ON THE MAJOR DUCTILE FRACTURE METHODOLOGIES FOR FAILURE ASSESSMENT OF NUCLEAR REACTOR COMPONENTS

Julio R. B. Cruz*, John D. Landes** and Arnaldo H. P. de Andrade*

*IPEN-CNEN/SP
Caixa Postal 11049
05422-970, São Paulo, SP, Brasil
e-mails: jrbcruz@net.ipen.br; aandrade@net.ipen.br

**The University of Tennessee, Knoxville
310 Perkins Hall
Knoxville, TN, 37996-2030, USA
e-mail: john-landes@utk.edu

ABSTRACT

In structures like nuclear reactor components there is a special concern with the loads that may occur under postulated accident conditions. These loads can cause the stresses to go well beyond the linear elastic limits, requiring the use of ductile fracture mechanics methods to the prediction of the structure fracture behavior. Since the use of numerical methods to apply EPFM concepts is expensive and time consuming, the existence of analytical engineering procedures are of great relevance. The lack of precision in detail, as compared with numerical nonlinear analyses, is compensated by the possibility of quick failure assessments. This is a determinant factor in situations where a systematic evaluation of a large range of geometries and loading conditions is necessary, like in the application of the Leak-Before-Break (LBB) concept on nuclear piping. This paper outlines four ductile fracture analytical methods, pointing out positive and negative aspects of each one. The objective is to take advantage of this critical review to conceive a new methodology, one that would gather strong points of the major existent methods and would try to eliminate some of their drawbacks.

INTRODUCTION

In many critical structures like nuclear power plant components, the concern is not for loading encountered under normal design conditions. Rather, loadings that might occur under postulated accident conditions are of concern. These can cause the stresses to go well beyond the linear elastic loading limits. In such circumstances, it is necessary to incorporate Elasto-Plastic Fracture Mechanics (EPFM) concepts in the procedures for structural integrity assessment of components with defects.

The methods for predicting a maximum load for ductile fracture where the loading is in the nonlinear deformation region need a scheme to incorporate both the deformation behavior of the structure as well as the fracture or cracking behavior. One of the earliest procedures to incorporate both the deformation and the fracture characteristics in a single analysis was the R-6 approach [1] developed in the United Kingdom. Although it does not incorporate elastic-plastic fracture mechanics parameters, its basic philosophy inspired other application schemes.

The R-6 method uses a failure assessment diagram (FAD) to determine safe areas of loading for the cracked structure (Fig. 1). The failure assessment curve represents a transition between two distinct failure mechanisms: brittle fracture governed by linear elastic fracture mechanics (LEFM) and plastic collapse governed by the limit load. The equation of this curve is derived from the expression of the effective stress intensity factor for a through crack in an infinite plate according to a modified version of the strip yield model of Burdekin and Stone [2] and is given by

$$K_r = S_r\left[\frac{8}{\pi^2}\ln\sec\left(\frac{\pi}{2}S_r\right)\right]^{-1/2} \quad (1)$$

In order to assess the significance of a particular flaw in a structure, one must determine the applied values of K_r and S_r, and plot the point in Fig. 1. These values are obtained through the following equations:

$$K_r' = \frac{K_I}{K_{Ic}} \quad (2)$$

$$S_r' = \frac{\sigma}{\sigma_c} \quad (3)$$

where σ is the applied stress and σ_c is the plastic collapse stress. If the applied conditions in the structure correspond to a point (K_r, S_r) inside the FAD, the structure is safe.

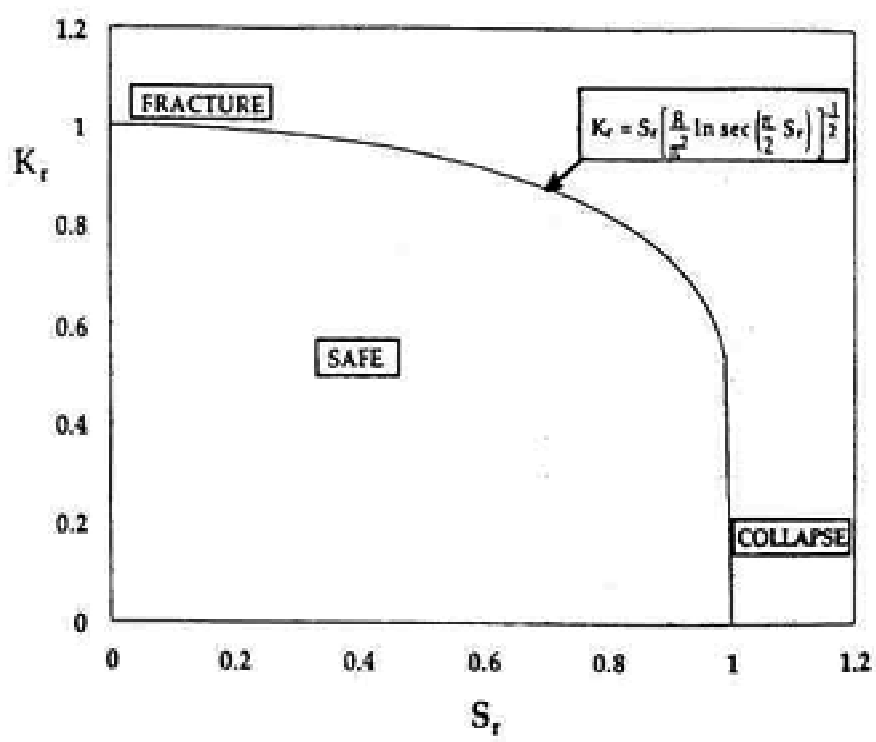

Figure 1. Strip Yield Failure Assessment Diagram

Further works from Milne [3] and Bloom [4] shown that the strip yield FAD could be extended to consider the ductile tearing failure mechanism. However, the failure assessment diagram based on the strip yield line was shown to be inadequate for representing geometry and strain hardening effects for materials which have high work hardening capacity (low values of n).

New methodologies incorporating EPFM concepts were developed. In the next sections, four ductile fracture engineering procedures are outlined: the DPFAD method, the Reference Stress approach, the Engineering Treatment Model, and the Ductile Fracture Method. The paper is concluded with a discussion about the similarities, strong points and weakness of each method.

DPFAD METHOD

The DPFAD - Deformation Plasticity Failure Assessment Diagram - [5] uses the same philosophy of the R-6 approach, but in this case the failure curve is obtained from the EPRI-GE *J*-estimation scheme [6], where the cracking driving force (CDF) is given by a sum of an elastic and a plastic component. The elastic component is obtained from plasticity corrected LEFM solutions and the plastic component is the deformation plasticity solution in terms of the *J-integral* for a cracked structure with a fully plastic ligament. The equation representing the EPRI-GE *J*-estimation scheme is given by

$$J = J_e(a_{eff}, P) + J_p(a, P, n) \quad (4)$$

The fully plastic solutions are expressed in terms of non-dimensional calibration functions that are tabulated in a handbook for various geometries as a function of a/W, n and the stress state (plane stress or plane strain). $J_p(a,P,n)$ has the following form for most geometries:

$$J_p = \alpha\,\sigma_o\,\varepsilon_o\,c\,h_1(a/W, n)\left(\frac{P}{P_o}\right)^{n+1} \quad (5)$$

where σ_o, ε_o and n are the coefficients of the Ramber-Osgood equation, c is the uncracked ligament, P is the applied load, P_o is a reference load, and h_1 is the calibration function.

The coordinates K_r and S_r of the DPFAD failure curve are

$$K_r = \left[\frac{J_e(a,P)}{J}\right]^{1/2} = \left[\frac{J_e(a,P)}{J_e(a_{eff},P) + J_p(a,P,n)}\right]^{1/2} \quad (6)$$

$$S_r = \frac{P}{P_o} \quad (7)$$

The coordinates of an assessment point on the diagram are calculated by

$$K_r'(a_o + \Delta a) = \left[\frac{J_e(a_o + \Delta a)}{J_R(\Delta a)}\right]^{1/2} \quad (8)$$

$$S_r'(a_o + \Delta a) = \frac{P}{P_o(a_o + \Delta a)} \quad (9)$$

The DPFAD approach is illustrated in Fig. 2. Starting from the initial crack length, a_o, and considering a certain amount of crack growth, several assessment points are determined by the two expressions above, resulting a so-called candy cane curve. The safety factor for crack initiation is obtained as OB/OA, while maximum safety factor corresponding to crack instability is obtained as OC/OD.

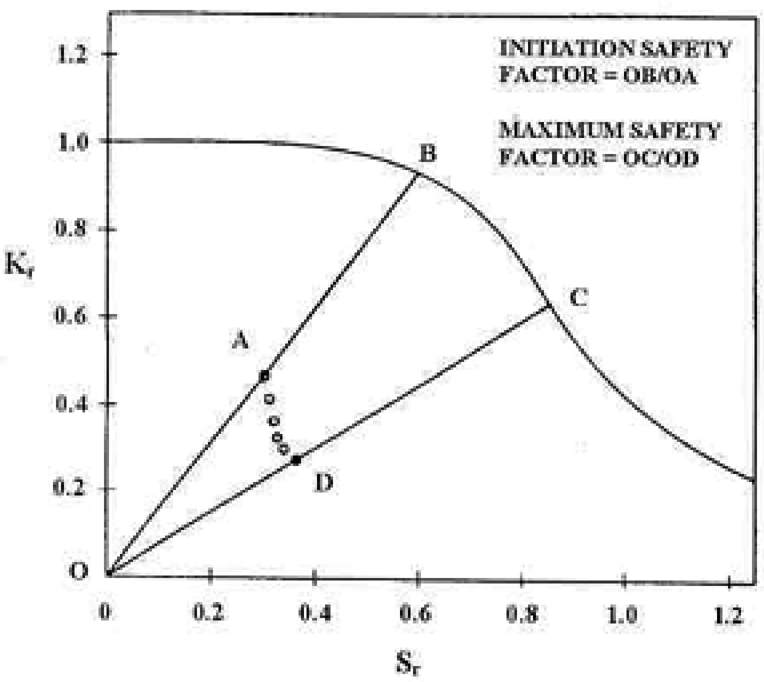

Figure 2. DPFAD Diagram

THE REFERENCE STRESS APPROACH

Ainsworth [7] proposed an alternative approach to DPFAD to eliminate the strong dependence of DPFAD on the Ramberg-Osgood exponent n. His formulation of J plastic (J_p) involved using a reference stress:

$$\sigma_{ref} = \frac{P}{P_y}\sigma_y \tag{10}$$

where P_y is the reference limit load and σ_y is the yield stress. He further defined the reference strain as the total axial strain when the material is loaded to a uniaxial stress of σ_{ref}. Substituting these definitions into Eq. 5 gives

$$J_p = c\, h_1(a/b, n)\, \sigma_{ref}(\varepsilon_{ref} - \sigma_{ref}/E) \tag{11}$$

Equation 11 still contains h_1, the geometry factor that depends on the power law hardening exponent n. Ainsworth proposed redefining P_o for a given configuration to produce another constant, h_1', that is insensitive to n. He noticed, however, that even without the modification of P_o, h_1 was relatively insensitive to n, except at high n values (low hardening materials). Since Ainsworth was primarily interested in developing a driving force procedure for high hardening materials (the strip yield FAD was considered suitable for low hardening materials), he proposed the following approximation [8]

$$h_1(n) \cong h_1(1) \tag{12}$$

where $h_1(n)$ is the geometry factor for a material with a strain hardening exponent of n and $h_1(1)$ is the corresponding factor for a linear material. Considering this approximation and some additional simplifications, Ainsworth arrived at a geometry-independent FAD where K_r and S_r coordinates are given by

$$K_r = \left[\frac{E\varepsilon_{ref}}{\sigma_{ref}} + \frac{S_r^2}{2(1+S_r^2)}\right]^{-1/2} \tag{13}$$

$$S_r = \frac{\sigma_{ref}}{\sigma_y} = \frac{P}{P_y} \tag{14}$$

The Central Electricity Generating Board in the United Kingdom (CEGB) introduced a modification of the second term on the right side of the above equation for K_r and formalized the new formulation as the R-6 Procedure Option 2 Revision 3 [9], in which K_r is expressed by

$$K_r = \left[\frac{E\varepsilon_{ref}}{\sigma_{ref}} + \frac{S_r^2}{2(E\,\varepsilon_{ref}/\sigma_{ref})}\right]^{-1/2} \tag{15}$$

THE ENGINEERING TREATMENT MODEL (ETM)

The ETM uses a simplified mechanical model of a cracked body for deriving analytical expressions which serve for estimating characteristic quantities like the *CTOD*, the *J-integral*, the load point displacement, etc. [10,11]. Within the framework of ETM the *CTOD* refers to the experimental definition δ_5 which measures *CTOD* at the specimen's (or structure's) side surface, spanning the original fatigue crack tip over a gage length of 5mm.

ETM assumes that the cracked body deforms under prevailing plane stress conditions. The material's stress-strain curve is approximated by a piece-wise power law:

$$\frac{\sigma}{\sigma_y} = \left(\frac{\varepsilon}{\varepsilon_y}\right)^n \quad \text{when } \sigma > \sigma_y \tag{16}$$

For convenience $\sigma_y = \sigma_{0.2}$. At loads, $F \leq F_y$ (contained yielding), available LEFM solutions are utilized with plasticity corrected crack length. These solutions are reasonable accurate up to the yield load. In the fully plastic state, i.e., for $F > F_y$, the method assumes that the behavior of the cross section as a whole is given by a function analogous to Eq. 16

$$\frac{F}{F_y} = \left(\frac{\delta_5}{\delta_y}\right)^n \tag{17}$$

or

$$\delta_5 = \delta_y \left(\frac{F}{F_y}\right)^{1/n} \tag{18}$$

where δ_y is the δ_5 value corresponding to $F = F_y$ and n is the strain hardening exponent taken from a tensile test (note that n here is the inverse of n from the Ramberg-Osgood equation). It is shown [12] that J can be related to the applied strain, ε, and to δ_5 through

$$\frac{J}{J_y} = \left(\frac{F}{F_y}\right)^{(1+n)/n} = \left(\frac{\varepsilon}{\varepsilon_y}\right)^{1+n} = \left(\frac{\delta}{\delta_y}\right)^{1+n} \qquad (19)$$

where J_y is the value of J at $F = F_y$. δ_y and J_y are simply calculated as a function of linear elastic solutions for K with $F = F_y$. Thus, the prediction of J or δ_5 in the fully plastic regime requires just the linear elastic solution for K, the limit load (F_y) and the strain hardening exponent. Figure 3 shows how to obtain the instability load using the ETM method.

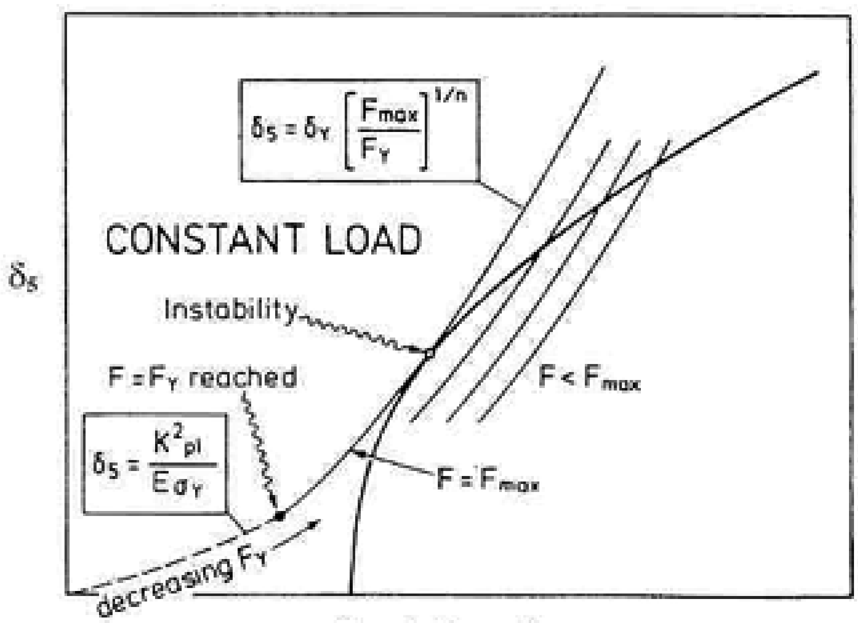

Figure 3. Determination of Instability (Maximum Load) for Load Control Using δ_5 - R curve

THE DUCTILE FRACTURE METHOD

The ductile fracture method [13-16] uses the load versus displacement record of a precracked laboratory test specimen, such as a compact specimen, and through a series of analysis steps directly predicts the complete load versus displacement behavior of a structural component containing a crack-like defect. The basics steps of the method are illustrated in Fig. 4.

First, the load versus displacement record for the specimen is reduced to provide two pieces of information: the calibration functions and the fracture toughness for the specimen. The calibration functions relate load, displacement and crack size. The fracture toughness relates crack driving force and crack extension in terms of a *J-R* curve. These two are then transferred to develop the calibration functions and the fracture toughness for the structural component.

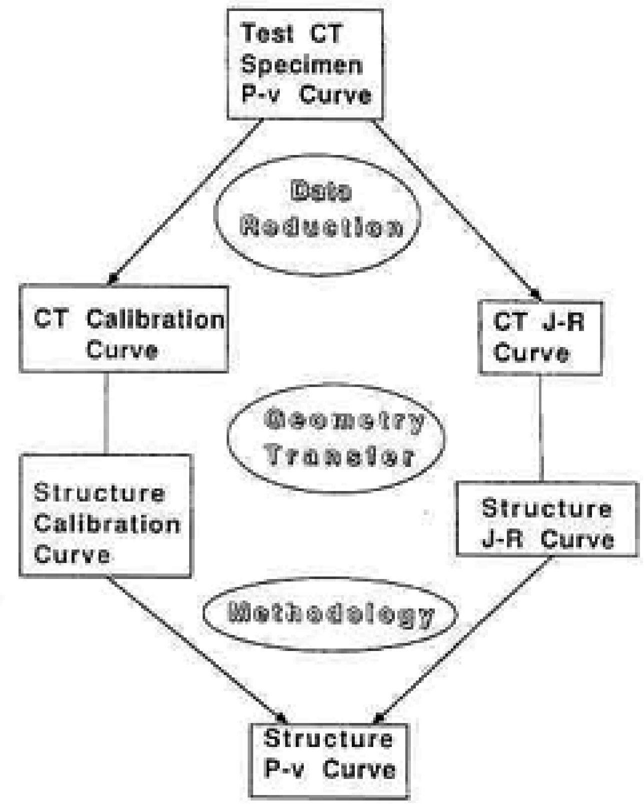

Figure 4. Flow Chart of Component Model Load versus Displacement Prediction from Test Specimen

These are now direct inputs for predicting the behavior of the structure. The complete load versus displacement curve for the structure is then determined for the ductile process where the cracking is growing while the load and displacement are changing. This can be done through a step by step procedure in which an independent variable is chosen to increment. 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.

The overall method assumes that the load separates into multiplicative functions of crack length, a, and plastic deformation, v_{pl}

$$P = G(a/W)H(v_{pl}/W) \qquad (20)$$

It is assumed a deformation function $H(v_{pl}/W)$ in the format

$$H(v_{pl}/W) = \frac{L + M\frac{v_{pl}}{W}}{N + \frac{v_{pl}}{W}}\left(\frac{v_{pl}}{W}\right) \qquad (21)$$

where L, M, and N are constants. This has been shown to describe the deformation results for most metals better than other forms such as the power law [17]. The same functional form is to be used for the geometry of the structural component.

The *G(a/W)* function is fixed for a given geometry and is known for many common geometries, including the compact specimen. If it is not known for the particular geometry of the structural component, this function must be determined. This can be done experimentally by testing blunt-notched specimens or numerically using blunt-notched finite element models.

When a specific material is considered, the $H(v_{pl}/W)$ function must be determined for that material and the specific geometry. This is the function that incorporates the material plastic deformation characteristics. This function can be determined from the laboratory test of the compact specimen. The transfer of calibration function from laboratory test specimen to structural component in Fig. 4 then involves the determination of the new $H(v_{pl}/W)$ function. One procedure to obtain this new $H(v_{pl}/W)$ function for the structural component is detailed in [16].

DISCUSSION AND CONCLUSIONS

The DPFAD method permits quick engineering assessments based on a source of tabulated calibration functions (the EPRI-GE Handbook) containing many representative geometries and loading conditions [6,18]. But, these calibration functions are obtained through numerical analyses which use ideal material behavior and many materials are not well represented by a Ramberg-Osgood stress-strain law. Material inputs like n and α are not usually generated in the standard tensile tests and often have to be obtained in an approximated way. In addition, the tabulated solutions of the handbook are given at discrete values of the input variables, requiring some judgment when interpolation and/or extrapolation of these variables are necessary. Also, DPFAD is geometry dependent, requiring the computation of a new assessment line for each new geometry and crack size.

In the Reference Stress Approach, the crack driving force (CDF) is a simplification of EPRI-GE *J*-estimation scheme. In this case, the plastic component involves the use of a reference stress. The basic purpose is to eliminate the strong dependence of the CDF on the Ramberg-Osgood coefficient, n. The R6 CDF provides a geometry independent failure assessment diagram and gives more accurate results than DPFAD for those materials poorly fit by the Ramberg-Osgood equation. It has been shown that the R-6 approach applied to semi-elliptical surface defects produces excellent agreement with several finite element studies, provided that the results are presented in terms of a global limit load for the reference limit [19]. As a negative aspect, the approach requires the complete stress-strain curve for the material in question.

The Engineering Treatment Model (ETM) assumes that the cracked body deforms under prevailing plane stress conditions and the material's stress-strain behavior is supposed to follow a piece-wise power law. The kind of treatment to obtain the CDF in the fully plastic regime is similar to the one employed in the EPRI-GE methodology, but in contrast to EPRI-GE no fully plastic influence functions have to be determine by finite element calculations. While the EPRI-GE Handbook offers for those cases for which solutions have been derived the most precise values, the ETM has the advantage of providing a geometry independent formulation of the driving force parameters *CTOD* and *J-integral*. The influence of size and geometry is contained in the quantities δ_y, J_y and F_y. It has been proved accurate; at least the behavior of laboratory specimen type geometries can be very well modeled in the regime of plane stress. But, the method has yet to be validated for plane strain conditions and its accuracy needs to be better evaluated for large structural components.

The basic assumption in the Ductile Fracture Method is that the load separates into multiplicative functions of crack length and plastic deformation (principle of load separation). An attractive feature of this method is that it gives a more complete description of the structure behavior in terms of parameters like load and displacement that are easier to work with in a structural design. It can be used to predict the overall behavior of the structural component for both linear and elastic-plastic deformation and for ductile or brittle fracture. It was found that the test specimen itself gives a better estimate of the deformation character of a cracked body than the tension test [20]. Therefore, it is expected that an approach that can develop the calibration functions for the structure directly from those of the fracture toughness test specimen, which is the case of the Ductile Fracture Method, gives more accurate results. The method has a higher level of complexity than the others presented and some efforts have to be done to simplify its application.

While experimental tests and numerical simulations have been used to demonstrate the adequacy of each method, new formulations or modifications of the existent approaches have been proposed to improve the accuracy of failure predictions.

The EPRI-GE Handbook has been proved to be a valuable tool to engineers working on ductile fracture problems because it represents the only source of tabulated calibration functions. Therefore, it is important to try to solve the difficulties inherent to its use. An example of that are the suggestions of Link et al. [20] to overcome the problem of interpolating input variables. Some of the guidelines given in [20] are based on fundamental principles of the Ductile Fracture Method. In another paper by Ainsworth [21], some modifications to the GE-EPRI *J*-estimation scheme are proposed using the Reference Stress Method.

Recently, Bloom [22] proposed an extension of the DPFAD method, which allows the use of material stress-strain data which do not follow the Ramberg-Osgood equation. The new approach, coined PWFAD (Piecewise Failure Assessment Diagram), led to a revision of ASME Code Case N-494 [23] to include a procedure for assessment of flaws in austenitic piping [24].

This constant development demonstrates the importance of the simplified methods for failure assessment of flawed structures. The present paper gave an overview on some of the major available methodologies, showing what they have in common, their positive aspects and shortcomings. Some recent works were cited to show that it is possible to use ideas and characteristics from one methodology to improve another one. The purpose of this paper was to get background for the development of a single methodology which could incorporate the best features of each of the existent methods, pursuing the goal of being both easy to use and capable of making accurate failure predictions.

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