METHODOLOGY FOR PLASTIC FRACTURE
A PROGRESS REPORT

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SUMMARY

This paper describes the progress of a study to develop a methodology for plastic fracture. Such a fracture mechanics methodology, having application in the plastic regime, is required to assess the margin of safety inherent in nuclear reactor pressure vessels. While linear elastic fracture mechanics and elastic-plastic procedures (such as the J-integral or crack opening displacement) appear to be adequate predictive techniques for some plant conditions, direct application to material under fully plastic deformation is questionable. The steels used to fabricate nuclear pressure vessels will deform significantly at the operating conditions prior to the inception of fracture. Indeed, it is likely that once initiated, flaws will propagate in a stable manner prior to final fracture. In addition, the energy required to effect plastic fracture is much greater than that associated with more brittle failure modes characteristic of low temperature fracture. Both of these characteristics must be embraced in a quantitative plastic fracture methodology. Such a methodology will permit a proper assessment of design safety margins without the need to assume unrealistically conservative boundary conditions which may result from the application of linear elastic fracture mechanics.

The initiation and growth of flaws in pressure vessels under overload conditions is distinguished by a number of unique features, such as large scale yielding, three-dimensional structural and flaw configurations, and failure instabilities that may be controlled by either toughness or plastic flow. In order to develop a broadly applicable methodology of plastic fracture, these features require the following analytical and experimental studies: development of criteria for crack initiation and growth under large scale yielding ; the use of the finite element method to describe elastic-plastic behavior of both the structure and the crack tip region; and extensive experimental studies on laboratory scale and large scale specimens, which attempt to reproduce the pertinent plastic flow and crack growth phenomena.

A variety of candidate criteria for crack initiation and growth are examined. For the case of crack initiation, these criteria include the J-integral, crack opening displacement, and strain amplitude. In the case of crack growth, the criteria examined include in addition the strain amplitude at the crack tip, work done in a crack tip process zone, and a generalized energy release-rate approach. Each test specimen configuration is analyzed through the finite element method in order to predict its experimental behavior. Specimens include the compact tension specimen and center cracked panels. The basic materials used in the program are a single heat of reactor grade A533 Grade B Class 1 steel, purchased in the form of a plate of size 4.5 m (178 in.) square and 0.2 m (8 in.) thick, and two alloys with yield strength-to-toughness ratios about five times larger than A533B.

This discussion centers on progress to date on the selection, through analysis and laboratory experiments, of viable criteria for crack initiation and growth during plastic fracture. A brief description is also given of future plans concerning the verification of such criteria through larger scale tests and of applications of the methodology in predicting the behavior of flawed pressure vessels.

Introduction

This paper describes an ongoing research program to develop a fracture mechanics methodology for plastic fracture for assessing the margin of safety inherent in nuclear reactor pressure vessels. The program is seeking a broadly applicable methodology that can account for large scale yielding of the vessel prior to the inception of fracture, stable crack extension, and the high energy flat and shear failure modes encountered under testing conditions. The research is being pursued at the General Electric Company and at Battelle Columbus Laboratories. It is examining existing and new criteria for crack initiation and growth under large scale yielding; the use of the finite element method to describe elastic-plastic behavior of both the structure and the crack tip region; and includes extensive experimental studies on laboratory scale and large scale specimens, which attempt to reproduce the pertinent plastic flow and crack growth phenomena.

The planned program consists of four phases:

1) Selection, through analysis and laboratory experiments, of viable criteria for crack initiation and growth during plastic fracture.
2) Selection of final criteria for crack behavior through further exhaustive laboratory tests, and the development of a methodology for predicting ductile fracture behavior in structures.
3) Verification of this methodology through engineering scale tssts.
4) Application of the methodology in predicting the behavior of flawed pressure vessels.

A detailed description of the program plans is given in [1]. The planned program will continue over a period of 38 months. During the first 18 months, investigators from the General Electric Company and at Battelle Columbus Laboratories are developing the fundamentals of crack initiation and growth under large scale plastic yielding conditions, leading to criteria for such crack behavior. For the remaining 20 months, the General Electric team will further verify the criteria through both laboratory and large scale tests and will apply the methodology for plastic fracture so developed.

During the initial phases of the program, a variety of candidate criteria for crack initiation and growth are being examined. In this study, crack initiation is taken to mean the start of crack growth from preexisting flaws or cracks. For the case of crack initiation, these criteria include the J-integral [2, 3], crack opening displacement [2, 4] and strain amplitude [5]. In the case of crack growth, the criteria to be examined include the J-integral [3], crack tip opening displacement [6], and crack opening angle [6]; and some approaches which include the strain amplitude at the crack tip, work done in a crack tip process zone, and a generalized energy release-rate approach. It is intended that analysis and testing complement one another. Each specimen configuration is analyzed through the finite element method, in order to predict its experimental behavior. As analysis and testing proceed, the range of candidate criteria will be narrowed to one or two and finally during the sixteenth month of the program, a decision will be made as to which criterion will be adopted for describing the process of crack initiation and growth during the remainder of the program. The basic material used in the General Electric program is a single heat of reactor grade A533, Grade B, Class 1 steel, in the form of a plate 4.5 m (178 in.) by 2.25 m (88 in.), and 0.2 m (8 in.) thick. The Battelle study will also make use of this heat. In addition, certain initial tests for a thickness effect study have been made on available A533B nozzle dropouts. A508 Class 2 steel forgings will be used to develop crack initiation and growth data, and tests will also be carried out on specimens containing weld metal cut from commercial weldments. The Battelle study also uses two "toughness scaled" model materials: 2219-T87 and 7075-T73 aluminum.

Whereas the global view of the program approach, particularly in its initial phases, is as described above, the details of the approaches being pursued by General Electric and Battelle investigators lay differing emphasis on one or another criteria, and also pursue differing experimental philosophies. Therefore, in the following discussion, the progress of the General Electric program will be described first, followed by the Battelle program. It should be emphasized, however, that continuous technical information exchanges are made and the developed methodology will contain features from both programs. In addition, specific attention has been paid during the program planning to make these programs complementary and to avoid duplication of effort.

2. Elements of the General Electric Program

2.1 Underlying Philosophy

Because the objective of this work is to identify and apply crack initiation and growth criteria for pressure vessels, this effort is oriented initially toward the study of predominantly flat fracture, and the earlier stages of crack growth. This view is supported by the results of the Heavy Section Steel Technology (HSST) Program [8] and tests on large plates at the Southwest Research Institute [9]: the growth of part-through cracks in A533B steel remains flat until after the point of maximum load is reached.

2.2 Definition of Fracture Criteria: The Analytical Strategy

The procedure being used for a systematic examination of the various fracture parameters will be outlined here. This procedure is also being used by others [10] in similar investigations. The following experimental information is available: the applied load, load line displacement, and the crack extension, which may be determined, for example, by the compliance method [11]. As shown in Figure 1a, the load line displacement vs. crack extension is the primary input for the finite element program. The crack length is increased incrementally corresponding to a given load line deflection so that the modeled curve follows the input curve closely. The crack extension is effected by a node shifting and releasing technique, which allows the model of crack growth to occur smoothly, and also allows computational economy in that a relatively crude mesh can be used effectively. Appropriate modifications of the ADINA code [12] have been made to implement these calculations. Figure 1b shows some of the output of the two-dimensional calculations for a compact tension (CT) specimen. There, load vs. load point displacement predicted under plane stress and plane strain conditions are compared with a test on HY 130 steel [13]. Figure 1c shows the computed results for several potential failure criteria: the crack opening angle, and the J-integral according to the plane stress computation. These are typical results. It is expected that the final identification of the fracture criteria will lie in such comparisons, where the identified criteria attain a constancy during crack growth. Thus far, the two criteria mentioned show considerable promise.

2.3 Side Grooved Compact Tension Specimens

Because of the high toughness of A533B in the upper shelf region, CT specimens of the size 1T to 4T invariably exhibit the formation of shear lips. In order to attain a flat fracture surface, the use of CT specimens with side grooves has been investigated. Figure 2 illustrates a comparison between measured and analytical results for the compliance of such 1 1/2T CT specimens. The analysis is based on three-dimensional elastic finite element calculations. The effect of the side grooving on the measured J-integral vs. crack extension is shown in Figure 3. There it is observed that the critical J for initiation appears more distinct for the side grooved specimen, which may be a potential advantage in terms of experimental sensitivity. The fracture surfaces of ungrooved and side grooved 1 1/2T CT specimens tested at 200°F are shown in Figure 4. There, it is observed that flat fracture is achieved with a 25% side groove. Similar results have been achieved for 4T CT specimens.

Because of the introduction of potentially significant three-dimensional stress fields through the use of side grooves, a three-dimensional elastic analysis of grooved and ungrooved CT specimens has been made. (An elastic-plastic study is also planned.) Some results are shown in Figure 5. There, it is seen that the plane strain constraint in a grooved specimen is relatively constant across the area near the crack front, whereas the stress intensity factor K_I rises in a region near the groove. Thus, the K_I can be kept close to the two-dimensional level over most of the specimen width and will only exceed it near the grooves. It is likely, however, that after large plastic deformation, the stress will level out and a nearly uniform stress field will exist ahead of the crack tip.

2.4 Rubber Infiltration for Crack Profile Measurement

It has been deemed desirable to develop a method of directly measuring the crack tip profile, since many of the potential criteria are related to the behavior of the crack tip. Success has been achieved in using a rubber infiltration technique at 200°F. This technique involves the use of a low viscosity silicone rubber (GE RTV 602) with a yellow pigment. After it is inserted into the cracked loaded specimen, and hardened, the specimen is broken and the cast parts easily from the fracture surface. A typical crack profile is shown in Figure 5, where the initial crack blunting followed by crack growth can be observed.

2.5 Metallurgical Aspects

The goal of the metallurgical investigation is to characterize the microstructure of A533B as it exists in thick sections, and to determine the microscopic mechanisms of crack initiation and growth. The microstructure of A533B is that of banded sulfide inclusions several microns in size and tempered bainite. Submicron sized carbides form in layers along bainite laths. This structure is especially prevalent in the interior regions of the plate where the cooling rate from the austenitization temperature is slower, resulting in upper bainite. The microscopic fracture mode in A533B above the ductile-brittle transition temperature is dimpled rupture, where voids are formed at dispersed phases, then grow and coalesce to cause final failure. Based on electron fractography and metallographic sectioning studies, void nucleation occurs first at inclusions, and for higher strains at the carbides. To date, it is not known what stress, strain, or work quantities control the void initiation and growth stages. It is planned to section interrupted tests of notched and smooth tensile tests as well as flat and side grooved precracked compact tension specimens. From studies of these specimens, it is intended to understand the microscopic fracture mechanisms which correspond to macroscopic crack initiation and growth. Simultaneously, an understanding of what controls the actual fracture will facilitate a selection of a realistic fracture criteria.

3. Elements of the Battelle Program

3.1 The Generalized Energy Release-Rate Criterion

It is not yet certain which stable crack growth criterion will ultimately be the most useful for the basis of a plastic fracture methodology. A highly promising candidate is a generalization of the basic energy-balance concept that has proven itself in linear elastic fracture mechanics. Two specific techniques of ordinary linear elastic fracture mechanics are included in this approach. First, a small "process zone" surrounding the crack tip is identified. This region is envisioned to contain the nonlinear irreversible processes that must be excluded from continuum-mechanics considerations. Second, a direct computation of the plastic-energy dissipation rate for the material outside of the process zone region is made. Two key assumptions are then required. The first is that the energy dissipation rate in the process zone is characteristic of the material. The second assumption is that the energy flowing to the process zone is unaffected by the details of the deformation occurring within it. Notice that only the first of these two assumptions underlies the concept itself. The second assumption is made only for computational convenience (i.e., so that the computations can be carried out by standard finite-element techniques), and is not essential to the idea.

Figure 7 depicts a process zone at the crack tip that encompasses the region where three-dimensional plasticity and/or heterogeneous void growth and coalescence processes are occurring. As shown in the figure, the remainder of the body is represented as an elastic-plastic continuum. Note that in the following, because the process zone cannot always be established on a physical basis, for clarity, it will be referred to as the "computational process"zone (CP-zone). It might be noted that a number of other investigators are also currently pursuing an energy-based concept for elastic-plastic fracture, see [10, 14-20]. The most important distinction between these are the procedure developed in our work is our computational process zone idea.

A statement of energy conservation during a quasi-static crack extension process in which a body containing a crack passes from a state (1) to a state (2), e.g., from crack length a to $a + \Delta a$ is given by $G = R$ provided that

$$G = \frac{1}{B\Delta a} \left\{ \int_A T_i \left[u_i^{(2)} - u_i^{(1)} \right] dA - \int_V \left[\int_{(1)}^{(2)} \sigma_{ij} \, d\epsilon_{ij} \right] dV \right\} \qquad (1)$$

where $\underline{T}$ denotes the surface tractions acting on a cracked body, $\underline{u}$ denotes the displacements on the surface of the body, $\underset{\sim}{\sigma}$ is the stress tensor, $\underset{\sim}{\epsilon}$ is the strain tensor, A is the surface area of the body, Δa is the crack length created from State (1) to (2), B is the thickness of the body at the crack tip, and V is the volume of the body outside a "process zone" surrounding the crack tip.

The parameter G , the generalized energy release rate, is the energy flow rate into the computational process zone. It is a parameter that can be computed from continuum mechanics considerations. The parameter R is the energy dissipation rate due to flow and fracture processes in the computational process zone. It depends on micromechanical processes and so must be obtained experimentally. Note that G is associated with a virtual crack extension and has meaning whether or not the crack actually extends. R is a material property which is numerically equal to G when (and only when) crack extension occurs.

The evaluation of G directly from Equation (1) would obviously involve a very awkward time-consuming integration over the entire body. A more computationally convenient form can be obtained by invoking the second of the two assumptions stated above. Then, because of the energy balance, Equation (1) can be reexpressed in the form

$$G = G_o + G_{cpz} \quad , \tag{2}$$

where G_o is the crack closure integral employed, for example, by Rybicki and Kanninen [19] to obtain elastic stress intensity factors, and G is the energy dissipated in the computational process zone.

3.2 Toughness Scaled Materials

An important consideration in this program is the validation of the criteria and analyses for the flaw sizes and shapes, fracture modes, and degree of plasticity encountered in practice. However, experimentation on a scale comparable to the full scale vessel is very costly and certainly unwarranted at this stage. For this reason "toughness scaled" materials are being employed. The idea is to select materials with reduced toughness levels consistent with the reduced size of the laboratory event, thereby preserving the values of the parameters that control the modes and mechanics of the full scale fracture event. These parameters are:

1) The crack length-to-plate-thickness ratio, a/B, which fixes the relative size of the flaw.
2) The nominal stress for crack extension-to-yield stress ratio, σ^*/σ_y, which reflects the extent of yielding of the structure prior to crack instability
3) The plastic zone size-to-plate thickness ratio, ρ/B, which controls constraint to flow near the crack tip and the mode (flat vs. shear) of the fracture.
4) The shear fracture energy-to-flat fracture energy ratio, $\frac{f}{1-f}\frac{R_{SH}}{R_F}$, which we believe will control the degree of tunneling by the crack front (see Figure 2).

The first set of entries in Table I lists LEFM estimates of these parameters for a full-scale" 200mm-thick, flat, A533B steel plate. The second entry illustrates that a simple reduction in the scale of the experiment from 200mm- to 25mm-thick drastically alters the values of the parameters. This finding necessitates the use of other materials as shown in the following entries.

Toughness scaling is accomplished by selecting experimental materials with toughness, thickness, yield stress and modulus so that the values of 2 scaling parameters of the full scale structure are preserved. The first parameter, $P_1 = 1/B\ (K_{Ic}/\sigma_Y)^2$ accomplishes the scaling for plane strain conditions (note: $P_1 \approx 5\ \rho/B$). The second, $P_2=(f/1-f)(R_{SH}/R_F)$, preserves the ratio of shear-to-flat fracture energy and extends scaling into the mixed-mode regime.

Entry 3 of Table I illustrates that the aluminum alloys 2219-T87 and 7075-T73, in thicknesses of from 5mm to 10mm, provide good representations of full-scale A533B fracture behavior. These alloys display the same fracture modes (flat fibrous and shear) as A533B steel and can be tested at room temperature, facilitating the measurement of crack extension. One shortcoming is that they do not produce the large shear-to-flat fracture energy ratio of the steel, and probably understate the degree of tunneling of the crack front (see

Figure 8). Entry 4 in Table 1, shows that a 25mm-thick plate of A533B tested at NDT-20°C also preserves the important parameters including the shear-to-flat fracture energy ratio even though the flat mode is produced by cleavage instead of a fibrous mechanism. Both the aluminum alloys and the steel are being tested with part-through and through-wall cracks to obtain the necessary experimental validation.

3.3 Application and Verification

The required steps to implement the methodology include

(1) The development of an elastic-plastic finite-element computer capability for the specimen configurations used in the experimental program.

(2) The determination of the proper dimensions of the CP-zone.

(3) Laboratory measurements of applied load (or displacement) vs. crack extension in test specimens of the pressure vessel steel of interest. The R-values for the steel are obtained by inserting these measurements into the computer program developed in (1).

(4) The development of a finite-element computer capability for pressure vessels and other engineering structures.

(5) Computations using R values determined in (3) to predict crack growth initiation, stable growth and unstable fracture in pressure vessels.

Thus, the analysis work can be divided into two phases: a Generation Phase and an Application phase. In the Generation Phase, R values for the material are deduced from measurements of the applied stress-crack growth response of laboratory specimens. In the Application Phase the progress of crack growth as a function of applied stresses and onset of fast fracture are predicted for an assumed flaw in a structure and a laboratory R value.

To illustrate the results obtained so far, a trial "Generation Phase" computation was performed using data obtained from a 600mm-wide, 2mm thick 2024-T3 aluminum, center cracked, tensile loaded panel. The applied load versus crack growth results, obtained by Broek [10,20] are shown in Figure 9. It can be seen that an increase in the crack length by stable growth of about 33 percent was obtained for about a 20 percent increase in load. It is important to note that the precracking, the stable growth and final fracture all proceeded with 100% shear fracture without any discernible changes in mode.

In addition to calculating the generalized energy-release rate for this experiment, values of the J integral and the conventional LEFM R-curve were also calculated. Calculations were made using a rectangular CP-zone 1.5mm parallel to the crack and 7.8mm normal to the crack. These results, as shown in Figure 10, reveal that the J integral and LEFM R-values monotonically increase during the stable growth process despite the absence of mode changes. This indicates the limited usefulness of J for other than simple predicting the onset of growth. The generalized energy-release rate, in contrast, appears to be very nearly a constant value throughout the stable growth regime.

4. Acknowledgments

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TABLE I: Parameters of Full Scale, Reduced Scale and Toughness Scaled Failure Events

	Toughness (a)		Parameters (b)			
% Shear	K_c $MNm^{-3/2}$	R Jmm^{-2}	a/B	ρ/B	σ^*/σ_Y	$\left(\frac{f}{1-f}\right)\frac{R_{SH}}{R_F}$
1. Full scale, 200 mm thick plate, A533B at 200°F (c)						
25	660	1.89	1	2.5	2.00	12.0
10	320	0.45	1	0.6	0.98	1.7
0	200	0.19	1	0.3	0.63	0
2. Reduced scale, 25 mm thick plate, A533B at RT (d)						
100	900	3.50	1	36.0	7.7	∞
3. Toughness scaled, 8 mm thick plate, 2219-T87 aluminum (e)						
50	110	0.160	1	2.60	2.00	19.00
25	61	0.050	1	0.81	1.00	3.00
10	40	0.021	1	0.34	0.73	0.43
0	33	0.016	1	0.26	0.64	0
4. Toughness scaled, 25 mm thick plate, A533B at NDT -20°C (f)						
25	230	0.240	1	2.20	1.85	12.0
10	110	0.057	1	0.52	0.90	1.6
0	75	0.024	1	0.22	0.58	0

(a) $R \equiv fR_{SH} + (1 - f)R_F$, $K_c = [RE/1 - \nu^2]^{1/2}$, where f is fraction of shear fracture, $R_{SH} = \phi B$, where R_{SH} is per unit area shear fracture energy, and ϕ the permit volume shear fracture energy, R_F is the per unit area flat fracture energy corresponding to K_{Ic}.

(b) $\rho = 0.2\,(K_c/\sigma_Y)^2$; $\sigma^* = K_c\,(\pi a)^{-1/2}$

(c) $\sigma_Y = 413\ MNm^{-2}$; $K_{Ic} = 200\ MNm^{-3/2}$; $\phi \approx 0.14\ Jmm^{-3}$

(d) $\sigma_Y = 413\ MNm^{-2}$; $\phi = 0.14\ Jmm^{-3}$

(e) $\sigma_Y = 344\ MNm^{-2}$; $K_{Ic} = 33\ MNm^{-3/2}$; $\phi \approx 0.078\ Jmm^{-3}$

(f) $\sigma_Y = 450\ MNm^{-2}$; $K_{Ic} = 75\ MNm^{-3/2}$; $\phi = 0.14\ Jmm^{-3}$

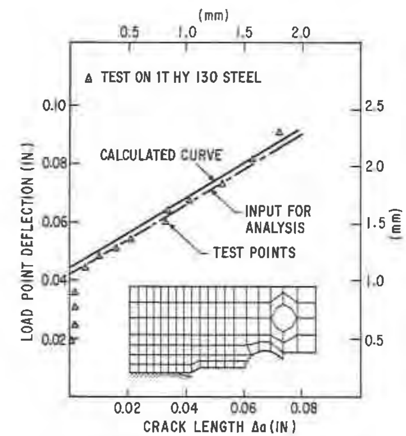

Figure 1a Compact Tension Specimen - Load Point Displacement vs. Crack Increment as Input

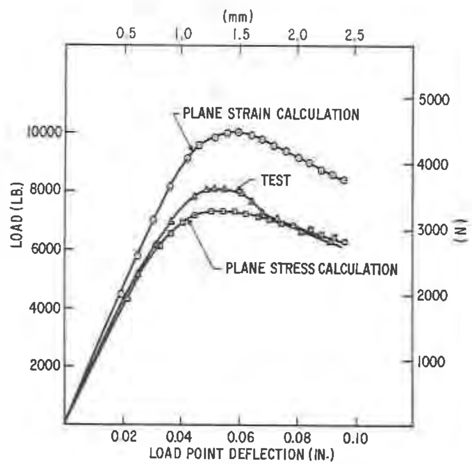

Figure 1b Result of Analysis - Load vs. Load Point Displacement

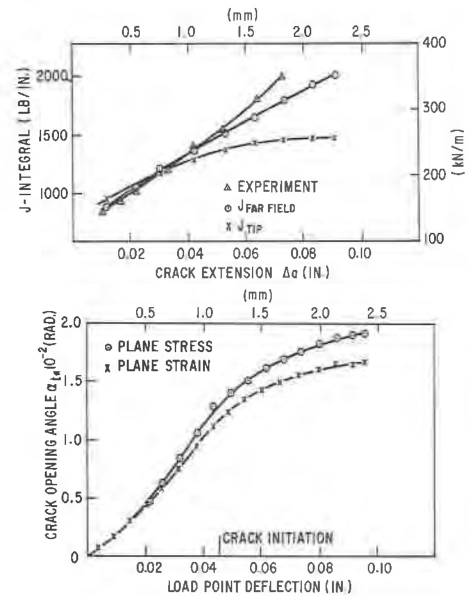

Figure 1c Result of Analysis - Crack Opening Angle and J-Integral vs. Load Point Displacement

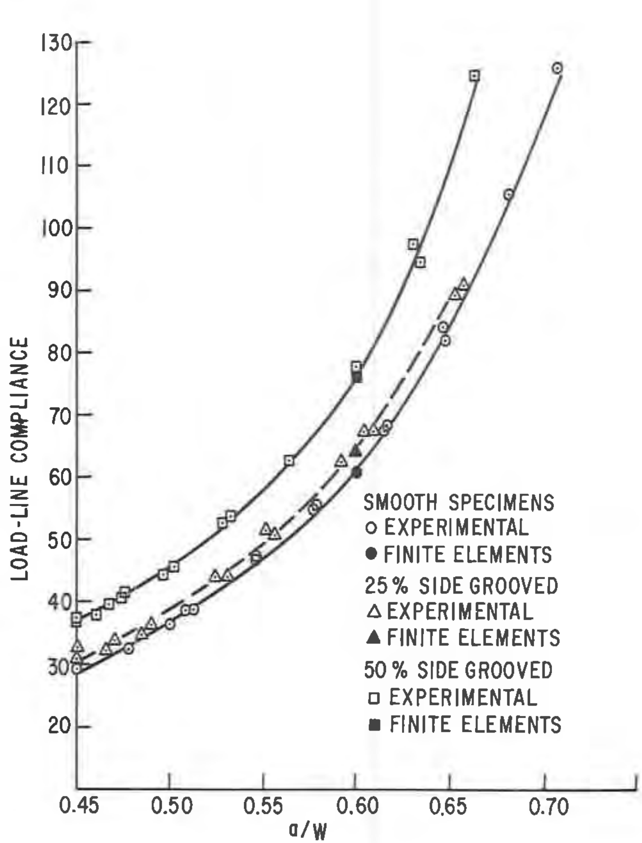

Figure 2 Measured and Calculated Compliance of Compact Tension Specimens

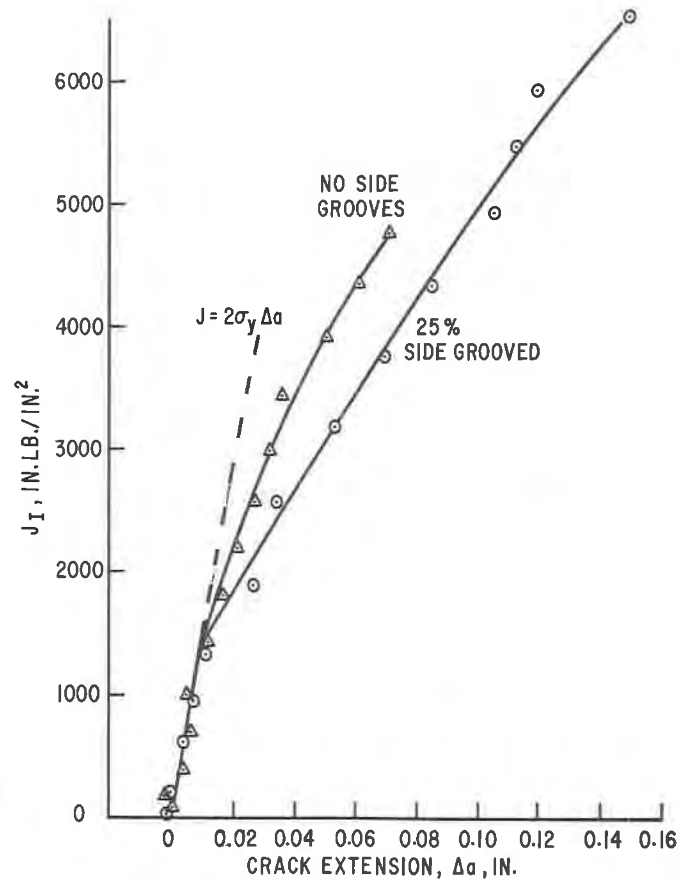

Figure 3 Effect of Side Grooves on J_I vs. Crack Extension

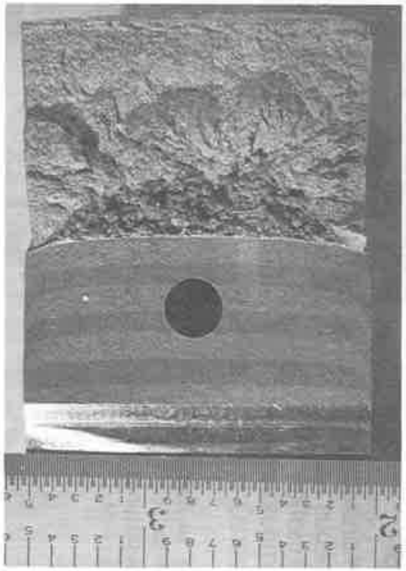

Figure 4a Fracture Surface:
1 1/2 T Ungrooved Specimen
Tested at 200°F

Figure 4b Fracture Surface:
1 1/2 T with 25% Grooves Tested at 200°F

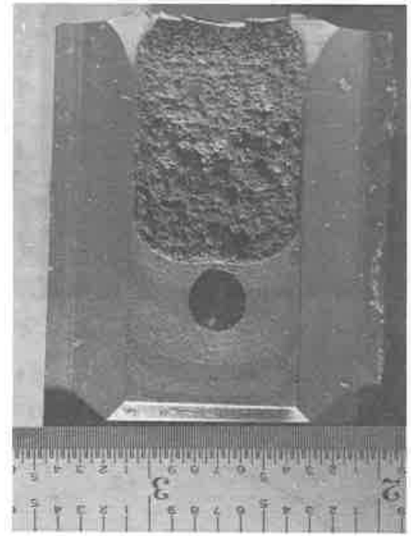

Figure 4c Fracture Surface:
1 1/2 T with 50% Grooves
Tested at 200°F

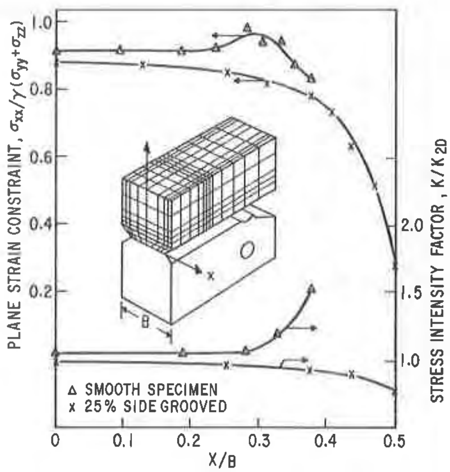

Figure 5 3D Elastic Analysis of Grooved Compact Tension Specimen

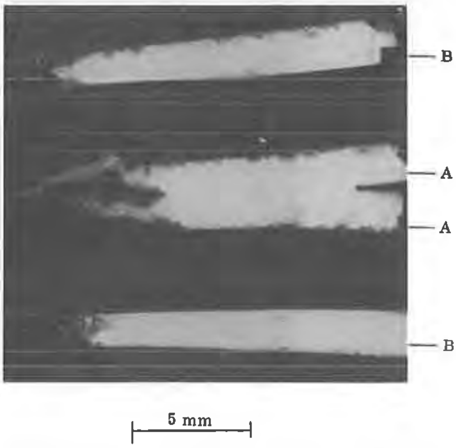

Figure 6 Replicas of Crack Profiles by Rubber Infiltration at 200°F. A-A, Cracks near Center; B-B, Cracks at 1/4 Thickness.

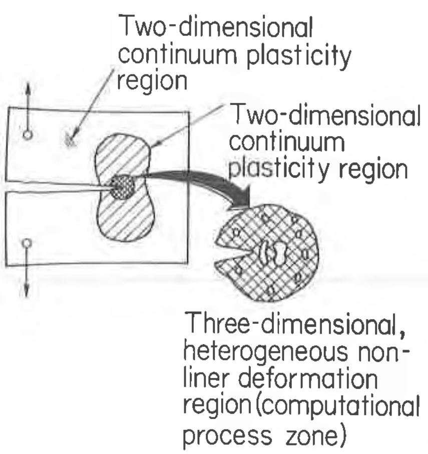

Figure 7 Elements of an Energy-Based Plastic Fracture Mechanics Analysis Showing the Computational Process Zone

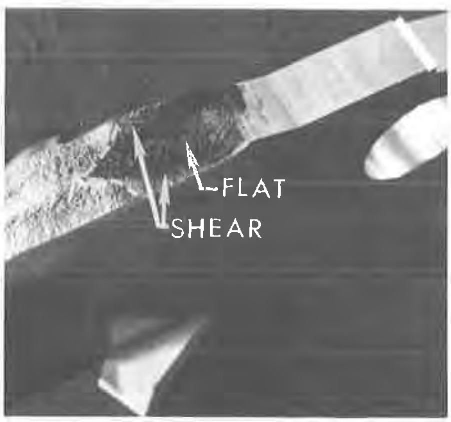

Figure 8 Mixed Mode Fracture Morphology of a Stable Crack Extending in a 12.7 mm Thick Compact Tension Specimen of 7075-T73 Aluminum. The white line shows the position of the crack front when the test was interrupted.

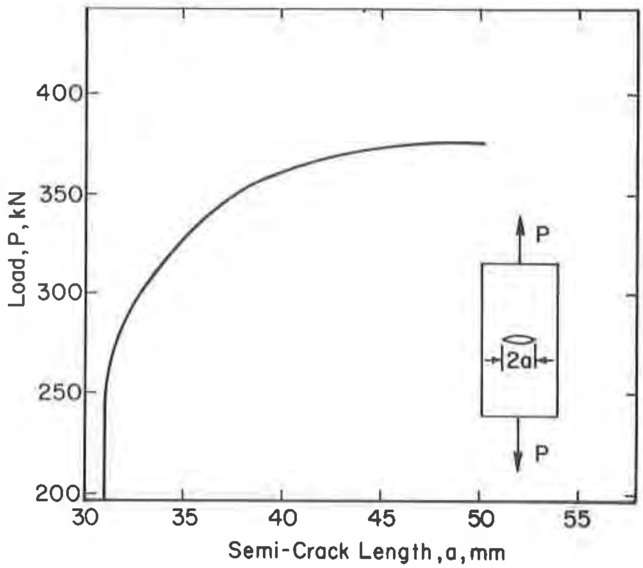

Figure 9 Measurements of Applied Load and Crack Extension in a 600 mm Wide, 2 mm Thick Center Cracked, Tensile Loaded 2024-T3 Aluminum Panel After Broek and Vlieger [10, 20].

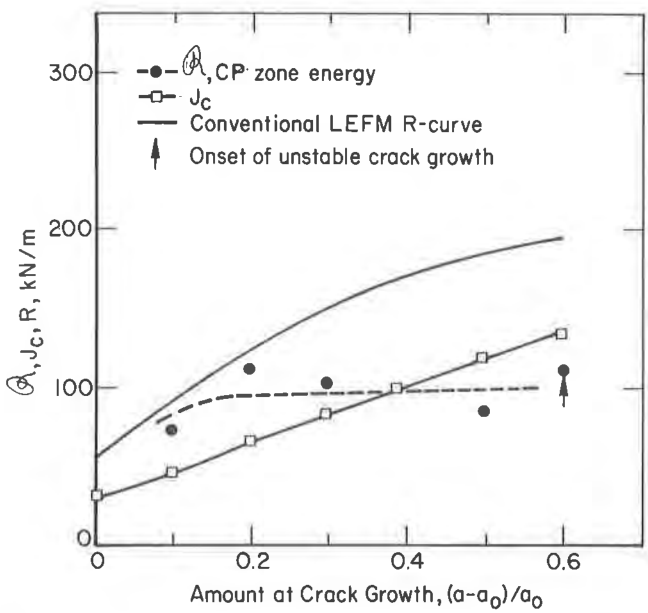

Figure 10 Results of Elastic-Plastic Finite Element Calculations of the Fracture Toughness Parameters, R, J_c and R with the Applied Load-Crack Extension Curve and Aluminum Panel shown in Figure 9.