CALCULATIONS OF THE SUPPORTING POWER OF PARTS WITH CRACKS IN CASES OF BRITTLE OR QUASI BRITTLE STATES OF MATERIAL

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ABSTRACT

The task is to provide a structural design method of complex geometry full-scale cast parts, made from middle steels with cracks, located in a stress concentration zone. Direct fracture experiment on the parts in the conditions providing brittle or quasi-brittle fracture is carried on. The crack propagation is assumed to go by way of separating to the first type. There exist three states of material: plastic, quasi-brittle, brittle states and the corresponding types of fracture. Fracture experiments of (automatic coupler) parts cases were carried on. More than 50 cracked parts from the cars in operation have been investigated. Considered the structural design of the cracked parts for the cases of the most dangerous brittle fractures. Using the section method for a case of a typical surface semi-elliptic crack gave the relationship of the maximum stress. Particular attention was paid to defining of the resistance to breaking (K_{Ic}) of every tested part. Considered the quasi - brittle fractures with somewhat large values of plastic deformation.

KEYWORDS

Crack, cracks propagation, brittle, states of material, plastic, quasi - brittle, fracture, cracked parts, structural design, calculation, stress intensity, stress concentration zone.

The task is to provide a structural design method of complex geometry full-scale cast parts, made from mild steels with cracks, located in a stress concentration zone.

As far as in solving of this rather complicated problem it is impossible to avoid some assumptions, direct fracture experiment on the parts after various operating service lives in the conditions providing brittle or quasi-brittle fracture is carried on; the accuracy of computation methods is evaluated by comparing the design and the experimental loads. Taking into consideration the detailed information on the automatic coupler of freight cars (Fig. 1), including its long service life, its operational failures, possibility of full - scale fracture experiment the problem was solved on the cast component, made from steel 20 L.

In the investigation danger area A (Fig.1) the component has the box section 175x130 mm with wall thickness of 23 mm. The cracks propagation is assumed to go by way of separating according to the 1-st type.

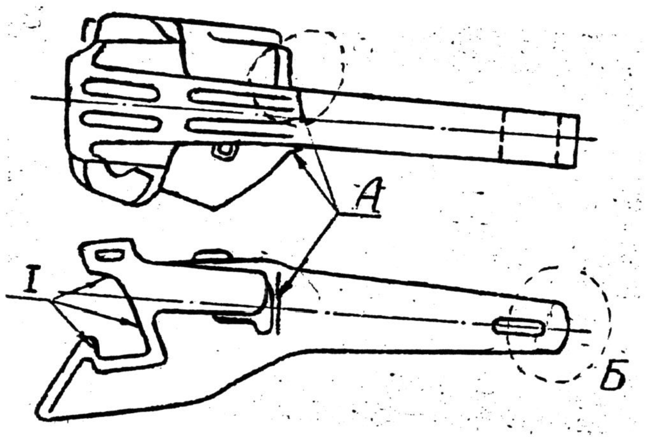

Fig.1 Places of situation cracks in the investigation part.

According to modern approaches there exist three states of material: plastic, quasi-brittle, brittle and the corresponding types of fracture. Boundary surfaces of different types of fracture are the first (T_{cr1}) and the second (T_{cr2}), critical temperatures of brittleness (Makhutov,1973). $T_e > T_{cr}$ means viscous fracture, $T_{cr1} > T_e > T_{cr2}$ - quasi - brittle fracture, $T_e < T_{cr2}$ - brittle fracture.

Critical temperatures of brittleness (the first and the second) were obtained by relation suggested in the Institute of Machine-dealing of the USSR Academy of Sciences (Makchtov,1973):

$$T^{e}_{cr1(2)} = T^{sp}_{cr1(2)} + \sum \Delta T_i \quad (1)$$

where $T_{cr1(2)}$ -the first or the second critical temperatures of the part brittleness;

ΔT -deviation of the first or the second critical temperatures of the specimen brittleness depending on different factors of the part.

The first critical temperature for the specimen was defined by the criterion of fracture type, namely %B=50; the second - by criterion $\sigma_c = \sigma_y = \sigma_u$; where σ_c - fracture stresses, obtained for the cracked eccentric tension specimen. For the cast part made from steel 20L $T^{sp}_{cr1} = -5^{o}C$; $T^{sp}_{cr2} = -120^{o}C$. Minimum value of T_{cr1} for "new" automatic couplers with cracks is equal to (+50C), it

is higher for the rest. The second critical temperatures of brittleness for a zone in question are presented in table 1.

Table 1. The automatic coupler case (a zone of cofferdam).

Lifetime (years)	0-8,5	8,5-12	12-20	20-30
T_{cr2}	-99...-59	-77...-47	-65...-21	-39...-15

Level analysis of critical temperatures obtained reveal that the investigated parts are either in a quasi-brittle or in a dangerous brittle state.

For checking of the conclusion obtained wide fracture experiments of automatic coupler cases were carried on. More than 50 cracked parts from the cars in operation have been investigated (Fig.2). In experiments breaking stress,

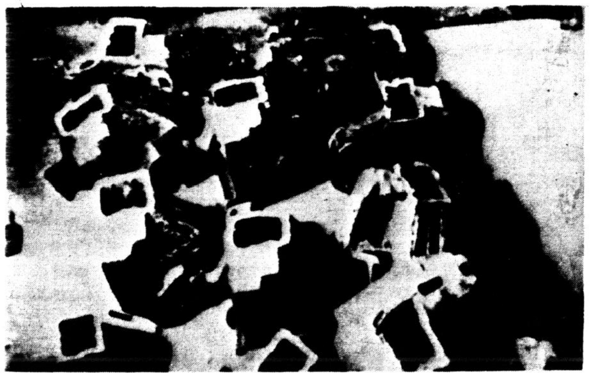

Fig.2. Parts which were tested on fracture.

temperature, eccentricity of loading, a portion of fibre in fracture, and what is more important, the diagrams of fracture, loading-operating of crack were recorded (Fig.3).

The diagram type evaluation was done in accordance with 3 conventional criteria (Markochev and Morozov, 1976); the conditions also were checked, where $\sigma_c / \sigma_{0,2} < 0,8$; σ_c - maximum stress. By the results of checking the fracture diagrams were divided into two groups: brittle and quasi - brittle. Thus, experimental data reaffirmed the theoretical results obtained (Fig.3): under low breaking stress the "old" (with longer lifetime) parts with $T_{cr2} = (-40...-15)^{o}$ C had brittle fracture; more "young" parts had higher breaking stress and their diagram corresponded to a quasi-brittle fracture.

Thus, reliability design algorithm of these parts during the design stage should provide the possibility for two types of fracture.

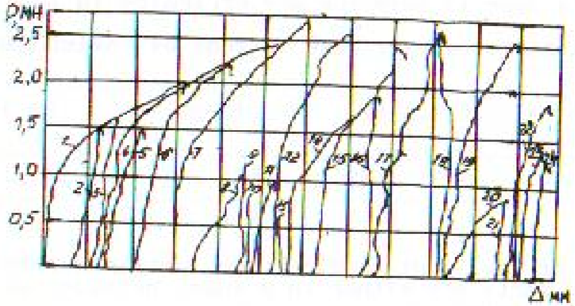

Fig. 3. Diagrams of loading - displacement, recorded in the fracture experiment for full scale parts with cracks under different temperatures.

First of all consider the structural design of the cracked parts for the cases of the most dangerous fractures. The standard reliability conditions in accordance with a conventional force criterion of fracture is used:

$$K_{Ides} > K_{Ic} \qquad (2)$$

where K_{Ides}-analytical expression of the stress intensity factor for the particular component;
K_{Ic} - the limiting value of the stress intensity factor.

For full scale parts of complex geometry it is very difficult to define the left as well as the right parts of the expression (2). Accurate solution of a problem at determining (K-taring) (K_{Ides}) for the full-scale parts meets great mathematical difficulties.

Considering that factor an engineering approach based on the method of section (Morozov, 1969) was used. It would be necessary to get information on the stress distribution in that particular section where a crack is located. The stress state investigation had been carried on by three methods: strain measurement by small length 1 mm gauges, volumetric photoelasticity and a method of finite elements in three-demensional variant (Kostenco, 1989). Combination of these three approaches permitted to get the true distribution picture of all parts of the stress tensor.

Using the section method for a case of a typical surface semi-elliptic crack (Fig. 4 shows only the upper shelf of a box section) gave the relationship for the fracture load P.

$$P = \sqrt{B/2 + \sqrt{(B/2)^2 + C}} \qquad (3)$$

$$B = 2/\pi \cdot (5 \cdot 10^4)^2/(0,05 + \mathcal{E}act)^2 \cdot F(\alpha,\varphi)\, K_{Ic}^2/\sigma_{1,0}^2 \cdot Foper$$

$$C = (5 \cdot 10^4)^4/(0,05 + \mathcal{E}act)^4\, K_{Ic}^4/6\pi \cdot \sigma_{1,0}^3 \cdot Foper;$$

$F_1(\alpha,\varphi) = 0,26\ell + 0,000587.$

$F_1(\alpha,\varphi)$ - a given function of the elliptic integral;
Foper - the result of the numerical integration of the experimental stresses field, obtained for load value P=1 MN (Meganewtons) and $\mathcal{E}act = 0$ by Simpson's rule, in Newtons;
$\mathcal{E}act$ - actual eccentricity of loading in m;
$\sigma_{1,0}$ - the stresses, estimated experimentally for P=1 MN (Meganewtons) and $\mathcal{E}act = 0$. Consider a mean stress along the cracks front depending on its location.

K - taring dependance was also defined:

$$K_{Ides} = \sigma_n \sqrt{\sqrt{36F_1^2(\alpha,\varphi) + 6 \cdot \pi \cdot Foper/\sigma_{1,0}} - 6F_1(\alpha,\varphi)} = \sigma_n \cdot Y_1 \qquad (4)$$

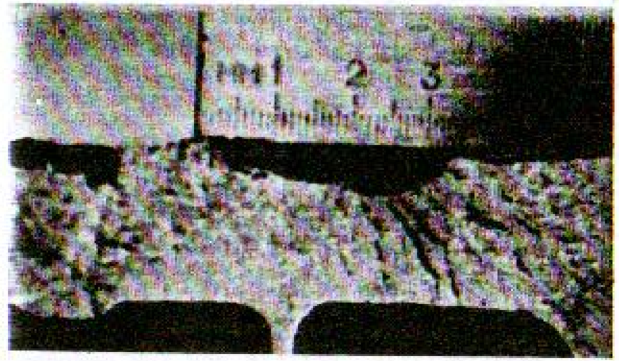

Fig. 4. Exploitation cracks in the parts of carriages.

The limiting value of the stress intensity factor in a wide temperature range on the eccentric tension full scale specimen with a thickness according to GOST 25.506-85 was defined. The results of these tests gave the values of K c under the temperature of brittle state (in this case $T^* = -230°C$) and the second critical temperature $T_{cr2}^p = -120°C$. The values of K_{Ic} for every particular part were defined by formulas (5 and 6) (Machutov, 1973).

$$K_{Ic} = \bar{K}_{Ic} \exp[-\beta_K(T_{cr2}^p - T_{expl})]; \qquad (5)$$

$$\bar{K}_{Ic} = K_{Ic}^* \exp[\beta_K(T_{cr2}^p - T^*)]; \qquad (6)$$

where $\bar{K}_{Ic}$ - the limiting value of the stress intensity factor of a part under the temperature T_{cr2}^p;
β_K - coefficient of dependance from the yield limit under the normal temperature;
T_{expl} - temperature at a moment of the part fracture;
K_{Ic}^* - stress intensity factor under the brittle state temperature T^* ($T^* = -230°C$ in the case).

Service life, testing temperatures, sizes of cracks geometrical dimension and other factors influence K_{Ic} by way of shifts of critical temperatures in a formula (1).

For evaluating of the service life influence upon K c the standard specimen of stretching were cut from the investigated zone of automatic couplers with various periods of lifetime. Testing results gave changes in yield limit of this part material caused by their life time. The shift of critical temperature from the cyclic damage was defined by Ioffe scheme; the value of K_{Ic} was defined by formulas (7 and 8).

Design value of breaking load Pdes, obtained from a formula (3), using (7), (8) were compared with experimental Pexp. Discrepancies have both positive and negative values and are within 23-30%.

Consider the quasi - brittle fractures with somewhat large values of plastic deformation. They are investigated from the viewpoint of non - linear mechanics of fracture. Some criteria of quasi - brittle fractures are known at the time. Here is given the calculation on the basis of the stress intensity factor (Makhutov, 1981, GOST 25. 506. -85.).

The fracture conditions are as follows:

$$\bar{K}_{I\varepsilon}\,des = \bar{\sigma}_{cp}^{\,n_\varepsilon}\,(\bar{\sigma}_{cp}\sqrt{\pi\cdot l}\ Y_o) = \bar{K}_{c\varepsilon},\quad when\ \bar{\sigma}_c > 1 \qquad (7)$$

where conventionally the left part describes operational conditions and constructional figures of the particular part, and the right $K_{c\varepsilon}$ - resistance characteristic of the part material under quasi-brittle fracture.

Consider the left part of the equation (7). Here: $\bar{\sigma}_{cp} = \sigma_{cp}/\sigma_{0,}$ - maximum relative local stress in a concentration zone at the fracture moment; $Y_o = Y_1/\sqrt{\pi l}$ - coefficient in the expression $K_{I\varepsilon}$, which is defined by the dependence (4). In accordance with the technique (Makhutov, 1981; GOST 25. 506. -85), design characteristics of the part material and loading conditions are as follows:

$$n_\varepsilon = (1 - m) / (m (1 + m));$$

$$\rho_{K\varepsilon} = (2 - 0,5\ (1 - m)(1 - \bar{\sigma}_{cp})) / (1 + m); \qquad (8)$$

where m - index of material hardening in elastoplastic zone (material constant), which is defined for smooth specimen, for example, by way of uniform narrowing ψ_s

$$m = 2,3\ lg\ (100/(100 - \psi_s)). \qquad (9)$$

The difficulties of the strength evaluation of cracked parts under quasi - brittle fracture are redoubled by the fact, that the left part of the criterion condition is changed by way of n_ε and $\rho_{K\varepsilon}$ and is influenced upon by the number of loadings, and loading level, the part dimensions, the temperature and some other factors. The situation described is similar to the small cycle fatigue design.

The factors in question are considered by means of the hardening index m in the elastoplastic zone, which is estimated

not as a material constant, but as a value, dependent from the loading prehistory in a formula (5,6).

The right part of the condition (7) Kc is defined according to GOST 25. 506. -85.

For calculation of particular part according to the equation (7), the limiting deformation intensity factor $K_{c\varepsilon}$ for this part material is needed, which is determined by the testing temperature, the degree of material cyclic damage, variations in crack sizes and also in dimensions of a specimen and a part. In this connection the right part of the criterion condition also needs some correction. The most convenient way to do this is to use the critical value of the deformation intensity factor (Makhutov, 1981) by means of fracture local deformation in the crack tip (ef) (11), which, in its turn is related with the relative local deformations of a smooth specimen $\bar{e}_c = \bar{e}_k$ according to (12), estimated by means of narrowing in the smooth specimen neck according to ψ loc with the formula (13)

$$\bar{K}_{c\varepsilon} = \bar{e}_f\sqrt{2\pi l_o} \qquad (11)$$

$$\bar{e}_f = De\cdot\bar{e}_c / I \qquad (12)$$

$$\bar{e}_c = 1 / e_y\ ln\ (1 / (1 - \psi_{loc})) \qquad (13)$$

where De - coefficient of fracture deformation reduction in a concentration zone under non-linear stressed state which is estimated according to (Makhutov, 1981);

I - coefficient of resistance rising to the plastic deformation by means of the volume stressed state (Makchutov, 1981);

l_o - initial dimension of a crack in a specimen;

e_y - deformation of initial yielding.

Some corrections were carried strictly according to the procedure without any relations to the factor in question: at first the changes of mechanical characteristics (σ_y and ψloc) influenced by the particular factor were defined; after that the values obtained σ_y, e_y and ψloc were put into (13), a local deformation in a crack tip (e_f) was defined according to (12).

The coefficients are defined according to the suggested scheme: C_2 - reveals influence of the temperature difference of the investigated specimen under the eccentric tension and a part (reflations σ_y and ψloc experimentally obtained and influenced by the temperature (Makhutov, 1981) were used); C_3 - defines the difference in dimensions of a specimen and a part according to conventional relation (Makhutov, 1981); defining of the coefficient C_4, revealing the difference in the crack dimensions in a specimen and in a part, was considered in detail.

The resulting deformation intensity factor of the particular part is defined on the basis of the specimen deformation intensity factor $K_{c\varepsilon}$ from a relation:

$$\bar{K}_{c\varepsilon} = \bar{K}'_{c\varepsilon}\cdot C. \qquad (14)$$

The analysis shows the values C and C to be negligible, that is why $C = C_1 \cdot C_4$.

On the basis of the condition (7) in the above mentioned tests the breaking loads Pdes of cracked full-scale parts (automatic couplers of the freight cars) for the cases of quasi-brittle fractures were calculated.

Comparing the calculated values with values obtained experimentally we see that the mean divergences are within (+20...25)%. The value of the breaking load Pdes, calculated without taking into consideration the system of corrections are received too. The analysis of the results show that the corrections of the both parts of the criterion equation (7) increase sufficiently (up to 15 ... 20%) accuracy of calculation.

Working up the calculations in question is necessary for obtaining the general algorithms for the design reliability prediction.

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