Summary

The papers in this publication are divided into two major sections: (1) an experimental and predictive round robin, and (2) the presentation of four elastic-plastic fracture criteria. The fracture criteria are used to predict the failure of flawed metallic structures under elastic-plastic conditions. The failure predictions are based upon theory, coupled with critical material parameters which are measured from laboratory fracture specimens. Each method describes the steps required for its application, and sample calculations are included. The results of a round robin are also discussed in which these and other methods were used to predict failure loads for cracked structural configurations based on data from compact specimens. By combining various predictive methods into one volume, a reference basis is provided to judge the performance of these methods and to assess their advantages as well as their limitations. It is hoped that the combined presentation of several methods will provide a basis for their improvement and possible consolidation.

Experimental and Predictive Round Robin

A round robin on fracture was conducted by ASTM Task Group E24.06.02 on Application of Fracture Analysis Methods. The objective of the round robin was to verify whether fracture analysis methods currently used could predict failure loads on complex structural components containing cracks. Results of fracture tests conducted on various-size compact specimens made of 7075-T651 aluminum alloy, 2024-T351 aluminum alloy, and 304 stainless steel were supplied as baseline data to 18 participants. These participants used 13 different methods to predict failure loads on other compact specimens, middle-crack tension specimens, and structurally configured specimens.

The methods used in the round robin included: linear-elastic fracture mechanics corrected for size effects or for plastic yielding, Equivalent Energy, the Two-Parameter Fracture Criterion (TPFC), the Deformation Plasticity Failure Assessment Diagram (DPFAD), the Theory of Ductile Fracture, the K_R-curve with the Dugdale model, an effective K_R-curve, derived from residual strength data, the effective K_R-curve, the effective K_R-curve with a limit-load condition, limit-load analyses, a two-dimensional finite-element analysis using a critical crack-tip-opening displacement (CTOD) criterion with stable crack growth, and a three-dimensional finite-element analysis using a critical crack-front singularity

parameter with a stationary crack. The failure loads were unknown to all participants except one of the task group chairman, who used one of the TPFC applications and the critical CTOD criterion.

For 7075-T651 aluminum alloy, the best methods (predictions within 20% of experimental failure loads) were: the effective K_R-curve, the critical CTOD criterion using a finite-element analysis, and the K_R-curve with the Dugdale model. For the 2024-T351 aluminum alloy, the best methods were: the TPFC, the critical CTOD criterion, the K_R-curve with the Dugdale model, the DPFAD, and the effective K_R-curve with a limit-load condition. For 304 stainless steel, the best methods were: the limit load (or plastic collapse) analyses, the critical CTOD criterion, the TPFC, and the DPFAD.

In conclusion, many of the fracture analysis methods tried could predict failure loads on various crack configurations for a wide range in material behavior. In several cases, the analyst had to select the method he thought would work the best. This would require experience and engineering judgment. Some methods, however, could be applied to all crack configurations and materials considered. Many of the large errors in predicting failure loads were due to improper application of the method or human error. As a result of the round robin, many improvements have been made in these and other fracture analysis methods.

Elastic-Plastic Fracture Mechanics Methodology

The K_R-curve method described by McCabe and Schwalbe uses as its basis the elastic-plastic resistance curve defined by ASTM Recommended Practice on R-curve Determination (E 561) to predict instability in a structure or specimen. The predictive capability is restricted to those cases where the specimen or component is stressed below net-section yield. The K_R-curve is a modified linear-elastic approach that has been extended to handle elastic-plastic crack-tip field conditions. An equivalence exists between K_R and J_R to the point of maximum load (bend configurations) and the approach is not different from the J_R prediction methodology in this region of equivalence. By eliminating elastic-plastic deformation requirements, the K_R method provides a simple approach to treat complex configurations. Instability can be predicted for any configuration for which a linear-elastic K_I analysis exists. Both the conditions of load control and displacement control are treated. The paper outlines the computational steps, and its application is illustrated with three example problems. The method has been used for ultra-high-strength sheet materials; certain restrictions apply for more-ductile materials.

Bloom presents a DPFAD to assess the integrity of a flawed structure. The approach is similar to the R-6 Failure Assessment Diagram developed by the Central Electricity Generating Board in the United Kingdom. This is a simple engineering procedure for the prediction of instability loads in flawed structures, which uses deformation plasticity, the J-integral estimation scheme, and hand-

book solutions. The DPFAD is broad-based in that it treats both brittle fracture and net-section plastic collapse. A failure assessment curve is defined in terms of stress-intensity-factor-to-fracture-toughness ratio against applied-stress-to-net-section-plastic-collapse-stress ratio. An assessment point is considered to be safe or unsafe based upon its position in the DPFAD. The method addresses ductile tearing by redefining the failure assessment curve as the boundary between stable and unstable crack growth. The method requires a fully plastic solution for flawed structures of interest. In addition, the amount of stable crack growth permitted in the analysis could be small in that the limits of J-controlled growth must be satisfied.

Ernst and Landes describe a failure prediction method based upon a modified $J(J_M)$-resistance curve. The method requires an experimentally determined J_M-resistance curve and two calibration functions that relate load, load-point displacement, crack length and J_M for the configuration of interest. An elastic-plastic analysis for J_M for the flawed structure of interest is required. The method enables one to compute the maximum load or instability load for load-controlled conditions and the entire load-load point displacement of the untested structure. Instability can also be computed using the J_M-T_M diagram where T_M is the tearing modulus of the material. The J_M parameter is different from the J-integral value computed from deformation theory (J_D). Specifically, J_M is no longer a path-independent integral. On the other hand, J_M appears to allow for crack extension far in excess of that permitted by J_D, thereby, providing a potentially superior parameter for flawed structural characterization. For the method to be applicable, both the crack growth mechanism and mechanical constraint must be the same in the structure as in the specimen used to obtain the J_M-resistance curve. In addition, this procedure does not treat cases where brittle (cleavage) failure may occur in structural steels.

In the V_R-curve method described by Newman, the crack growth resistance to fracture is expressed in terms of crack-tip-opening displacement. Basically, the V_R curve method is quite similar to the K_R or J_R methods, except that the "crack drive" is written in terms of displacement instead of K or J. Unlike the K_R and J_R methods, however, the V_R-curve method cannot be applied for crack extensions beyond maximum load. The reason for this behavior was not given. A relationship between crack-tip-opening displacement, crack length, specimen type, and tensile properties is derived from the Dugdale model. Because the Dugdale model is obtained from superposition of two elastic crack problems, the V_R-curve method can be applied to any crack configuration for which these two elastic solutions have been obtained. The method requires an experimentally determined V_R-resistance curve on the material of interest. The V_R-curve can be determined from either load-crack extension data or from failure load data using the initial crack length. In the latter method, no crack extension data are required. Thus, fracture tests conducted 20 to 30 years ago can be used to obtain the V_R-curve. The analysis procedures used to predict stable crack growth and instability of any

through-the-thickness crack configuration made of the same material and thickness, and tested under the same environmental conditions, are presented. Three example calculations and predictions are shown. The various limitations of the method are also given.

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