Summary

The papers in this publication can be divided into three major sections: (1) the presentation and analytical evaluation of elastic-plastic fracture criteria; (2) experimental evaluation, including both the toughness evaluation of materials in the elastic-plastic regime and the evaluation of various fracture criteria and characterizing parameters; and (3) application of elastic-plastic methodology to the evaluation of structural components, including the application to fatigue crack growth analysis.

These papers demonstrate that the elastic-plastic fracture field is in a stage of rapid development. New approaches and parameters are emerging and no single approach has been adopted by all of the workers in this field. However, the field has reached a state of development where certain trends can be identified. Ductile fracture characterization, which in the past had largely been based on criteria taken at the point of initiation of stable crack growth, has been extended so that stable crack growth and ductile instability are analyzed. Fracture-characterizing parameters, which are mainly divided into field parameters and local crack-tip parameters, were once viewed as presenting opposing approaches but are now generally regarded as having a common basis. Detailed aspects of developing elastic-plastic fracture techniques, such as establishing limitations on the use of criteria and on test specimen type and size, are now being actively pursued, implying that a level of confidence in the underlying concepts has been reached. Further evidence of this confidence is demonstrated by attempts to apply the methodology to structural analysis and phenomena other than fracture toughness.

Results from individual papers are summarized in the following sections.

Elastic-Plastic Fracture Criteria and Analysis

The papers in this section are concerned with the development of criteria and parameters to characterize elastic-plastic fracture. In many papers, finite-element analysis is applied to determine how well these parameters characterize the crack-tip stress and strain fields under conditions of large-scale plasticity. Much of the emphasis in these papers is on stable crack growth and instability characterizations of fracture.

Paris et al have proposed a method for characterizing fracture at the point of ductile instability. Characterization of stable crack growth is based on the J-integral where the slope of the J versus crack growth resistance curve is given by a nondimensionalized parameter called the tearing modulus, T. The instability condition is formulated in a manner similar to the linear elastic fracture mechanics (LEFM) R-curve approach. When an applied mechanical crack drive of a specimen or structure, labeled T_{applied}, is equal to or greater than the material resistance to crack advance, labeled T_{material} ($T_{\text{applied}} \geq T_{\text{material}}$), tearing instability ensues. The instability condition was formulated for a large number of geometries and loading configurations in this paper. The result is a simple methodology for using laboratory tests to evaluate the tearing instability condition for many types of structures. Some initial experimental verification of this method is given in a second paper by Paris et al in this publication; however, much more remains to be done. This proposed method suggests many areas for future research both in analytical developments and in experimental verification and material property evaluation.

A paper by Hutchinson and Paris provides some rationale for the method proposed in the previous paper by taking a theoretical approach to evaluate the use of the J-integral for characterizing stable crack growth. A criteria for J-controlled crack growth is formulated by determining a region of proportional loading ahead of an advancing crack. The criterion is formulated in terms of a nondimensional size parameter, ω, which is a ratio of the size of the proportional loading region to the uncracked ligament. The condition for J-controlled and growth is $\omega \gg 1$.

Shih et al evaluated five parameters for characterizing stable crack initiation and growth, using nine criteria for the evaluation. The two chosen as the most viable were the J-integral and crack-tip opening displacement, δ. Finite-element investigations show that both parameters characterize the near-tip deformation. For stable crack growth, nondimensional parameters were developed similar to those of Paris et al and labeled T_J for crack growth characterized by J and T_δ for crack growth characterized by a crack opening angle. A J-characterization of the crack growth was determined to be valid up to a crack extension equal to 6 percent of the remaining ligament; however, crack opening angle remained constant over a much larger range of crack extension, suggesting that T_δ would be preferred over T_J. Complete ductile fracture characterization is given by a two-parameter approach, either J_{Ic} and T_J or δ_c and T_δ, which characterizes both the initiation and the growth of a stable crack. The analysis suggested the use of side grooves for experimental evaluations to ensure uniform flat fracture.

Kanninen et al used a finite-element approach to evaluate eight parameters for stable crack growth and instability. They also set nine requirements for choosing the appropriate parameter to characterize stable crack growth. From the parameters evaluated, four were found to vary with crack extension while four did not. The four that did not vary were: (1) crack tip opening angle, (2) work involved in separating crack faces per unit area of crack growth, (3) generalized energy release rate based on a computational process zone, and (4) critical crack-tip force for stable crack growth. These four parameters were judged to be more suitable for stable crack growth and instability characterization. The concept of a J-increasing R-curve was viewed as being fundamentally incorrect because the crack-tip toughness does not increase with an advancing crack.

Sorensen used finite-element techniques to study plane-strain crack advance under small-scale yielding conditions in both elastic-perfectly plastic and power hardening materials. The stress distribution ahead of a growing crack was found to be nearly the same as that ahead of a stationary crack; however, strains are lower for the growing crack. When loads are increased at fixed crack length, the increment in crack-tip opening is uniquely related to the increment in J; when an increment of crack advance is taken at constant load, the incremental crack tip opening is related logarithmically to J. When separation energy rates are calculated for large crack growth steps, the use of J as a correlator is sensitive to strain hardening properties and details of external loading.

McMeeking and Parks used finite-element techniques to study specimen size limitations for J-based dominance of the crack-tip region. They analyzed deeply-cracked center-notched tension and single-edge notched bend specimens using both nonhardening and power loading laws where deformation was taken from small-scale yielding to the fully plastic range. The criterion used to judge the degree of dominance was the agreement between stress and strain for the plastically blunted crack tip with those for small-scale yielding. They found good agreement for the bend specimen when all specimen dimensions were larger than 25 J/σ_o, where σ_o is the tensile yield. This size limitation is equivalent to one proposed for J_{Ic} testing. The center-notched tension specimen, however, would require specimen dimensions about eight times larger (200 J/σ_o), although loss of dominance is gradual and this requirement is somewhat arbitrary.

Nakagaki et al studied stable crack growth in ductile materials using a two-dimensional finite-element analysis. They looked at three parameters: (1) the energy release to the crack tip per unit crack growth, using a global energy balance; (2) the energy release to a finite near-tip "process zone" per unit of crack growth; and (3) crack opening angle. Their work confirmed numerically an earlier observation by Rice that the crack-tip energy release rate approaches zero as the increment of crack advance approaches zero for perfectly plastic material. From these present results, they are not ready to propose an instability criterion. However, they cannot base such a criterion on the magnitudes of an energy release parameter since these depend on the magnitudes of the growth step; therefore, a generalized Griffith's approach cannot be used for ductile instability.

Miller and Kfouri presented results from a finite-element analysis of a center-cracked plate under different biaxial stress states. Comparisons were made of: (1) crack-tip plastic zone size, (2) crack-tip plastic strain intensity and major principal stresses, (3) crack opening displacements, (4) J-integral, and (5) crack separation energy rates. They found that, for biaxial loading, brittle crack propagation can be best correlated with plastic zone size. Crack-tip plastic strain intensity is more relevant to initiation while crack opening displacement is more relevant to crack propagation. Stable crack propagation was not uniquely related to J.

D'Escatha and Devaux used elastic-plastic finite-element computations to evaluate a fracture model based on a three-stage approach—void nucleation, void growth, and coalescence. The purpose of this model is to predict the fracture properties of a material represented as the initiation of cracking, stable crack growth, and maximum load. The problem in a fracture model is to use two-dimensional analysis to predict fracture for a more realistic three-dimensional crack problem. Various parameters used to correlate stable crack growth were evaluated by this model, including crack opening angle, J-integral, and crack-tip nodal force. The next step will be an experimental evaluation of the present results.

The papers in this section were mainly concerned with the presentation and analytical evaluation of ductile fracture criteria. A common theme is that fracture evaluation should include more than simply the initiation of stable crack growth; stable crack growth characterization and ductile instability prediction must also be included. While there is no agreement as to which parameter should be used, the types of parameters are mainly field-type or crack-tip parameters. Field-type parameters such as the J-integral have a lot of appeal and are shown to be useful for correlating stable crack growth under a restricted set of conditions. A crack-tip parameter such as crack opening angle has fewer restrictions and has more general support for correlating stable crack growth. The results presented here suggest many areas for future study. More analysis is needed to determine the best single approach to ductile fracture characterization. The approaches presented must be evaluated with critical experimental studies. The optimum approach must lend itself to relatively simple evaluation of material properties and must be easily applicable to the evaluation of structural components. This approach may include one or a combination of methods suggested here or may be one that is developed in future studies of ductile fracture criteria.

Experimental Test Techniques and Fracture Toughness Data

The papers in this section deal with experimental evaluation of elastic-plastic techniques and fracture toughness determination for several materials. A number of papers deal with various aspects of the analysis used to determine the J-integral from the experimental load versus load-line displacement records for various specimen types. A critical evaluation of the present analysis techniques along with proposed new techniques for elastic-plastic specimen analysis are presented in this section. Also included are a number of papers describing the results of elastic-plastic fracture toughness testing using both J-integral and crack opening displacement (COD) techniques.

The paper by Paris et al outlined the test procedure and results used to verify the tearing instability model described in the previous section. An experimental technique with a variable-stiffness testing system was used by Paris et al to vary the applied tearing modulus, T_{applied}, for each test. The value of T_{applied} at the point of ductile instability was determined by continuously increasing the value of T_{applied} until instability occurred. This value of T_{applied} was then compared with the value of the material tearing modulus, T_{material}, determined from the slope of the J versus crack extension curve developed for the material of interest. The results of the tests on single-edge notched bend specimens showed extremely good agreement between the predicted value of instability and the actual experimentally determined instability for the material tested. It was emphasized by the authors that, as the applied tearing modulus is a function of the compliance of the overall system, the ductile instability phenomenon is very much dependent on the overall stiffness of the testing system or the structure under consideration. Future research in this area was discussed by the authors and consisted of testing a wider range of specimen types and variable geometries of a given generic specimen type.

Landes et al evaluated the approximation techniques used to calculate the value of J from the area under the load displacement curves for the most commonly used test specimens. This was accomplished by testing compact, three-point bend, and center-crack tension specimens each with blunt notches of various lengths. The values of J determined from the energy rate definition of the J-integral were compared with the various area methods of approximating J to evaluate the accuracy of the various approximation techniques. It was found that a correction factor for the tension component in a compact specimen was necessary. A modified Merkle-Corten correction factor was proposed for both simplicity and accuracy when calculating the value of J for a compact specimen. The three-point bend approximation was found to be accurate if the total energy aplied to the specimen in the approximation formula is used. The value of J calculated from the approximation formula for the center-cracked panel was also found to be quite accurate when compared with the value of J calculated by the energy rate definition.

McCabe and Landes proposed the use of an effective crack length to calculate the resistance to crack growth by the K_R technique. It was found that by using a secant method to calculate the effective crack length, the value of J at any point on the load displacement curve could effectively be calculated by using the relationship between K and J. A comparison of the results from this technique with the values of J calculated from the energy rate definition of J and the value of J calculated from the Ramberg-Osgood approximation of the load displacement curves was presented. The results from the secant method showed that this technique is a very good approximation to the value of J calculated from the energy rate definition.

In the next two papers by Dawes and Royer et al, the effect of specimen thickness on the critical value of J was noted. Dawes presented data showing that the critical values of both COD and J can be affected by section thickness and that therefore care should be taken to match or overmatch the plastic constraint in the test specimen to that of the structure. Dawes also proposed that the crack-tip COD should be defined as the displacement at the original crack-tip position. The data presented by Dawes show that is it possible to overestimate the value of K_{Ic} when using results from a J_{Ic} test on smaller specimens. While Royer et al also note a size effect for the three-point bend specimen, none was found for the compact specimen. It was pointed out that while the compact specimen showed no effect of size on the critical value of J, this result may possibly be fortuitous due to the type of material under investigation.

The paper by Milne and Chell discusses a proposed mechanism which may account for the specimen size effect on J_{Ic} found by them. For ferritic steels, a shift in the transition temperature due to increased triaxiality of larger specimens may well account for a size dependency on J_{Ic}. It is concluded by Milne and Chell that obtaining K_{Ic} from the small-specimen J_{Ic} test can possibly lead to nonconservative values of K_{Ic}. The mechanism attributed to this phenonmenon is one of a loss of through-thickness constraint which may cause crack-tip blunting during the test.

Using an analysis which employed the assumption of elastic-perfectly plastic behavior, Berger et al evaluated the various forms of the Merkle-Corten formula for the correction factors for the tension component in the compact specimen. A comparison was made of the equation which separates the elastic and plastic portions of the load displacement curve with various modified forms of the correction formula. It was found that the simplified form of the Merkle-Corten equation, which utilizes the total displacement as limits of integration, slightly overestimates the previously discussed form. The authors also proposed that a fixed displacement value should be used to determine the critical value of J rather than the intersection of the J versus Δa line and the theoretical blunting line.

Munz suggested in his paper that linear-elastic toughness testing need not be restricted to the size criteria defined in the ASTM Test for Plane-Strain Fracture Toughness of Metallic Materials (E 399-74). It was noted that the size dependence of K_Q as determined by the 5 percent secant offset method is due primarily to the crack-tip plasticity and the existence of a rising plane-strain crack growth resistance curve. A proposed variable secant method is presented which would allow specimens of up to six times smaller than the present size criterion permits to be tested for K_Q values.

Andrews and Shih presented a study on shear lip formation during testing and the effects of side grooving specimens. They noted that the shear lip dimensions found in the specimens were independent of the specimen dimensions. However, side grooving the specimens to a depth of 12½ percent of the thickness completely suppressed shear lip formation. The J versus Δa crack growth resistance curve was shown to be affected both by the thickness of the specimen and side grooving of the specimen. By measuring the crack-tip opening displacement using a linear variable differential transformer (LVDT) near the center of the specimen, Andrews and Shih showed that a crack growth resistance curve could be developed which is independent of specimen geometry and side grooving.

An interactive computerized J-integral test technique was described in the paper by Joyce and Gudas. By using a data acquisition system along with a computer, they showed excellent agreement between the values of J_{Ic} obtained from the unloading compliance technique and those obtained from the heat tinting method. The advantages of an interactive data reduction process occurring while the test is still in progress were discussed. This technique also allows for future reanalysis of the data by storing the data points on a magnetic tape system. The data from a test sequence on the computerized test technique showed that a nonconservative error in J_{Ic} could be obtained when using specimens with subsized remaining ligaments or specimens with insufficient thickness.

In the paper by Wilson an evaluation of a number of toughness testing methods to characterize various plate steels was made. The methods evaluated were Charpy V-notch (CVN), dynamic tear (DT), and J_{Ic}. The materials tested were A516, A533B, and HY130 manufactured by conventional steel-making techniques and also by a calcium-treated technique. A conventionally manufactured A543 material was also evaluated at the centerline and quarter-point positions of a plate. It was found that the J_{Ic} method of testing was far more sensitive to material quality than the other methods. It is postulated that this sensitivity may well be due to the acuity of the crack in the J_{Ic} specimen compared with the machined notch and the pressed notch of the CVN and the DT specimens, respectively. The results of these tests show that the J_{Ic} tests indicate a significant improvement in the toughness of the calcium-treated steels over the conventionally manufactured steels.

Nine pressure vessel materials were evaluated using static and dynamic initiation toughness results in the paper by Server. It was found from these test results that a nine-point average of the crack front gave a higher value of J_{Ic} than a three-point average of the crack front. The dynamic test values always gave greater slopes of the J versus Δa crack growth resistance curves and in many cases the dynamic values of J_{Ic} were higher than the corresponding static values.

Logsdon presented the results of a dynamic fracture toughness test on SA508 Cl 2a material using elastic-plastic techniques. A temperature-versus-toughness curve at testing rates up to 4.4×10^4 MPa$\sqrt{m}$/s was developed using the K_{Id} procedure at low temperatures and J_{Id} at higher temperatures. The results of these tests show that this material is suitable for nuclear applications. It was also shown that the necessary deceleration of the J_{Id} multispecimen test, due to the speed of testing to prescribed displacement values, had no effect on the results of the J_{Id} test.

In the paper by Tobler and Reed a presentation of the techniques used to test an electroslag remelt Fe-21Cr material at cryogenic temperatures was made. The toughness values at 4, 76, and 295 K were found by using J_{Ic} techniques. It was noted from the tension test results that, once plastic deformation occurred, a slight martensitic transformation took place at room temperature; at 76 and 4 K, however, an extensive martensitic transformation took place. The toughness of this material was found to be adversely affected as the temperature was reduced from 295 to 4 K while the yield strength increased by a factor of 3.

The problems of testing high-ductility stainless steel were presented in a paper by Bamford and Bush. Tests were conducted on 304 forged and 316 cast stainless steel at both room temperature and 316°C. The authors pointed out that the present recommended size requirements for J_{Ic} may be too restrictive as no change was noted in the slope of the crack growth resistance curve when passing from the proposed valid region to the nonvalid region. An acoustic emission system was also used in order to detect the initiation of crack growth. While the acoustic emission test showed large increases in count rate during the test, there was no obvious means of detecting crack initiation. The extensive plasticity achieved during the test also obscured the crack initiation point as defined by an increase in the electric potential of an electric potential system used. The unloading compliance technique was found to work favorably on the compact specimen; however, difficulty was encountered when using the three-point bend specimen.

The papers in this section were concerned mainly with the evaluation of various elastic-plastic criteria using experimental methods. There were basically two areas of investigation in this section: (1) the evaluation of the actual criteria, and (2) the results of fracture toughness testing when using a particular criterion. While a number of papers show an effect of size on both COD and the J-integral, others do not. Various testing procedures are used to show these size effects, creating a future need for a common method of testing. This section also shows encouraging results in the development of an instability criterion for ductile fracture. Future work in these areas should of course be directed at both size effects on the various elastic-plastic criteria and on the development of a test technique which correctly describes initiation and stable crack growth resistance up to and including ductile instability. The papers presented in this section will aid future studies in elastic-plastic criteria and testing methods.

Applications of Elastic-Plastic Methodology

The use of elastic-plastic fracture methodology to analyze structural components marks its emergence from the status of being mainly a research technique to that of being a useful engineering tool. The papers in this section include generalized methods for applying elastic-plastic fracture methodology, specific applications to structural components, and the application of elastic-plastic parameters to fatigue crack growth-rate correlation.

Chell discussed methods for using a Failure Assessment Curve to make failure predictions for structures subjected to thermal, residual, or other secondary stresses where a failure collapse parameter is not definable. A procedure is introduced which transforms points on a failure diagram from an elastic-plastic fracture analysis into approximate equivalent points on the Failure Assessment Diagram. A method for assessing the severity of a mechanical load superposed on an initial constant load is also presented. The paper concludes that the Failure Assessment Curve will provide a good lower-bound failure criterion for most mechanical loading.

Harrison et al reviewed methods for applying a COD approach to the analysis of welded structures. The COD test is particularly useful in studying fracture toughness of materials in the transition between linear-elastic and fully plastic behavior. Design curves are developed relating a nondimensional COD to applied strain or stress. These curves are useful for (1) selection of materials in design of structures, (2) specification of maximum allowable flaw sizes, and (3) failure analyses. Many examples are cited where the COD design curve has been used for these evaluations on structures designed for real applications. Examples of structures analyzed by COD methods include pipelines, offshore structures, pressure vessels, and nuclear components.

McHenry et al used elastic-plastic fracture mechanics analysis methods to determine size limits for surface flaws in pipeline girthwelds. Four criteria were used: (1) a critical COD method based on a ligament-closure force model, (2) the COD procedure based on the Draft British Standard, (3) a plastic instability method based on critical net ligament strain, and (4) a semi-empirical method based on full-scale pipe rupture tests. The critical flaw sizes determined varied significantly, depending on the fracture criterion chosen, and experimental work will be needed to determine which method most accurately predicts girthweld fracture behavior.

Simpson and Clarke used a crack growth resistance (R-curve) approach based on small fracture mechanics type specimens to determine critical crack lengths in Zr-2.5Nb pressure tubes. The R-curves were based on COD as the mechanical characterizing parameter. Their results showed little specimen size effect on the R-curve shape. R-curves based on a J-integral approach were shown to be consistent with the COD approach. Effects of temperature and hydrogen on the R-curve shape were investigated. Predictions of critical crack lengths in pressure tubes based on an R-curve procedure gave results which were consistent with published burst testing data.

Macdonald used a three-dimensional elastic-plastic fracture model to correlate the fracture strength of two structural steels in the form of beam-column connections. The model was based on the combination of (1) a three-dimensional elastic-plastic finite-element stress analysis, (2) a plastic stress singularity for a crack, and (3) the maximum tensile stress theory of fracture. From these a plastic singularity strength parameter, K_f, was developed. Cracking occurred by mixed mode (crack opening and sliding). Experimental results correlated with K_f showed a relatively small scatterband.

Merkle used approximate elastic-plastic fracture methods to analyze the unstable failure condition for inside nozzle corner cracks in intermediate test vessels. The method was applied to two vessels tested in the heavy section steel technology (HSST) program (Vessels V-9 and V-5). Semi-empirical methods were developed for estimating the nozzle corner pressure-strain curve. Two approximate methods of fracture analysis were used: one used an LEFM approach based on strain which did not consider stable crack growth; the second used a tangent modulus method which incorporated stable crack growth by using a maximum load fracture toughness value. The beneficial effect of transverse contraction was included in the analysis. Calculations of failure strain and fracture toughness agreed well with measured values.

Hammouda and Miller used elastic-plastic finite-element analyses to predict the effect of notch plasticity on the behavior of short cracks under cyclic loading. This analysis was used to predict crack growth behavior in a regime where LEFM methods do not apply. Consideration of the interaction between the crack tip and notch field plasticity can account for fatigue crack growth where a linear elastic analysis would predict that the fatigue threshold stress intensity factor is not exceeded. Crack propagation from a notch initially proceeds at a decreasing rate and in some cases cracks initiate but become nonpropagating.

Brose and Dowling studied the effect of planar specimen size on the fatigue crack growth rate properties of 304 stainless steel on specimen widths of 5.08 and 40.64 cm (2 and 16 in.). The objective was to evaluate size criteria intended to limit crack growth testing to the linear elastic regime and to evaluate the use of a cyclic value of J-integral, ΔJ, for correlation of crack growth rate data on specimens undergoing gross plasticity. The results show that crack growth rates correlated by ΔJ on small specimens having gross plasticity are equivalent to results from large specimens in the linear elastic regime, where the data are correlated by ΔK. No significant size effects were observed.

Mowbray studied fatigue crack growth of chromium-molybdenum-ranadium steel in the high-growth-rate regime where a cyclic J-integral value, ΔJ, was used to correlate growth rate. A compact-type strip specimen was used which gave rise to constant crack growth rate under simple load control at essentially constant ΔJ. These results supported previous results by Dowling and Begley which showed that crack growth rate in the high-growth-rate regime is controlled by ΔJ. An approximate analysis was used to determine ΔJ from cyclic load range for the strip specimen.

The papers in this section consider methods for applying elastic-plastic fracture techniques to the analysis of structures. The prominent technique for using small-specimen results to analyze large structural components is one based on crack opening displacement concepts. The COD was one of the first proposed elastic-plastic fracture parameters and has gained some degree of acceptance as an engineering tool. Other methods for application of elastic-plastic techniques include the Failure Assessment Diagram, R-curve techniques, plastic instability, and the plastic stress singularity. Again, no single method of analysis is generally accepted; many areas for future studies are identified by these papers.

A cyclic value of J-integral, ΔJ, is shown experimentally to correlate fatigue crack growth rate in the high-growth-rate regime. This approach is gaining more acceptance and has promise of becoming a useful tool for analyzing fatigue crack growth under large-scale plasticity.

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