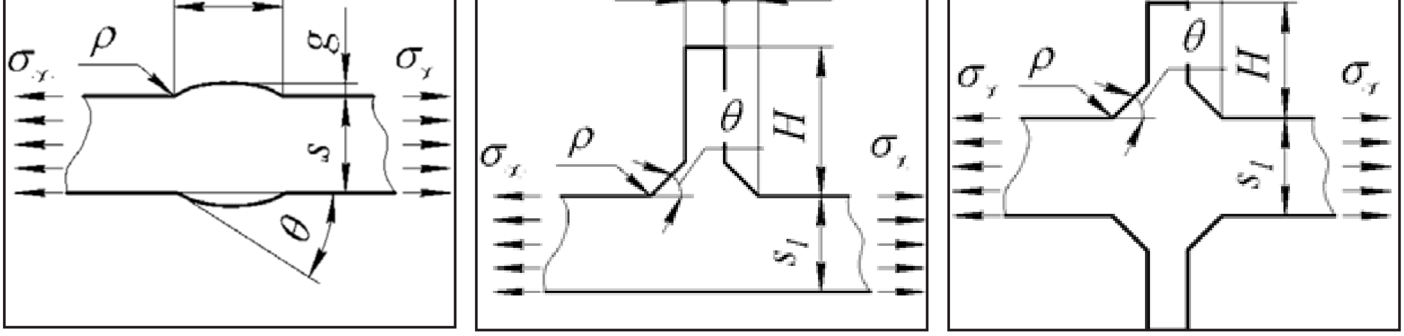

Fig. 1. Computational scheme adopted in work [45] to determine the SCF according to formulas (2)-(4)

(which was a significant advantage of the work in comparison with other publications). However, gradient values in the work were not presented in numeric values or diagrams. In addition, formulas (2)-(4) corresponded to tension and were not useful as regards the bending of welded joints. It should also be noted that work [52] discussed tests of butt welds with symmetric excess weld metal.

Work [53] concerning the low-cycle fatigue strength of butt welded joints demonstrated the divergence between stress concentration factor values obtained theoretically using methodology [6] and experimental data. The tests did not reveal any significant increase in the toe radius and angle in the process of elastic-plastic deforming. In addition, the calculated values differed from the experimental data. The authors formulated a conclusion that the concentration of stresses in the weld was affected by the nearest stiffening rib, being the concentrator of stresses. Work [53] discussed the testing of butt joints with an asymmetric weld, yet the values of stress concentration factor in relation to the weld face and weld root were determined using formula [42] related to butt joints with symmetric excess weld metal.

Works [1-10, 12-26, 31-42, 35-53] unequivocally demonstrated the effect of welded material properties and welding conditions on the SCF of the toe curvature radius. The above-presented conclusion is consistent with the results of work [54] concerned with the effect of the toe radius on the fatigue of welded joints.

Conclusions

1. Stresses in stress concentration zones were identified using theoretical and experimental methods. The theoretical methods involved the analytical solving of elasticity theory problems in relation to idealised models simulating the geometrical shape of the weld, whereas the experimental methods consisted in the identification of the correlation between stress field changes in specimens and those in geometrical parameters.

2. The advantage related to theoretical methods was the identification of the mathematical correlation between stresses and geometrical parameters, which provided the possibility of performing design calculations of welded structures allowing for the concentration of stresses. A significant disadvantage of such methods is the fact that idealised models reproduce very few types of actual welds. As a result, the idealisation of the same welded joint using various models may lead to significantly diverging results of calculations.

3. Experimental methods are noteworthy as they provide the possibility of introducing stress in a welded joint of any configuration. However, such methods do not enable the calculation of geometrical parameters according to preset loads. The ultimate objective of experimental methods is the obtainment of experimental dependence concerning the identification of the maximum stress concentration factor at a test point. However, dependences of stress distribution in the entire welded joint remain unknown. Disadvantages of experimental methods also include the limited range of the applicability of obtained empirical formulas resulting from limited dimensions of modelling specimens.

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