APPLICATION OF FRACTURE MECHANICS IN THE FRACTURE ANALYSIS OF WIDE PLATES

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ABSTRACT

This paper discusses the influence of flow behaviour of structural steels described by the Ramberg-Osgood law, state of stress and J-controlled crack growth when considering application of the estimation procedure according to Shih et al. for the prediction of failure loads of wide plates and CT-specimens.

KEYWORDS

Fracture mechanics, wide plates, yield behaviour, EPRI-estimation procedure.

INTRODUCTION

The use of elasto-plastic fracture mechanics on work-hardened structural materials is required for the prediction of load capacity and tearing instability in flawed structures, where there is extensive plastic deformation and slow stable crack growth before failure. In this regime the critical failure loads should be calculated with the R-curve approach (Paris et al., 1977), where the J-Δa curve which describes the material crack growth resistance development beyond the crack initiation phase, is compared to the J-integral crack driving force obtained from an estimation procedure or FE calculation, for predicting instability in a flawed structure.

This paper deals with the application of Shih's et al. (1981) estimation procedure which has been used to calculate J applied-values for the prediction of failure loads of wide plates and CT-specimens.

APPLICATION OF THE J ESTIMATION PROCEDURE TO STRUCTURAL STEELS

The estimation procedure combines the elastic (Tada et al., 1973 and the fully plastic solutions to produce the elastic-plastic estimate of J-integral crack driving force for various laboratory specimen configuration, specific values of crack length to width ratio and strain hardening exponents. The solutions are tabulated for plane stress and plane strain.

Therefore the J estimate takes yielding behaviour and stress state into consideration.

INFLUENCE OF FLOW BEHAVIOUR

The J-analysis in the elastic-plastic regime involves a complication not present in the elastic regime. The crack driving force in terms of J does not only depend on the applied load and specimen configuration, but also on the flow characteristics of the material, which are the yield stress and the strain hardening behaviour. In the estimation analysis the material is assumed to be governed by Ramberg-Osgood's stress strain curve in uniaxial tension, that is

$$\frac{\varepsilon}{\varepsilon_o} = \frac{\sigma}{\sigma_o} + \alpha\left(\frac{\sigma}{\sigma_o}\right)^N$$

where σ_o, α, N are the material constants, σ_o is the effective yield stress, $\varepsilon_o = \sigma_o/E$ and N is the strain hardening exponent. For a given specimen configuration the fully plastic crack solutions (Shih et al., 1981) were derived from plane strain FE calculations with constant $\sigma_o/E = 0.002$ ($\sigma_o \cong 420$ MPa), α is taken to be 3/7 and the strain hardening exponent was varied over a practical range for structural metals. Under these circumstances the theoreticaly considered strain behaviour shown in Fig. 1 deviates considerably from those of existing bcc steels, although the strain hardening exponent changes in the same manner. The reason for the differences in strain hardening behaviour is the misinterpretation of the strain hardening exponent. The strain hardening exponent does not describe the strain hardening of a material (Hesse, W. and W. Dahl, 1983). The N-value in Fig. 1 strongly depends on the level of yield strength for the same strain hardening $d\sigma/d\varepsilon(\varepsilon)$ in all steels.

Therefore, the application of the estimation scheme of Shih et al. is questionable for materials with $\sigma_o \neq 420$ MPa and $\alpha \neq 3/7$, because the h-functions are derived for a flow behaviour which can be described only with $\sigma_o/E = 0.002$, $\alpha = 3/7$ and a variation of N (Fig. 1).

A comparison of evaluated "applied" J as a function of P/P_o (P is the applied load and P_o is the plastic limit load) according to the estimation scheme and FE-calculations confirms the questionableness of application for materials with $\sigma_o \neq 420$ MPa (Twickler et al.).

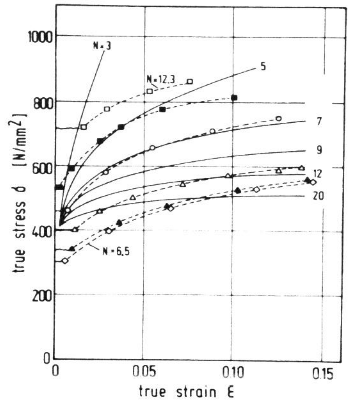

Fig. 1. True stress as a function of true strain
a) --- for many bcc steels ($6{,}5 \leq N \leq 12.5$)
b) —— according to Ramberg-Osgood for $\sigma_o = 420$ MPa, $\alpha = 1.0$, $3 \leq N \leq 20$

Fig. 2 and 3 show the results for materials with the same strain hardening $d\sigma/d\varepsilon(\varepsilon)$ at different yield levels governed by a Ramberg-Osgood law (Fig. 2). Only in the case of $\sigma_o = 420$ MPa does the estimation procedure produce a solution with sufficient accuracy in the entire range. The deviation in predicted J value is greater than 20 % for $\sigma_o = 820$ MPa (Fig. 3).

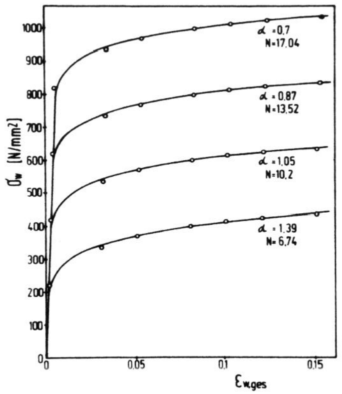

Fig. 2. True stress - true strain curves with different yield strength and the same strain hardening

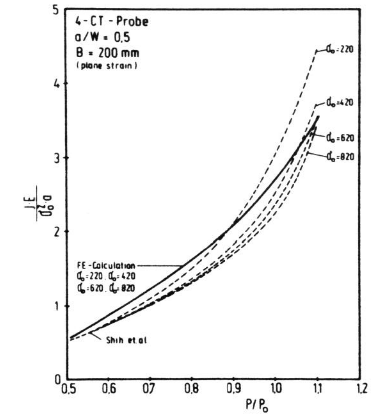

Fig. 3. J-integral crack driving force as a function of P/P_O for theoretical material behaviour with the same strain hardening at different yield strength

The results indicate that the estimation procedure tends to overestimate the failure loads for materials with σ_O > 420 MPa and α < 3/7 and to underestimate for α > 3/7 and σ_O < 420 MPa (Fig. 4).

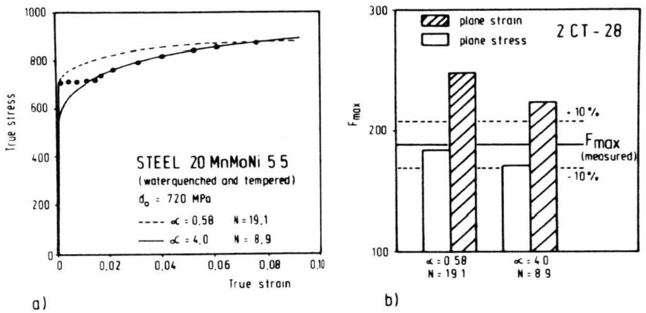

Fig. 4. Influence of approximation of stress-strain curve of the calculated maximum loads

INFLUENCE OF STRESS STATE

In many cases the exact state of stress of a specimen configuration is unknown and generally situated between the boundary conditions of plane strain and plane stress which can be calculated according to the estimation scheme. Consequently the state of stress assumed for an analysis can have an important effect on the results and must be judged individually. Fig. 5 shows the calculated instability loads of CT-specimens in comparison to the experimental loads being between plane strain and plane stress. The assumption of plane strain gives conservative predictions of the instability loads of structures in which the stress state is really plane strain. In all other cases one has to assume plane stress to avoid an overestimation of the real behaviour.

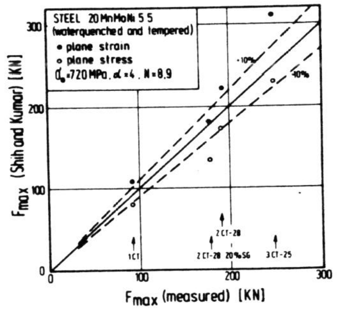

Fig. 5. Comparison of calculated and measured maximum loads of CT-specimens

CONTROLLED CRACK GROWTH

The engineering approach of Shih et al. supposes that the J-integral is a parameter, which characterizes the stresses and strains in front of the crack tip for the case, of large deformations and some stable crack growth. Several analyses criteria have been developed for establishing regions of acceptable J-controlled crack growth (Hutchinson, J.W. and P.C. Paris, 1979). If these conditions are met, the stress and strain field at the crack tip is characterized by the J-integral.

One criterion relates the value of J and flow stress to the size of the remaining ligament for a stationary crack tip, another criterion relates the value of J and the slope of the R-curve for an advancing crack tip to the size of the remaining ligament. The maximum allowable crack extension is also limited. Additionally the state of stress has to be plane strain. These criteria are dependent on the type of loading, being much more severe, when loading is primarily tension.

Results have shown, that crack initiation and limited stable crack extension can be characterized by J independently of specimen size, when the type of loading of the specimens is mainly bending (Landes, J.D., 1979). Up to this time no results are available to show, that this behaviour can be characterized by J, when the specimens are subjected to mainly tensile loading, because the conditions for J controlled crack growth are not met. This is due to the fact that, for structural steels very large specimen sizes are needed to meet the requirement. Many large structures have tension as the primary loading. An important question is therefore, how to handle the prediction of instability, when the conditions for J controlled crack growth cannot be met in the structure, for which the instability load shall be calculated. For very tough materials very high values of J are attained, and therefore the conditions for J controlled crack growth are violated. The results obtained up to now indicate, that the toughness values in terms of J are higher at a given amount of stable crack extension, when the crack growth is not J controlled. In such a case the assumption of J controlled crack growth should give a conservative prediction of the instability load, but additional work has to be done to prove these observations.

APPLICATION TO WIDE PLATE SPECIMENS

Centre notched wide plate specimens from steel A and steel B (plate B 1) were tested at 293 K. The fracture behaviour at this temperature was fully ductile. Calculations of the instability loads according to the concept of Shih and Kumar were made on the basis of J_R-curves, which were determined with CT-specimens without sidegrooves. For the plate B 1 the R-curve was measured additionally to CT-specimens with sidegrooves, which had a depth of 20 % of the nominal specimen thickness. It was assumed, that the stress state in the wide plates is plane stress, as some finite element calculations have shown (Rosezin, H.J. and W. Dahl, 1981). In Fig. 6 the calculated maximum loads for a wide plate specimen with a notch length 2a of 30.4 mm are compared to the experimentally determined load. The slope of the J_R-curve used has an influence on the calculated loads. If the J_R-curve determined with the CT-specimens with sidegrooves was used in the calculations, lower instability loads were estimated than in the case, that the R-curve of the CT-specimens without sidegrooves was taken, which has the greater slope. Also, how the true stress true strain curve of the material was approximated, has an influence on the calculated loads. If the plastic part of the stress-strain curve beyond the Lüders-plateau is described by the Ramberg-Osgood law, higher values for the constant α and lower values of N were estimated. Using these constants, conservative predictions of the experimental maximum load were made in all cases. If the elastic part of the stress-strain-curve is better described, lower values of α and higher values of N were determined. In this case only the calculations based on the R-curve from CT-specimens with sidegrooves gave a conservative prediction of the experimental load.

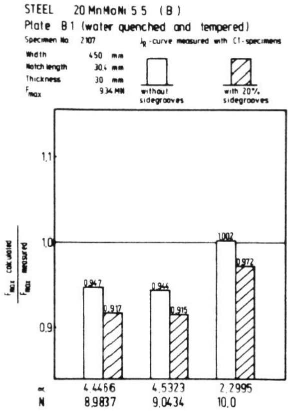

Fig. 6. Comparison of calculated and measured maximum loads of a wide plate specimen

Bases on these results the maximum loads of different specimens form steel A were calculated on the basis of the constants α and N, which were determined by describing the plastic part of the true stress-true strain curve beyond the Lüders-plateau. As it is shown in Fig. 7, the calculated loads agree within 10 % with the experimentally determined loads of the wide plate specimens, but there are some results, which were overestimated by the calculations.

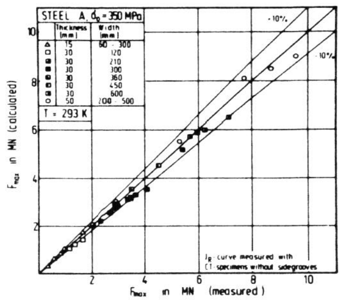

Fig. 7. Comparison of calculated and measured maximum loads of wide plate specimens, steel A

Examination afterwards has shown, that the crack growth in the wide plate specimens was not J-controlled due to the fact, that the remaining ligament was too small. Some other difficulties arose during the calculations. The instability loads of the wide plates were reached at stable crack extensions of several millimeters. It was not possible to determine the R-curve up to these crack extensions experimentally for the given plate thickness, because the maximum allowable crack growth is limited to a certain amount to guarantee, that the crack growth is J-controlled in the CT specimens, with which the R-curve was determined. Therefore it was necessary, to extrapolate the R-curves to higher values of stable crack extension, which was made with a power function. From the extrapolation of the R-curve some uncertainties can arise, because the material resistance against crack growth is perhaps overestimated. This problem is much more stringent, if the instability loads for real structures has to be calculated, where a greater crack extension is expected at the instability.

CONCLUSIONS

- The theoretical strain behaviour which has been considered in the estimation procedure to produce the elastic-plastic estimate of J-integral crack driving force strongly deviates from those of real structural steels, although the strain hardening exponent has been changed over a practical range. Therefore, the application of the estimation scheme of Shih et al. is questionable for materials which do not correspond to the considered flow behaviour.

- In case of the prediction, where the state of stress of a specimen configuration is not really known or the stable crack growth is not J controlled many uncertainties exist for calculating the exact failure load.

- If the crack growth is not J controlled in a given structure, additional work has to be done to prove wheter the application of a J-Δa curve determined for conditions of J controlled crack growth gives conservative predictions of instability loads.

- In large structures the instability occurs at crack extensions of several millimeters. In many cases it is, for a given plate thickness, not possible to determine the J_R-curve up to the required values of Δa due to the fact, that the uncracked ligament of the CT-specimens is too small. The R-curve has to be extrapolated to higher value of Δa. It is not clear, that the extrapolated R-curve describes the real material behaviour conservatively, so the instability loads can be overestimated.

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