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FRACTURE MECHANICS COMPUTATION TO ESTIMATE THE CONSTRAINT PARAMETERS AND CRACK PATH ORIENTATION

PRORAČUNI MEHANIKE LOMA ZA ODREĐIVANJE PARAMETARA OGRANIČENJA I ORIJENTACIJE PUTANJE PRSLINE

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- T stress
- Q parameter
- stress triaxiality
- plastic constraint factor

Ključne reči
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- T napon
- Q parametar
- troosno stanje napona
- faktor ograničenja plastičnosti

Abstract

The paper provides some critical review of the history and states of art of methods taking account the constraint parameters. The methods proposed in the literature which measure T stress at constant distance near the crack or notch tip are not conservative. The example of CT specimen loaded in mode I obtained by using 2D finite element method with the software ANSYS 15.0, is taken to support this argument. Numerical results confirm that the T-stress is not constant near or on the back of the crack/notch tip. A numerical method based on the volumetric method developed by Pluvinage is used to define the T-stress value to be take into account. This method is characterised by the determination of the effective stress T_{ef} over an effective distance X_{ef} ahead of the crack tip.

Izvod

U radu je dat kritički osvrt na istoriju i napredne metode koje uzimaju u obzir parametre ograničenja. Metode predložene u literaturi, u kojima se meri T napon na konstantnom rastojanju u blizini vrha prsline ili zareza, nisu konzervativne. Za podržavanje ovog argumenta, uzima se primer CT epruvete opterećene u modu I, kod koje je primenjena 2D metoda konačnih elemenata u softveru ANSYS 15.0. Numerički rezultati potvrđuju da T napon nije konstantan u blizini ili na suprotnoj strani vrha prsline/zareza. Numerička metoda, koja se zasniva na zapreminskoj metodi koju je razvio Plivinaž, je primenjena za definisanje T napona. Metoda je karakteristična po tome što se efektivni napon T_{ef} određuje duž efektivnog rastojanja X_{ef} ispred vrha prsline.

INTRODUCTION

Mechanical properties are not intrinsic to the material but depend on geometrical factors such as specimen geometry, thickness, surface roughness and length, defect geometry such as the relative length, radius, or opening angle, loading mode, and environment. Figure 1 gives an example of the influence of ligament size through crack length and width ratio *a/W* on fracture toughness J_{Ic} of a cast steel /1/. One notes an important decrease of J_{Ic} with ligament size. This effect is attributed to constraint which is low for low value of *a/W*. Here, the constraint is defined as the resistance of a structure against crack-tip plastic deformation. Two ways are used to define the constraint: (i) analysis of modification of the crack tip distribution by geometrical or loading parameters; (ii) analysis of the plastic zone size after the same kind of modifications.

If we compare the stress distribution obtained in a reference situation (generally small scale yielding) with another general one, the stress distribution is modified in two ways: there is a shift of the stress distribution and a small rotation. These modifications of the stress distribution are considered as transferability problems. The shift of the stress distribution is introduced into the plastic constraint, which is used as the transferability parameter. In the literature, we can note the following constraint parameters: plastic constraint factor L /2/; stress triaxiality β /3/; Q parameter /4/; T stress /5-11/; and A_2 /12/. Constraint has a strong influence on the shape and size of the plastic zone /13/. For example, in plane strain the plastic zone has a typical shape of a butterfly wing. For, low constraint, it is oriented in the crack as above direction. For high constraint, the wings are oriented in the reverse crack extension direction /14/. The relative size of the plastic zone, or plastic strain isolines, is used also to define constraints such as A_P and φ /14/. Because the constraint can dramatically alter the material's fracture toughness and in order to increase the accuracy of structural integrity assessment (such as for pressure vessels and pipes), it is important to develop a clear understanding of its effect on the fracture behaviour of materials. The fracture toughness is normally measured from tests of deep edge cracked bend or compact tension specimens, according to well-known testing procedures. Local conditions ahead of the crack tip are assumed to be plane strain with high constraint. However, crack tip constraint is reduced in structures or components and fracture toughness is increased for specimens of small thickness or with notches. In recent years, there has been considerable effort to create a framework for including constraint effects in fracture mechanics approaches to explain the geometry and loading condition dependencies of the fracture toughness of specimens and structures with cracks. The two-parameter fracture mechanics methodology seems to be very attractive for this purpose /15-18/. This methodology suggests employing a constraint parameter in addition to the classical crack tip one parameter, for example, the stress intensity factor or the J-integral.

The brittle-ductile transition temperature (DBTT) for steel is also not intrinsic to a material but depends on the specimen type and loading mode used for the tests. A linear relation was found by Wallin /19/ between the transition temperature T_0 specific to the material failure master curve (MFMC) $K_c = f$ (temperature), and the T stress,

$$T_0 = T_{0.Tstress=0} + aT_{stress}\,, \qquad (1)$$

is a parameter which depends on the yield stress. A similar relation has been found for X65 pipe steel by Capelle et al. /20/ between various transition temperatures T_t; ($T_{t,tensile}$, T_0 and $T_{K1/2}$) and critical effective T stress, $T_{ef,c}$,

$$T_t = T_{t.Tef,c=0} + 0.14T_{ef,c}\,. \qquad (2)$$

It is well known now that fracture toughness (K_c or J_c) decreases when thickness increases. The fracture toughness is maximal for plane stress conditions and trends asymptotically to a minimum called K_{Ic} or J_{Ic} if the plane strain conditions are satisfied. Therefore a description of fracture resistance cannot be done with a single parameter. To describe the effect of thickness B on fracture toughness 'a triaxial stress constraint' T_{zz} has been introduced, /21/. Therefore, it is necessary to divide into in-plane constraint and out-of-plane constraint. The in-plane constraint relates to the specimen dimension in the direction of growing crack that is the length of the un-cracked ligament, while the out-of-plane constraint relates to the specimen dimension parallel to crack front that is the specimen thickness. Cotterel /22/ has pointed out the role of T stress in crack curving. The T stress is a stress which acts parallel to the crack direction. Therefore, this stress combined with the opening stress induces a mixed mode of loading with a biaxiality ratio. If T stress is positive, the crack curves according to the criterion of maximum tangential stress introduced by Erdogan and Sih /23/. If a constraint parameter is required, the question arises which of the different possibilities to choose (T, Q, β, L, A_2, A_P, φ, and so on). The constraint parameters A_P and φ have been very recently introduced, in 2011 and in 2014, respectively /13, 14/. An important and actual question is to know if these parameters are able to describe simultaneously in plane and out of plane constraint, or if a third parameter is necessary.

T-STRESS AND CRACK PATH

Cotterel /22/ has pointed out the role of T stress in crack curving. The T stress is a stress which acts parallel to the crack direction. Therefore, this stress combined with the opening stress induces a mixed mode of loading with a biaxiality ratio Θ:

$$\Theta = \frac{T\sqrt{\pi a}}{K_I}\,. \qquad (3)$$

The maximum stress along the $\sigma_{\theta\theta}$ distribution is not always null for $\theta = 0$ and angular deviation can occur only for positive values of T stress. When the T stress is negative, the maximum $\sigma_{\theta\theta}$ is always along the direction of propagation $\theta = 0$.

If T stress is positive, the crack curves according to the criterion of maximum tangential stress introduced by Erdogan and Sih, /23/. By applying this criterion, the opening stress is given by

$$\sigma_{\theta\theta} = \frac{K_I}{\sqrt{2\pi r}}\left[\frac{3}{4}\cos\frac{\theta}{2} + \frac{1}{4}\cos\frac{3\theta}{2}\right] + T\sin^2\theta\,, \qquad (4)$$

$$\frac{\sigma_{\theta\theta}\sqrt{2\pi r}}{K_I} = \left[\frac{3}{4}\cos\frac{\theta}{2} + \frac{1}{4}\cos\frac{3\theta}{2}\right] + \frac{T\sqrt{2\pi r}}{K_I}\sin^2\theta\,. \qquad (5)$$

The evolution of the ratio $\sigma_{\theta\theta}\sqrt{(2\pi r)}/K_I$ with the direction of propagation θ is plotted in Fig. 1 for positive or negative values of T. The maximal opening stress is indicated by a black spot for positive T stress. For negative T stress, this maximum occurs for negative values of opening stress, and bifurcation cannot occur because the crack surfaces cannot overlap, for more details see /24-27/.

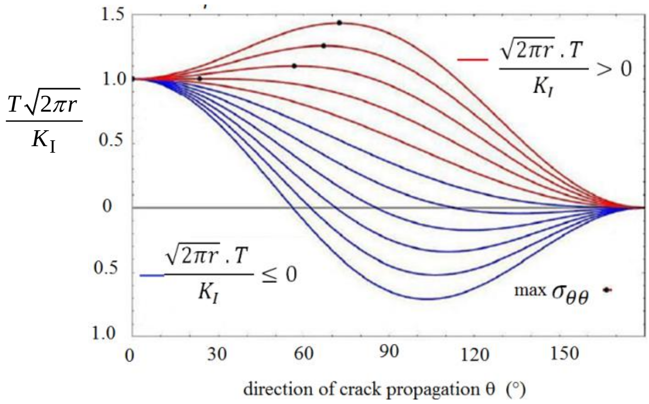

Figure 1. Evolution of the ratio $\sigma_{\theta\theta}\sqrt{(2\pi r)}/K_I$ with crack propagation direction θ in the presence of T stress, /28/.

The bifurcation direction θ^* is given when the first derivative of Eq.(5) is equal to zero.

$$\theta^* = \cos^{-1}\left[\frac{1+\sqrt{1+\frac{1024\pi}{9}X_{ef}\left(\frac{T_c}{K_{Ic}}\right)^2}}{\frac{512\pi}{9}X_{ef}\left(\frac{T_c}{K_{Ic}}\right)^2}\right], \qquad (6)$$

and the second derivative must be negative. Chao et al. /26/ introduced the RKR criterion in this analysis. At fracture $K_I = K_c$, $T = T_c$, and $\sigma_{\theta\theta} = \sigma_c$ for $x = X_{ef}$ /29-35/. The bifurcation direction is θ^*, and X_{ef} is the size of the fracture process volume, or effective distance. The condition on the second derivative implies that for crack curving,

$$\frac{T_c}{K_c} > \frac{3}{8}\frac{1}{\sqrt{2\pi X_{ef}}}\,. \qquad (7)$$

Figure 2 gives an example of a DCB specimen with positive T stress and crack curving. The CT specimen also has a positive T stress and non-curving crack.

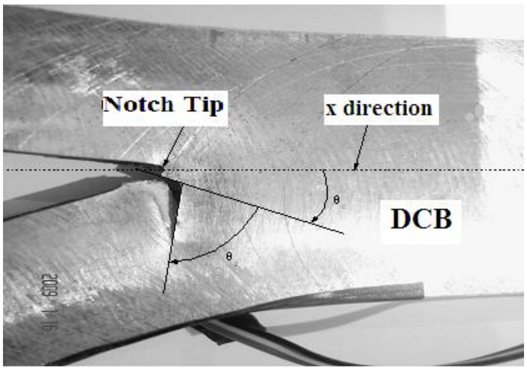

Figure 2. DCB specimen with positive T stress-induced crack curving $T/K = +7.9$; $X_{ef} = 0.53$ mm.

For negative T stress, after initiation the crack propagates first in an unstable manner, and then after several millimetres, in a stable manner /36/. During propagation in a stable manner, crack tip opening angle CTOA remains constant, and its constant value is a characteristic of the fracture resistance of the material /37, 38/. It is noted that during stable crack propagation, both CTOA and T stress are constant, Fig. 3.

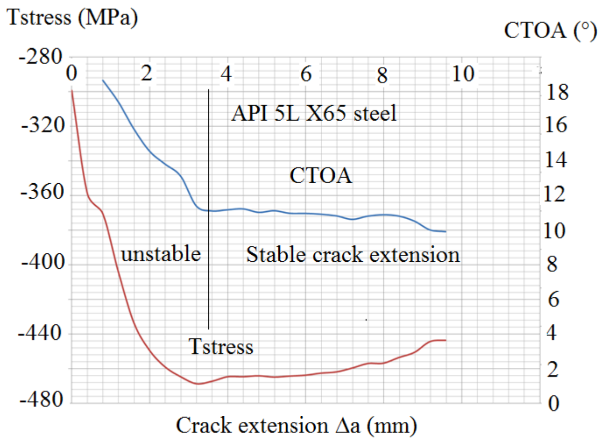

Figure 3. Evolution of CTOA and T stress during crack propagation for steel API 5L X65.

FATIGUE CRACK PROPAGATION AND CONSTRAINT

In high cycle fatigue region, the crack propagation rate is often described by the Paris law /39-42/. The relation between the fatigue crack growth rate *da/dN* and range of stress intensity factor ΔK is assumed to be a material curve independent on specimen geometry, and only depends on the range of the stress intensity factor /43-45/. It has been proved that for the given value of K, the fatigue crack growth rate depends on specimen geometry as well /46-48/. In Fig. 4, experimental data of /49/ are obtained from two different specimen geometries with different constraint levels, namely on centre-cracked plate tension specimen (CCT), and on compact tension specimen (CT). The CT specimen produces a high level of constraint (T stress is positive), and the CCT specimen represents the geometry with low constraint (negative values of T stress). The material used for the experiments is 0.65 % C carbon steel (cyclic yield stress 202 MPa, hardening exponent 0.3).

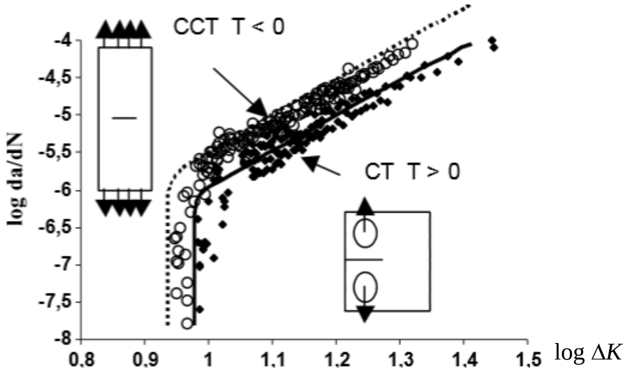

Figure 4. Influence of specimen geometry on fatigue crack growth rate vs. stress intensity factor range, /49/.

Hutar et al. /49/ have introduced the concept of effective stress intensity factor given by Eq.(8), where λ is a function of the ratio (T/σ_0); σ_0 is flow stress; $\lambda(T/\sigma_0)$ is given by Eq. (9). Its evolution with (T/σ_0) is given in Fig. 5.

$$K_{\mathrm{I}}^{ef} = \lambda\left(\frac{T}{\sigma_0}\right) K_{\mathrm{I}}\,, \tag{8}$$

$$\lambda\left(\frac{T}{\sigma_0}\right) = 1 - 0.85\left(\frac{T}{\sigma_0}\right)^3 - 0.52\left(\frac{T}{\sigma_0}\right)^2 - 0.30\left(\frac{T}{\sigma_0}\right). \tag{9}$$

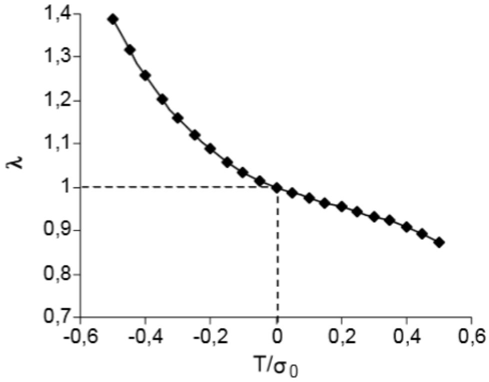

Figure 5. Dependence of λ with the ratio T/σ_0, /35/.

The Paris equation is modified as follows:

$$\frac{da}{dN} = C\left[\Delta K_{\mathrm{I}}^{ef}(K_{\mathrm{I}},T)\right]^m, \tag{10}$$

where: C, m are material parameters corresponding to zero level of constraint. The use of the effective stress intensity factor range, as defined in Eq.(10), gives a fatigue crack propagation law independent of specimen geometry used for the test, as can be seen in Fig. 6.

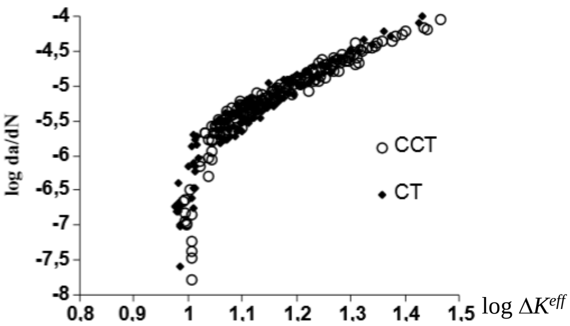

Figure 6. Use of effective stress intensity factor range leads to fatigue crack propagation rate independent of specimen geometry, /49/.

CONCLUSIONS

Most problems of transferability in fracture toughness can be treated with the help of a constraint parameter, or a characteristic length. If a constraint parameter is required, the question arises which of the different possibilities to choose from (T, Q, β, L, A_2, A_P, φ, and so on).

Constraint parameters A_P and φ are introduced very recently, in 2011 and 2014, respectively, /31, 32/. Parameter A_2 is similar to T (T = $4A_2$). In the light of these considerations, our discussion is focused on the following four parameters: T, Q, β, and L.

T stress according to its definition is only used for elastic situations but is often extended to elastic plastic fracture. Q is used only for elastic plastic fracture. We have seen that for pure brittle fracture, the Q parameter reduces to a relative difference of fracture toughness K_{Ic}. L is used strictly for plastic collapse in order to calculate limit load. Stress triaxiality β is used for any stress strain behaviour.

Determination of T stress needs only a single fracture test. This is an advantage compared to the Q parameter. A second advantage is that it can be determined numerically or experimentally. This is particularly interesting in the case of a complex part of a structure. The major difficulty with the T stress concept is that T stress is not constant along a ligament ahead of a defect. Therefore, a conventional value is needed. It has been proposed to use the effective distance, or extrapolation of the T stress evolution to origin, but these two definitions are not always in agreement.

The point of the Q parameter is to obtain an idea of the relative shift of the opening stress distribution at defect tip. It suffers from the following problems: (i) its definition is purely conventional at a non-dimensional distance of ($\sigma_0 r/J$ = 2) which rarely corresponds to the characteristic or effective distance; (ii) Q is valid with a condition of homothety of the stress distribution given in /49/. For low strength steels, this condition is not generally fulfilled. Q determination needs two tests, the second as reference, which has to be performed according to small-scale yielding conditions. This is not easy to realise if the material does not have the required thickness. The plastic constraint L represents the elevation of net stress compared with the gross stress. It is difficult to define the net stress value which should be taken into account because the stress distribution is not constant over the ligament. Several definitions can be used: the maximum local stress, effective stress, or average stress. A definition based on a local failure criterion, the volumetric method, is certainly more realistic.

Stress triaxiality has the main advantage that it can be used for any kind of failure (brittle, elastic-plastic, or plastic collapse). Because the stress triaxiality varies along the ligament, a conventional definition of the prescribed value is also necessary (this value can be the value of the maximal, or corresponding effective distance). Its sensitivity to geometrical parameters such as the relative defect length reduces its interest as a reliable constraint parameter.

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