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ROUTINES FOR THE ASSESSMENT OF CRACKED PIPING OF PWR NUCLEAR REACTORS PRIMARY SYSTEMS

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ABSTRACT

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.

The following simplified methods for evaluation of the ductile behavior of cracked piping systems were considered in this work: J-T Method (J Integral versus the Tearing Modulus T) [1], Method R6 [2] and DPFAD Method (Deformation Plasticity Failure Assessment Diagram) [3].

Calculation routines [5], related to the above defined methods, were applied for the determination of the instability loads for some primary piping systems of Pressurized Water Reactors, with through-wall circumferential cracks, subjected to bending moments, made with steels of high toughness. Variations in geometry and materials were considered.

Parametric information obtained from EPRI / GE manual [4] were used for the application of the calculation routines [5]. Those routines were implemented using electronic calculation sheets as computational tools. The instability loads (bending moments) obtained for the considered pipes, as a result of the application of the calculation routines, are compared with the results from experiments obtained from the literature.

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 assessment, being mainly important in the analysis of the accident conditions postulated in codes and standards. For components fabricated with ductile materials, the sudden rupture of the material is followed by a considerable amount of slow and stable growth of the crack. In these cases the capacity to support loads can increase well beyond the limit imposed by the resistance to fracture of the material expressed by J_{Ic} (limit of resistance to fracture for the initiation of the stable growth of the crack). The three methods considered in this work to assess the described structural behavior are next shortly described.

2. J-T METHOD [1]

This method involves the plotting of two curves on the J-T space, where J is the J-integral and T is the tearing module. One is the material J-T curve and the other is the applied J-T curve for the crack initial length and is 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, witch represents the material resistance to fracture. Applying the schema defined at the EPRI-GE manual [4], 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 space J-T 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* and, afterwards, considering a small extension of the crack to determine Δa and ΔJ.

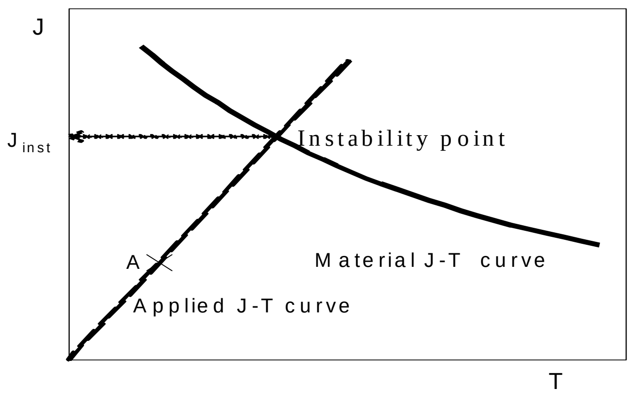

Figure 1. Determination of J corresponding to the instability point.

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 interception establishes the value of unstable J (J_{inst}) and the length of the unstable crack. Once that the value of J_{inst} is determined, the instability load can be obtained from a graphic of applied J versus the normalized loading (Fig. 2).

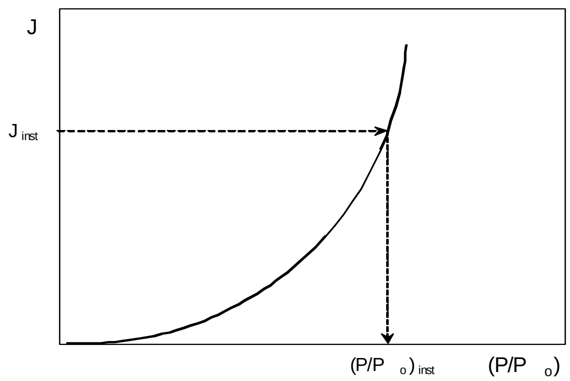

Figure 2. Determination of the instability load.

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 [3] is based on the use of a evaluation diagram for the failure analysis (FAD - *Failure Assessment Diagram*). Failure should be understood as, the structural collapse of the mechanical component. The collapse verification is made by plotting *assessment points* on the diagram (Fig. 3). S_r e 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.

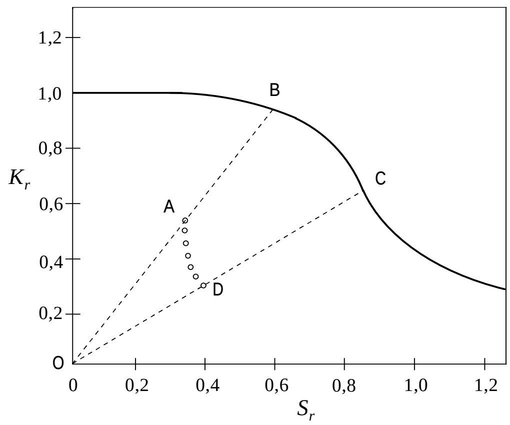

Figure 3. Diagram DPFAD.

The evaluation (failure) curve is generated considering the scheme for the J definition defined on the EPRI-GE manual [4], where the crack driving force is given by the sum of the elastic and the plastic parts. 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 remanent ligament.

Starting with the initial crack length, a_o, and considering a certain amount of crack growth, several assessment points are determined, resulting on 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 [2,6], is 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.

Considering the characteristics of the materials referred in our work, we applied a failure curve [2,7] that represents an empiric adjustment of lower bound values (conservative), obtained only from parameters associated to material stress and strain curves with lower bound values gathered from experimental failure curves for a specific variety of materials.

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 little 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, witch is more appropriate for materials where the failure of the component is preceded by ductile tearing and where exists the possibility of the complete definition of their respective J_R curves.

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, 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.

5. RESULTS (EXPERIMENTS / CALCULATIONS)

The implementation of the calculation routines related to the mentioned methods was done using the electronic data sheet software *MS-EXCEL*, as described in [5]. The values of the instability load (maximum bending moment) obtained in some experiments (found in literature, see [5]) and also the respective values obtained with the application of the calculation routines for the three described methods are presented on Tab.1. The percent deviations of the calculation results versus experimental values are also shown.

6. CONCLUSIONS

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 (not 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 in account a great variety of materials, and among them the austenitic steels can be found. Been of easier application, its results have smaller 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 prediction of collapse in similar piping (materials, geometry and type of loading). The considered cracked piping cases demonstrated that the calculation routines presented consistent results with a good level of accuracy related to the maximum loads supported by these pipes.

In the development of this work it was possible to identify the importance of the adequate characterization of the materials.

For the computational implementation of the described methods and associated calculation routines the following important aspects should be high-lighted:

1. Gathering quality experimental data, 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), in special the initial length of the crack, considering the adequate definition of the associated parameters;
3. If feasible, always proceed the use of the informations and parameters obtained from materials (base metal / welding) effectively used in the components, following the recommendations of applicable standards;
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 [4]. For pipes, considering the application of specific parameters, it is allowed in some cases extrapolations in the order of 20% beyond of the minimum and maximum limits of the ratio R/t (pipe half diameter / pipe thickness). A qualitative analysis of the tendency of the parametric curves defined in this manual [4], gives a rather good indication of the possibility to perform eventual extrapolations of greater magnitude with adequate accuracy;
5. Proceed a sensitivity analysis to choose the acceptable levels of numerical and graphical approaches, during the execution of the iterative calculations for the definition of the several variables related to the application of the methods;
6. The type of loading imposed to the component and type of stress acting at the crack tip have to be in accordance with the applicable analysis method and with the case of the EPRI manual [4].

Furthermore, 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 security margins obtained (critical crack length / maximum allowable load).
During the implementation of the calculation routines using the electronic data sheet software *MS-EXCEL*, there are conditions to implement adjustments and approaches of values. It is not yet accessible to us, a friendly interface for the input of data, visualization of results and printing of specific reports. These facilities can be developed taking as reference the flowcharts, calculation routines and examples exposed in [5].

REFERENCES

1. Paris, P.C.; Johnson, R. E. - *A Method of Application of Elastic-Plastic Fracture Mechanics to Nuclear Vessel Analysis*, Elastic-Plastic Fracture: Second Symposium. Volume II, ASTM STP 803, pp. II-5-II-40, (1983).
2. Milne, I.; Ainsworth, R. A.; Dowling, A. R.; Steward, A. T. (CEGB-Central Electricity Generation Board) - *Assessment of the Integrity of Structures Containing Defects*, CEGB Report R/H/R6 – Revision 3, 1986, *International Journal of Pressure Vessels & Piping* **32**, pp. 3-104, (1988).
3. Bloom, J. M.; Malik, S. N. - *Procedure for the Assessment of the Integrity of Nuclear Pressure Vessels and Piping Containing Defects*, EPRI Topical Report NP-2431, Research Project 1237-2, Electric Power Research Institute, Palo Alto, CA, (Jun. 1982).
4. Zahoor, A. - *Ductile Fracture Handbook. Volume 1: Circumferential Throughwall Cracks*, Report EPRI NP-6301-D/N14-1, Electric Power Research Institute, Palo Alto, (1989).
5. Jong, R. P. – *Avaliação de tubulações trincadas em sistemas primários de reatores nucleares PWR* - Dissertação (Mestrado) - Instituto de Pesquisas Energéticas e Nucleares (IPEN), São Paulo, (set. 2004).
6. BS-7910 - *Guide on methods for assessing the acceptability of flaws in metallic structures* – British Standard, (1999).

7. Ainsworth, R. A. - *Failure assessment diagrams for use in R6 assessments for austenitic components*, *International Journal of Pressure Vessels & Piping* **65**, pp. 303-309, (1996).

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

Original Experiment Code CASE (literature)	Material	Maximum Load (Bending Moment - kN.m): Value obtained by calculation, METHOD J-T	DPFAD	R6	Experimental Result CASE (literature)	Percent Deviation (%) of the value obtained by calculation versus the experimental result, METHOD 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

OBSERVATIONS:
(1) – Austenitic material; experiment performed at the operation temperature (280 ºC);
(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 ºC).