On catastrophic fracture of steel structures at temperatures lower than cold brittleness threshold

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Abstract. The paper considers crack propagation in elements of homogeneous steel structures and those with welded joints. For analysis of failure of the structures, diagrams of quasi-brittle fracture have been plotted. When constructing quasi-brittle fracture diagrams, the model of elastic-plastic material having an ultimate strain was used. The data report for quasi-brittle fracture diagrams of common elements of structures has been given. Analysis of parameters used in the proposed model was carried out for temperatures near or lower the brittleness threshold. Parameters of the model are selected from two laboratory experiments (critical stress intensity factor and classical stress-strain diagram) performed at appropriate temperatures. It has been established that weld structures with cracks in the vicinity of a welded joint exhibit decreased crack toughness. The effect of structure break under monotonic loading conditions is clearly visible inasmuch as ultimate loads essentially decrease with increasing a crack length. The attention is given to the parameter characterizing plastic material deformation and exhaustion of plasticity resource under preliminary plastic material deformation. After the plasticity resource is exhausted, the temperature of brittleness threshold approaches a room temperature.

1. Introduction
Uzhik [1] describes (in the second chapter of his book) breakdowns of bridges, large petroleum reservoirs, gas holders, and ships at low temperatures. Given in Fig 6 from [1] are typical points of stress concentrations and nucleation cracks caused by them, which can lead to failure of a structure with decreasing temperature. Crack nucleation (points of stress concentrations) provoke [1, p 20]: “…1) welded joints or sites adjacent to shuts; 2) points of stress concentrations caused by the form of structural elements; 3) local defects (flaws, hollows, etc.) arising during production of some structural elements or due to poor quality treatment”. When studying catastrophic breakdowns, it is worthwhile to pay attention to the loading that, as a rule, is a force controlled. Break of a structure occurs under action of loadings due to finite sizes of structural element with a crack. Except for indicated points of fracture, which are mechanical in nature, attention should be given to degradation of properties of structural steels associated with the structure [2, 3].

A scheme of loading (the case of a force control) of a quasi-brittle material [4-6], which describes catastrophic breakdowns of homogeneous and weld structures due to decrease of a temperature below the cold brittleness threshold is considered below.

2. Diagrams of quasi-brittle fracture of compact specimens
Judging from catastrophic breakdowns [1], all structure have, in one form or another, nucleus defects such as cracks. If crack lengths didn’t reach a critical value at room temperatures, the structures continued to be used. Mechanical characteristics of the material (steel) change with decreasing temperature. The proposed model [4-6] uses a non-classic scheme of material fracture.

Suppose that when a macro-specimen was tested in laboratory experiment, a $\sigma - \varepsilon$ diagram of quasi-brittle material was obtained for various temperatures $T$, i.e., $\sigma = \sigma(T)$, $\varepsilon = \varepsilon(T)$. The simplest approximation of a real $\sigma - \varepsilon$ diagram of a tested material is a two-link polygonal line. During approximation, the original material is changed by and elastic ideally-plastic material, which has an ultimate strain. Parameters of this approximation $E, \sigma_Y, \varepsilon_0, \varepsilon_1, \mu$ are as follows: $E = \text{const}$ is the modulus of elasticity, $\sigma_Y(T)$ is the yield tensile strength and constant stresses acting in modified fashion of the Leonov-Panasyuk-Dagdale model, $\varepsilon_0(T)$ is the maximum elastic material strain ($\sigma_Y = E\varepsilon_0$), $\varepsilon_1(T)$ is the maximum material strain, $\mu = \text{const}$ is the Poisson coefficient. The $\sigma - \varepsilon$ approximation of the diagram within the range $\varepsilon_0 < \varepsilon < \varepsilon_1$ may be interpreted as a perfect plasticity. It has been accepted in the study proposed below that the modulus of elasticity and Poisson coefficient are independent of temperature, that approximately corresponds to behavior of steels at low temperatures.

Let $r$ be the grain diameter, more exactly, effective diameter of fracture structure for material with a regular structure [6]. The Neuber-Novozhilov approach permits solutions having a singular component with integrable singularity to be used for structural media. An opening mode crack is under consideration. Let this plane opening mode crack be propagating rectilinearly. Apart from a length $l_0$ of a real crack-cut, introduce into consideration a length of a model crack-cut. The lengths of model cracks are $l = l_0 + \Delta$, the pre-fracture zone with the length $\Delta$ being located on the continuation of a real crack. The fracture problem has two linear scales: if the grain diameter $r$ is defined by a material structure, then the second linear scale is developed by the system itself. It is the pre-fracture zone length that is the second linear scale $\Delta$, which varies in accordance with the fact how the following parameters are changed (1) a real crack length, and 2) load intensity. It should be emphasized that the critical pre-fracture zone length $\Delta^*$ is a well-defined parameter ($l^* = l_0 + \Delta^*$ is the critical macro-crack length) under single loading.

When plotting diagrams of quasi-brittle fracture, sufficient fracture criteria [4-6] are used when short, long, and medium length macro-cracks are considered. The sufficient criterion may be represented in the form of two relations for short macro-cracks

$$\frac{1}{r_0} \int_0^r \sigma_y(x, 0) dx = \sigma_Y, \quad (1)$$

$$2\nu(-\Delta^*, 0) = \delta^*. \quad (2)$$

Here $\sigma_y(x, 0)$ are normal stresses on the crack continuation; $Oxy$ is the rectangular coordinate system, the coordinate origin being coincident with a model crack tip in the modified Leonov-Panasyuk-Dagdale model, where the $x$-axis is directed along the crack plane and the $y$-axis is directed along the normal to the crack plain; $2\nu = 2\nu(x, 0)$ is the model macro-crack opening ($x < 0$); $\delta^*$ is the critical opening of this crack, $\Delta^*$ is the critical length of a pre-fracture zone (critical values derived via sufficient and necessary fracture criteria are labeled by superscripts $^*$ and $^0$, respectively). Attention is given to the fact that the proposed criterion (1) and (2) is two parametric.

A field of normal stresses $\sigma_y(x, 0)$ on the continuation of model cracks $x > 0$ can be represented as a sum of two summands
are forces applied at the

\( g170 \) /g186 /g170 /g186 .

\( YKK \) P t w l w K l . (4)

in a compact specimen with a sharp crack is represented in the form

\( a \)

and material with weld joint is half as large as the plasticity zone width in the homogeneous material, i.e.,

\( a_w = a / 2 . \)

After appropriate transformations, the initial equalities of criterion (1) – (2) go into approximate equalities for compact specimens with sharp cracks, if we take into account relations (3)-(7)

\[ \sigma_\beta(x,0) \equiv K_1 / (2\pi x)^{1/2} + \sigma_{nom}, \quad K_1 = K_{1o} + K_{IA} > 0, \]

\[ K_{1o} > 0, \quad K_{IA} < 0, \quad (3) \]

where \( \sigma_{nom} \) are nominal stresses, in other words, estimates of regular members of solutions in the vicinity of model crack tips, and these members have no singularities; \( K_{1o} \) is the stress intensity factor (SIF) generated by specified test conditions; \( K_{IA} \) is the SIF generated by constant stresses \( -\sigma_y \) acting in a pre-fracture zone.

The first and second summands in relation (3) are singular and regular parts of the solution, respectively. The total SIF \( K_1 \) at the model crack tip is positive inasmuch as the low-scale yielding is considered.

The specimen with a crack is shown in Fig. 1 (\( P \) are forces applied during tests, \( w \) and \( t \) are the width and thickness of the specimen, respectively). The proposed approximation of normal stresses at tips of model cracks for compact specimens with a sharp crack has the following form at tips of model cracks for compact specimens with a sharp crack

\[ \sigma_{nom} = \sigma_{1nom} + \sigma_{2nom}, \quad \sigma_{1nom} = P\left[ t(w-l)\right]^{-1}, \quad \sigma_{2nom} = 3P\left[ t(w-l)^2\right]^{-1}. \quad (4) \]

Here \( \sigma_{1nom} \) and \( \sigma_{2nom} \) are nominal stresses under tension and bending, respectively. The singularity of nominal stresses \( \sigma_{nom} \) for \( l \to w \) reflects the break process of a structure at catastrophic failure of steel structures under conditions of low temperatures.

Under conditions of low-scale yielding for compact specimens with sharp cracks, we have for the total SIF

\[ K_1 = K_{1o}(P/tw) + K_{IA}(l, \Delta, \sigma_Y) > 0, \quad K_{1o} = (P/tw)Y(l/w)\sqrt{\pi l}, \quad K_{IA} \approx -2\sigma_Y \sqrt{2\Delta / \pi}, \quad (5) \]

\[ Y(l/w) = 16,7 - 104(l/w) + 370(l/w)^2 - 574(l/w)^3 + 361(l/w)^4. \]

Opening of model cracks \( 2\nu \) in a compact specimen with a sharp crack is represented in the form

\( 2\nu(-x,0) \equiv \left[ (\eta + 1) / G \right] K_1(l, \Delta, l / w)[-(x) / 2\pi]^{1/2}, \quad K_1 > 0, \eta_d = 3 - 4\mu, \eta_s = (3 - \mu) / (1 + \mu). \quad (6) \]

Coefficients \( \eta_d \) and \( \eta_s \) are given for the plane strain and plane stress states, \( G = E / 2(1 + \mu) \) is shear modulus, and \( \mu \) is the Poisson ratio.

The critical opening of model cracks \( \delta^* \) in relation (2) is calculated as

\[ \delta^* = (\varepsilon - \varepsilon_0)a, \quad (7) \]

\[ a = \left[ K_{1o}^2 / \left[ 2\pi (\sigma_Y)^2 \right] \right]^{3/2 + (1 - 2\mu)^2}, \quad a_w = \left[ K_{1o}^2 / \left[ \pi (\sigma_Y)^2 \right] \right]^{3/2 + (1 - 2\mu)^2}. \]

Identify the pre-fracture zone width in relation (7) with the width of plasticity zones at the real crack tip for compact specimens with sharp cracks made of a homogeneous material \( a \) and material with weld joint \( a_w \) (the joint plane is located in the tip plane [9-12]). The plasticity zone width \( a_w \) in the material with weld joint is half as large as the plasticity zone width in the homogeneous material, i.e.,

\[ a_w = a / 2 . \]
If in two laboratory experiments, the critical SIF specimens made of homogeneous material and material with weld joint (specific implementation of calculations, parameters curves 1 – 3 and for curves 4 – 6, respectively. In calculations, plotted in Fig. 2 are dimensionless critical stresses \( \sigma_0^c / \sigma_Y \) within the wide range of variation of crack lengths.

The last inequality (9) is a restriction at which quasi-brittle fracture occurs under conditions of low scale yielding of homogeneous material in a pre-fracture zone.

Under conditions of critical stresses \( \sigma_0^c / \sigma_Y \) corresponding to the necessary fracture criterion, we have the following relation

\[
\frac{\sigma_0^c}{\sigma_Y} \approx \left[ \frac{1}{1 - l^* / w} + \frac{3(1 + l^* / w)}{(1 - l^* / w)^2} + Y \left( \frac{l^*}{w} \right) \sqrt{2 \frac{l^*}{r}} \right]^{-1}.
\] (8)

\[
\frac{\Delta^*}{l^*} = \left[ \frac{3 + 2(1 - 2\mu^2)}{2(1 - 2\mu^2)^2} \right] \left( \frac{\sigma_0^c}{\sigma_Y} \left( \frac{l^*}{w} \right) \right)^2 \frac{\sigma_0^c}{\sigma_Y} \left( \frac{l^*}{w} \right) \left( \frac{\varepsilon_1 - \varepsilon_0}{\varepsilon_0} \right) \left( \frac{\varepsilon_1 - \varepsilon_0}{\varepsilon_0} \right) < 1.
\] (9)

If in two laboratory experiments, the critical SIF \( K_{lc} \) and classical \( \sigma - \varepsilon \) diagram (more precise, its approximation), then, by three parameters \( r, \sigma_Y, \left( \varepsilon_1 - \varepsilon_0 \right) / \varepsilon_0 \), with allowance made for the Poisson ratio \( \mu \), it is possible to construct two critical curves \( \sigma_0^c / \sigma_Y \), \( \sigma_0^c / \sigma_Y \) in the plane “crack length – stress” within the wide range of variation of crack lengths.

Plotted in Fig. 2 are dimensionless critical stresses \( \sigma_0^c / \sigma_Y \) (curves 1 and 4), \( \sigma_0^c / \sigma_Y \) (curves 2, 3, 5, and 6) of compact specimens with sharp cracks, solid and dashed lines reflecting behavior of specimens made of homogeneous material and material with weld joint \( \left( \frac{\varepsilon_1 - \varepsilon_0}{\varepsilon_0} = 3 \right) \). For a specific implementation of calculations, parameters \( w / r = 500 \) and \( w / r = 2000 \) were chosen for curves 1 – 3 and for curves 4 – 6, respectively. In calculations, \( \mu = 0 \) was taken, inasmuch as the Poisson ration has weak influence on critical parameters. Pairs of curves 1 – 3 and 4 – 6 represent quasi-brittle fracture diagrams for studied specimen made of homogenous material. Pairs of curves 1 – 2 and 4 – 5 represent diagrams for studied specimen made of material with weld joint (the weld joint is located in the plane of a crack).

**Figure 2.** Critical stresses \( \sigma_0^c / \sigma_Y \) and \( l / w \quad \sigma_0^c / \sigma_Y \) of compact specimens

**Figure 3.** Critical stresses \( \sigma_0^c / \sigma_Y \), \( \sigma_0^c / \sigma_Y \) versus \( l / w \).
The conditional critical stresses $\sigma^0 / \sigma_Y$ (curve 1), $\sigma^*_0 / \sigma_Y$ (curves 2 and 3) of compact specimen are plotted in Fig.3 versus the $l / w$ ratio. When constructing the curves, relations (8) and (10) were used, the calculations being made for $2l / r = 1$ and $(\varepsilon_1 - \varepsilon_0) / \varepsilon_0 = 3$. Solid and dashed lines correspond to homogeneous and welded structures. The relatively weak dependence of critical stresses on growth of short racks $l / w$ from 0.01 to 0.2 has been revealed.

3. Quasi-brittle fracture diagrams of specimens-counterparts of constructions

Apart from relations (8) and (10) for critical stresses of compact specimens, we give analogous relations of critical stresses (relations (11)-(13)) and representations of fracture diagrams (Figs. 4 and 5) of tensile band with cracks and critical moments of a bending specimen. Solid lines were used for homogeneous structures in Figs. 4 and 5 and dashed lines were used for structures with weld joints in the same figures. All the calculations were made for $(\varepsilon_1 - \varepsilon_0) / \varepsilon_0 = 3$.

\[ \sigma^*_0 / \sigma_Y = \left[ \frac{1}{1 - 2\lambda} + \frac{1}{8\pi} \left( \frac{1 - 2\mu^2}{2} \right) \left( \frac{\varepsilon_1 - \varepsilon_0}{\varepsilon_0} \right) \right]^{-1} Y(\lambda) \sqrt{\frac{2l^2}{r}}, \]

\[ Y(\lambda) = \cos^{-1/2} \frac{\lambda}{\pi\lambda}, \quad \lambda = \frac{l}{w} = \left( \frac{l}{r} / \frac{w}{r} \right). \]

Critical stresses $\sigma^*_0 / \sigma_Y$ of a tensile band of the width $w$ with two edge cracks of the length $l$ have the form

\[ \sigma^*_0 / \sigma_Y = \left[ \frac{1}{1 - \lambda} + \frac{1}{8\pi} \left( \frac{1 - 2\mu^2}{2} \right) \left( \frac{\varepsilon_1 - \varepsilon_0}{\varepsilon_0} \right) \right]^{-1} Y(\lambda) \sqrt{\frac{2l^2}{r}}, \]

\[ Y(\lambda) = \left[ 1 + 0.122 \cos^2 \left( \frac{\pi\lambda}{2} \right) \right] \sqrt{\frac{2l}{r}} \cos \left( \frac{\pi\lambda}{2} \right), \quad \lambda = \frac{l}{w} = \left( \frac{2l}{r} / \frac{w}{r} \right). \]

The bending moments $M$ for symmetrical three-point bending can be represented as $M = PL / 4$, $L = 4b$, where $L$ is the length of a bending beam span, $b$ is the height of a bending specimen. The bending moments $M'$ of specimens with a crack of length $l$ under bending ($t$ is the beam thickness) are as follows.
was shifted into the region of low-cycle loading [13]. The impact of cold plastic deformation of mild steels on an ultimate loading parameter when a response of the system to applied loading is formed. This parameter characterizes plastic properties not only of the original material, but also of material subject to cold plastic deformation in the pre-fracture zone under low-cycle loading [13]. The impact of cold plastic deformation of mild steels on an ultimate loading has been shown earlier. In some cases, the brittleness threshold \( T_0 \) was shifted into the region of ambient temperatures after essential plastic deformation. When cold-formed steel profiles are formed, they are usually hardened. When plasticity reserve of material is already partly consumed in locations where the profile is bent, use of such profiles provokes crack initiation when works are carried out under conditions of low temperatures.

**4. Using quasi-brittle fracture diagrams in analyzing catastrophic failure**

Consider the diagrams of quasi-brittle fracture of structural elements for analysis of catastrophic failures. The visual appearances of these diagrams do not change for various loading conditions. In order to select parameters of a proposed fracture model, the data derived from a critical SIF and from a \( \sigma - \varepsilon \) diagram at corresponding temperatures are needed. All elements with weld joints could be capable to withstand lesser loads as compared to homogeneous structures. The effect of break of a structure under monotonous loading is pronounced inasmuch as the critical loadings are essentially decreased with increasing a crack length.

Figure 5. The scheme of loading and critical moments \( M^* \) of bending specimens.

Attention should be paid to the special role of the \( (\varepsilon_1 - \varepsilon_0) / \varepsilon_0 \) parameter when a response of the system to applied loading is formed. This parameter characterizes plastic properties not only of the original material, but also of material subject to cold plastic deformation in the pre-fracture zone under low-cycle loading [13]. The impact of cold plastic deformation of mild steels on an ultimate loading has been shown earlier. In some cases, the brittleness threshold \( T_0 \) was shifted into the region of ambient temperatures after essential plastic deformation. When cold-formed steel profiles are formed, they are usually hardened. When plasticity reserve of material is already partly consumed in locations where the profile is bent, use of such profiles provokes crack initiation when works are carried out under conditions of low temperatures.

**5. Conclusion**

The data report for quasi-brittle fracture diagrams of common elements of structures of homogeneous structures produced by welding has been given. For plotting such diagrams, one of versions of the quasi-linear fracture mechanics is used. It has been established that welded structures with cracks in the vicinity of a weld joint exhibit decreased resistance to cracking. When analyzing parameters entering the proposed model, the data on deformation of steels at temperatures in the vicinity of the cold brittleness threshold or lower are used. Diagrams of quasi-brittle fracture are proposed to be used when analyzing catastrophic failures of structural elements operating at temperatures lower than the cold brittleness threshold. The attention is given to the fact that steel structures after plastic deformation have decreased operational integrity.

\[
M^* = \frac{6M^*}{bh^2\sigma_f} = \left[ \frac{1}{1 - \lambda} \right] \left[ \frac{1 - r / b}{1 - \lambda} \right] + \sqrt{\frac{2}{\pi}} \left[ \frac{1 - 3 + 2(1 - 2\mu)^2 \varepsilon_1 - \varepsilon_0}{8\pi(1 - \mu^2)} \frac{\lambda}{\varepsilon_0} \right] Y(\lambda) \left[ \frac{l' / b}{b / r} \right] \]

\[
Y(\lambda) = \frac{1.99 - \lambda(1 - \lambda)(2.15 - 3.93\lambda + 2.7\lambda^2)}{(1 + 2\lambda)(1 - \lambda)^{3/2}}, \quad \lambda = l' / b = (l' / r) / (b / r)
\]
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