PROBLEMS OF EXAMINATION OF MODERN CRITICAL WELDED STRUCTURES

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An important stage of diagnostics of the state of critical welded structures is prediction of their residual life based on strength analysis by limiting state. In the absence of crack-like raisers spontaneous macrofailure of structural elements in a number of cases is the result of plastic instability, related to porosity initiation and development. This work deals with the main problems of modelling tough fracture of welded structures and proposes methodological basis for description of mechanisms of their limiting state. In particular, complex finite element models of simultaneous development of 3D stress-strain state of elastoplastic material with strengthening and pore formation have been developed. Condition of initiation of tough fracture pores is determined by limit value of Odqvist parameter, and pore development — by Rice–Tracey law. Thus, limiting state of a structure at developed plastic flow of metal is due to discontinuity growth, local redistribution of load and reduction of actual load-carrying cross-section. Application of the proposed methodology was illustrated by examples of calculation of limiting inner pressure of pipeline elements, allowing for initial stress-strain state at site and repair welding, structural inhomogeneity, and surface defects of local wall thinning. It is shown that in the absence of geometrical raisers, physical inhomogeneity has little influence on limiting load at static loading of the considered welded structures. This is in agreement with the available experience of pipeline system operation that proves applicability of developed approaches of numerical analysis for effective solution of practical problems of diagnostics of the state of modern welded structures. 12 Ref., 1 Table, 4 Figures.

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Practical experience all over the world shows that periodical technical examination of the state of modern critical structures is the most effective measure, ensuring reliability of their operation. Technical examination of such structures consists of a whole number of stages, among which technical diagnostics of the state and appropriate prediction of safe residual operating life have a special place. Continuous development of diagnostic means and technologies allows obtaining every year more and more accurate data on the state of various structures, in particular welded structures. Advance of technical diagnostics stimulates respective development of methods of predicting safe residual operating life. A lot of attention in this case is given to modern development of computational engineering, as well as numerical methods of modelling continuum deformations and concurrent processes of fracture mechanics. For welded structures, for which strength analysis is usually performed by limiting state, extremely important for solving practical problems of prediction of safe residual operating life, based on concrete data of technical diagnostics, is development of methods of mathematical modeling of deformation processes up to states close to the limiting state and mathematical description of limiting state mechanisms, that is by far not always reduced to comparison of calculated maximum stresses or deformations with limiting values for the given structural material under the respective loading conditions. In other words, unlike strength analysis by allowable stresses (deformations), calculation by limiting loads requires, as a rule, application of more precise methods of non-linear mechanics of deformation (allowing for physical or geometrical nonlinearity, or for one and the other simultaneously), as well as involvement of respective criteria of formation of discontinuity (fracture), depending on loading conditions, material properties, etc., determining the fracture mode.

Over the last decades brittle fracture is believed to be the best studied in this respect that can be related to a number of factors, of which the following are the most important: large-scale negative consequences of such failures, small differences between prior deformation of fracture zone and the elastic one, i.e. urgency at relatively simple initial parameters. Nonetheless, creation of modern, quite rigorous linear theory of fracture

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mechanics of bodies with cracks and approximate non-linear theory for the same purpose took several decades. At prediction of safe residual operating life of critical welded structures with detected (or hypothetical) crack-like defects, modern theories of fracture mechanics of bodies with cracks allow solving a number of practical tasks [1, 2, etc.] under various loading conditions (static, cyclic, temperature, in aggressive medium, etc.). Popularity of modern theories of fracture mechanics of bodies with cracks is determined, primarily, by absence of the need for detailed analysis of stress-strain sate in the «hot zone» along a quite indeterminate crack border, operating with the respective integral characteristics of the following type:

- stress intensity factor K_j (j = I, II, III) and its critical value K_{jc}, MPa·m$^{1/2}$;
- released energy per a unit of crack growth length J_j and its critical value J_{jc}, J/m;
- crack opening displacement δ and its critical value δ_c, mm;
- reference stresses σ_{ref}, determining the state of plastic collapse along the crack border at a specified yield limit σ_y of material in this zone, MPa.

Algorithms for calculation of these characteristics, as well as experimental procedures for determination of their critical values, have been quite profoundly studied, particularly for K_j and σ_{ref} [2, 3, etc.], as well as for J_j that determines minimum deviations of various investigation results on limiting loads for specific tasks.

In case of absence of a crack-like defect and sufficiently tough material of welded structure, for instance, thinning of bearing wall of a welded pressure vessel or pipeline, calculations by admissible stresses can lead to tough fractures of the type of plastic instability [4] that is characteristic for high-strength steels with a small coefficient of deformation strengthening. Such calculation data are by far not always confirmed by experience that is due to additional mechanisms of compensation of section reduction at tension.

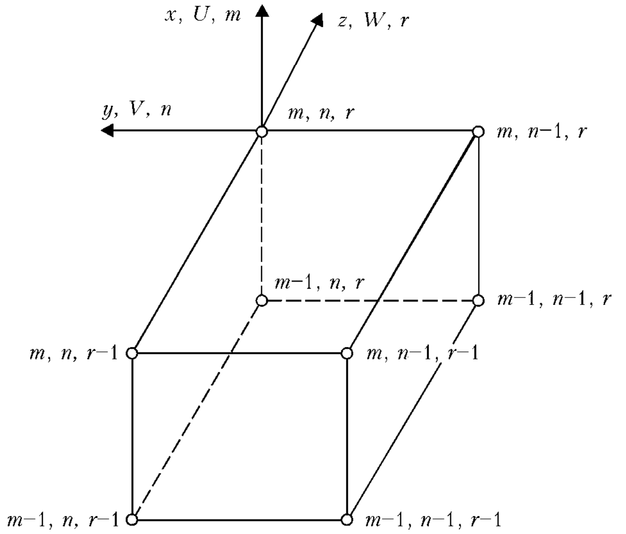

Figure 1. Schematic of finite element in x, y, z coordinate system, with displacement in the respective directions V, U, W and node numbering m, n, r

Process of pore formation at developed plastic flow of structural steels is universally recognized as one of such mechanisms. In the general form, regularities of pore initiation and development processes, as well as the influence of pore formation on deformation processes and fracture have been defined, mainly, on the basis of experimental investigations already in the 1970s. However, their actual application [5–8, etc.] is rather complicated and requires a number of material characteristics that can be obtained only through combination of experiment and calculations (actually, on rather simple samples [5]). Nonetheless, the real progress of development of computational engineering and methods of solving deformation problems in 3D definition, allowing for physical and geometrical non-linearity, noticeably changes the opinions on realization of complex mathematical models. Respective developments are performed in various organizations, including PWI — for welded structures. Main postulates of such development and some cases of its application when solving practical problems are given below.

The work is based on simultaneous consideration of deformation and pore formation processes in an arbitrary 8-node finite element (FE), used to simulate a continuum in an orthogonal system of coordinates x, y, z. Within the considered FE (Figure 1), distribution of stresses, strains and temperatures is taken to be uniform.

Porosity develops at a certain level of plastic deformations, characterized by Odqvist parameter κ_s:

$$\kappa_s = \int d\varepsilon_i^p, \tag{1}$$

where $d\varepsilon_i^p = \frac{\sqrt{2}}{3}\sqrt{d\varepsilon_{ij}^p d\varepsilon_{ij}^p}$; $d\varepsilon_{ij}^p$ are the components of plastic deformation increment tensor (i, $j = x, y, z$).

Pores formed in FE are uniformly distributed through its volume V_{FE}; volume fraction of discontinuity ρ_V is determined by the ratio of volumes of pores V_{pore} and entire finite element V_{FE}.

Accordingly, condition of the start of pore formation process in a concrete FE is given by the following equation:

$$\begin{cases}\rho_V = 0 \quad \text{at} \quad \kappa < \kappa_s, \\ \rho_V \geq \rho_V^s \quad \text{at} \quad \kappa \geq \kappa_s,\end{cases} \tag{2}$$

where ρ_V^s is the conditional initial volume fraction of pores.

By analogy with ρ_V concept, the following characteristics are introduced: ρ_S — relative area of pores in FE cross-section, i.e.

$$\rho_S = \frac{S_{\text{pore}}}{S_{\text{FE}}} \tag{3}$$

and ρ_l — relative length of FE linear size, taken up by pores, i.e.

$$\rho_l = \frac{l_{\text{pore}}}{l_{\text{FE}}}. \tag{4}$$

There exists a connection $\rho_V = 3\rho_l$ between ρ_V, ρ_S and ρ_l, $\rho_S = 2\rho_l$ at $\rho_l << 1$.

Pores initiating in FE grow with development of plastic deformations by Rice–Tracey law [5], i.e.

$$d\rho_l = \rho_l K_1 \exp\left(K_2 \frac{\sigma_m}{\sigma_i}\right) d\varepsilon_i^p, \tag{5}$$

where $\sigma_m = \frac{1}{3}(\sigma_{xx} + \sigma_{yy} + \sigma_{zz})$ is the mean normal stress in the given FE; $\sigma_i = \sqrt{\frac{1}{2}\sigma_{ij}\sigma_{ij}}$ is the stress intensity in this FE; σ_m/σ_i is the characteristic of stressed state rigidity; $K_1 = 0.28$; $K_2 = 1.5$.

It follows from (5) that value $d\rho_l$ is the relative increment of FE linear dimensions due to porosity, i.e. increment of deformation tensor components can be given by the following sum:

$$d\varepsilon_{ij} = d\varepsilon_{ij}^e + d\varepsilon_{ij}^p + \delta_{ij}(d\varepsilon_T + d\rho_l), \qquad \delta_{ij} = 1 \text{ at } i = j,\ \delta_{ij} = 0 \text{ at } i \neq j, \tag{6}$$

where $d\varepsilon_{ij}^e$, $d\varepsilon_{ij}^p$, $\delta_{ij}d\varepsilon_T$, $\delta_{ij}d\rho_l$ are the components of deformations increment due to stresses by Hooke's law, plastic deformation, change of temperature and porosity, respectively.

Proceeding from the method of successive tracing of development of elastoplastic deformations and the assumption that at the tracing step σ_m/σ_i value changes only slightly, relationship (5) becomes

$$\ln \frac{\rho_l}{(\rho_l)^{*)}} = K_1 \exp\left(K_2 \frac{\sigma_m}{\sigma_i}\right)^{*)} (\kappa - \kappa^{*)}), \tag{7}$$

where index *) refers this value to the previous tracing step.

Accordingly, after $\rho_l = (\rho_l)^{*)} + \Delta\rho_l$ substitution into (7)

$$\Delta\rho_l = (\rho_l)^{*)} \left\{ \exp\left[K_1 \exp\left(K_2 \frac{\sigma_m}{\sigma_i}\right)^{*)} (\kappa - \kappa^{*)})\right] - 1\right\}, \quad (\kappa^{*)} > \kappa_s). \tag{8}$$

Substitution of Δ for d operator in (6) allowing for (8) yields an expression for total deformation increment $\Delta\varepsilon_{ij}$, allowing for pore growth in this FE per tracing step. Further on the algorithm of solution of deformation problem corresponds to that from [1, 5].

At realization of plastic flow conditions the following dependence is used:

$$\sigma_i = \sigma_s(T, \kappa)(1 - 2\rho_l), \tag{9}$$

where $\sigma_s(T, \kappa)$ are the deforming stresses in the material at temperature T and Odqvist parameter κ to (1).

Equations of constraint between tensor σ_{ij} and $\Delta\varepsilon_{ij}$ are as follows:

$$\Delta\varepsilon_{ij} = \psi(\sigma_{ij} - \delta_{ij}\sigma_m) + \delta_{ij}(K\sigma_m + \Delta\varepsilon_T + \Delta\rho_l) - b_{ij}, \qquad b_{ij} = \frac{1}{2G}(\sigma_{ij} - \delta_{ij}\sigma_m)^{*)} + (K\sigma_m)^{*)}, \quad (i, j = x, y, z), \tag{10}$$

where $K = \frac{1 - 2\nu}{E}$; E is the Young's modulus; ν is the Poisson's ratio; $G = \frac{E}{2(1 + \nu)}$ for material of this FE; ψ is the function of material state, determined by yield condition, i.e.

$$\psi = \frac{1}{2G} \text{ if } \sigma_i < \sigma_s(T, \kappa)(1 - 2\rho_l); \qquad \psi > \frac{1}{2G} \text{ if } \sigma_i = \sigma_s(T, \kappa)(1 - 2\rho_l); \tag{11}$$

$\sigma_i > \sigma_s(T, \kappa)(1 - 2\rho_l)$ state is inadmissible.

Plastic deformations are determined from the following equation:

$$\Delta\varepsilon_{ij} = \left(\psi - \frac{1}{2G}\right)(\sigma_{ij} - \delta_{ij}\sigma_m), \quad (i, j = x, y, z). \tag{12}$$

Realization of conditions (11) is performed in each tracing step iteratively, using (12), (1), (7), (8) and respective dependence $\sigma_s(T, \kappa)$ on κ and T [5]. At each iteration by ψ, stresses σ_{ij} are found from (10):

$$\sigma_{ij} = \frac{1}{\psi}\left(\Delta\varepsilon_{ij} + \delta_{ij} \frac{\psi - K}{K} \Delta\varepsilon\right) + J_{ij}, \tag{13}$$

where

$$\Delta\varepsilon = \frac{\Delta\varepsilon_{xx} + \Delta\varepsilon_{yy} + \Delta\varepsilon_{zz}}{3},$$

$$J_{ij} = \frac{1}{\psi}\left[(b_{ij} - \delta_{ij}b) + \delta_{ij}\left(K\sigma^{*)} - \frac{\Delta\varepsilon_T + \Delta\rho_l}{K}\right)\right],$$

$$b = \frac{1}{3}(b_{xx} + b_{yy} + b_{zz}).$$

Tensor $\Delta\varepsilon_{ij}$ and displacement increment vector ΔU_i are connected by the following relationship:

$$\Delta\varepsilon_{ij} = \frac{1}{2}(\Delta U_{i,j} + \Delta U_{j,i}), \quad (14)$$

where the comma in the index corresponds to differentiation within FE, i.e. in the system of coordinates x, y, z (see Figure 1). From (14) at $\Delta\varepsilon_{ij} << 1$ it follows that

$$\Delta\varepsilon_{xx} = \frac{\Delta U_{m,n,r} - \Delta U_{m-1,n,r}}{x_{m,n,r} - x_{m-1,n,r}},$$

$$\Delta\varepsilon_{yy} = \frac{\Delta V_{m,n,r} - \Delta V_{m,n-1,r}}{y_{m,n,r} - y_{m,n-1,r}},$$

$$\Delta\varepsilon_{zz} = \frac{\Delta W_{m,n,r} - \Delta W_{m,n,r-1}}{z_{m,n,r} - z_{m,n,r-1}},$$

$$\Delta\varepsilon_{xy} = \frac{1}{2}\times \quad (15)$$

$$\times\left[\frac{\Delta U_{m,n,r} - \Delta U_{m,n-1,r}}{y_{m,n,r} - y_{m,n-1,r}} + \frac{\Delta V_{m,n,r} - \Delta V_{m-1,n,r}}{x_{m,n,r} - x_{m-1,n,r}}\right],$$

$$\Delta\varepsilon_{xz} = \frac{1}{2}\times$$

$$\times\left[\frac{\Delta U_{m,n,r} - \Delta U_{m,n,r-1}}{z_{m,n,r} - z_{m,n,r-1}} + \frac{\Delta W_{m,n,r} - \Delta W_{m-1,n,r}}{x_{m,n,r} - x_{m-1,n,r}}\right],$$

$$\Delta\varepsilon_{yz} = \frac{1}{2}\times$$

$$\times\left[\frac{\Delta U_{m,n,r} - \Delta U_{m,n,r-1}}{z_{m,n,r} - z_{m,n,r-1}} + \frac{\Delta W_{m,n,r} - \Delta W_{m,n-1,r}}{y_{m,n,r} - y_{m,n-1,r}}\right],$$

where $x_{m,n,r}$, $y_{m,n,r}$, $z_{m,n,r}$, ... are the coordinates of FE components (see Figure 1) allowing for their changes at differentiation, i.e.

$$\begin{aligned} x_{m,n,r} &= x^{*)}_{m,n,r} + \Delta U_{m,n,r},\\ y_{m,n,r} &= y^{*)}_{m,n,r} + \Delta V_{m,n,r},\\ z_{m,n,r} &= z^{*)}_{m,n,r} + \Delta W_{m,n,r}. \end{aligned} \quad (16)$$

Stress tensor components (13) satisfy static equations for inner FE and respective limiting conditions. In its turn, components of $\Delta U_i(\Delta U, \Delta V, \Delta W)$ vector meet the respective conditions on the boundary.

Resolving system of algebraic equations relative to displacement increment vector in FE nodes at each step of tracing and iteration by ψ is determined as a result of minimizing the (functional Lagrange variation principle) [9]:

$$\begin{aligned} \mathrm{E}_1 = &-\frac{1}{2}\sum_V (\sigma_{ij} + J_{ij})\Delta\varepsilon_{ij}V_{m,n,r} + \\ &+ \sum_{S_P} P_i \Delta U_i \Delta S_P^{m,n,r}, \end{aligned} \quad (17)$$

where $\sum_V$ is the operator of summation by inner FE; $\sum_{S_P}$ is the operator of summation by surface FE, in which components of force vector P_i (i = $= x, y, z$) are assigned, i.e. system of equations

$$\frac{\partial \mathrm{E}_1}{\partial \Delta U_{m,n,r}} = 0, \quad \frac{\partial \mathrm{E}_1}{\partial \Delta V_{m,n,r}} = 0, \quad \frac{\partial \mathrm{E}_1}{\partial \Delta W_{m,n,r}} = 0 \quad (18)$$

allows deriving a solution for increments of displacement vector in each step of tracing and iteration by ψ for the respective FE. State of plastic instability for the considered FE at the specific tracing step is determined by the value of function ψ.

It follows from (12), (13) that at increase of function ψ, plastic deformation increments $\Delta\varepsilon^p_{ij}$ grow and stresses σ_{ij} decrease. If in the previous tracing step Odqvist parameter $\kappa^{*)}$, and plastic instability develops at deformation ε_f, then, equating $\kappa^{*)} + \Delta\varepsilon^p_i = \varepsilon_f$, we can evaluate $\left(\psi - \frac{1}{2G}\right)_{\mathrm{cr}}$ values, above which the process of plastic instability is quite real in this FE, i.e.

$$\left(\psi - \frac{1}{2G}\right)_{\mathrm{cr}} \ge \frac{\varepsilon_f - \kappa^{*)}}{1.5\sigma_i} \approx \frac{\varepsilon_f - \kappa^{*)}}{1.5\sigma_s(\kappa, T)}. \quad (19)$$

Thus, condition (19) can be considered to be the upper constraint for function ψ in terms of plastic instability. In other words, if the iteration process by ψ in the considered FE at a given loading step yields rising ψ values higher than ψ_{cr} by (19), then it can be assumed that the element is not able to take the load in this step, $\psi \to \infty$ and $\sigma_{ij} \to 0$, respectively.

Another variant of loss of performance of this FE is also possible: true maximum principal stresses $\frac{\sigma_1}{1 - 2\rho_l}$ exceed cleavage stresses S_c, that is possible at high deformation strengthening of

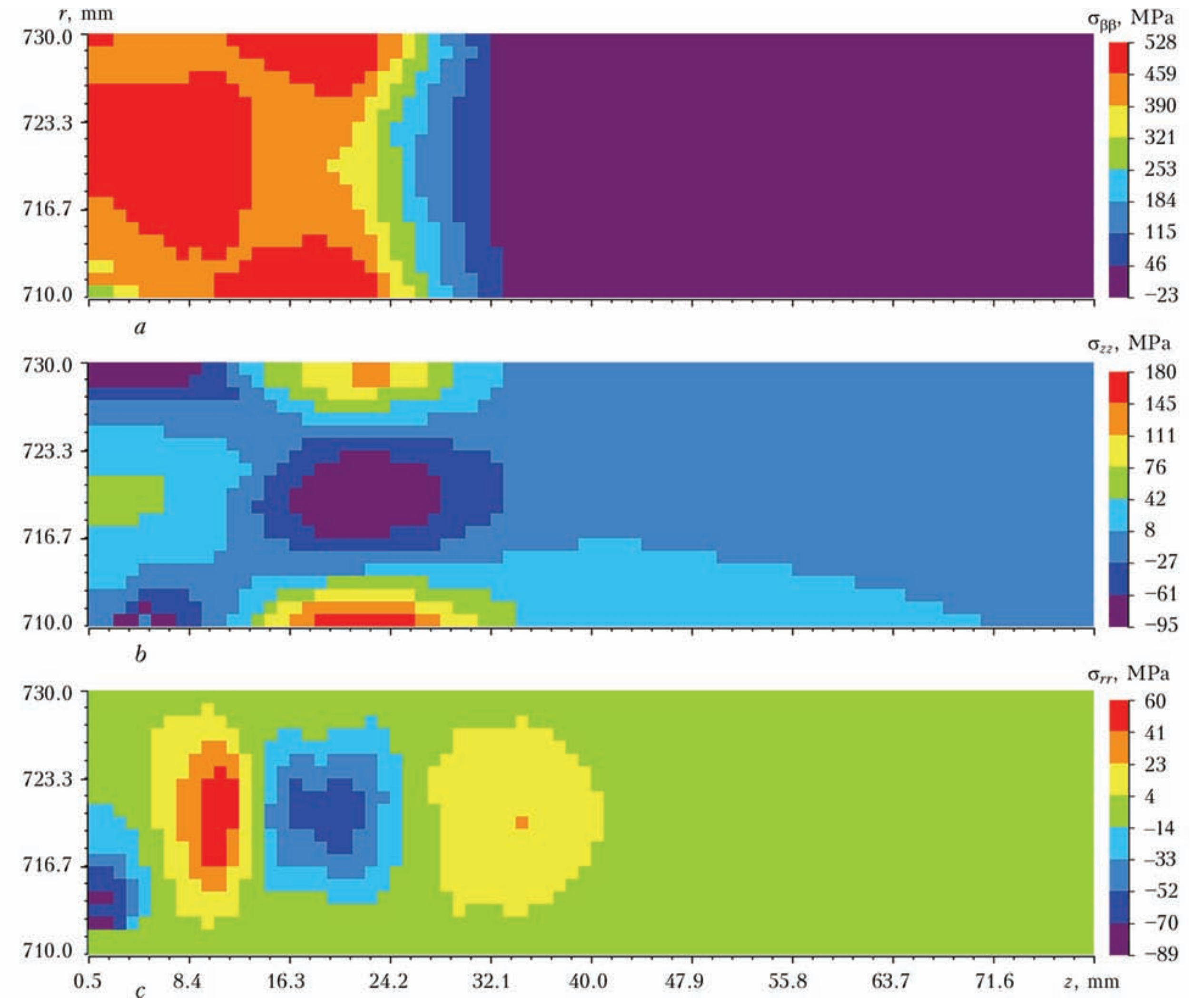

Figure 2. Distribution of residual stresses in the zone of circumferential weld: *a* — circumferential $\sigma_{\beta\beta}$; *c* — longitudinal σ_{zz}; *c* — radial σ_{rr}

material. In this case, it should be also assumed that at this tracing step and in all the subsequent ones this element cannot take the load, i.e. $\psi \to \to \infty$, $\sigma_{ij} \to 0$.

Eventually, we can define two main conditions, when a given FE irreversibly looses its ability to take the load:

$$\psi > \frac{1}{2G} + \frac{\varepsilon_f - \kappa^{*)}}{1.5\sigma_s(\kappa, T)} \text{ is the plastic instability;}$$

$$\frac{\sigma_1}{1 - 2\rho_l} > S_c \text{ is the cleavage fracture.} \qquad (20)$$

If the process of the above «zeroing» to conditions (20) proceeds at this loading step, covering an ever greater number of adjacent FE, and does not allow moving to the next step, then this step determines the limit load of «spontaneous fracture».

Such an approach requires additional knowledge of process parameters:

κ_s, ρ_V^s are the parameters of pore initiation;

ε_f, S_c are the parameters of finite element «zeroing».

For structural steels values S_c are quite well-known [1, etc.]. As regards ε_f, recommendations of [5, 8] can be used, connecting ε_f to rigidity of stressed state σ_m/σ_i by empirical dependencies of type [8]

$$\varepsilon_f = 0.07 + 2.99 \exp(-1.5\sigma_m/\sigma_i)... \qquad (21)$$

In the absence of experimental data for κ_s and ρ_V^s, $0.005 < \kappa_s < 0.03$ and $0.01 < \rho_V^s < 0.05$ can be approximately taken. Here it should be taken into account that at the stage of developed pore formation (close to limiting state) influence of possible errors of selection of initial κ_s, ρ_V^s values on derived solution decreases markedly.

Given below is a number of examples of application of the above-described approach for pipe $2R \times \delta = 1420 \times 20$ mm from steel X70 loaded by inner pressure.

The following steel properties were assumed: yield limit $\sigma_y = 490$ MPa, Young's modulus $E =$

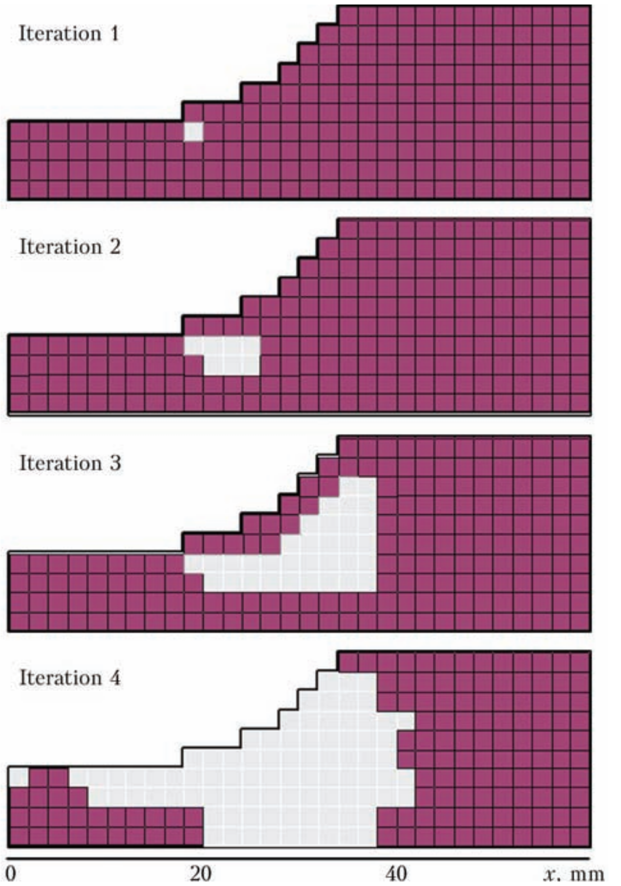

Figure 3. Development of macrofracture by the mechanism of plastic instability in the longitudinal section of surface defect of pipeline element at $P = 17.7$ MPa (finite elements, which have lost their load-carrying capacity, are shown in grey): iteration 1 — macrocrack initiation; 2, 3 — defect development; 4 — violation of pipe wall integrity

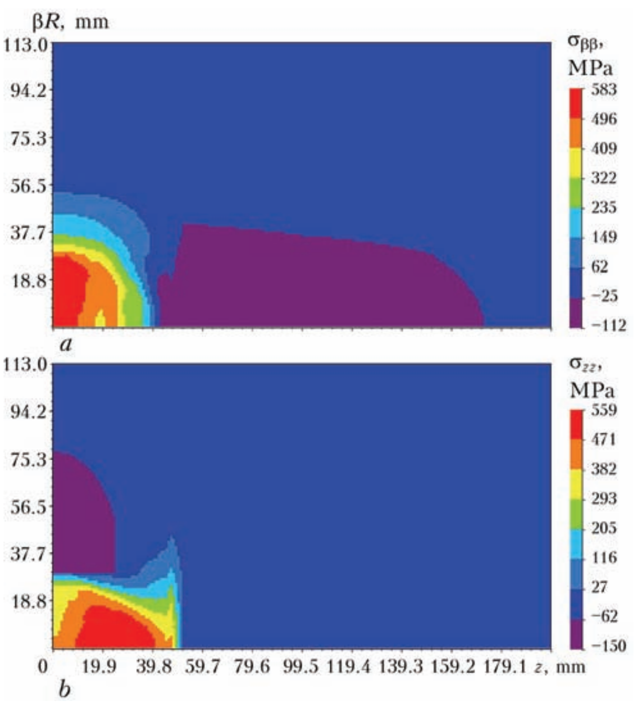

Figure 4. Residual stresses after arc welding up of thinning defect $s \times c \times a = 66 \times 40 \times 14$ mm in $2R \times \delta = 1420 \times 20$ mm pipe from steel X70 on outer surface $r = 70$ mm: *a* — circumferential $\sigma_{\beta\beta}$; *b* — longitudinal σ_{zz}

$= 2\cdot10^5$ MPa, cleavage stress $S_c = 1000$ MPa, $\sigma_s(\kappa) = \sigma_y + A\kappa^m$, where $A = \sigma_T^{1-m}F^m$ and $m = 0.14$ are the coefficients. Metal microstructure is ferritic-pearlitic.

Case 1. Pipe, geometrically ideal and physically uniform in the initial condition, is loaded by inner pressure P. Stresses $\sigma_{\beta\beta}$, σ_{rr}, σ_{zz} arising in pipe wall are non-uniformly distributed at $P \neq 0$ across wall thickness that causes certain physical inhomogeneity, which is manifested at pore initiation ($\kappa > \kappa_s = 0.01$) and growth, because of different values σ_m/σ_i and fracture mechanisms. However, as shown by our calculations, this non-uniformity is small, therefore, at $P = 19.4$ MPa porosity is found through the entire volume, and at $P = 19.5$ MPa spontaneous fracture both by the mechanism of plastic instability and by microcleavage takes place.

Limit load of $19.4 < P_{\lim} < 19.5$ MPa is close to the actual upper limit load for steel X70 in the absence of stress raisers, either geometrical or physical.

Case 2. Conditions are the same, as in Case 1, but pipe metal has residual (initial) balanced stresses $\sigma_{ij}^{\mathrm{res}}$, shown in Figure 2, i.e. maximum stresses $\sigma_{\beta\beta}$ are on the level of yield limit (490 MPa) that is characteristic, in particular, for stressed state in the vicinity of circumferential site welds.

According to calculations, limiting state corresponds to limit load $19.21 < P_{\lim} < 19.22$ MPa, i.e. compared to the previous case lowering on the level of up to 2 % (in absence of raisers and without any essential development of dissipated damage of metal in welding heating area) confirms the known postulate that under static loading of steel structures the influence of residual stresses on the limit load is negligible.

Case 3. Conditions are the same, as in Case 1, but structural inhomogeneity (typical distribution of microstructural components of pipe steel in the area of circumferential site weld: martensite — 0.32–0.35, bainite — 0.67–0.64, ferrite-pearlite — 0.02–0.01 with inhomogeneity width of about 15 mm) and changes of mechanical properties of material of the respective FE, related to this inhomogeneity, are in place [10]. Results of calculation of limit load are indicative of the fact that within microstructural (phase) inhomogeneity, caused by welding temperature cycle, no noticeable changes in the limit static load take place, but fracture mode changes as follows: plastic instability in the volume of structural inhomogeneity and microcleavage in the homogeneous part of the structure that is also in quite good agreement with the experimental data.

This work dealt with quite a number of similar examples of variation of residual (balanced) stress distributions of the type of welding stresses, as well as microstructural changes and their combinations, which, however, do not change the conclusion following from Cases 1–3 that in the absence of geometrical raisers the considered physical inhomogeneity has little influence on limit load at static loading of steel welded structures. Here it should be noted that the factor of the influence of structural transformations and kinetics of stress-strain state of metal in the area of the weld and HAZ in welding on characteristics of pore initiation (κ_s, ε_f, S_c) and degree of dissipated damage ρ_V^s requires additional investigations.

Case 4. A typical problem is assessment of the state of structures with geometrical non-uniformity of the type of pipe wall thinning, which is this Case is solved with the same assumptions as in [11], but at greater deformations. Thinning of ellipsoidal shape on the pipe outer surface is described by the following equation in the cylindrical system of coordinates r, β, z:

$$\left(\frac{R-r}{a}\right)^2 + \left(\frac{2\beta r}{c}\right)^2 + \left(\frac{2z}{s}\right)^2 = 1, \qquad (22)$$

where a, c, s are the overall dimensions of thinning by wall thickness (a), around the circumference (c), along pipe axis (s); $\beta = 0$ and $z = 0$ in the plane of symmetry.

For the considered pipe at working pressure $P = 7.5$ MPa a case of external surface defect was analyzed. Defect dimensions were $s = 66$ mm, $a = 14$ mm, $c = 40$ mm that is allowable [2]. It should be noted that the above value of operating pressure allows for safety factors typical for the conditions of operation of pipeline elements (2–3). Therefore calculation of limiting state in this case requires detailed modeling of fracture processes in the raiser area. As shown by investigations within the above-described methodology, limiting state of a pipe with a defect is reached at the pressure of 17.7 MPa by the mechanism of plastic instability. Nature of spontaneous fracture in the area of geometrical anomaly is determined by the order, in which FE loose their ability to take the load according to (20). Proceeding from the results of calculations (Figure 3), fracture initiates on the periphery of a surface defect and develops in its longitudinal section under the impact of circumferential stresses in the pipe wall.

Case 5. One of the technological processes of restoration of load-carrying capacity of pipes with detected defects of local thinning type is surfacing by welding [12]. In this case operational loss of pipe wall metal is compensated by deposited metal and overall dimensions of the structure are restored to normative values. Here residual welding stresses develop in the area of repaired defect, the influence of which on load-carrying capacity of the pipe requires additional investigations. In particular, developed procedure of evaluation of limiting state of structures by tough fracture mechanism allows determination of limit pressure preceding spontaneous development of macrofractures in the region of local non-uniformity of the stressed state. Figure 4 gives the results of calculation of characteristic residual stresses in the field of welding up a defect of ellipsoidal shape, parameters of which are given in Case 4. These data illustrate high local stresses, reaching the yield limit of the considered steel. Here limit pressure, at which plastic instability of such a pipe develops, is equal to $P = 19.4$ MPa by the results of computational investigation that, alongside the conclusions of Case 3 on insignificant influence of structural inhomogeneities on the kinetics of initiation and development of tough fracture pores, confirms the effectiveness of defect repair by surfacing in terms of safe residual operating life of a pipeline element.

Results of calculation of limit loads of pipeline elements ($2R \times \delta = 1420 \times 20$ mm) under the impact of inner pressure depending on structure initial state

Initial structure state	Fracture pressure, MPa	Fracture mode
Uniform structure	19.5	Microcleavage
Presence of local residual stresses characteristic for site circumferential welds	19.2	Microcleavage
Structural inhomogeneity of welds	19.5	Plastic instability in structural inhomogeneity zone, microcleavage in the uniform part
Geometrical inhomogeneity of the type of semielliptical wall thinning	17.7	Plastic instability in defect peripheral part
Presence of local residual stresses induced by repair welding	19.4	Plastic instability in residual stress area

The Table gives comparative results of calculation of limiting state (Cases 1–5), which lead to the general conclusion that the influence of characteristic welding processes (site or repair welding) on pipeline element metal (structural transformations, residual stress-strain state) in terms of the magnitude of limit operating load is insignificant by tough fracture criteria.

Conclusions

1. Numerical procedure of investigation of processes of tough fracture of structures under external load impact was developed. For this purpose a model of pore initiation and development was constructed on the basis of finite element analysis of complex stress-strain state of structural elements at developed flow of material. Pores leads to lowering of structure load-carrying capacity, and as a result — to its spontaneous fracture. Proposed approach allows tracing of the kinetics of structure state right up to limiting state.

2. Typical cases of loading pipeline element by inner pressure are considered. It is shown that the influence of structural inhomogeneity of pipe steel, as well as initial stress-strain sate induced, in particular, by site welding, on the limiting load that can be taken by such a structure is insignificant.

3. Limiting states were studied according to tough fracture mechanism of pipeline section with an external ellipsoidal defect of the type of local wall thinning, in particular, after repair by surfacing. It is shown that in terms of development of tough fracture such a kind of repair does not lower the load-carrying capacity of the restored structural element, despite the high residual stresses in the repaired defect area.

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