CRACK INITIATION AND GROWTH UNDER FULLY PLASTIC CONDITIONS WITH APPLICATIONS TO PRESSURE VESSEL STEELS

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ABSTRACT

This paper describes progress made in a three year research program, sponsored by the Electric Power Research Institute to develop a methodology for fracture under large scale plasticity conditions. The ultimate goal in the development of such a methodology is to establish an improved basis for analyzing the effects of flaws (postulated or detected) on the safety margins of pressure boundary components of light water-cooled-type nuclear steam supply systems. The primary application emphasis is for reactor pressure vessels. Additionally, application to thinner section components such as piping can be foreseen. The program undertaken consists of four distinct phases of study. This paper summarizes the results of extensive experimental and analytical investigations undertaken to evaluate potential criteria for crack initiation and growth, the selection of final criteria and the development of a methodology for analyzing crack growth and stability in flawed structures. The experimental evidence obtained to date suggest that parameters based on the J-integral and the crack tip opening displacement δ are viable characterizations of crack initiation and stable growth. Theoretical and finite element investigations of the extending crack support these experimental observations. These investigations show that crack initiation is characterizable by the critical value of J and δ and stable crack growth is characterizable by the J or δ resistance curves if some minimal requirements are met. Thus appropriate measures of material resistance to crack growth are given by the dimensionless parameters $T_J (= \frac{E}{\sigma_o^2} \frac{dJ}{da})$ and $T_\delta (= \frac{E}{\sigma_o} \frac{d\delta}{da})$. The two parameter characterization of fracture properties by J_{IC} and T_J or by δ_{IC} and T_δ is analogous to the characterization of deformation behavior by yield stress and strain hardening exponent. Relationships between J_{IC} and T_J and between δ_{IC} and T_δ are explored.

A simple procedure which utilizes the J and COD resistance curves for examining crack growth and instability is discussed. An example of their use in predicting the fracture behavior of test specimens is given.

1. Introduction

This paper summarizes progress made in a three year research program sponsored by the Electric Power Research Institute (EPRI), to develop a methodology for plastic fracture. The ultimate goal in the development of such a methodology is to establish an improved basis for analyzing the effects of flaws (postulated or detected) on the safety margins of pressure boundary components of light water nuclear steam supply systems. The primary application emphasis is for reactor pressure vessels. Application to thinner section components such as piping can be foreseen.

The program undertaken consists of four distinct phases of study:

1. Evaluation of potential criteria for crack initiation and growth under large scale plasticity conditions through analyses and laboratory experiments.
2. Selection of final criteria through further exhaustive laboratory tests, and the development of a methodology for predicting plastic fracture behavior in structures.
3. Verification of this methodology through engineering scale tests.
4. Application of the methodology in predicting the behavior of flawed pressure vessels.

This paper focuses on the first two phases of the program.

Ferritic pressure vessel steels like A533B and A508 have a ductile-to-brittle fracture transition temperature which is close to room temperature. Below the transition temperature the brittle fracture mode is usually cleavage. In this regime, life predictions can be made using linear elastic fracture mechanics and plane strain fracture toughness K_{IC}. Above the transition temperature, the fracture mechanism is usually dimpled rupture, and large plastic strains are required for crack initiation and propagation. Raising the temperature above the transition temperature first increases the toughness which is then followed by a region of relatively constant toughness - the upper shelf. The purpose of this research is to select and verify fracture criteria which can be used to predict the initiation and stable crack growth behavior of pressure vessels operating in the upper shelf temperature range where crack propagation will occur under conditions of large scale plasticity.

The experimental results from the Heavy Section Steel Technology program, and tests on large plates at the Southwest Research Institute, showed that the growth of part-through cracks in A533B steels remained flat for a considerable amount of crack extension; shear fracture developed only after the attainment of maximum load. In our investigations, attention has therefore been focused on flat fracture under essentially plane strain and large scale plasticity conditions.

2. Summary of Experimental and Analytical Investigations

The progress of ductile fracture from an existing sharp-tipped flaw may be separated into four regimes: the blunting of the initially sharp crack tip, crack initiation, stable crack growth, and unstable crack propagation. For high toughness materials on the upper shelf, there is significant crack tip blunting and substantial stable crack growth. More importantly, the resistance of the material to further crack extension increases with increasing crack growth. In this case, the assessment of the margin of safety of flawed structures based on the onset of crack extension is conservative, since the 'toughness' of the material will increase significantly with relatively small crack extension.

In our investigations, a close coupling was maintained between testing and analysis. The tests on A533B steels were carried out at the upper shelf temperature of 93°C. Several specimen types and crack lengths were employed to obtain crack growth under widely different fully plastic deformation fields. Crack growth analyses using finite element models of the test configurations were carried out in order to isolate viable fracture criteria from the test results. A detailed discussion of the potential fracture criteria evaluated in the study, the strategy employed in the evaluation, procedures for measuring the J-integral, crack opening displacement (COD) and crack extension (Δa), detailed examination of the analytical and experimental results, and finally an assessment of these fracture parameters that were found viable are given in an EPRI Special Report, and published papers (Shih and co-workers, 1977, 1978).

The following main conclusions emerged from these investigations:

1. Macroscopically flat fracture surfaces with a straight leading edge can be produced by employing side-grooves on test specimens. Side-groove depths of 25 percent of the specimen thickness are recommended for A533B steels and similar materials since they promote an essentially uniform plane strain constraint along the crack front while producing minimal effect on specimen compliance and stress intensity factor (Shih, deLorenzi, and Andrews, 1977a).

2. The experimentally determined J and COD (measured at the original crack tip) resistance curves appear to be independent of specimen size and initial crack length when plane strain flat fracture occurs and if certain minimal size requirements are met (Shih, deLorenzi, and Andrews, 1977b; Andrews and Shih, 1977).

3. Analytical investigations also show that J and COD can be employed to characterize crack initiation and growth. The slope of the J-resistance curve (dJ/da) appears to be constant for a relatively short interval of crack extension, while the slope of the COD-resistance curve ($d\delta/da$, also called the average or nominal crack opening angle) and the local crack opening angle (COA) remain practically constant over the range of crack extension explored in our experimental and analytical investigations. The J-based criteria appear to be valid for limited range of crack growth; the range of validity depends on strain hardening properties and crack configuration. For A533B steels at the upper shelf, the J criteria is valid for crack growth up to 6% of the original uncracked ligament for test specimens subjected primarily to bending, e.g. compact specimen. The COD-based criteria appear to be valid for larger amounts of crack growth (Shih, deLorenzi, and Andrews, 1977b; Andrews and Shih, 1977).

4. The tearing modulus ($T_J = (E/\sigma_o^2)dJ/da$) proposed by Paris and co-workers (1977) as a measure of material resistance to stable growth is constant over relatively short intervals of growth. Our investigations suggest that a tearing modulus based on the COA ($T_\delta = (E/\sigma_o)d\delta/da$) is an attractive alternative. The latter modulus is measurable directly and appears to be constant over a larger range of crack growth. Fracture toughness associated with crack initiation is measured by J_{IC} or δ_{IC} while fracture resistance associated with crack growth is measured by T_J or T_δ. The two parameter characterization of fracture properties by J_{IC} and T_J or δ_{IC} and T_δ are analogous to the characterization of material deformation properties by the yield stress and the strain hardening exponent (Shih, deLorenzi, and Andrews, 1977b).

5. A simple explicit expression relating the crack tip opening displacement δ_t to J has been derived based on the assumption that the Hutchinson-Rice-Rosengren (HRR) singularity dominates over finite intervals at the crack tip. The coefficient d_n that relates δ_t to J is a function of the hardening exponent n and σ_o/E (Shih, 1978).

6. Small scale yielding finite element calculations for several hardening exponents were carried out. The values of d_n determined from the finite element results are in good agreement with the values derived from the HRR singularity. Further support for the J and COD relationship were found through fully plastic finite element analyses of the cracked bend bar (CBB) for several hardening exponents (n = 3, 10 and ∞). The latter results also suggest that the HRR singularity does indeed characterize the stress and strain state of the crack tip region in the CBB for the complete range of elastic-plastic deformation (Shih, 1978).

7. By exploiting a deformation theory of plasticity, a relationship between the slope of the J resistance curve dJ/da and the crack opening angle $d\delta/da$ has been derived. Available finite element results for the growing crack seem to support this relationship (Shih, 1978).

8. Extensive experimental data on crack initiation and growth has been summarized. The crack tip opening displacement at initiation and the crack opening angle predicted from the simple relationship between J and δ_t and between dJ/da and $d\delta/da$ appear to be in reasonably good agreement with the actual experimental measurements (Shih, 1978).

9. Detailed finite element solutions showed that the size of the region dominated by the HRR singularity is substantially larger in the cracked bend bar (or compact specimen) than in the center-cracked panel. The study suggests that the proposed minimum specimen size for J toughness testing which require all relevant specimen dimensions to exceed 25 to 50 times J/σ_o is adequate to ensure a valid J characterization of the crack tip region in the cracked bend bar and compact specimen. However the specimen dimensions will have to be considerably larger to ensure a J characterization of the crack tip region in center-cracked panel. McMeeking and Parks (1977) suggested a size requirement of 200 times J/σ_o. While the loss of dominance of the HRR singularity in the center-cracked panel occurs rather gradually, it appears that a size requirement of 200 J/σ_o, though arbitrary, is consistent with the results obtained by Shih and German (1978).

10. Analytical and numerical studies show that several requirements must be met to ensure that crack growth is characterizable by J. In addition to the size requirement discussed in the preceding paragraph, the slope of the J-resistance must be sufficiently large. The dimensionless parameter $(1/\sigma_o)(dJ/da)$ must be significantly larger than 0.1 for J-controlled crack growth (Shih and Dean, 1978).

11. Available experimental data suggest a relationship between the material resistance to crack initiation and the resistance to stable tearing. The tearing modulus T_J (based on J) increases rapidly with increasing fracture toughness J_{IC} and their relationship is essentially linear in the high toughness regime. A similar relationship is observed between the tearing modulus T_δ (based on COD) and the COD at crack initiation δ_{IC}. These general trends are also supported by a simple crack growth model (Shih, Wilkinson and Dean, 1979).

3. Discussion of Fracture Parameters

The work of Begley and Landes (1972) led to the characterization of crack initiation in terms of J_{IC} under both small scale and large scale yielding conditions. Subsequent experimental investigations by Clarke and co-workers (1976) and by Griffis and Yoder (1976) revealed the presence of stable crack growth under large scale yielding conditions; they characterized the onset of growth by J_{IC}. Paris and co-workers (1977) proposed that the material resistance to crack growth can be characterized by the J-resistance curve and observed that the slope of the J-resistance curve is constant for small amounts of growth. Their analyses show that crack growth is stable if the tearing modulus T $(E/\sigma_o^2(dJ/da))$ is larger than some dimensionless parameter which depends only on the geometric configuration.

The results from our analytical and experimental investigations support the characterization of the onset of flat fracture by a single parameter, namely J_{IC} or δ_{IC} under large scale yielding conditions. The results also strongly suggest that stable flat crack growth is characterizable by the J-resistance or the COD-resistance curve if some conditions are satisfied. A typical variation of J, dJ/da, δ and the average and local COA's α_a and α_ℓ with crack extension is illustrated in Fig. 1. This figure shows that while J_{ff} (J evaluated at remote contours) continues to increase, J_{nf} (J evaluated in the near field) begins to level off after some crack extension. Thus $(dJ/da)_{nf}$ falls to zero and violates one of the requirements for J-controlled growth. On the other hand, both the average or local crack opening angles, α_a and α_ℓ undergo an initial transient and then remain constant for a considerable range of crack growth.

The tearing modulus ($T_J = (E/\sigma_o^2)dJ/da$) proposed by Paris and co-workers (1977) as a measure of material resistance to crack growth is constant over amounts of growth (of order several δ_{IC}). Our investigations suggest that a tearing modulus based on the COA ($T_\delta = (E/\sigma_o)d\delta/da$) is physically more appealing and appears to be constant over larger amounts of crack growth. High values of T_J or T_δ correspond to greater material resistance to continuing crack extension. Shih (1978) also showed that within certain restrictions, there is a direct relationship between J and δ and between dJ/da (or T_J) and $d\delta/da$ (T_δ)*. If the conditions for J-controlled crack growth are met, then the crack driving force determined from estimation schemes based on deformation plasticity theory (Shih, 1979) in conjunction with J_{IC} and T_J (or the J-resistance curve itself) can be employed to analyze crack growth and fracture instability. Similar analyses can be carried out based on the COD crack driving forces.

4. Relationship Between Crack Initiation and Growth Parameters

There is ample experimental data which suggest a relationship between the material resistance to crack initiation and the resistance to stable tearing. In particular the data provided by Paris and co-workers (1977), Knott and co-workers (Clark and others, 1978), Andrews and Shih (1977) and Garwood (1977) show that the slope of the J and COD resistance curve increases with increasing values of J_{IC} and δ_{IC} respectively. Experimentally measured T_J and the corresponding value J_c for a number of materials are summarized in Fig. 2. Details are given by Shih, Wilkinson and Dean (1979). The slope of the J-resistance curve is determined over an interval corresponding to crack growth of 6% of the remaining ligament. Both the slope of the J-resistance curve and J_c are normalized by E/σ_o^2. The tearing modulus $(E/\sigma_o^2)dJ/da$ is dimensionless while $(E/\sigma_o^2)J_c$ has dimension of distance, and is a measure of the extent of plastic deformation. The trend suggested by the experimental data is clear - the tearing modulus rises rapidly at lower values of J_c and then an almost linear relationship exists between T_J and J_c. Experimentally measured T_δ (based on the COD-resistance curve) and δ_c are summarized in Fig. 3. The trend of data is similar to Fig. 2.

A crack growth model suggested by Rice and Sorensen (1978) may be modified to suggest a relationship between J_c and dJ/da. If the critical opening displacement δ_c, at some fixed distance $\Delta\ell$ behind the advancing crack is proportional to J_c/σ_o, then the following expression emerges

$$T_J = (E/\sigma_o^2)dJ/da = \bar{J}_c - (\beta/\alpha)\ell n\ (\lambda e\ \bar{J}_c) \tag{1}$$

where $\bar{J}_c = (E/\sigma_o^2)J_c/\Delta\ell$ and e is the natural logarithm base. From available solutions, $\alpha \simeq 0.5$, $\beta \simeq 4.0$; the undetermined parameters are λ and $\Delta\ell$. The solid line in Fig. 2 is obtained by setting λ to 0.1 and $\Delta\ell$ to 0.7 mm in expression (1).

Expression (1) also suggests a relationship between δ_c and $d\delta/da$ if the latter is proportional to dJ/da. Thus

$$T_\delta = (E/\sigma_o)d\delta/da = \bar{\delta}_c - (\beta/\alpha)\ell n\ (e\lambda\ \bar{\delta}_c) \tag{2}$$

where $\bar{\delta}_c = (E/\sigma_o)\delta_c/\Delta\ell$. The solid line in Fig. 3 is obtained from (2) by setting λ to 0.1 and $\Delta\ell$ to 0.7 (the same values were employed in Fig. 2).

The relationship between initiation and growth parameters expressed by (1) and (2) are in agreement with the general trend of the experimental data. As such it is meant to suggest trends only and is not for the purpose of precise correlations between material resistance to crack initiation and growth.

*These relationships are briefly discussed in paper G6/5 in the 1979 SMiRT Proceedings.

5. Applications of J-Controlled Crack Growth

The requirements for J-controlled crack growth and its consequences are discussed in papers by Hutchinson and Paris (1977) and Shih and Dean (1979). An engineering procedure for treating crack growth and stability in flawed structures which exploits the deformation theory of plasticity and the consequences of J-controlled crack growth is discussed by Shih (1979). In subsequent paragraphs we present some pertinent results from our studies for A533B steels (Kumar and Shih, 1979).

Fully plastic solutions have been obtained for compact specimens for a wide range of crack length to width ratios and hardening exponent n. These solutions and analyses based on them are applicable to situations where the cracked configurations are completely yielded, i.e., the plastic strains are large compared to the elastic strains everywhere in the body. By exploiting the functional forms of the fully plastic solutions and the linear elastic solutions, simple approximate formulas have been obtained for J, δ and relevant displacement quantities which interpolates over the range from small scale yielding to fully plastic conditions. Based on these approximate formulas, the crack driving force in terms of J for compact specimens are determined. In Fig. 4 the contours of J at different levels of applied load and displacement are given for a particular compact specimen. The experimentally measured A533B steel J-resistance curve is drawn on the figure at the crack length appropriate to the crack configuration being examined. The amount of crack extension to maximum load and the maximum load are indicated in the figure. J-driving force contours can be easily recomputed to take into account test machine compliance and the resulting driving force diagram employed for evaluation of crack growth instability.

The crack driving force diagrams together with the material J-resistance curve contain all the information required to examine the deformation behavior of the test specimen, the rate of crack growth (the load line displacement vs. crack extension), and other pertinent behavior. The predicted load displacement behavior of the compact specimen is compared with the measured data in Fig. 5 - the predicted curve is slightly lower than the measured data and the trends are in complete agreement.

We also note that the J crack driving force contours for a particular test specimen may be employed together with the measured load displacement for that specific specimen to estimate the material J-resistance curve. This is particularly useful in fracture tests on irradiated specimens or similar situations where the measurements necessary to determine the J-resistance curve are not available and is discussed in greater detail by Shih (1979) and Kumar and Shih (1979).

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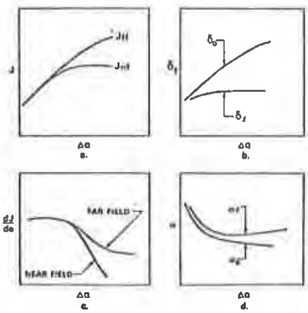

Fig. 1. Typical variation of J, δ, dJ/da and α (or $d\delta/da$) with crack extension.

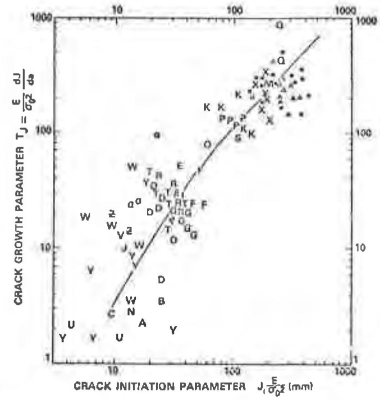

Fig. 2. Relationship between material resistance to crack initiation and crack growth as measured by J_c and T_J.

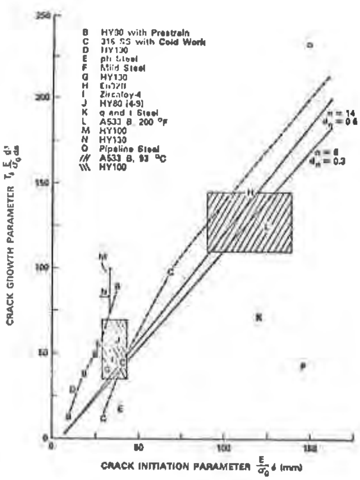

Fig. 3. Relationship between material resistance to crack initiation and crack growth as measured by δ_c and T_δ.

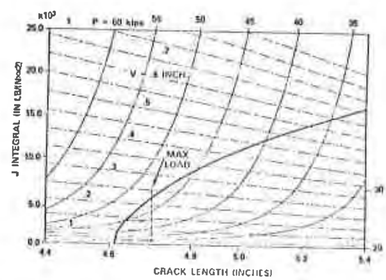

Fig. 4. J-integral crack driving force contours for several levels of applied load (per unit thickness) and load line displacement for A533B steel 4T compact specimen.

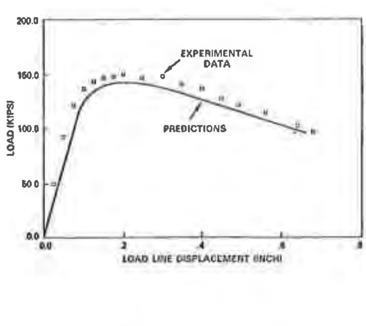

Fig. 5. Comparison of measured and predicted load displacement behavior of A533B steel 4T compact specimen.