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PROPOSAL FOR THE IMPROVED DESIGN OF RELIABLE FAILURE ASSESSMENT DIAGRAMS FOR COMPONENTS WITH SURFACE CRACK

PREDLOG ZA POBOLJŠANU KONSTRUKCIJU POUZDANIH DIJAGRAMA PROCENE LOMA KOD KOMPONENATA SA POVRŠINSKOM PRSLINOM

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Abstract

Failures of engineering structural components and structures can typically be traced to surface cracks. A serious difficulty associated with predicting structural integrity in this case is that the surface cracks are three dimensional, whereas fracture mechanics methods are based on two-dimensional assumptions. The basic requirement for the applicable fracture mechanics method are behind accuracy its simplicity and robustness. According to current FAD methods, the last two requirements are fulfilled. The increased conservatism of the results shows, however, that the requirements concerning the accuracy cannot be always fulfilled. The advance in this respect is achieved by the method presented in this paper considering that the plastic zone at the crack tip is the feature representing the ability of the most engineering material to reduce the stress peaks and thus to weaken the crack effect. The rigorous consideration of plastic zone correction by the construction of FAD in the actual codes is less advisable. The verification of the alternative approach is achieved based on experiments. The agreement with the experimental results is for the proposed method very successful. In case of R-6 Option 2 representative for current methods, in opposite, the results indicate a systematic deviation from the experimental results, which lies in the structure of the current formula of FAD.

Ključne reči
- FAD
- karakterizacije površinske prsline
- plastična zona
- EPML
- preostala čvrstoća
- verifikacija

Izvod

Lomovi kod inženjerskih nosećih komponenata i konstrukcija se obično mogu pratiti od površinskih prslina. Ozbiljnu prepreku povezanu sa predviđanjem integriteta konstrukcija u ovom slučaju predstavljaju površinske prsline, koje su trodimenzionalne, a pri tom su metode mehanike loma zasnovane dvodimenzionalnim pretpostavkama. Osnovni zahtevi za primenu metoda mehanike loma oslanjaju se na tačnosti, jednostavnosti i robusnosti. Kod savremenih metoda dijagrama procene loma (FAD), poslednja dva zahteva su ispunjena. Povećana konzervativnost rezultata pokazuje, međutim, da se zahtevi s obzirom na tačnost ne mogu uvek ispuniti. Napredak u tom smislu se postiže metodom predstavljenom u ovom radu, gde se plastična zona na vrhu prsline smatra za veličinom kojom se ogleda mogućnost da se kod većine inženjerskih materijala smanje lokalni maksimumi napona i time oslabi uticaj prsline. Rigorozno tumačenje korekcije plastične zone konstrukcijom FAD u važećim programima nije preporučljivo. Verifikacija alternativnog pristupa se postiže na bazi eksperimenata. Slaganje sa eksperimentalnim rezultatima je vrlo dobro kod predložene metode. Suprotno ovom, u slučaju programa R-6 Option 2, kao predstavnikom tekućih metoda, rezultati pokazuju sistematsko odstupanje u odnosu na eksperimentalne rezultate, što se objašnjava strukturom postojeće formule u okviru FAD.

INTRODUCTION

Failures of engineering structural components and structures have been mostly traced to surface cracks. There are a large number of such design examples, including components as engine crankshafts, turbine disks and blades, pressure vessels, tanks, pipes and similar. Especially for a surface crack containing a thin structure, the limit collapse of a ligament is usually the main cause of structure rupture or loss of function. This means, in spite of small dimensions at a stress level employing significant yielding, the critical section is strongly influenced by the presence of a surface crack.

A serious difficulty associated with predicting structural integrity is that the surface cracks are three dimensional, whereas fracture mechanics methods using characterization parameters as K_{Ic}, J_{Ic}, COD are derived and measured based on two-dimensional assumptions. Therefore, there is a relative uncertainty concerning the use of a critical value K_{Ic} for predicting failure of surface-cracked components. Because of this, the K_{Ie} has been proposed, determined on surface crack specimens and limited to the LEFM application.

To avoid uncertainties, for material characterization purposes, the specimen dimensions must in all directions be sufficiently large to isolate the crack tip plastic stress distribution from the borders of the specimen, with the unified condition dominating all length of the crack tip. Otherwise, the measured critical values would not be a characterization of the material, but would also depend on the size and geometry employed in the test or in the actual structure. These dependencies, caused by yielding conditions, represent a main problem in fracture mechanics, being still not entirely resolved - that of transferability of results from laboratory testing to real assessment case, especially if non-linear effects are prominent.

Study of the formula relating to the critical load of the surface crack ligament is, therefore, an important project in the area of elastic-plastic fracture assessment.

Relevant investigations presented here /1, 9/ are mostly based on space structure experience and corresponding materials. Accordingly, the problem of lightweight, thin wall structure appears as dominating subject and to some extent, limits the verification of the applicability of results to the relevant circumstances examined.

SURFACE CRACKS CHARACTERISATION

One of the most complete studies of the stress intensity factor distribution for the surface crack was carried out by Raju and Newman /6/. They arranged the numerically evaluated data as the equations to allow consideration of different shape and size of surface cracks. The solution based on the standard theoretical approach shows that for the consideration of crack effect – not only crack size, *a*, but also crack shape (represented by shape factor *Q*) has to be considered.

However, the author's investigation /1/ and experience show that the useful and simple normalisation based on only one parameter can be achieved using “effective” crack size derived from the crack area (Fig. 1). The representation based on the crack area has practical advantages:

– Crack size is represented by the crack size value which directly corresponds to the NDI signal.
– The imperfection of the crack shape compared to the theoretical elliptical form can also be taken into account (but with caution due to limitation concerning acceptable shape deviations).

The theoretical solution for surface cracks is furthermore based on remote or cross-section stress not influenced by the presence of crack. As our investigations show /1/, this representation is also less adequate for practical application (compare graphs in Fig. 1). Even though, both diagrams show that the values for different specimen thickness are different, this effect can be partly compensated if instead of the remote stress, the net-section stress (this means section reduced by the area of the crack) is used. Using this representation, the corresponding differences can be reduced to their real values.

In addition, for the selection of real parameter, different regimes of yielding must be considered (Fig. 2). If yielding is limited to the crack tip and contained in the surrounding wide elastic volume, the deformation behaviour of the structure, (represented by the stiffness line) stays linear and the contribution of plasticity in macro-scale is negligible. This is the case managed by LEFM parameters as *K*. In this case, also the difference between the gross section and net section stress application practically does not exist.

After further increase in load, causing no failure, the plasticity area may increase apart from the crack tip. Due to 3D-form of surface crack this goes in all directions. For thin wall structures, due to limitation in one direction, this may lead to the yielding through the wall or ligament yielding. Both the computation of elastic stress intensity factors and the application of plane-strain fracture toughness become less valid for this case and the current analytical methods cannot reliably predict, for example whether a pressure vessel will leak or burst at failure. And finally, in the case of sufficient load and/or size limitations in both directions, net section yielding may occur. For the application of EPFM, the constant relationship between the gross section and net section stress is weakened and the net section stress becomes the determining parameter.

In the case of real structures, however, the crack can be so small that for very ductile materials the crack effect may almost fully vanish and the conditions of gross volume or large scale yielding will appear.

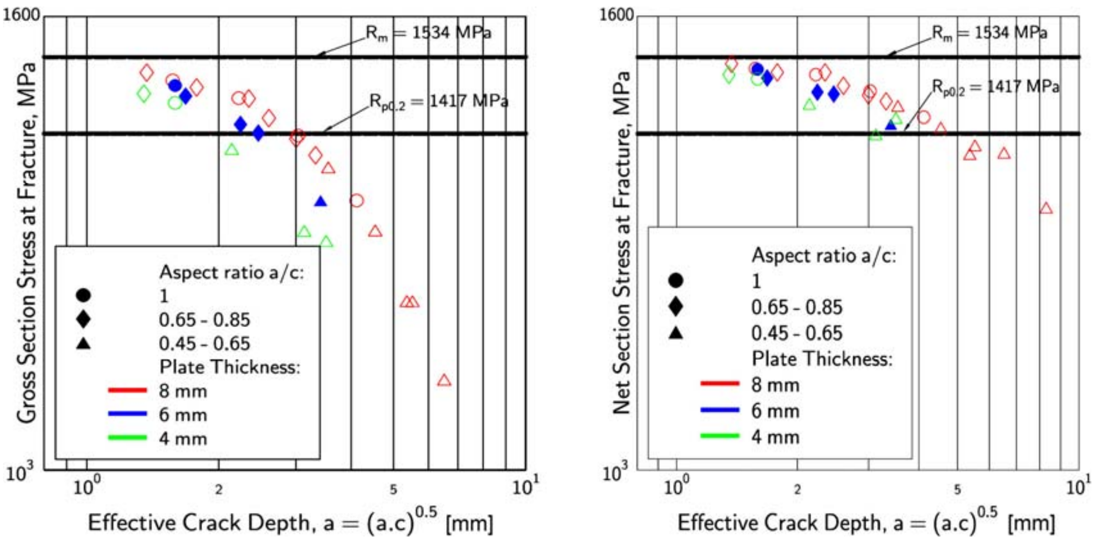

Figure 1. Results of test with SCT specimens /1/.
Slika 1. Rezultati ispitivanja sa SCT epruvetama /1/

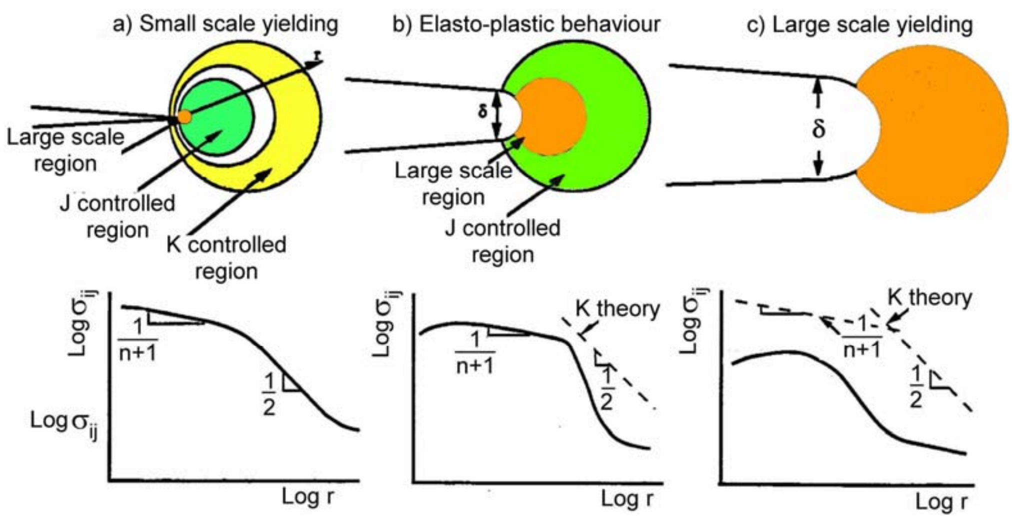

Figure 2. Stress distribution at the crack tip for different condition of yielding /7/.
Slika 2. Raspodela napona na vrhu prsline za različite uslove tečenja /7/

The designation of net section stress may have some inconveniences. For a uniform applied tensile load and symmetrical crack configuration, the exact net section stress is evaluated based on the applied load and the net cross-section area. However, for non-symmetrical crack configurations, applied bending loads etc., the net section stress is not obvious and because of this, maybe less accurately defined.

In the case of a centre-cracked panel subjected to tensile loading σ, consideration of force equilibrium leads to the following simple expression for effective net section stress

$$\sigma_n = \sigma_\infty \frac{A_g}{A_n} \tag{1}$$

where A_g is the area of the gross section and A_n is the area of the net section.

The necessity of net section application and its relation to the so-called reference stress will be discussed later.

RESIDUAL STRENGTH FOR COMPONENTS WITH SURFACE CRACKS

In 1976, based on the so-called strip yield model, developed starting from the endless plate with the through-crack, the R6 method has been initiated (also known as FAD – *Failure Assessment Diagram*). It was assigned lastly by SINTAP (*Structural Integrity Assessment Procedures* for European industry) /8/ and similar codes also to the case of structures with surface cracks. However, numerous experimental results showed significant differences in the behaviour of specimens with a surface or a through crack. Also our experimental results within the ESA (European Space Agency) financed project /9/, have shown decisive differences in this respect.

The main discrepancy appears because the stress intensity along the contour of the surface cracks is uneven, where the unevenness even further increases under elastic-plastic loading conditions. Since the crack opening depending on the stress intensity is hindered locally, the overall failure may occur only after stress intensity redistribution.

In fact, as already shown here (Fig. 1), the failure is dependent on the total energy, i.e. the area of the crack and not on local values. Because the deformation and failure are controlled by the energy in cross section, for a suitable component evaluation, the consideration of two parameters that are under general conditions representative of stored energy, stress and strain in the critical net section with the crack, is necessary.

To avoid the application of the strip-yielding model not relevant for the surface crack case, the FAD is defined here as a plot of the failure envelope of the cracked structure, defined in terms of two parameters:

- K_r... The square root of the ratio of the applied linear elastic J-integral J_{el} (which is dependent on the geometry and loading) to the actual elastic-plastic values of J-integral causing the relative reduction in material fracture toughness, J_{mat} for this case:

$$K_r = \sqrt{\frac{J_{el}}{J}} \tag{2}$$

- L_r... The ratio of the applied stress to the stress at which the plastic yielding in the critical net section of the cracked structure begins.

For further evaluation, the well-known LEFM solution for J-integral

$$J = \frac{K^2}{E} \tag{3}$$

is rearranged as the product between two K-constituents, one for stress and another for strain:

$$J = K_\sigma \cdot K_\varepsilon \quad \text{where} \quad K_\varepsilon \approx \frac{K}{E} \tag{4}$$

The separation of stress and strain ingredients in the new solution can be applied in all areas between "elastic" and "plastic". As the numerical values of K_σ are not dependent on multiaxiality (plane stress or plane strain conditions) the same is assumed for K_ε.

Constitutive laws based on classical plasticity generally define total strain as the sum of its elastic and inelastic components, $\varepsilon = \varepsilon_{el} + \varepsilon_{pl}$ with independent constitutive relationships describing each. Therefore,

$$J = K_\sigma (K_{\varepsilon(el)} + K_{\varepsilon(pl)}) = \frac{K^2}{E} + K_\sigma K_{\varepsilon(pl)} = \\ = J_{el}(a,\sigma) + J_{pl}(a,\sigma,\varepsilon_{pl}) \quad (5)$$

Plasticity at crack tip

In the above equation for the elastic part of the J-integral the Irwin's plastic correction is not considered. This correction assumes power balance based on the K and crack remains sharp. In addition, the condition of constant volume required by plastic deformation ($\nu = 0.5$) has been ignored in this correction. Neither of these presumptions is correct within EPFM, i.e. for ductile materials. In fact, there is no theoretical basis for this correction and its application significantly distorts the real relationship.

As well known (see Fig. 3), ductile materials are able (due to plasticity) to reduce the crack (or notch) effect (stress redistribution, blunting), where the Irwin's plasticity correction goes exactly in another direction (increase of crack size giving more severe stress intensity values).

It has also been shown, for example, by the stress concentration formula from Neuber for the ellipse of length $2a$ and end radius of curvature r, subjected to an in-plane tension

$$\sigma_{\max} = (\sigma_Y)_\infty \left[1 + 2\left(\frac{a}{\rho}\right)^{\frac{1}{2}} \right] \quad (6)$$

that the value of $\sigma_{\max}$ is very sensitive to the size of the crack tip root radius. Relating to it, in the theory, the assumed sharp crack is usually in reality in case of ductile materials replaced with a notch blunted under load, which is the physically more meaningful crack-tip representation for the investigation of failure behaviour. To eliminate the effect of root radius, for example, the usual test specimens have the initial machined crack extended by fatigue. This may not be necessary for very brittle materials.

On top of it, under plane strain conditions, the correction is significantly smaller than under plane stress conditions, even though the corresponding situation becomes more severe. Therefore, if we consider that the PZ (plastic zone) at the crack tip represents, under given conditions, the ability of the ductile material to reduce the stress peaks and thus to weaken the crack effect, the correction with the amount on the opposite side cannot be adequate.

The arbitrariness of the PZ correction can be demonstrated in many additional cases.

Based on the typical relationship

$$r_y = \frac{1}{\beta\pi}\left(\frac{K}{\sigma_0}\right)^2 \quad (7)$$

it can be shown that the values of r_p strongly depend on the selection of the σ_0 (Fig. 4), which should correspond to the mean stress level within of the plastic zone radius. A typical selection of engineering yield strength (with the 0.2% offset) is arbitrary. Considering the singularity of the K-solution, the corresponding stress level could be higher (flow or rupture strength) and can also be based on the true properties.

The portion of the J-integral based on plastic zone correction is calculated considering the elastic properties only

$$J_{pz} = \frac{\phi\, r_y}{a} J_e \quad (8)$$

Therefore the corresponding J-increase is related to the estimated a-increase, but not to the strain increases (plastic displacements). The consequence is that it is not affected by the multiaxiality even though the plastic displacements and plastic term J_p are strongly affected.

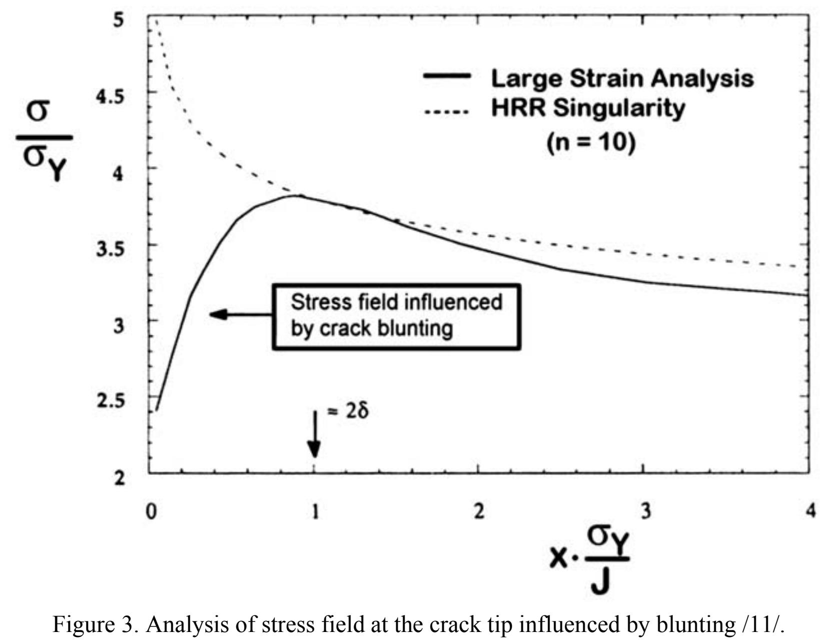

Figure 3. Analysis of stress field at the crack tip influenced by blunting /11/.
Slika 3. Analiza naponskog polja na vrhu prsline pod uticajem zatupljenja /11/

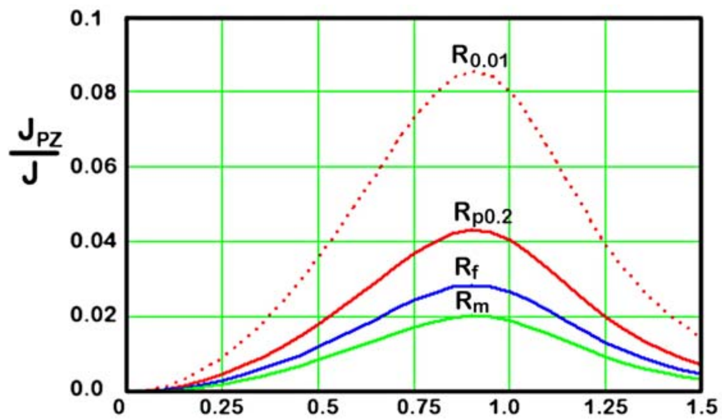

Figure 4. J_{PZ} in the dependence on σ_0 selection.
Slika 4. J_{PZ} u zavisnosti od izbora σ_0

As long as the plastic zone is uniquely related to K only, for a small crack and for the same stress intensity values K, not only higher stress must be applied, but also the plastic zone to crack size ratio becomes relatively larger than for a long crack. Furthermore, for very small cracks, the same K requires stresses close to yield and the plastic zone becomes undefined. In addition, for short cracks the effect of local crack front irregularities and consequent local K and constraint variations may be not averaged out, which combined with the effects of microstructural variations may even lead to different growth mechanisms.

As the stress distribution according to K is not based on stress balance for the reference section, the PZ correction also should not be based on any kind of local balance. On the other hand, as the plasticity at the crack tip causes the increased opening of the crack (wedge effect) this cannot be without stress redistribution to the rest of the section.

The effective or adjusted crack length is sometimes determined experimentally using the compliance method, especially in experiments intended to obtain the crack resistance curve. This method requires complex instrumentation and it is still not very clear how reliable is its application in calculating the loading curves K or J vs. a in an actual structure with entirely different loading and geometry.

Therefore, it becomes apparent that further progress in the field of fracture mechanics demands appropriate elastic-plastic solutions that can describe what occurs in the plastic zone as a function of loads and mechanical properties. A number of different FE calculations show the results which are in complete disagreement with the PC-correction (Fig. 3).

As a consequence, the plastic zone correction in FAD construction should be neglected until additional analysis establishes its general need and removes its arbitrariness.

It is clear, thus approaching yield strength the inelastic part of strain becomes significant compared to the elastic part, so that negative effects get on an importance, but this is sufficiently considered by the second term (ε_{pl}) in the above Eq.(5).

Generalised form of FAD

The typical solution for a surface crack has the form

$$K_\sigma = \sigma_N f_0 \sqrt{\pi a} \tag{9}$$

or (in analogy) for strain,

$$K_\sigma = (\varepsilon_{el} + \varepsilon_{pl})_N f_0 \sqrt{\pi a} \tag{10}$$

After substitution in Eq.(2)

$$K_r = \left[\frac{\frac{K_\sigma^2}{E}}{\frac{K_\sigma^2}{E} + K_\sigma K_{\varepsilon_{pl}}} \right]^{\frac{1}{2}} = \left[\frac{K_\sigma}{K_\sigma + E K_{\varepsilon_{pl}}} \right]^{\frac{1}{2}} \tag{11}$$

where (9) $K_{\varepsilon(pl)} = (\varepsilon_{pl})_N f_0 \sqrt{\pi a}$, from (8) and (11):

$$K_r = \sqrt{\frac{\sigma_N}{\sigma_N + E\,\varepsilon_{pl}}} = \sqrt{\frac{L_r \sigma_Y}{L_r \sigma_Y + E\,\varepsilon_{pl}}} \tag{12}$$

In the above equation, the actual strain is evaluated according to the stress-strain curve of the material. For this purpose the use of the well known Ramberg-Osgood approximation is typical,

$$\sigma = B\varepsilon^n \quad \text{or} \quad \varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{B}\right)^{\frac{1}{n}} \tag{13}$$

leading to the solution for FAD based on stress-strain curve (12):

$$K_r = \sqrt{\frac{L_r \sigma_Y}{L_r \sigma_Y + E\left(\frac{L_r \sigma_Y}{B}\right)^{\frac{1}{n}}}} \tag{14}$$

It is interesting to compare this solution with the R6 solution:

$$K_r = \left[\frac{E\,\varepsilon_{ref}}{L_r\,\sigma_Y} + \frac{L_r^3\,\sigma_Y}{2E\,\varepsilon_{ref}} \right]^{-\frac{1}{2}} \tag{15}$$

which can also be written as

$$K_R = \sqrt{\frac{L_r \sigma_Y}{E\,\varepsilon_{ref} + \frac{1}{2}\frac{L_r^4\,\sigma_Y^2}{E\,\varepsilon_{ref}}}} \tag{16}$$

and because $\varepsilon = \varepsilon_{el} + \varepsilon_{pl}$

$$K_R = \sqrt{\frac{L_r\,\sigma_Y}{L_r\,\sigma_Y + E\,\varepsilon_{pl} + \frac{1}{2}L_r^2 \frac{(L_r\sigma_Y)^2}{E\,\varepsilon_{ref}}}} \quad (17)$$

Compared to the solution Eq.(11), an additional reduction factor in the denominator appears

$$\frac{1}{2}L_r^2 \frac{(L_r\,\sigma_Y)^2}{E\,\varepsilon_{ref}} \quad (18)$$

The origin of this difference can be derived starting from relationships (2) and (15)

$$J = \left[\frac{E\,\varepsilon_{ref}}{\sigma_{ref}} + \frac{\sigma_{ref}^3}{2E\,\sigma_Y^2\,\varepsilon_{ref}}\right] J_{el} \quad (19)$$

When the reference stress is under the stress at the first deviation from linearity the first term is just 1 and we get

$$J = \left[1 + \frac{L_r^2}{2}\right] J_{el} = \left[1 + \frac{1}{2}\left(\frac{\sigma_{ref}}{\sigma_Y}\right)^2\right] J_{el}$$

or, after consideration of (9)

$$J = \left[1 + \frac{r_Y}{a}\right] J_{el} \quad (20)$$

This shows that the difference between both approaches is based on consideration of PZ correction. This means, the additional increase of the plastic portion of the J-integral for the design of FAD (in R-6, SINTAP, etc.) is based on some inhomogeneous relationship according to Eq.(2):

$$K_r = \frac{J_{el}(a)}{J_{el}(a_{eff}) + J_{pl}} \qquad L_r = \frac{\sigma}{\sigma_Y} \quad (21)$$

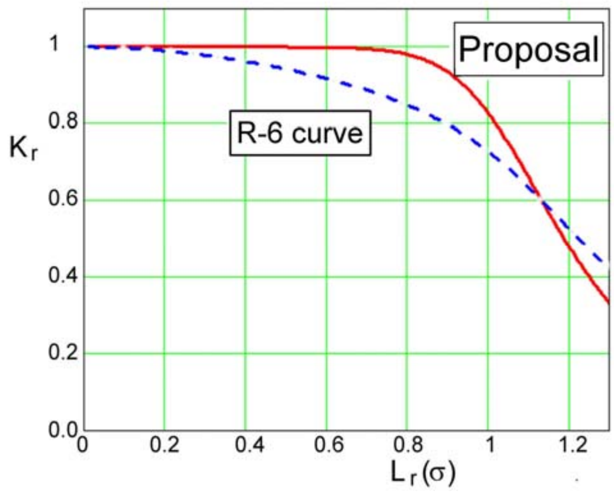

Figure 5. Comparison of FAD based on R-6 calculation and the proposed method.
Slika 5. Poređenje FAD na osnovu proračuna R-6 i predložene metode

A comparison of FAD calculated based on both methods is presented in the following Fig. 5. Using the proposed method no continual residual strength reduction (based on K_{Ic}, J_{Ic}, etc.), in full agreement with the practical evidence, originates in the linear-elastic range (up to 60–70% of yield strength). The reduction in the plastic region below and above yield strength is determined by the intensity of the strains in the cross section weakened by crack.

Based on the R6 curve, the measures of the material resistance K_{Ic}, J_{Ic}, etc. are only unchanged for $L_r = \sigma = 0$ in the cross-section. Furthermore, the additional margin of safety is only effective below yield strength, where above yield strength the R6 curve produces even non-conservative results.

The significant advantage of the proposed more general form of FAD is also that the plastic zone correction can be, if found necessary (for example for less ductile and less known materials) considered in the evaluation of L_r and K_r coordinates in FAD for a given case. For this, the PZC can be more exactly calculated using the relationships which are more better adapted to the actual situation. This will in any case produce more insight and more accurate diagram relationships for the given situation.

Because the measurement of the failure resistance cannot be performed under the conditions $\sigma = 0$, it is necessary to discuss that in more detail.

Crack behaviour under load

A typical intermediary process during the loading of the specimen of ductile engineering material with a representative crack cross-section is illustrated in Fig. 6 /12/.

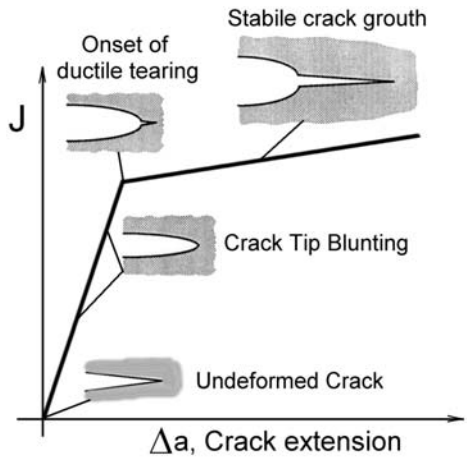

Figure 6. Crack growth behaviour under loading.
Slika 6. Rast prsline pod dejstvom opterećenja

Afterward observed under a scanning electron microscope, the typical fracture surface is usually anticipated by the phenomena of a characteristic region near the crack tip called the stretch zone. This stretch zone (Fig. 7) corresponds to the amount of crack tip blunting that precedes the actual crack extension and therefore, thus has a correlation with the initiation fracture toughness of the material. It has been found that even in the case of fracture under conditions of general plastic yield, the stretch zone dimensions remain constant for specimens of different geometry. Indeed, the blunted crack tip radius is about one half of the crack opening displacement (COD) value. Without blunting, COD will be zero (compare Fig. 6). This enables us to consider under certain conditions the size of the stretch zone as a material constant. Taking COD equal to J/σ_Y results in a formalism of the apparent crack growth due to crack tip blunting being given by

$$\Delta a = \frac{1}{2}\frac{J}{\sigma_Y} \quad (22)$$

The relationship (21) represents the equation for the first so-called blunting line in Figure 6. At this line the blunting increases with the loading until a load is reached where a crack advance occurs. The blunting line, thus, simulates the resulting apparent increase in crack length, Δa, during stretching or blunting of the initial crack (Fig. 6).

The point where enhanced crack advance occurs within the blunted crack is characterized externally by the change of slope of the J versus crack extension curve. From this point, the blunting process is finished and the crack advances by tearing with a considerably higher rate.

This model for the fracture process may not strictly characterize the actual physical process. Cracking may be incubated ahead of the original blunted crack as voids are opened and joined. However, if effective, this local event will introduce some discontinuity in global crack growth that cannot be submitted under the stabile crack growth by tearing. Therefore, this model is accepted as a general description of the fracture process which is related to a fracture parameter such as J_{Ic}.

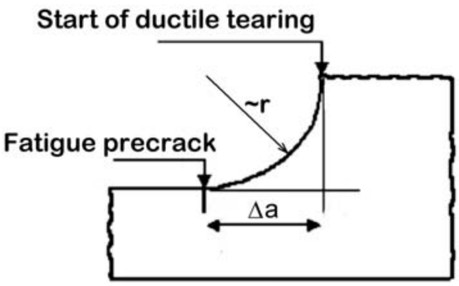

Figure 7: Stretched zone caused by blunting.
Slika 7. Zona razvlačenja izazvana zatupljivanjem

Two important conclusions can be made based on above described behaviour:

– The fracture toughness properties of ductile materials cannot be measured by net-section or reference stress equal to zero. For the evaluation of material properties, therefore the blunting line procedure was adopted to account for the increase in crack length owing to crack tip blunting. In addition, because the finding of very small scattering amounts of local tearing cannot be clearly separated from the blunting, the initiation toughness is usually not defined with respect to zero tear length but with a small non-zero tear length of 0.2 mm used in all actual standards.
– Through the blunting there is also some small apparent increase in crack length, Δa under the loading up to the onset of fracture by tearing. Compared to the plastic zone, however, the size of crack increase based on blunting is about two scales smaller and the corresponding correction not significant.

Main differences in the approach

On first sight, by ignoring the PZ correction the both solutions (12) and (17) will converge to each other. However, there are some important differences in approach here:

R6 solution is derived based on some simplification and generalisation of EPRI Engineering Approach in /10/ which is developed based on FEM calculations. The FAD according to Eq.(12) is derived starting from the analytical LEFM relationship.

Due to difficulties in accurate evaluation of net section stress in the R-6 development, the idea is introduced of so-called reference stress attributing it to the case of plastic collapse stress state. An additional aim of the reference stress introduction is also to choose a reference load, so that the dependence of the function h_1, which appears in the EPRI scheme for J_p, on the crack length, component geometry and n is minimised and can be replaced by an alternative function, h_1^*, which no longer depends on the stress-strain curve exponent n, /13/.

Uncertainties concerning net section and reference stress evaluation are nearly the same. Under simple conditions the net section stress is equivalent to the reference stress. In the case of a tension specimen containing a crack, for example the difference between the net section stress for uniaxial loading and the reference stress does not exist. The same is the case for infinite bodies which are dominated by the large section yielding, due to the applied stress.

In fact, the J-integral controlled fracture and collapse are extremely strange to each other and the proof for some smooth transition between the both does not exist. The assumption about ideal plastic material for collapse condition evaluation concerning K_r evaluation is not valid. In addition, due to the cut-off of FAD-line in R-6, the FAD area proposed for application is mostly far separated from the collapse conditions and more near to fracture mechanics behaviour, and the applications of stress state based on collapse conditions appear less appropriate.

Accordingly, in the proposed solution nothing but the net section approach is used. The calculation of net section stress for different components and crack geometries is based on Appendix B of Annex 2 of ESACRACK User's Manual ESA PSS-03-209 (Issue 2 2. January 1995) /14/.

Furthermore, in a R-6 subroutine, for the evaluation of corresponding stress and strain, based on reference stress definitions, recommended is the application of the true stress-true strain curve. In general, the true stress-strain curve is the secondary curve, recalculated from the experiment, warped with some simplification and errors. Even though in the application area with limited strains, the differences between true and engineering stress and strain are very small, the application of true stress-true strain curve requires consideration of immediate net or reference section dimensions reduced by yielding. On top of it, the cut-off of the FAD line requires the application of engineering properties (flow stress). To avoid possible errors based on this, the application of engineering or a nominal curve is more appropriate.

It should be mentioned, however, that neither the true stress-strain diagram nor the engineering stress-strain diagram accounts for the fact that the state of stress within the necked-down region is multiaxial and influenced by cavity development. A continuous use of nominal or engineering stress curve after necking is no longer accurate.

VERIFICATION OF THE METHOD

For the verification of the method, systematic investigation considering theoretical and experimental proofs have been carried out, as presented in /1/. A full detail on it can be found there.

The agreement between the FE-results and the analytical solution according to Eq.(4) for a given K solution and geometry is, as shown in Fig. 8, very good. Therefore, the proposed relationship appears to be not only a very simple but also an accurate and robust method for the assessment of failure behaviour of structures with a surface crack under elastic-plastic conditions.

The applicability of the method is also large-scaled proved through numerous tests using uniaxial specimens and thin-walled components with surface defects (Fig. 9).

The evaluation of all experimental results is shown in Fig. 10. Compared are the prediction for both calculation models. Results show the same trend as in FAD (Fig. 5). The agreement with experimental results and the apparent scatter are for the proposed method wholly successful. In the opposite, in case of R-6 Option 2, the results indicate a systematic deviation from experimental results, which lies in the structure of R-6/Option 2 formula of FAD, Eq.(15). The uselessness of the PZ correction in case of ductile materials is clearly demonstrated. It can be, however, tolerated for condition $S_r \leq 1$, leading to additional safety margins.

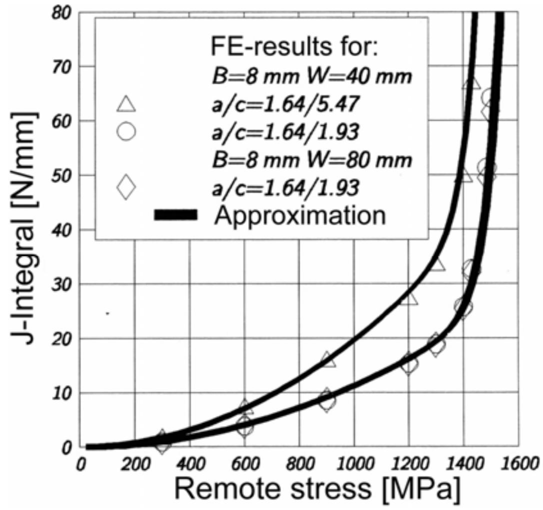

Figure 8. Comparison of FEM results with the prediction for different specimen size and crack dimensions.
Slika 8. Poređenje rezultata FEM sa predviđanjem za epruvete različitih dimenzija i prslina

Figure 9. Fractured cylinder specimens with surface crack.
Slika 9. Polomljena cilindrična epruvete sa površinskom prslinom

DISCUSSION AND PRACTICAL APPLICATION OF THE METHOD

Increased accuracy of the proposed method for the construction of FAD, both below and above the yield strength in comparison to existing methods (R-6, SINTAP, etc.), avoids the unnecessary conservatism by the design in this most important area for applications.

However generally, FAD is a substitution for EPFM procedure(s). It expresses the reduction of fracture mechanics properties caused by yielding and in this way allows the corresponding treatment of the integrity of the structure by simple LEFM methods. Really, the relevant properties are either unchanged or even higher. The latter cannot be effectively treated within FAD approach and this is also the handicap of the method.

The main advantage of the FAD method, besides the simplicity in approach, is that the solutions for K are already given for many practical cases. Therefore, the FAD allows treatment of a much greater range of structural and engineering parameters than it is possible by using existing EPRI handbook solutions. As previously shown, the FAD construction in R-6, SINTAP etc. is based on Eq.(21) and this allows further simplification compared to the standard LEFM procedure, as the crack extension by PZ correction is already included in Eq.(15).

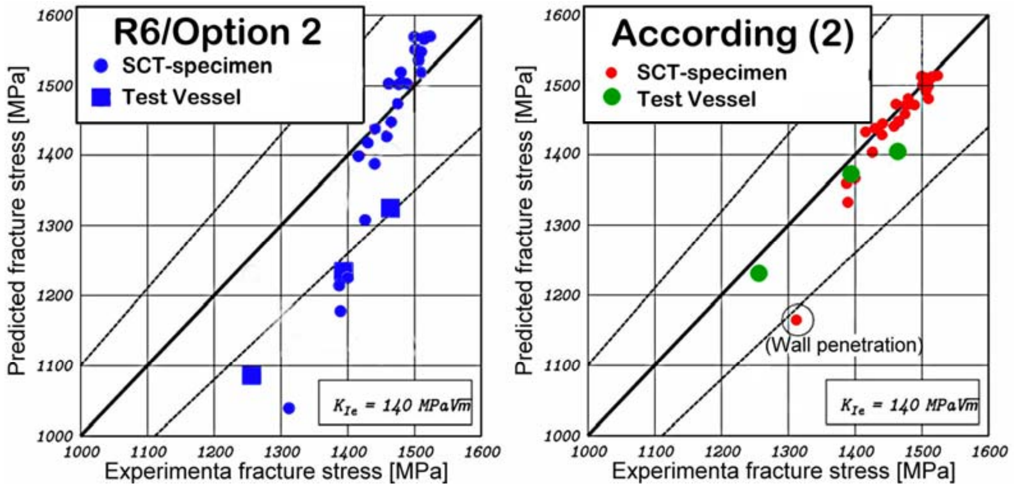

Figure 10. Verification of numerical prediction.
Slika 10. Provera numeričkog predviđanja

In case of FAD, the actual stress-strain curve of the material may also be used rather than the Ramberg-Osgood representation. Because some materials are not well described by the Ramberg-Osgood equation and for these materials the EPRI scheme can provide an inaccurate measure of *J*, this approach may be more representative of the yielding behaviour of real materials.

However, the consideration of the instable behaviour of the material at yield start (Luders tensile behaviour), though recommended in SINTAP, should be under heavy restriction. First of all, the results of measurements in this respect are strongly dependent on test conditions (specimen form, thickness, haul-off speed, specimens without crack, etc.). This shows that the corresponding behaviour is not stable and reliable. Under multiple excessive loading as, for example, repeated proof loads, the effect of cyclic softening has to be considered. Especially, structures exposed to cyclic service loading may show significant reduction in yielding behaviour compared to pre-service conditions (Fig. 11).

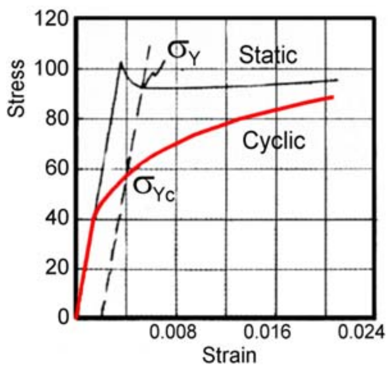

Figure 11. Cyclic response of mild steel materials.
Figure 11. Ciklična karakteristika kod niskougljeničnih čelika

For current and future advances in fracture assessment procedures the "transferability problem" is certainly a major driver. Transfer of properties measured on labour specimens to components and their application within integrity analysis is of fundament importance. Here must be clear that the labour specimens constitute an ideal case and may characterize the behaviour for limited cases only. In the case of a surface crack, for example, investigations carried out by the author /1/ have shown that substantial characteristics allowing reliable transfer of measured properties are the compatibility of the specimen and structure wall thickness.

The principal disadvantage of the FAD approach for residual strength assessment of a structural member or details is that, different to the general laws of fracture mechanics that quantify the critical relationship between stress, flaw size and fracture toughness, in the FAD are represented only the two first of those influencing variables.

A critical value of any single of the quantities can be, however, determined if the other two are known. The critical crack size for a specified applied load can be determined, for example, after predicting the crack development and plotting the corresponding assessment points, L_r and K_r, as a function of crack size. The crack size that produces a crossing point with the FAD curve defines the critical crack size (Fig. 12). It is clear that FAD does not give any idea on how the crack for this calculation should change. The representation of calculated results in this respect is however very perceptible and useful.

The both ends of FAD appear rather questionable. At the beginning for $L_r = 0$ the crack size becomes undefined and at the end of the diagram, the so-called cut-off based on flow stress is less accurately determined.

Similar problems can appear when combining primary and secondary stresses, or more exactly for the case of force- and displacement controlled loading mix. Primary stresses generally arise from externally applied loads and moments, while secondary stresses are localized and may be redistributed or equalised by sufficient plasticity. Primary stresses are capable of leading to plastic collapse. Secondary stresses are not assumed and therefore, only primary stresses are used to compute S_r. However, also the secondary stresses can contribute to crack growth and fracture if they are tensile and large near a crack. In LEFM analyses, as crack growth, the total stress intensity is simply the sum of primary and secondary components. Therefore, in general, FAD oriented to the collapse loading conditions only may not fulfil the requirements for reliable fracture mechanics analyses.

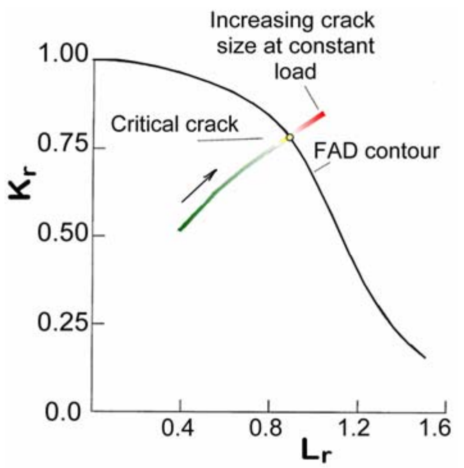

Figure 12. Determining the critical crack size using the FAD approach.
Slika 12. Određivanje kritične veličine prsline korišćenjem FAD pristupa.

In fact, the FAD, itself, cannot take into account the effect of any variables that might occur as a result of crack growth or structural redundancy.

CONCLUDING REMARKS AND OUTLOOK

The essential requirements for the applicable fracture mechanics method in engineering are behind accuracy, its simplicity, and robustness. In current FAD methods, the last requirements are fulfilled. The increased conservatism of results shows, however, that the requirements concerning the accuracy cannot be always fulfilled. Especially in the case of a lightweight thin-wall structure in transport, aerospace and similar, the corresponding requirement representing lower costs and weight of design may be a main driver for the successful application of the method. The advance in this respect is the main goal of the method presented here.

Concerning the fracture, the length of the plastic zone *per se* should not be considered as a parameter directly contributing to the appearance of breakage. It is rather the feature representing the ability of the most engineering material to reduce the stress peaks and thus to weaken the notch and/or crack effect. Therefore its consideration for the construction of FAD in the actual manner is out of place. The only plausible explanation for its application is because on the safe side, but not to increase the accuracy. Cut-off in these respects also further contribute to the general simplification of the method.

A reference to the collapse load at the place and as the generalisation or the substitution of the net section stress (for evaluation of S_r) is not theoretically based and may require further verification. The procedure which is based on fracture mechanics approach and parameters, i.e. unrelated to plastic collapse is more appropriate for construction of FAD. Distinguishing in this respect between net-section and gross-section yielding is also important.

The actual FAD suggests that the values of material characterisation parameter are evaluated for the stress at section (net section or reference, it does not matter) equal zero, what is clearly not the case (and not possible). Based on experience the reduction of material properties at FAD for $L_r \leq 0.5$–0.6 should be zero.

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