General Methodology for Predicting Structural Behavior Under Ductile Fracture Conditions

R. E. LINK,* R. HERRERA** and J. D. LANDES**
*David Taylor Research Center, Annapolis, MD 21402, USA
**Department of Engineering Science and Mechanics, University of Tennessee, Knoxville, TN 37996, USA

ABSTRACT

A general methodology for predicting load-displacement relationships for a structural element undergoing fracture is proposed based on a procedure which combines deformation properties (calibration curves) and fracture properties (resistance curves). The focus of this paper is the method for determining calibration curves. Both analytical and experimental methods are discussed. The analytical calibration curves are taken from the EPRI/GE Handbook. Methods for using this Handbook are explored and suggestions made for handling interpolations of the various input variables.

KEYWORDS

Fracture; structural analysis; elastic-plastic; calibration curves; J-R curve.

DUCTILE FRACTURE METHODOLOGY

Structural components which fail in a ductile manner can be analyzed by a two sided approach, Figure 1 (1). The one side of the analysis relates the deformation behavior of the structure to externally measured parameters. For a flawed structure a load or stress parameter could be related to a displacement or strain parameter and a defect size. For example $P = P(v, a)$ where P is load, v is displacement and a is defect or crack size. This functional relationship is often called the calibration function. Missing from the calibration function is the relationship between displacement and crack length. This relationship comes from the second side of Figure 1, the fracture toughness, in which a fracture parameter, in this case J, is related to the crack length extension Δa. Since $J = J(v, a)$ can also be determined from the calibration function, the information needed to predict ductile fracture behavior is complete.

A traditional output of the method is a relationship between J and tearing modulus, T, (2) from which ductile instability could be predicted (3). J and T are not commonly used design parameters. A more useful result from a design point of view is the load versus displacement behavior of a structure. From this both maximum load bearing capacity and ductile instability can be predicted for the structure (4). A schematic of the load versus displacement prediction is shown in

Figure 2. The calibration curves can describe load and displacement behavior for a fixed crack length (dashed lines) and the fracture toughness determines crack length change in relationship to the load and displacement. Combining these gives the actual structural behavior (solid line).

An obvious requirement to make the method work is that the two parts of the input, calibration function and fracture toughness be appropriate for the structure being analyzed. Calibration functions are largely determined analytically but require tensile test results to characterize the flow behavior in the analysis. Fracture toughness is determined experimentally. Since the structure being analyzed is often of a different size and geometry from the test specimen used to generate the R curve, care must be taken to insure that the R curve used in the analysis properly represents the structure (5). This topic will not be pursued further in this paper, rather attention will be given to the selection of proper calibration curves for the methodology.

CALIBRATION CURVES

Calibration curves are usually determined analytically; numerical methods such as finite element analysis are often used. A number of these solutions have been tabulated in a Handbook (6) so that they can be used by engineers and designers without the need for reproducing a full finite element program. These solutions represent the only easy to use source of these calibration functions.

The Handbook solutions require an input of material properties from a true stress-true strain tensile test in the form of

$$\frac{\varepsilon}{\varepsilon_o} = \frac{\sigma}{\sigma_o} + \alpha\left(\frac{\sigma}{\sigma_o}\right)^n \qquad (1)$$

where ε is strain, σ is stress and α and n are constants. The solution also requires geometric constants such as structural dimensions and defect size. Finally a choice of structural constraint, plane strain or plane stress is required. The solutions in the Handbook are given for discrete values of material hardening, n, and defect size to width ratio a/W. Often, for an actual application, the values of these as well as the constraint does not fit any of the tabulated values and an interpolation must be made simultaneously on the three parameters, n, a/W, and the constraint. This presents a difficulty in using these Handbook solutions which has not been resolved.

Interpolation in a/W can be eliminated by making the solution continuous. The normalization procedures of Ernst (7) can be used for this. Experimentally it has been demonstrated that load, P, and displacement, v, can be related as a continuous function of crack length, a, for bend type specimen geometries by normalizing the load as follows:

$$P_N = \frac{PW}{Bb^2 g\left(\frac{b}{W}\right)} = H\left(\frac{v_{pl}}{W}\right) \qquad (2)$$

where W is specimen width, B is specimen thickness, b is W - a and g(b/W) is a known function (7). This normalized load is a function, H, of the plastic component of displacement, v_{pl}. For the range of a/W between 0.5 and 0.75 the Handbook solutions are given in Figure 3 for plane stress and n = 7 in the format of P_N versus v_{pl}/W. This normalization significantly reduces the a/W dependance and therefore it can be used for interpolation of a/W. Thus only two other parameters require interpolation, n and constraint.

The values of n and α from equation 1 are needed as input for the Handbook solutions. These can be generated from true stress-true strain tensile results. If these are not available an approximation suggested by Bloom (8) can be used to generate these values based on yield and ultimate tensile strengths. The method for interpolating between tabulated Handbook calibration points for n has not been developed. This work will suggest in a later section that an interpolation of n may not be necessary.

As an alternate method, calibration functions, could be determined experimentally using a blunt notch geometry. This must be of a geometry identical to the structure being analyzed but containing a defect with a blunt notch so that the deformation properties can be generated without any crack growth.

PREDICTIVE METHODOLOGY

Given an appropriate set of calibration curves for a structure and the correct material J-R curve, an evaluation of the load displacement behavior can be made in a step by step procedure. This is illustrated in the flow diagram of Figure 4. The basic approach is to choose v_{pl} as the independent variable and to calculate all of the other parameters as v_{pl} is incremented from zero to a final value.

EXAMPLES

Some examples of the results from this calculation procedure are given in Figures 5 through 8. In these examples load displacement records are calculated for the compact specimen geometry. The results are used to examine the different ways to generate calibration curves, particularly in handling the interpolations required in the Handbook solutions.

Figure 5 shows the result for a calculation of an experimental load and displacement record for a compact specimen of A508 steel using the calibration curve and R curve determined from that experiment. As expected the prediction matches the experiment. This only shows that there is no error introduced in the calculation procedure since the result is used to determine the input and the calculation is a closed loop analysis.

Figures 6, 7, and 8 show predictions based on various methods for generating a calibration curve. Figure 6 shows the prediction for the same specimen but using calibration curves generated from Handbook solutions (6) for both plane stress and plane strain. The compact specimen is of standard thickness and is side grooved giving it a constraint better predicted by a plane strain calibration curve and is the best choice here without any interpolation.

Figure 7 shows the same solution but with the hardening exponent n being varied. The result shows the minor effect of the hardening exponent. This suggests that an interpolation in n may not be necessary. Rather the Handbook solution should be used for the tabulated n value that is closest to the material n.

Figure 8 shows an alternate method for generating a calibration curve for an A533 B steel specimen. In this case a blunt notched specimen of an identical material is used to generate the calibration curve. The calibration curve generated from the Handbook solution for the plane strain case is also determined for comparison. The result is that the two predictions agree well and both predict the experimental results fairly well. The blunt notch calibration curve is slightly better than the Handbook one.

DISCUSSION AND SUMMARY

The ductile fracture methodology works well for predicting the load displacement behavior of test specimens. The focus here was the evaluation of methods for determining the calibration curve as input to the method. The two methods, experimental and numerical (Handbook), both give good results. For an experimental solution a blunt notched specimen can be used. This appears to give a slightly better result than a Handbook calibration curve. In generating Handbook solutions there are three sets of variables to be considered the defect size to specimen width ratio, a/W, the hardening exponent, n, and the constraint, plane strain or plane stress. From these results the suggestion for handling the a/W interpolation is to plot the load versus displacement in the normalized format suggested by equation 2. The exponent n does not need to be interpolated. When no true stress-true strain tensile results are available the Bloom approximation can be used. The calibration solutions in the Handbook corresponding to the closest value of n can be used. Finally, the constraint issue was not resolved by this work. For the full thickness compact specimen plane strain gives good results. Other geometries and thicknesses may require the plane stress solution or interpolation. To solve this an experimental calibration of constraint may be necessary.

REFERENCES

1. H. A. Ernst and J. D. Landes, "Elastic-Plastic Fracture Mechanics Methodology Using the Modified J, J-M Resistance Curve Approach" Journal of Pressure Vessel Technology, Tranactions of the ASME, Vol. 108, No. 1 February 1986, pp. 50-56.
2. Paris, P. C., Tada, H., Zahoor, A., and Ernst, H. A., "The Theory of Instability of the Tearing Mode of Elastic-Plastic Crack Growth," Elastic-Plastic Fracture, ASTM STP 668, J. D. Landes, J. A. Begley and G. A. Clarke, Eds., American Society for Testing and Materials, 1979, pp. 5-36.
3. Paris, P. C. and Johnson, R. E., "A Method of Application of Elastic-Plastic Fracture Mechanics to Nuclear Vessel Analysis," Elastic-Plastic Fracture Second Symposium, Volume II - Fracture Resistance Curves and Engineering Applications, ASTM STP 803, C. F. Shih and J. P. Gudas, Eds., ASTM 1983, pp. II-5 - II-46.
4. Ernst, H. A. "Some Salient Feature of the Tearing Instability Theory," Elastic-Plastic Fracture Second Symposium, Volume II - Fracture Resistance Curves and Engineering Applications, ASTM STP 803, C. F. Shih and J. P. Gudas, Eds., ASTM 1983, pp. II-133 - II-155.
5. Landes, J. D., McCabe, D. E., and Ernst, H. A., "Fracture Testing of Ductile Steels, Electric Power Research Institute, MP-5014, Final Report of Research Project 1238-2, January 1987.
6. Kumar, V., German, M. D., and Shih, C. F., "An Engineering Approach for Elastic Plastic Fracture Analysis," Electric Power Research Institute NP 1931, Topical Report, July 1981.
7. Ernst, H. A., Paris, P. C., and Landes, J. D., "Estimations on J-integral and Tearing Modulus T from a Single Specimen Test Record," Fracture Mechanics, Thirteenth Conference, ASTM STP 743, Richard Roberts, Ed., American Society for Testing and Materials, 1981, pp. 476-502.
8. Bloom, J. M., and Malik, S. N., "Procedure for the Assessment of the Integrity of Nuclear Pressures and Piping Containing Defects," EPRI Final Report NP-2431, June 1982.

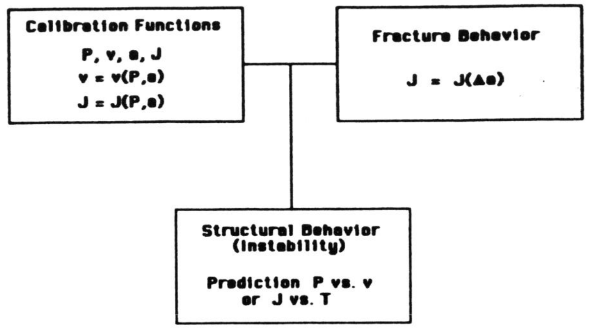

Figure 1 Schematic of Ductile Fracture Methodology.

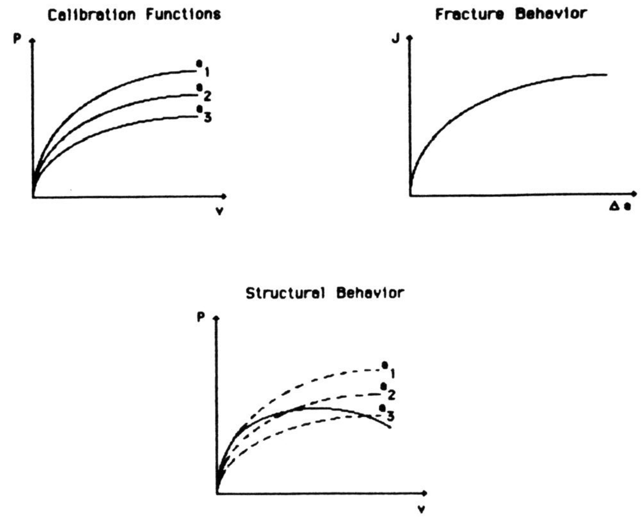

Figure 2 Load Displacement Prediction from Ductile Fracture Methodology.

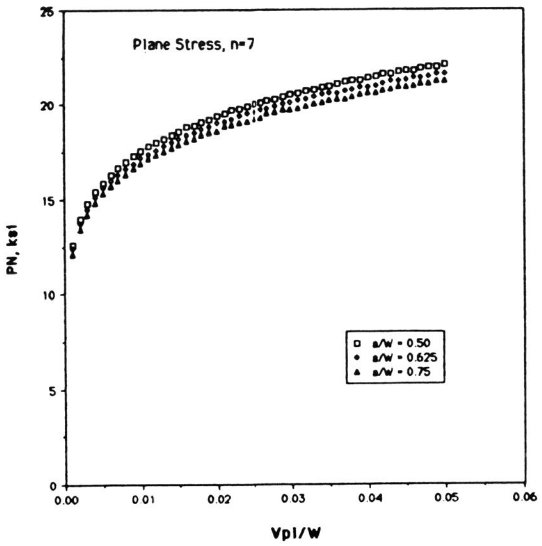

Figure 3 Handbook Calibration Curves in a Normalized Format, Plane Stress and N = 7.

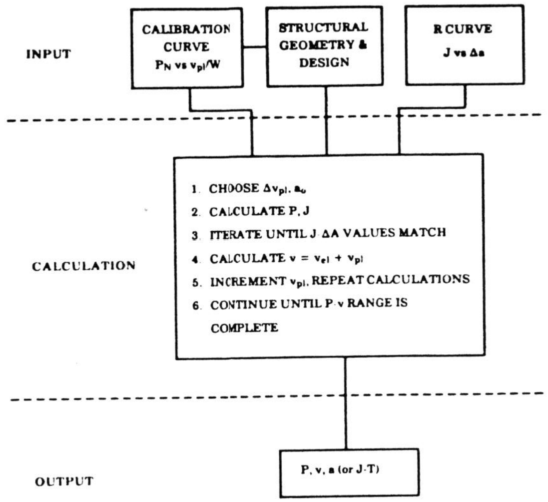

Figure 4 Flow Diagram of Methodology Calculations

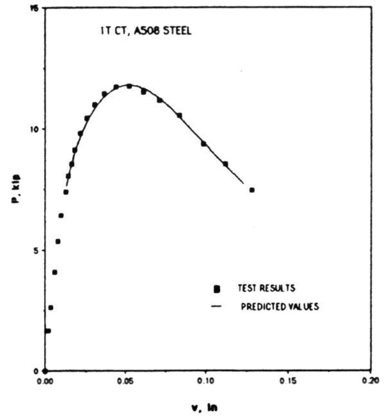

Figure 5 Load Displacement Prediction for A508 Steel Using the Experimental Calibration Curve.

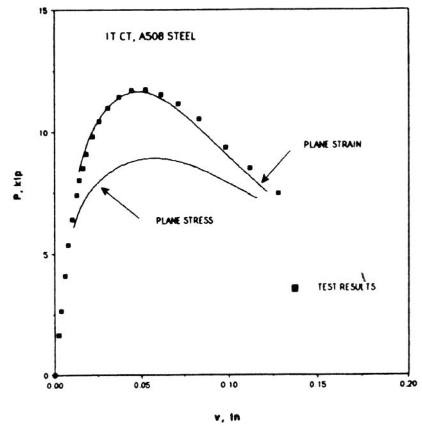

Figure 6 Load Displacement Prediction for A508 Steel Using the Handbook Calibration Curves (6) for Plane Strain and Plane Stress.

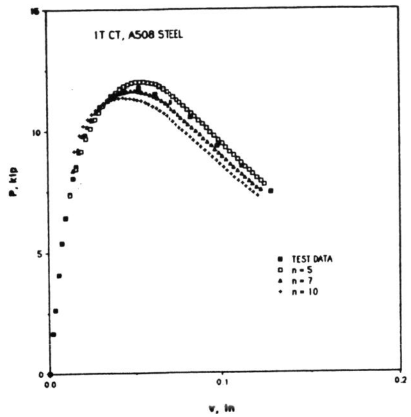

Figure 7 Load Displacement Prediction for A508 Steel Using the Handbook Calibration Curves Varying Hardening Exponent, n.

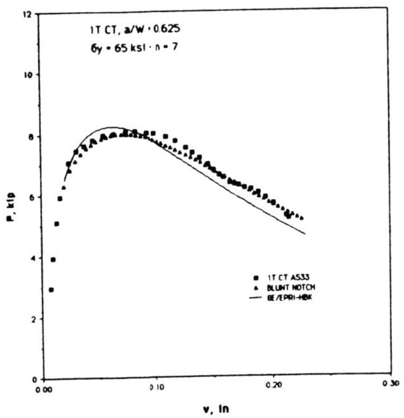

Figure 8 Load Displacement Prediction for A533-B Steel Comparing Experimentally Generated (Blunt Notched) and Handbook Calibration Curves.