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A DISCUSSION ABOUT SIMPLIFIED METHODOLOGIES FOR FAILURE ASSESSMENT OF NUCLEAR REACTOR COMPONENTS

Julio R. B. Cruz
IPEN-CNEN/SP, São Paulo, SP, Brazil
e-mail: jrbcruz@net.ipen.br

John D. Landes
University of Tennessee, Knoxville, TN, USA
e-mail: john-landes@utk.edu

Arnaldo H. P. de Andrade
IPEN-CNEN/SP, São Paulo, SP, Brazil
e-mail: aandrade@net.ipen.br

ABSTRACT

Failure of nuclear reactor components like pressure vessels and piping must be avoided for all phases of reactor operation. Especially severe loading conditions come from postulated accident scenarios during which the integrity of the component is required. The use of Fracture Mechanics concepts to investigate the mechanical behavior of flawed structures in the non-linear regime is a complex subject due to the fact that the crack driving force (expressed in terms of J or *CTOD*) is not only a function of the cracked geometry, but depends also on the plastic flow properties of the material. Since the numerical solutions by the finite element method are expensive and time consuming, the existence of simplified engineering procedures is of great relevance. These allow a ready identification of the main parameters affecting the crack driving force, and permit a fast and simple evaluation of the structural integrity of the cracked component. This paper presents an overview of the major simplified ductile fracture methodologies that have been proposed in the literature trying to point out their similarities, strong points and negative aspects. Once the best characteristics of each method are identified, they could then be combined to develop a single methodology, one that would be both easy to use and capable of making accurate failure predictions.

INTRODUCTION

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 nonlinear characterizing parameters like J or *CTOD* for the prediction of the structure fracture behavior.

The first progress that allowed a simplified and direct use of the nonlinear parameters in the assessment of structural components was the development of the EPRI-GE Handbook of J solutions (Kumar et al., 1981). This handbook also contained some *CTOD* solutions, but was directed mainly at the J solutions. With the handbook, J could be determined as a function of applied load for many structural component types that may be loaded beyond the linear elastic limits. Also, the load versus displacement curve for the structure with the non-growing crack could be determined. The original handbook solutions were for simple components like rectangular bars and sheets with central or edge cracks loaded with simple tension or bending. J and displacements solutions for more complex geometries such as pipes with longitudinal and axial cracks and pipe elbows and T-joints were included in a new version of the handbook (Zahoor, 1989). The handbook solutions could be used in some simple applications schemes, like determining the load that corresponds to a J_{Ic} value. The simple use of the J_{Ic} to specify the fracture limit was not always satisfactory because it did not account for the stable portion of the growing crack. Often the value of J in the full R curve characterization of the fracture condition could increase by several times above the simple initiation of the R curve behavior that was characterized by the J_{Ic} value. The further development of application schemes involved the use of the stable cracking part of the R curve. The question then was how to incorporate the growing crack into the prediction scheme for the structure.

One of the first approaches developed to deal with the stably growing crack was concerned with the conditions that would mark the end of the region of stable crack growth. This required that a ductile instability point could be determined from the geometry and loading of the structural component using the R curve fracture resistance. The characterization of ductile instability involved the definition of the tearing modulus, T, of Paris et. al (1979) and an application scheme was then developed which became known as the J-T diagram (Paris and Johnson, 1983). The T based instability characterization more often involved the prediction of stability in a grossly overloaded structure, usually after maximum load had already been reached. Methods for predicting maximum load were also developed.

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The methods for predicting a maximum load for ductile fracture where the loading was in the nonlinear deformation region needed a scheme to incorporate both the deformation behavior of the structure as well as the fracture or cracking behavior. Five of these methods are briefly described in the next sections followed by a discussion about the positive and negative aspects of each one of them. They are presented in a chronological order and include the original R-6 failure assessment diagram, the DPFAD method along with brief comments on EPRI/GE *J*-estimation scheme, the Reference Stress approach, the Engineering Treatment Model, and the Ductile Fracture Method.

THE ORIGINAL R-6 DIAGRAM

One of the earliest schemes to incorporate both the deformation and the fracture characteristics in a single analysis was the R-6 approach (Harrison et al., 1976) developed in the UK. Although it does not incorporate elastic-plastic fracture mechanics (EPFM) 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 (1966) and is given by

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

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:

$$K_r' = \frac{K_I}{K_{Ic}} \tag{2}$$

$$S_r' = \frac{\sigma}{\sigma_c} \tag{3}$$

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.

Further works from Milne (1979) and Bloom (1980) shown that the strip yield FAD could be extended to consider the ductile tearing failure mechanism. For ductile fracture analysis up to the point of crack initiation, the applied K_r is replaced by:

$$K_r' = \sqrt{\frac{J_e(a,P)}{J_{Ic}}} \tag{4}$$

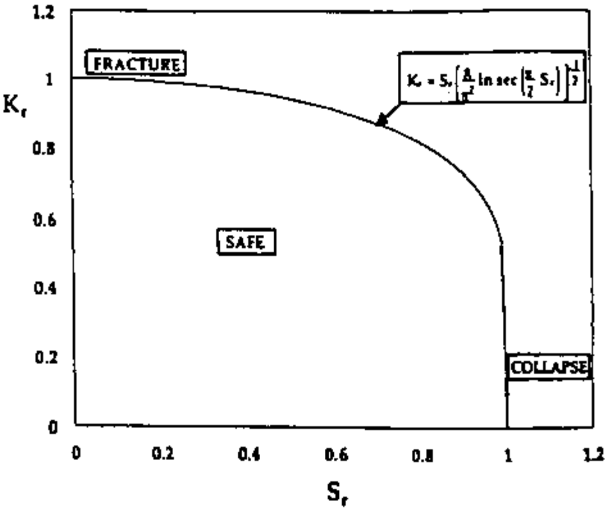

Figure 1 - Strip yield failure assessment diagram

where J_e is the J value obtained from the elastically calculated stress intensity factor. During stable crack growth, the applied K_r and S_r are redefined as

$$K_r'(a_o + \Delta a) = \sqrt{\frac{J_e(a_o + \Delta a)}{J_R(\Delta a)}} \tag{5}$$

$$S_r'(a_o + \Delta a) = \frac{\sigma}{\sigma_c(a_o + \Delta a)} \tag{6}$$

where J_e, J_R and σ_c are functions of the amount of slow stable crack growth, Δa.

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).

EPRI-GE METHODOLOGY / DPFAD

In the EPRI-GE methodology (Kumar et al., 1981), the cracking driving force (CDF) takes account of strain hardening and is based upon the *J*-controlled crack growth concept. The CDF is given by a sum of an elastic and a plastic component, where 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

$$J = J_e(a_{eff}, P) + J_p(a, P, n) \tag{7}$$

The fully plastic solutions are obtained from the HRR representation for the crack tip field quantities. Ilyushing's principle is used to show that the field quantities increase in direct proportion to the load or displacement parameter raised to some power dependent on n (the strain hardening exponent). In this way the resulting plasticity solutions are shown to be scaleable and can be 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:

$$J_p = \alpha \sigma_o \varepsilon_o c\, h_1(a/W, n) \left(\frac{P}{P_o} \right)^{n+1} \quad (8)$$

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 DPFAD - Deformation Plasticity Failure Assessment Diagram - (Bloom and Malik, 1982) 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. The coordinates K_r and S_r of the failure curve are

$$K_r = \left[\frac{J_e(a,P)}{J} \right]^{1/2} = \left[\frac{J_e(a,P)}{J_e(a_{eff},P) + J_p(a,P,n)} \right]^{1/2} \quad (9)$$

$$S_r = \frac{P}{P_o} \quad (10)$$

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

$$K_r'(a_o + \Delta a) = \left[\frac{J_e(a_o + \Delta a)}{J_R(\Delta a)} \right]^{1/2} \quad (11)$$

$$S_r'(a_o + \Delta a) = \frac{P}{P_o(a_o + \Delta a)} \quad (12)$$

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.

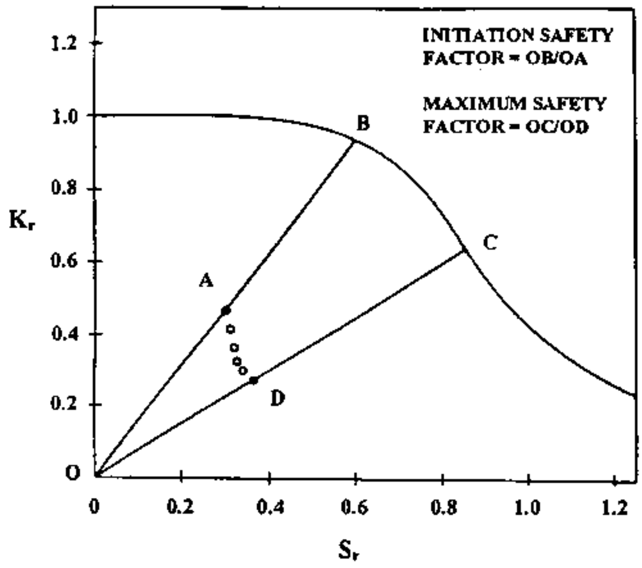

Figure 2 - DPFAD diagram

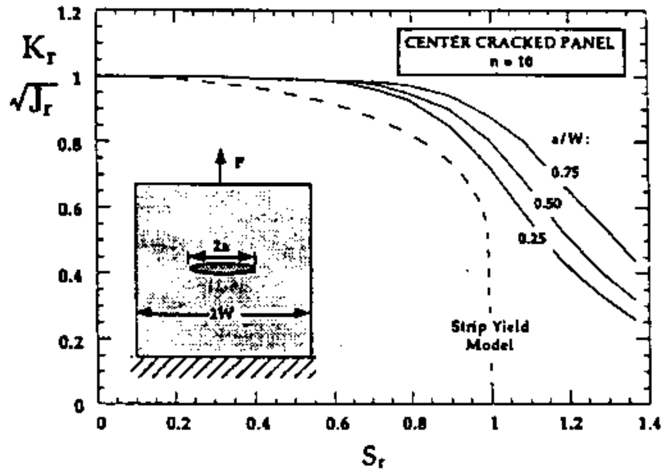

Figure 3 - DPFAD for a center cracked panel with various *a/W* ratios

Figure 3 shows that DPFAD is geometry dependent, while the strip yield diagram (original R-6 approach) is geometry independent. The shape of the EPRI-GE failure curve depends not only on the geometry of the cracked body, but also on the stress state (plane stress or plane strain). Besides that, the shape of the failure line also varies with the strain hardening exponent. This makes fracture analysis based on EPRI-GE equations more complicated because a different FAD must be generated for each configuration analyzed.

THE REFERENCE STRESS APPROACH (R6 PROCEDURE REVISED)

Akhrust and Milne (1983) demonstrated that the EPRI-GE estimation scheme and DPFAD, in particular, are quite sensitive to the fit of the stress-strain data to the Ramberg-Osgood equation, mainly for those materials with a high strain hardening capacity ($n < 7$). The EPRI-GE equations for fully plastic J assume that the material's stress-plastic strain curve follows a simple power law. Many materials, however, have flow behavior that deviates considerably from a power law and applying EPRI-GE equations for such materials may result in significant errors (Anderson, 1991).

Ainsworth (1984) 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:

$$\sigma_{ref} = \frac{P}{P_y}\sigma_y \tag{13}$$

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. 8 gives

$$J_p = c\, h_1(a/b,n)\,\sigma_{ref}(\varepsilon_{ref} - \sigma_{ref}/E) \tag{14}$$

For materials that obeys a power law, Eq. 14 agrees precisely with Eq. 8 provided that $P_o = P_y$, but the former is more general in that is applicable to all types of stress-strain behavior.

Equation 14 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). Once 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

$$h_1(n) \cong h_1(1) \tag{15}$$

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

$$K_r = \left[\frac{E\varepsilon_{ref}}{\sigma_{ref}} + \frac{S_r^2}{2(1+S_r^2)}\right]^{-1/2} \tag{16}$$

$$S_r = \frac{\sigma_{ref}}{\sigma_y} = \frac{P}{P_y} \tag{17}$$

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 (Milne et al., 1988), in which K_r is expressed by

$$K_r = \left[\frac{E\varepsilon_{ref}}{\sigma_{ref}} + \frac{S_r^2}{2(E\,\varepsilon_{ref}/\sigma_{ref})}\right]^{-1/2} \tag{18}$$

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. (Schwalbe, 1986) (Schwalbe and Cornec, 1991a). 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:

$$\frac{\sigma}{\sigma_y} = \left(\frac{\varepsilon}{\varepsilon_y}\right)^n \quad \text{when } \sigma > \sigma_y \tag{19}$$

For convenience $\sigma_y = \sigma_{0.2}$. At loads, $F \le F_y$ (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. 19

$$\frac{F}{F_y} = \left(\frac{\delta_5}{\delta_y}\right)^n \tag{20}$$

or

$$\delta_5 = \delta_y \left(\frac{F}{F_y}\right)^{1/n} \tag{21}$$

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 (Schwalbe et al., 1991b) that J can be related to the applied strain, ε, and to δ_5 through

$$\frac{J}{J_y} = \left(\frac{F}{F_y}\right)^{(1+n)/n} = \left(\frac{\varepsilon}{\varepsilon_y}\right)^{1+n} = \left(\frac{\delta}{\delta_y}\right)^{1+n} \tag{22}$$

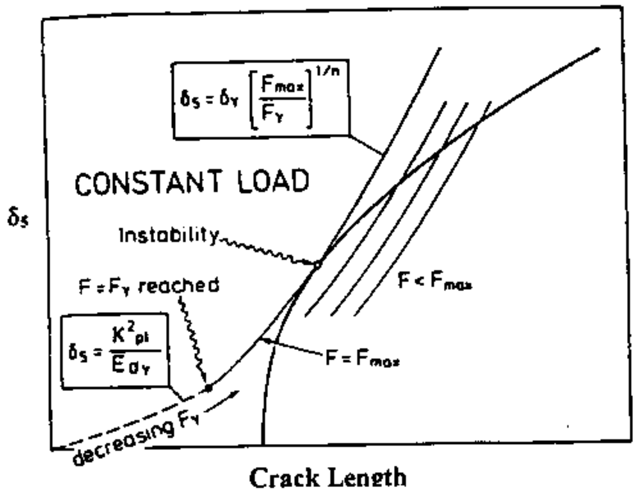

Figure 4 - Determination of instability (maximum load) for load control using δ_5 - R curve

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.

This kind of treatment is similar to the fully plastic solution 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. Figure 4 shows how to obtain the instability load using the ETM method.

THE DUCTILE FRACTURE METHOD

The ductile fracture method (Ernst and Landes, 1985) (Ernst and Landes, 1986) (Link et al., 1989) (Landes et al., 1993) 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. 5.

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.

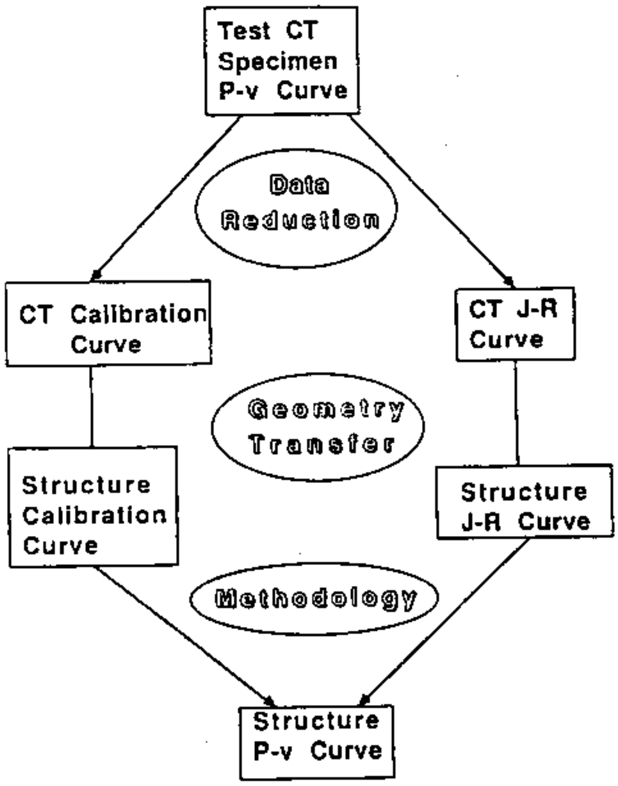

Figure 5 - Flow chart of component model load versus displacement prediction from test specimen

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}

$$P = G(a/W)H(v_{pl}/W) \qquad (23)$$

The first step for developing calibration functions and fracture toughness for the compact specimen has been described previously as a method primarily to develop *J-R* curves directly from load versus displacement records without the need for online crack monitoring equipment, named the method of normalization (Landes et al., 1991). It is assumed a deformation function $H(v_{pl}/W)$ in the format

$$H(v_{pl}/W) = \frac{L + M\frac{v_{pl}}{W}}{N + \frac{v_{pl}}{W}}\left(\frac{v_{pl}}{W}\right) \quad (24)$$

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. 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.

What is needed to predict the behavior of the structural component is a relationship between the primary variables load, displacement and crack length, and a separate relationship between these variables and a fracture parameter. The principle of load separation (Eq. 23) provides part of the necessary information. Regarding the fracture parameter, *J*, it can be determined as a sum of an elastic and a plastic component

$$J = J_{el} + J_{pl} = \frac{K^2}{E'} + \frac{\eta_{pl}}{Bb}\int_0^{v_{pl}} P dv_{pl} \quad (25)$$

where E' is the effective modulus, K is the linear elastic crack-tip stress intensity factor, η_{pl} is a coefficient for the plastic area, B is the thickness, and b is the uncracked ligament (W-a). η_{pl} is given by

$$\eta_{pl} = -\frac{b}{w}\frac{G'(a/W)}{G(a/W)} \quad (26)$$

where G' is the derivative of G with respect to a/W. Therefore $G(a/W)$ can be determined if the η_{pl} coefficient is known and vice versa. Also, the following expressions are used:

$$v = v_{el} + v_{pl} \quad (27)$$

$$v_{el} = C(a/W)P \quad (28)$$

where $C(a/W)$ is a compliance function. Therefore, the calibration functions needed for a new geometrical shape, not regarding material, are the compliance $C(a/W)$, the K solution, and the $G(a/W)$ function or η_{pl}. All of these calibration functions can be obtained with a knowledge only of the cracked geometry.

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. 5 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 (Landes et al., 1993).

The fracture toughness of the structure could be obtained from the *J-R* curve of the test specimen if the influence of the geometry and constraint were well understood. Many of the results reported in the literature do not follow consistent trends, so these influences cannot be incorporated quantitatively (Link et al., 1991a). Fortunately, it has been demonstrated that the behavior of the structure is often more sensitive to the calibration function then to the *J-R* curve, and the lower bound provided by the test specimen works very well (Landes et al., 1993).

DISCUSSION AND CONCLUSIONS

Basically, four application schemes for failure assessment of cracked components incorporating EPFM concepts were described in this paper. The main characteristics of these methods are summarized bellow, where the positive and negative aspects of each one are emphasized.

a) EPRI-GE Methodology / DPFAD

Basic assumption: the material is supposed to obey a Ramberg-Osgood stress-strain law.

Positive aspects:

- Permits quick engineering assessments, employing only a hand calculator, based on a source of tabulated calibration functions (the Handbook) containing many representative geometries and loading conditions;
- May be considered reliable and accurate, at least for those materials whose stress-strain behavior is well represented by a Ramberg-Osgood equation.

Negative aspects:

- The handbook solutions are based on numerical results which use ideal material behavior and have little experimental verification;
- 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;
- Many materials do not exhibit a power law stress-strain behavior;
- The tabulated solutions are given at discrete values of the input variables, requiring some judgment when interpolation and/or extrapolation of these variables are necessary;
- The failure assessment diagram obtained from the EPRI-GE J-estimation scheme (DPFAD) is geometry dependent, requiring the computation of a new assessment line for each new geometry and crack size.

b) The Reference Stress Approach (R-6 Option 2)

The 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.

Basic assumptions:

- $h_1(n)/h_1(1) = 1$
- It is assumed that the plastic zone corresponds to the case of an infinite plate under tension in plane stress conditions for $n \rightarrow \infty$.

Positive aspects:

- The R6 CDF provides a geometry independent FAD;
- It gives more accurate results than EPRI-GE methodology 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 load (Miller, 1986).

Negative aspects:

• The approach requires the complete stress-strain curve for the material in question.

c) The Engineering Treatment Model (ETM)

Basic assumptions:

• The cracked body deforms under prevailing plane stress conditions;

• The material's stress-strain behavior is supposed to follow a piece-wise power law.

Positive aspects:

• The method provides a geometry independent formulation for the cracking driving force parameters, which makes its application easy; it is not necessary to predetermine influence functions like in the EPRI-GE methodology;

• 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.

Negative aspects:

• The method has yet to be validated for plane strain conditions;

• Its accuracy needs to be better evaluated for large structural components.

c) The Ductile Fracture Method

Basic assumption: the load separates into multiplicative functions of crack length and plastic deformation (principle of load separation).

Positive aspects:

• The method 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 (Link et al., 1991b). 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.

Negative aspects:

• The method has a higher level of complexity than the others presented. Some routines should be computationally implemented in order to simplify its application.

• To make the method work better, more effort must be given to the development of *G(a/W)* for complex geometries.

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. (1991b) to overcome the problem of interpolating input variables. Some of the guidelines given in (Link et al., 1991b) are based on fundamental principles of the Ductile Fracture Method. In another paper by Ainsworth (1995), some modifications to the GE-EPRI *J*-estimation scheme are proposed using the Reference Stress Method. According to Ainsworth, this method introduces approximations compared to the basic GE-EPRI approach, but enables values of *J* to be estimated for materials not well described for cases where GE-EPRI solutions are not available, provided that stress intensity factor and limit load solutions are known.

Recently, Bloom (1994), using ideas developed by Ainsworth (1984), 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 (1991) to include a procedure for assessment of flaws in austenitic piping (Bloom, 1995).

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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