Fracture Mechanics, a Practical Tool for Preventing Failures

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INTRODUCTION

The objective of this paper is to give a brief review of the conventional linear elastic fracture mechanics (LEFM) design approach and to show how the J integral fracture criterion[1,2] provides a direct extension of fracture mechanics into the elastic-plastic and fully plastic range. It is important to note that consideration is given mainly to plane strain problems. In the linear elastic plane strain approximation the extent of plasticity must be small compared to the crack size (linear elastic) and thickness (plane strain). With the J_{Ic} fracture criterion the section may be fully plastic as long as the flow field at crack initiation is of the plane strain type.

LEFM DESIGN APPROACH

In linear elastic fracture mechanics the stress intensity factor, K, gives a one parameter characterization of the crack tip region. Hence a wide range of processes occurring near the crack tip can be described in terms of this parameter.

Crack initiation occurs when K reaches a critical value. If the crack tip plastic zone at this point is small compared to the thickness, this critical K value is termed K_{Ic}. The final instability point will depend on the loading and compliance of the structure and the crack growth resistance of the material. However, in many cases final instability occurs at or near enough to K_{Ic} to make it the only rational design point. A wide variety of techniques are available to compute stress intensity factors as a function of loading, geometry and crack size and shape. Safe operation in the absence of subcritical crack growth is assured by limiting the combination of applied stresses and permissible crack sizes such that the maximum applied K is below K_{Ic}.

When subcritical crack growth is a factor due to fatigue and/or static loading in an aggressive environment, rates of crack growth can again be described in terms of K. Thus, with appropriate information in the areas of material properties, stress analysis and defect characterization and a stress intensity expression for the loading and cracked-body geometry of interest, LEFM can be employed to develop quantitative fracture prevention procedures.

THE J_{Ic} FRACTURE CRITERION

Problems are often encountered in applying LEFM to the lower-strength, higher-toughness materials commonly used for many structural applications. In order to meet the requirement of essential elastic behavior the structures of interest must be very large, K_{Ic} test specimens themselves become massive, and critical crack sizes at elastic stress levels are large enough to be of little practical concern. More often the question arises of relatively small defects adjacent to stress concentration sites where the extent of plasticity rules out linear elastic fracture mechanics. As the following paragraphs attempt to show, the J_{Ic} fracture criterion provides a direct extension of fracture mechanics into the elastic plastic and fully plastic range. It speaks directly to the above problems of cracks imbedded in regions of contained plasticity and reasonably sized test specimens.

The J integral is a path independent integral formulated by Rice.[1] It applies strictly to two dimensional linear and nonlinear elastic problems. Assuming the deformation theory of plasticity is a reasonable approach with metals, J can be applied to this problem. As advanced by Begley and Landes,[2] J can be viewed as a single parameter

characterization of the crack tip plastic field. This is possible from the description of the strain hardening plastic crack tip singularity given by Hutchinson[3] and Rice and Rosengren.[4] Combining J with the HRR crack tip model the near tip values of stress and strain can be described as functions of J and the flow properties. This is directly analogous to the stress field equations of linear elastic fracture mechanics.

In the elastic range J becomes equal to G, the crack driving force. Hence, it is equivalent to the K approach in this range. If J_{Ic} is a valid fracture criteria it must be constant from essentially elastic to fully plastic conditions. Thus J_{Ic} must equal G_{Ic}. Begley and Landes[2] showed this to be true for a rotor-forging steel. Landes and Begley[5] further showed no effect of test geometry on J_{Ic}. J_{Ic} is defined as the J level causing the first significant crack growth.

The technique for experimentally measuring J_{Ic} is not difficult. It is fully explained Ref. 2. A simple formula for deep cracked bend bars is given in Ref. 6. With this formula only one test is needed rather than a number of specimens of various crack lengths as originally performed by Begley and Landes.[2]

Figure 1 shows K_{Ic} values for a forging steel as function of temperature. At the upper shelf level, a K_{Ic} number obtained from J_{Ic} tests of small fully plastic bend bars is also shown.

$$J_{Ic} = G_{Ic} = \frac{1-\nu^2}{E} K_{Ic}^2$$

The agreement between G_{Ic} from an eight inch thick essentially elastic compact tension specimen and a fully plastic J_{Ic} specimen is very good. The other curve in the figure is for A533B steel. It shows how small J_{Ic} specimens can be used to obtain K_{Ic} values further up the temperature scale where ASTM requirements for valid K_{Ic} tests makes specimens prohibitively large. Thus. it is now possible to obtain the critical fracture toughness parameter with small specimens over a wide range of temperatures for the tough materials.

APPLICATION OF THE J_{Ic} CONCEPT

The problem of a small crack imbedded in a region of contained plasticity is important technically. It is used here to illustrate one application of the J_{Ic} concept. Consider the region containing a stress raiser shown in Fig. 2. The shaded area represents a plastically yielded zone. The question is, "What defect size can be tolerated in this region?" Solving this problem using the J integral requires (1) the fracture toughness of the material using K_{Ic} or J_{Ic} specimens, and (2) an elastic-plastic analysis of the problem to find J as a function of the loading parameter and crack size. The former requirement is not difficult; the latter may require considerable effort. However, once the analysis is obtained, say by a finite element computer program, J can be computed at any desired load level. In order to prevent fracture, appropriate precautions can be taken to insure that the applied level of J in the structure never exceeds J_{Ic}.

SUMMARY

The application of a J_{Ic} fracture criterion provides a logical extension of LEFM to elastic-plastic or fully plastic loading conditions. The basic concepts and method of applications for fracture prevention are directly analagous. The basic difficulty in utilizing the concept now becomes computational, rather than experimental, that is; determination of J expressions for the geometry and loading conditions of practical interest.

REFERENCES

1. Rice, J. R., "A Path Independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks," Transactions of the American Society of Mechanical Engineers, Journal of Applied Mechanics, June 1968, pp. 379-386.
2. Begley, J. A. and Landes, J. D., "The J Integral as a Fracture Criterion," Proceedings of the 1971 National Symposium on Fracture Mechanics, ASTM STP 514, to be published.
3. Hutchinson, J. W., "Singular Behavior of the End of a Tensile Crack in Hardening Material," Journal of the Mechanics and Physics of Solids, Vol. 16, 1968, pp. 13-31.
4. Rice, J. R. and Rosengren, G. F., "Plane Strain Deformation Near a Crack Tip in a Power-Law Hardening Material," Journal of the Mechanics and Physics of Solids, Vol. 16, 1968, pp. 1-12.
5. Landes, J. D. and Begley, J. A., "The Effect of Specimen Geometry on J_{Ic}," Proceedings of the 1971 National Symposium on Fracture Mechanics, ASTM STP 514, to be published.
6. Rice, J. R., Paris, P. C., and Merkle, J. G., "Further Results on J Integral Analysis and Estimates," Presented at the Sixth National Symposium on Fracture Mechanics, Philadelphia, Pennsylvania, August 1972.

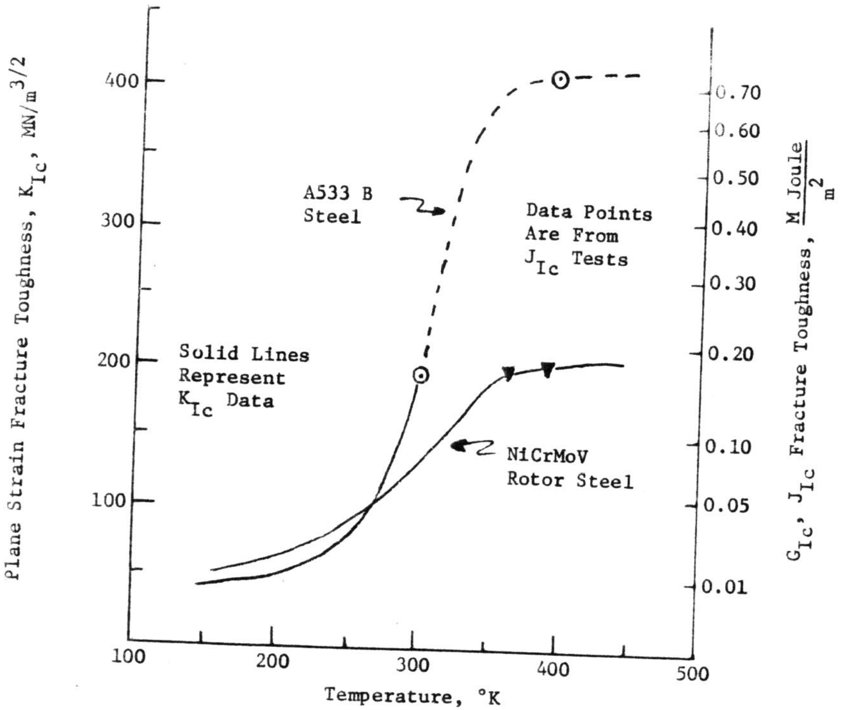

Figure 1 - Plane Strain Fracture Toughness Versus Test Temperature

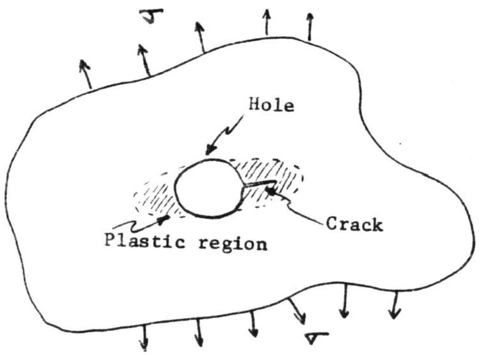

Figure 2 - Cracked Plate Contained Plasticity Problem