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Load Capacity of Steel Structures with Cracked Components

Résistance des constructions métalliques avec des éléments fissurés

Tragfähigkeit von Stahlkonstruktionen mit gerissenen Gliedern

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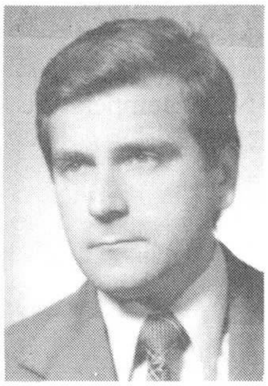

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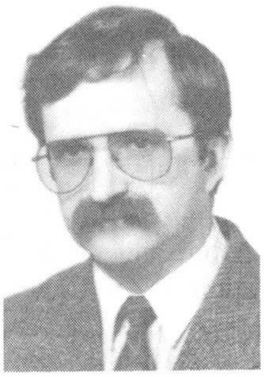

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SUMMARY

The analysis of existing steel structures with cracked structural members is presented. The Fracture Analysis Diagram method is used in the analysis. Two components of the safety vector are considered: relative stress and stress intensity coefficient. The second component is adjusted in the analysis. Decrease of its value can be obtained by fixing the reinforcing ribs with the use of bolts and by elastic straps that fully cover the crack and which are elastically connected with a cracked member.

RÉSUMÉ

Le rapport présente l'analyse de constructions métalliques avec des éléments structuraux fissurés. La méthode de l'analyse du diagramme de la fissure est utilisée. Deux composantes du vecteur de la sécurité sont considérées: contrainte relative et coefficient de l'intensité des contraintes. La deuxième composante est ajustée dans l'analyse. La diminution de leur valeur peut être obtenue par la fixation de tôles de raidissement à l'aide de vis et par des fers plats élastiques, qui couvrent entièrement la fissure et qui sont fixés élastiquement à l'élément fissuré.

ZUSAMMENFASSUNG

Im Artikel ist die Analyse bestehender Stahlkonstruktionen mit gerissenen Konstruktionsgliedern vorgestellt. Für die Analyse wurde die Methode der Rissdiagrammanalyse angewendet. Zwei Komponenten des Sicherheitsvektors werden untersucht: Relative Spannung und der Koeffizient der Spannungsintensität. Die zweite Komponente wird in der Analyse errechnet. Die Verminderung ihres Wertes kann auf verschiedene Weisen erreicht werden. Zwei Möglichkeiten werden im Referat besprochen: die Befestigung der Verstärkungsrippen mit Schrauben einerseits und elastische Laschen, die den Riss vollkommen bedecken und mit dem gerissenen Glied elastisch verbunden sind andererseits.

1. INTRODUCTION

Brittle fractures have their origin in metallurgical discontinuities or in weld defects. The initial faults increase with the increase of monotonic load or cyclic load. Crack growth intensifies in winter seasons, when material ductility decreases. Irwin's constant K_{IC} represents the notch toughness of material and is correlated with fracture toughness measured with Charpy specimens [1]:

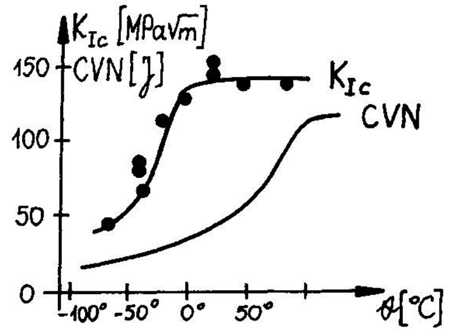

Fig.1 CVN vs. temperature and K_{IC} vs. temperature curves [2]

$$K_{IC} = \sqrt{0.22\,(CVN)^{3/2}\,E}$$

where: CVN - Charpy V-notch impact,
E - elastic modulus.

K_{IC} vs. temperature and CVN vs. temperature curves [2] are shown in Fig.1.

2. LIMIT STATES OF CRACKED COMPONENTS

The existing crack in structural component can remain unchanged if its half-length is not greater than the critical value:

$$l_{cr} = \frac{K_{IC}^2}{M \cdot \sigma^2}$$

where:

- l - half-length of a crack,
- M - geometrical coefficient, representing position and shape of the crack,
- σ - the applied stress.

Values of M for cases shown in Fig. 2 are presented by Tada, Paris and Irwin [8]. On the basis of the critical value l_{cr} and the basic Paris equation [4]:

$$\frac{dl}{dN} = C\,(\Delta K)^m$$

the ability of survival of the cracked structural member, measured by the number of load cycles, can be determined, as:

$$N_{cr} = N + \frac{1}{C(\Delta K)^m (m-2)} \left[1 - \left(\frac{l}{l_{cr}} \right)^{\frac{m}{2}-1} \right]$$

where $\Delta K = K_{max} - K_{min} = (\sigma_{max} - \sigma_{min})\sqrt{Ml}$,
N - number of load cycles for the crack of length 2l,
C, m - material constants, proposed in [6] as $m = 3$, $C = 1.315 \times 10^{-4} / 895.4^m$.

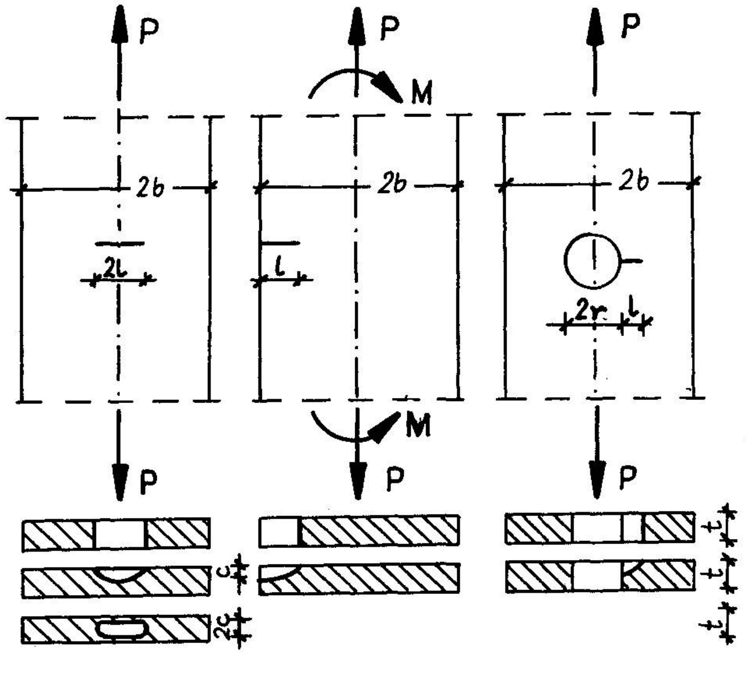

Fig.2 Characteristic cracks types

Further, for the case shown in Fig. 2a the two ways of safety improving are presented. Fitness for purpose second level criterion is suggested for load capacity analysis [6]:

$$K_r = S_r \left[\frac{8}{\pi^2} \ln \sec\left(\frac{\pi}{2} S_r \right) \right]^{-0.5}$$

where:

$K_r = n_k K_I / K_{IC}$, $K_I = \sigma\sqrt{Ml}$,

$S_r = n_\sigma \sigma / \sigma_e$,

$\sigma_e = 0.5\,(\sigma_y + \sigma_u)$,

σ_y - material yield strength,

σ_u - ultimate strength,

n_k , n_σ - safety coefficient for brittle and ductile fracture, respectively.

While safety coefficient n_σ for ductile fracture are fixed in specifications of many countries, value of the coefficient n_k is still under intensive investigation, nowadays. Many authors usually assume, that $n_k \geq 2$.

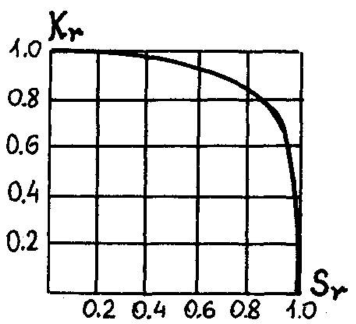

Fig.3 Limit capacity curve

In case of elements too thin for plane-strain behavior, i.e. when

$$\beta_t = \frac{\left(K_{IC} / \sigma_y\right)^2}{t} \langle 0.4$$

instead of K_{IC}, the following alternate value should be used in calculations:

$$K_C = K_{IC}\sqrt{1 + 1.4\beta_t^2}\,.$$

The idea of suggested methods of strengthening is to decrease the stress intensity coefficient K_{IC} to such an extend that the capacity of the structure would be described by parameters K_r and S_r which are below the limit capacity curve (Fig.3).

3. STRENGTHENING METHODS

3.1 Method I

In the first method, strengthening of cracked structural member is recommended by drilling of two relieving holes on the axis which is perpendicular to the axis of the crack (Fig. 4). Moreover, two steel straps connected with the cracked member symmetrically on its both sides, as shown in Fig.4

are recommended. This method is far more safe than popular drilling two holes through two tips of the crack. It should be noted, that drilling just two holes is not secure method of strengthening. In such a case there is a danger that the crack propagation can be initiated by the following factors:

- additional mechanical energy yielded during drilling,
- careless drilling, crack tip can be beyond the drilled hole, in the stress concentration zone.

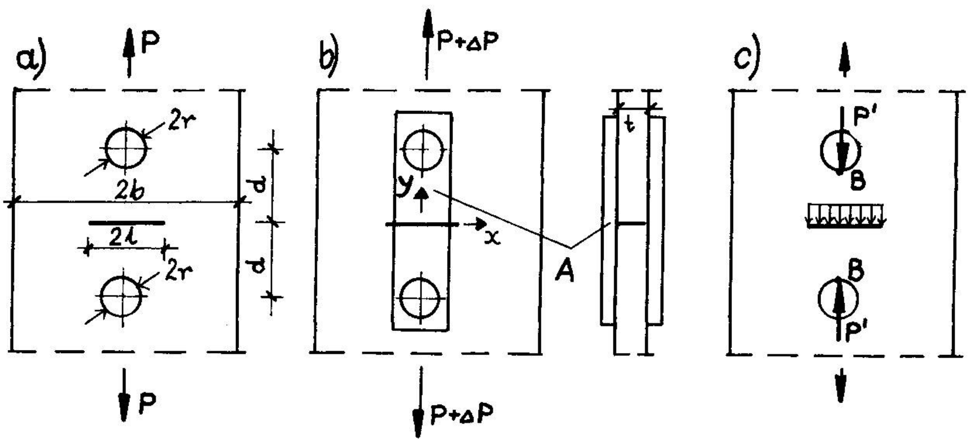

Fig.4 Strengthening method I

Newman's method [3] applied to the holes shown in Fig. 4a, gives:

$$K_I = \sigma\sqrt{Ml}\cdot F\left(\frac{d}{r}, \frac{l}{r+l}\right),$$

and the diagram of function F is presented in Fig.5. For d/r = 2 and r/l = 1, F≈ 0.6. Such a result allows to load the cracked component with the relative stress $S_r \approx 0.97$.

The holes drilled in a proposed way let to apply additional reinforcing straps (Fig.4b) connected with bolts or pins to the cracked component. The bolts or pins carry the force P' - part of load ΔP which increased the force P during strengthening. The force P' can be determined from the displacements compatibility condition in points B (Fig. 4c), as: P' = VEA / d, where:

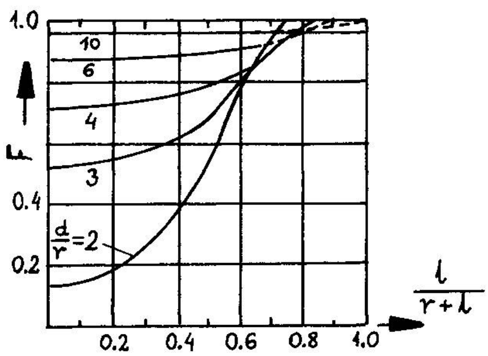

Fig. 5 Diagram of function F

$$V = \{1.82 \times \mathrm{Im}\overline{Z} - 1.3\,(d-r)\mathrm{Re}\overline{Z}\}_{z=i(d-r)}, \quad \overline{Z} = \int Z dz, \quad z = x + iy,$$

$$\overline{Z} = \Delta\sigma\cdot z/\sqrt{z^2 - l^2} - P'l/\pi z\sqrt{z^2 - l^2}$$ - Westergaard's function.

Force P' decreases the stress intensity coefficient K_I [5] by:

$$\Delta K_I = \Delta\sigma\sqrt{Ml} - \frac{\left(6.6 + l^2/c^2\right)\sqrt{2l/c}\,P'}{\sqrt{\pi c}\left(4 + l^2/c^2\right)^{\frac{3}{2}}}$$

3.2 Method II

In the second method the component is stiffened by two-dimensional finite strap. It is supposed that the elastic strap fully cover the crack and is elastically connected with a component along its contours (Fig.6).

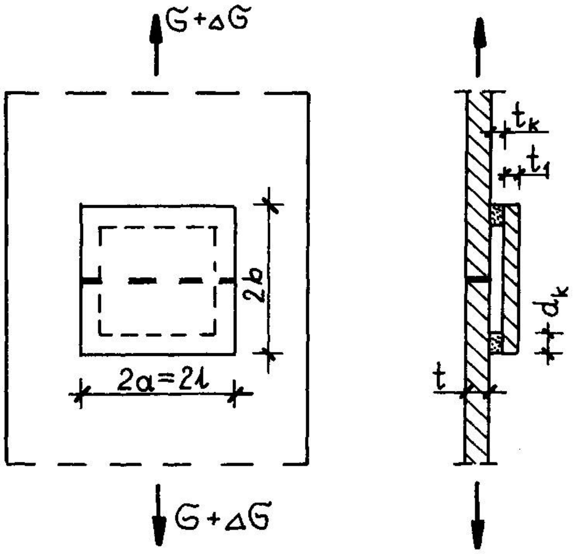

Fig.6 Strengthening method II

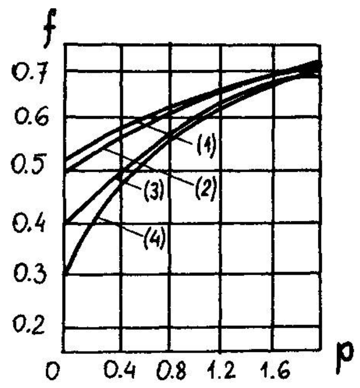

Fig.7 Diagram of function f [7]

For this method, the K_I can be calculated from the formula:

$$K_I = \sqrt{Ml}\left(\sigma + \Delta\sigma \cdot f\right),$$

where the function f depend on the shape of straps and on the flexibility of the glue:

$$p = 2\pi G_l t_l t_k / G_k d_k l \,.$$

Diagrams of function f for some kind of straps are shown in Fig. 7 [7]:

(1) - circular shape of radius l,
(2) - ellipse with the semi-axes: l and 0.5l
(3) - square, of side 2l,
(4) - rectangular 2a * 2b (b=0.38l).

4. CONCLUSION

Steel structure with cracked structural members can be strengthened for its longer life in relatively easy ways. Obviously, the load capacity of such a strengthened structure is lower than before cracks have occurred, however, the value of capacity can be determined using clear engineering procedure.

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