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INFLUENCE OF THE MATERIALS MECHANICAL PROPERTIES ON THE STRUCTURAL INTEGRITY ASSESSMENT OF CRACKED PIPING OF PWR NUCLEAR REACTORS PRIMARY SYSTEMS

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Abstract. *The structural integrity assessment methods of cracked components manufactured with ductile materials request the evaluation of parameters of the Elastic-Plastic Fracture Mechanics (EPFM) and of the Limit Load Analysis (LL). Since the use of numerical methods to apply the concepts of EPFM and LL may be costly and time demanding, the existence of the so-called simplified methods for cracked piping evaluation is still considered of great relevance. The following simplified methods for evaluation of the ductile behavior of piping systems are available in the literature and were considered in this work: J-T Method (J Integral versus the Tearing Modulus T), R6 Method and DPFAD Method (Deformation Plasticity Failure Assessment Diagram). The methods were applied for the computation of instability loads of some piping systems, with through-wall circumferential cracks, subjected to bending moments, made with high toughness steels. Changes in the values of the materials properties were considered. The estimated instability loads were compared with experimental results obtained in the literature. From those comparisons, some conclusions and comments could be made, being the main focus of the work the aspects related to the characterization of the materials properties to the appropriate application of the methods to cracked piping of pressurized water nuclear reactor (PWR) primary systems, in evaluations of the LBB (Leak-Before-Break) concept. As the methods are strongly dependent on the properties, some recommendations must be followed. These properties are basically expressed by means of the stress-strain curves and fracture resistance curves (J_R curves).*

***Keywords**: LBB, fracture mechanics, limit load, piping, materials*

1. Introduction

Methods for the structural integrity assessment of components containing flaws play a fundamental role in the decision of the service adequacy, aging management programs development and life extension evaluation, being particularly important in the analysis of the accident conditions postulated in codes and standards. For components fabricated with ductile materials, the sudden rupture is followed by a considerable amount of slow and stable crack growth. In these cases, the load bearing capacity can increase well beyond the limit imposed by the material fracture resistance expressed by J_{Ic} (fracture resistance for the initiation of stable growth of the crack).

The methods for assessment of cracked components manufactured with ductile materials request the evaluation of parameters of the Elastic-Plastic Fracture Mechanics (EPFM). Since the use of numerical methods to apply the concepts of EPFM may be costly and time demanding, the existence of the so-called simplified methods, for cracked piping evaluation is still considered of great relevance.

In sections 2, 3 and 4, three of the main simplified methods found in the literature are briefly described. These methods were implemented using computational tools (Jong, 2004) and applied to several cases of piping with throughwall circumferential cracks, subjected to bending moments, in order to obtain the maximum load supported by these piping. The results obtained with the application of the methods, and the respective results obtained experimentally, are presented in section 5. In section 6, some recommendations for the correct application and analysis of the results obtained with the application of the methods are presented, in particular several important aspects related to the influence of the mechanical properties of the materials on the evaluations.

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2. J-T Method

This method (Paris e Johnson, 1983) involves the plotting of two curves on the J-T space, where J is the J-integral and T is the tearing modulus. One is the material J-T curve and the other is the applied J-T curve for the initial crack length and as a function of the applied load. The intersection of these two curves corresponds to the instability point (Fig. 1).

The material J-T curve is obtained from the J_R curve, which represents the material resistance to fracture. Applying the scheme defined by the EPRI-GE manual (Zahoor, 1989), the applied J can be calculated as a function of the loading and, then, numerically differentiated to obtain the applied T. If the initial growth of the crack is neglected, when this curve is plotted in the J-T space it will become a straight line, which can be defined connecting the origin to a single point in the J-T space (point A). To determine this loading line, one must calculate J twice, first for the initial crack length a_o and, afterwards, considering a small extension of the crack to determine Δa and ΔJ.

The point A represented in Fig. 1 can be defined using Eq. (1):

$$T_{aplicado} = \frac{E}{\sigma_o^2}\left(\frac{\Delta J}{\Delta a}\right) \tag{1}$$

where E corresponds to the modulus of elasticity and σ_o corresponds to the flow stress (generally adopted as the average of the yield stress and ultimate stress).

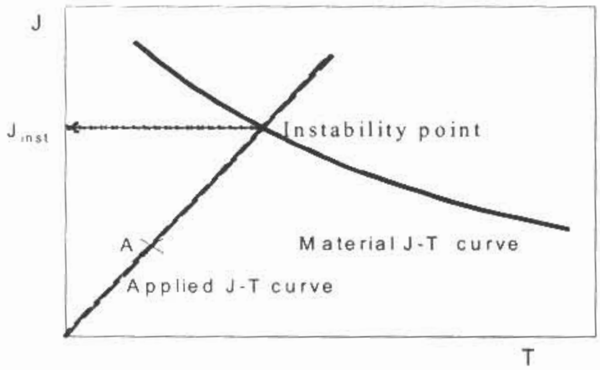

Figure 1. Determination of J corresponding to the instability point.

The applied J-T curve is a straight line that begins at the origin, passes trough A and intercepts the material J-T curve. This point of intersection establishes the value of unstable J (J_{inst}) and the length of the unstable crack. Once the value of J_{inst} is determined, the instability load can be obtained from a graphic of applied J versus normalized loading, as illustrated in Fig. 2.

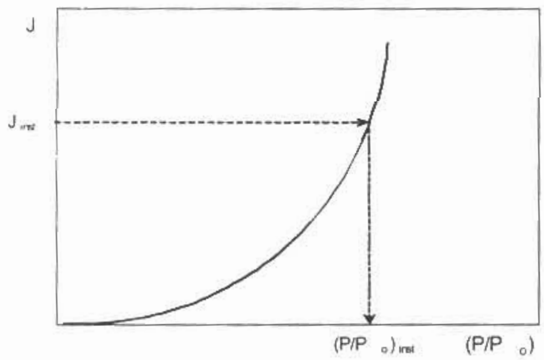

Figure 2. Determination of the instability load.

In Fig. 2, P_o is a reference load that depends on the actual crack length. To take into account the growth of the crack, Δa (obtained at curve J_R for $J=J_{inst}$), the instability load P_{inst} is calculated applying Eq. (2).

$$P_{inst} = (P / P_o)_{inst} \cdot P_o(a_o + \Delta a) \tag{2}$$

The load that corresponds to the beginning of the stable growth of the crack is determined, in a similar way, taking $J = J_{Ic}$.

3. DPFAD Method

The DPFAD (Deformation Plasticity Failure Assessment Diagram) Method (Bloom e Malik, 1982) is based on the use of an evaluation diagram for the failure analysis (FAD - Failure Assessment Diagram). Failure should be understood as the structural collapse of the mechanical component. Failure evaluation is done by plotting the assessment points in the diagram, Fig. 3. S_r and K_r are the generic parameters associated with the load and the material characteristics, respectively. Assessment points located above or at the DPFAD curve indicate instability (collapse), while points located inside the region defined by the curve indicate stability.

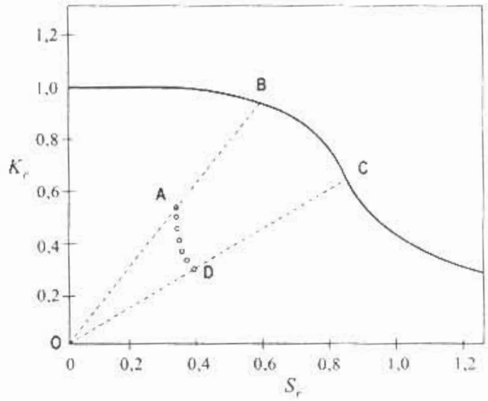

Figure 3. Diagram DPFAD.

The evaluation (failure) curve is generated considering the scheme for the J definition defined by the EPRI-GE manual (Zahoor, 1989), where the crack driving force is given by the sum of an elastic and a plastic part. The elastic part of J is obtained from solutions of the Elastic Fracture Mechanics, with corrections to consider the plasticity at the crack tip, and the plastic part is the solution for the J-integral, based on the plasticity deformation theory, of a cracked body with a totally plastic ligament. The coordinates K_r and S_r of the evaluation curve are defined by:

$$K_r = \left[\frac{J_{el}(a,P)}{J}\right]^{1/2} = \left[\frac{J_{el}(a,P)}{J_{el}(a_{ef},P)+J_{pl}(a,P,n)}\right]^{1/2} \quad (3)$$

$$S_r = \frac{P}{P_o} \quad (4)$$

where J_{el} e J_{pl} are, respectively, the elastic part and plastic part of J-integral, a is the length of the crack, a_{ef} is the effective length of the crack, P is the applied load, P_o corresponds to a reference load and n is the material strain hardening factor. The coordinates of an assessment point at the diagram ~~is~~ are defined by:

$$K_r'(a_o + \Delta a) = \left[\frac{J_{el}(a_o + \Delta a)}{J_R(\Delta a)}\right]^{1/2} \quad (5)$$

$$S_r'(a_o + \Delta a) = \frac{P}{P_o(a_o + \Delta a)} \quad (6)$$

where J_{el}, J_R e P_o are functions of the amount of stable growth of the crack Δa. Starting with the initial crack length, a_o, and considering a certain amount of crack growth, several assessment points are determined, resulting in a curve with a characteristic candy cane shape, Fig. 3. The safety factor related to the beginning of the stable initiation of the crack is given by the ratio OB/OA, while the maximum safety factor corresponding to the crack instability is given by the ratio OC/OD.

4. R6 Method

The R6 Method, described in Milne *et al.* (1988) and BS-7910 (1999), is also based on the use of a failure assessment diagram and on the verification of the structural collapse of a mechanical component or its stability, in a similar way as exposed in the DPFAD method.

This method offers three options for failure curves. The option 3 failure curve depends on the stress-strain characteristics of the material and on the geometry of the component. This curve can be achieved based on the values of J calculated with the use of the finite element technique or by means of experiments for a cracked component fabricated with a specific steel. The option 2 failure curve (Ainsworth, 1996) is only dependent on the parameters associated to the stress-strain curve of the material. This curve represents the lower bound values of the option 3 failure curves obtained experimentally.

Considering the characteristics of the materials referred in our work, we applied the failure curve option 1 (Milne et al., 1988; Ainsworth, 1996), that represents an empiric adjustment of lower bound values (conservative), presented on option 2 failure curves for a specific variety of materials. This curve, which is independent of geometry, is the most representative for austenitic materials and can be described by Eqs. (7 ; 8).

$$K_r = (1 - 0{,}14\, L_r^2)[0{,}3 + 0{,}7\, exp(-0{,}65\, L_r^6)] \quad for\ L_r \leq L_r\, max \tag{7}$$

$$K_r = 0 \quad for\ L_r > L_r\, max \tag{8}$$

where: $L_r = M / M_0$ and $L_r\, max = (\sigma_{uts} + \sigma_{ys})/ 2\, \sigma_{ys}$

The R6 method can use three categories (levels) of integrity assessment depending on the application and the involved materials. The category level-1 is the simplest and is more appropriate for situations where the failure can occur due to brittle fracture without the occurrence of ductile tearing.

Category level-2 is appropriate for situations where the brittle fracture is preceded by a small amount of ductile tearing. This category considers the toughness increase due to this amount of ductile tearing.

In our work, we applied the category level-3, which is more appropriate for materials where ductile tearing precedes the failure of the component and where the possibility of the complete definition of their respective JR curves exists.

For the implementation of the category level-3 evaluation, it is necessary to postulate some ductile crack growth, taking as reference the considered material J_R curve, establishing the failure assessment points, $L_r^{'}$ and $K_r^{'}$, for the several increments of crack growth, to be plotted on the FAD diagram, Fig. 3. The limit condition occurs when, at a specific condition of maximum admissible load, only 1 (one) assessment point touches the general failure curve and all other assessment points are located on the outside of this curve.

For the analysis in this category, the coordinates of the assessment points on diagram FAD are defined by Eqs.(9 ; 10):

$$K_r^{'}(a_o + \Delta a) = \left[\frac{J_{el}(a_o + \Delta a)}{J_R(\Delta a)} \right]^{1/2} \tag{9}$$

$$L_r^{'}(a_o + \Delta a) = \frac{P}{P_o(a_o + \Delta a)} \tag{10}$$

where J_{el}, J_R e P_o are functions of the amount of stable growth of the crack Δa. Starting with the initial crack length, a_o, and considering a certain amount of crack growth, several assessment points are determined.

5. Obtained Results (experiments / calculations)

At Tab. 1 the values of the instability load (maximum bending moment), obtained in some experiments (found in literature) and also the respective values obtained with the application of the calculation routines for the three described methods (Jong, 2004), are presented. The percent deviations of the calculation results versus experimental values are also shown.

Table 1 – Experimental results obtained in literature and values obtained with calculations – J-T, DPFAD and R6 Methods.

		Maximum Load (Bending Moment - kN.m)						
Original Experiment Code CASE (literature)	Material	Value obtained by calculation			Experimental Result CASE (literature)	Percent Deviation (%) of the value obtained by calculation versus the experimental result		
		METHOD				METHOD		
		J-T	DPFAD	R6		J-T	DPFAD	R6
1.1.1.23 (1)	SA-358 316L	2.468,6	2.150,0	2.361,3	3.063,5	-19,4	-29,8	-22,9
4111-5 (1)	SA-358 316	1.228,8	1.228,8	1.186,3	1.257,1	-2,2	-2,2	-5,6
4131-5 (1)	SA-376 TP304	37,3	37,3	23,7	37,7	-1,2	-1,2	-37,1
4141-1 (1)	SA-376 TP304	39,4	41,2	39,1	37,5	5,1	9,9	4,2
4141-3 (1)	SA-358 304	335,9	335,9	438,4	377,0	-10,9	-10,9	16,3
4141-5 (1)	SA-376 TP304	29,0	29,5	25,8	30,7	-5,5	-4,0	-16,2
SFB1 (3)	SA-508 Cl3 (2)	100,2	99,2	88,7	105,7	-5,2	-6,2	-16,1
STB1 (3)	SA-335 GrP22	63,3	63,0	51,4	66,0	-4,1	-4,5	-22,1
SPBM TWC8-3 (4)	SA-333 Gr6	92,9	93,7	91,0	88,7	4,7	5,6	2,5
SPBM TWC8-2 (4)	SA-333 Gr6	122,2	119,9	120,9	124,7	-2,0	-3,9	-3,1
SPBM TWC8-1 (4)	SA-333 Gr6	157,4	151,1	162,7	155,2	1,4	-2,7	4,8
			Medium Percent Deviation (%)			-3,6	-4,5	-8,7

NOTES:

(1) – Austenitic material; experiment performed at the operation temperature (280 °C);
(2) – Pipe fabricated from a forging of the indicated material;
(3) – Non austenitic material; experiment performed at temperature between 10 and 15% higher than the operation temperature;
(4) – Non austenitic material; experiment performed at room temperature (25 °C).

6. Conclusions and recommendations

Based on the results presented on Tab.1, it is possible to observe that, applying the J-T and DPFAD Methods, it is possible to achieve maximum bending moments with values close to those obtained from the experiments. In some cases the values of the predictions made with the applied methods were lower (non conservative) and in other cases higher (conservative) than the values obtained experimentally.

With regard to R6 method, we adopted in our work a generic failure curve that takes into account a great variety of materials and, among them, the austenitic steels can be found. Being of easier application, its results have less agreement than the results obtained from the application of J-T and DPFAD Methods.

The obtained deviation margins indicate that these methods can be used for the prevision of collapse in similar piping (materials, geometry and type of loading).

For the analysis of the results obtained from the application of the methods, some sensitivity analysis has to be performed to verify the confidence in the safety margins obtained (critical crack length / maximum allowable load).

In the development of this work it was possible to identify the importance of the adequate characterization of the materials. The following important aspects should be high-lighted:

1. The importante of gathering quality experimental data, as those listed in Tab. 2, related to the mechanical properties of materials (base metal / welding), to be applied on the analyses (stress-strain curves and J_R curves), by means of the execution of specific tests and fulfillment to the limits of extrapolation and applicability of the variables. It is important to capture the failure mode that occurred at the execution of those specific tests (ductile tearing / plastic collapse);
2. Precise definition of the geometric characteristics of the cracks and components (pipes) (see Tab. 2), in special the initial length of the crack, considering the adequate definition of the associated parameters;
3. If feasible, always make use of stress-strain curves and J_R curves obtained from tests executed with the materials (base metal / welding) effectively used in the components, considering their dimensions, geometry and relevant temperatures at which they will be submitted and also the fabrication and welding procedures applied to the components. Generally, in cases of pre-existing installations, the mechanical properties of similar materials obtained in specific databases are applied instead of the properties of the actual component, due to its unavailability. In these cases, the use of more conservative values of the mechanical properties must be considered, for selected similar materials. Sensitivity analysis must be performed on the safety margins that results from the application of the simplified methods. The safety margins obtained for the cases of pre-existing installations are generally more conservative than for the new installations. This is due to the fact that for new installations it is possible to execute previous tests and experiments (pipe and test specimens), in order to obtain the mechanical properties, parameters and behavior of materials of the specific components. The materials to be applied on new installations do not need to be analized considering lower bound mechanical properties, which can be too conservative. With the knowledge of the specific information of the materials to be used in the components, the sensitivity analysis to be applied on the results obtained for these cases will correspond to the deviations encountered in the executed tests and experiments;
4. Fulfillment of certain dimensional limits and of the range of applicability of the parameter related to the strain hardening of the material, for the use of the parametric curves presented in the EPRI manual (Zahoor, 1989). The dimensional limits suggested to obtain specific parameters defined at this manual, for pipes submitted to pure bending or axial load, containing throughwall circumferential cracks, are: $0{,}0625 \leq \theta/\pi \leq 0{,}5$ (crack length) and $5 \leq R/t \leq 20$ (pipe transverse dimensions), where θ represents the half crack angle, R represents the pipe half diameter and t the pipe wall thickness. It is allowed in some cases, extrapolations in the order of 20% beyond the minimum or maximum limits of the ratio R/t. A qualitative analysis of the tendency of the parametric curves defined in this manual (Zahoor, 1989) (see example at Fig. 4) gives a rather good indication of the possibility to perform eventual extrapolations to higher values with adequate accuracy;
5. The recommendations related to the material properties, required parameters and geometry for the execution of the analysis in piping can be summarized as described next:

- Studies developed by EPRI demonstrated that for the prediction of leak rates, in piping with troughwall circumferential cracks, the use of properties and parameters gathered from BEST FIT type stress-strain curves for the base and weld metal are more appropriate, providing more conservative results for the leak rates estimations. With the adoption of BEST FIT type curves, the material is considered stiffer with a smaller crack opening, resulting in a greater crack length associated with a detectable leak rate;
- The J_R curves should be of the LOWER BOUND type, in order to obtain more conservative results regarding the maximum allowable loads;
- Two basic situations involving the mechanical properties of the material of the section submitted to the greater stresses and, at the same time, having the least favorable material properties, must be considered: one is relative to the base metal and the other to the weld metal. In the application of the assessment methods, for the base metal case, its own LOWER BOUND type stress-strain curve and J_R curve should be used. For the weld metal, the use of the stress-strain curves related to the base metal and the use of the J_R curve of the weld metal, both LOWER BOUND type, give the most conservative approach (NUREG -1061-Vol. 3, 1984);
- The applicability range of the stress-strain curves must be adjusted to guarantee adequate results. In the case of austenitic steel piping, the appropriate range of strain values is limited to the maximum value of 8%;
- Under small yield conditions, the parameter J can be considered independent of geometry regarding fracture analysis;
- Test specimens with thickness of the same order as existing in the piping, without lateral indentation tend to agree in a more precise way to the piping behavior, regarding their resistance to fracture;
- When applying the considered assessment methods, before using the information related to the extrapolation (correction) of the J_R curves that were obtained from test specimens, a sensitivity analysis has to be performed. In some cases, as a function of the value of da, the maximum load can be estimated with a good level of accuracy, even considering the J_R curve obtained directly from tests executed with specimens C(T), without any correction;
- The fabrication process that induces deformations in non preferential directions, as for example, the forging process, is much more favorable than the lamination process, because it increases the random crystalline orientation of the metal grains. The mechanical conformation process, used to give a specific shape to the component, is another factor that has great influence in its resistance to fracture.

Table 2 – Information to be obtained in tests related to pipes and associated materials

Test parameters
Experiment number
Piping material identification number
Piping material
External diameter
Piping *SCHEDULE*
Thickness of the pipe wall
Test temperature
Internal span for 4 point bending experiment
External span for 4 point bending experiment
Test pressure
Initial crack length
Crack depth
Type of crack
Experimental Results
Load / Bending moment at crack initiation
Maximum load
Load cycles (in cyclic test)
Material properties
Yield stress σ_{ys}
Ultimate stress σ_{uts}
Percentage strain
Area reduction
σ_0, ε_0 parameters , and Ramberg-Osgood coefficients α, n (*)
J_{Ic} (J critical – at crack initiation)
dJ / dA (initial slope of J_R curve)
J_R extrapolated curve parameters $(C\ ,\ m)$ (**)
Results of the *Charpy* test (at room temperature)
J_R curves (at interest temperatures)
Stress-strain curve, as a function of temperature
E – Elasticity modulus
ν - Poison coefficient
Chemical composition of the material

(*) $$\left(\frac{\varepsilon}{\varepsilon_0}\right) = \left(\frac{\sigma}{\sigma_0}\right) + \alpha\left(\frac{\sigma}{\sigma_0}\right)^n$$

(**) $$J = C(\Delta a)^m$$

Tension tests (stress-strain curves) allow the definition of the following parameters:

E, σ_0, ε_0, σ_{uts}, σ_{ys}, α, n, ν

Test specimens C(T) type allow the definition of the following parameters:

J_{Ic} , C , m

The imposed loads on tests executed using displacement control are preferable than the tests performed with load control, because the response of the component being tested tends to be more stable. This is due to the fact that, in ductile materials, the crack driving force decreases with the growth of the crack and, in order to occur a new advance in the crack extension, the displacement has to be increased. Considering this characteristic, generally the plotting of experimental points (J_R curves), for these materials, is executed using the loads imposed via displacement control, which permits a significative stable crack growth. In the utilization of this control technique, the load is imposed to the component being tested, increasing the displacement of a determined point (section) at a constant rate and is defined as a "quasi static" loading.

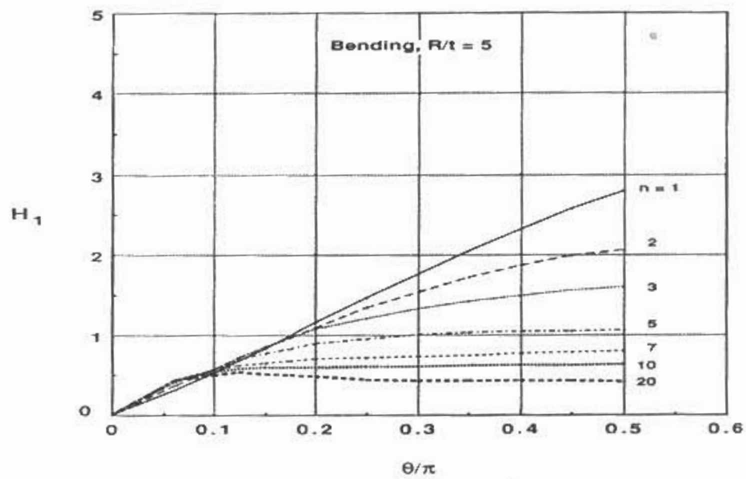

Figure 4 - Example of parametric curves for $\underline{n}$ and $\underline{\theta/\pi}$ to obtain the value of factor H1, considering the rate R/t = 5
EPRI manual (Zahoor, 1989)

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8. Responsibility notice

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