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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). The following simplified methods for evaluation of the ductile behavior of cracked piping systems are available in the literature and were considered in this work: *J–T method* (*J*-integral versus the tearing modulus *T*) [Paris, P.C., Johnson, R.E., 1983. A method of application of elastic–plastic fracture mechanics to nuclear vessel analysis. In: Elastic–Plastic Fracture: Second Symposium, vol. II, ASTM STP 803, pp. II-5–II-40], *R6 method* [Milne, I., Ainsworth, R.A., Dowling, A.R., Steward, A.T., 1988. Assessment of the Integrity of Structures Containing Defects. CEGB Report R/H/R6 – Revision 3, 1986. International Journal of Pressure Vessels and Piping 32, 3–104] and *DPFAD method* (Deformation Plasticity Failure Assessment Diagram) [Bloom, J.M., Malik, S.N., 1982. 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, CA, USA]. Calculation routines by Jong, R.P. [2004. Structural Integrity Assessment of Cracked PWR Piping Systems. M.Sc. Dissertation, Nuclear Technology Program, University of São Paulo (in Portuguese)], related to the above defined methods, were applied for the computation of the instability loads for some pipes of primary piping systems of Pressurized Water Reactors (PWR), with through-wall circumferential cracks, subjected to bending moments, made with high toughness steels. Changes in geometry and values of the materials properties were considered. The estimated instability loads (bending moments) obtained for the considered pipes were compared with experimental results obtained from 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 PWR primary systems, in evaluations of the LBB (Leak-Before-Break) concept.

Keywords: LBB; Fracture mechanics; Limit load; Piping; PWR

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.

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2. *J–T* method

This method by Paris and Johnson (1983) 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, which represents the material resistance to fracture. Applying the schema defined at the EPRI-GE manual (Zahoor, 1989), 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 and, afterwards, considering a small extension of the crack to determine Δa and ΔJ.

The applied $J-T$ curve is a straight line that begins at the origin, passes through 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 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).

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 by Bloom and Malik (1982) 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* in the diagram (Fig. 3). S_r and K_r are the generic parameters associated with the load and the material characteristics. Assessment points located above or at the DPFAD curve indicate instability (collapse), while points located inside the region defined by the curve indicate stability.

The evaluation (failure) curve is generated considering the scheme for the J definition defined on the EPRI-GE manual, 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 remnant ligament.

Starting with the initial crack length, a_0, 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 (Milne et al., 1988; BS-7910, 1999) 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 (Milne et al., 1988; Ainsworth, 1996), which 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

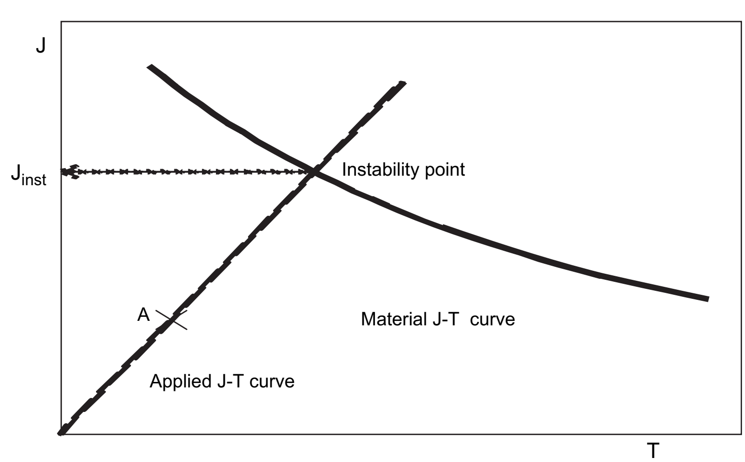


Fig. 1. Determination of J corresponding to the instability point.

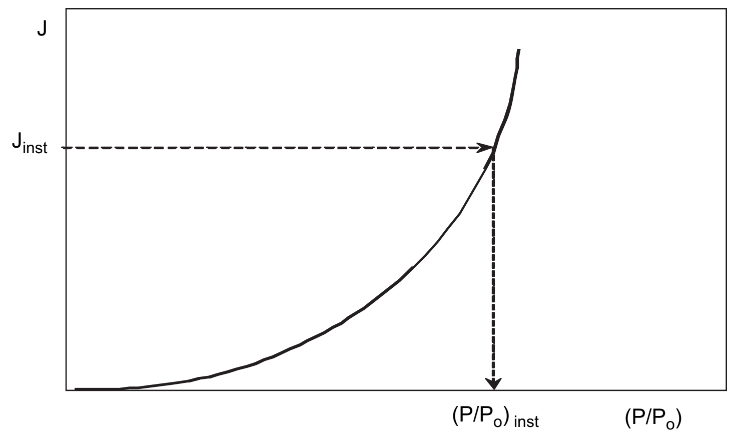


Fig. 2. Determination of the instability load.

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, which is more appropriate for materials where the failure of the component is preceded by ductile tearing and where the possibility of the complete definition of their respective J_R 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, 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 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 methods described in the previous sections was done using the electronic data sheet software *MS-EXCEL* (Jong, 2004).

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 are presented in Table 1. The percent deviations of the calculation results versus experimental values are also shown.

In Appendix 1, more information is given to clarify the application of the methods used in this work; for one of the cases described in Table 1 (CASE 4111-5 – Austenitic Pipe SA-358 type 316), details of how each one of the three methods was applied, the references and formulas that were used, and the respective graphical results obtained.

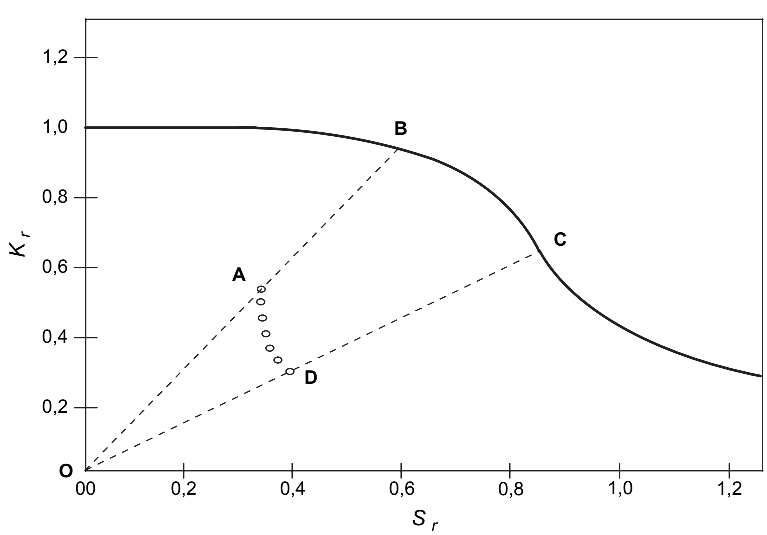


Fig. 3. Diagram DPFAD.

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	Material	Value obtained by calculation			Experimental result	Percent deviation (%) of the value obtained by calculation versus the experimental result		
CASE (literature)		Method			CASE (literature)	Method		
		J–T	DPFAD	R6		J–T	DPFAD	R6
1.1.1.23[a]	SA-358 316L	2468.6	2150.0	2361.3	3063.5	−19.4	−29.8	−22.9
4111-5[a]	SA-358 316	1228.8	1228.8	1186.3	1257.1	−2.2	−2.2	−5.6
4131-5[a]	SA-376 TP304	37.3	37.3	23.7	37.7	−1.2	−1.2	−37.1
4141-1[a]	SA-376 TP304	39.4	41.2	39.1	37.5	5.1	9.9	4.2
4141-3[a]	SA-358 304	335.9	335.9	438.4	377.0	−10.9	−10.9	16.3
4141-5[a]	SA-376 TP304	29.0	29.5	25.8	30.7	−5.5	−4.0	−16.2
SFB1[c]	SA-508 Cl3[b]	100.2	99.2	88.7	105.7	−5.2	−6.2	−16.1
STB1[c]	SA-335 GrP22	63.3	63.0	51.4	66.0	−4.1	−4.5	−22.1
SPBM TWC8-3[d]	SA-333 Gr6	92.9	93.7	91.0	88.7	4.7	5.6	2.5
SPBM TWC8-2[d]	SA-333 Gr6	122.2	119.9	120.9	124.7	−2.0	−3.9	−3.1
SPBM TWC8-1[d]	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

[a] Austenitic material; experiment performed at the operation temperature (280 °C).
[b] Pipe fabricated from a forging of the indicated material.
[c] Non-austenitic material; experiment performed at temperature between 10% and 15% higher than the operation temperature.
[d] Non-austenitic material; experiment performed at room temperature (25 °C).

6. Discussion and recommendations

Based on the results presented in Table 1, it is possible to observe that applying the J–T and DPFAD methods makes it 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.

In the development of this work, it was possible to identify the importance of the adequate characterization of the materials. The recommendations related to the material properties, required parameters, pipe and crack geometry for the execution of piping analysis can be summarized as follows:

(a) Studies developed by EPRI demonstrated that for the prediction of leak rates, in piping with through-wall circumferential cracks, the use of properties and parameters gathered from BEST FIT type stress–strain curves for the base and weld metal is 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.
(b) The J_R curves should be of the LOWER BOUND type, in order to obtain more conservative results regarding the maximum allowable loads.
(c) Two basic situations involving the mechanical properties of the material of the section submitted to the highest 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, 1984).
(d) 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%.
(e) Under small yield conditions, the parameter J can be considered independent of geometry regarding fracture analysis.
(f) 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.
(g) 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.

(h) 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.

For the computational implementation of the described methods and associated calculation routines, the following important aspects should be highlighted:

(a) The importance of gathering quality experimental data, as those listed in Table 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 of 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).

(b) Precise definition of the geometric characteristics of the cracks and components (pipes) (see Table 2), in special the initial length of the crack, considering the adequate definition of the associated parameters.

(c) 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 analyzed 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

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

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

Observations.
(a) Tension tests (stress–strain curves) allow the definition of the following parameters: E, σ_0, ε_0, σ_{uts}, σ_{ys}, α, n, ν.
(b) Test specimens $C(T)$ type allow the definition of the following parameters: J_{Ic}, C, m.
(c) 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 significant stable crack growth. In the utilization of this control technique, the load is imposed on the component being tested, increasing the displacement of a determined point (section) at a constant rate and is defined as a ‘‘quasi-static’’ loading.

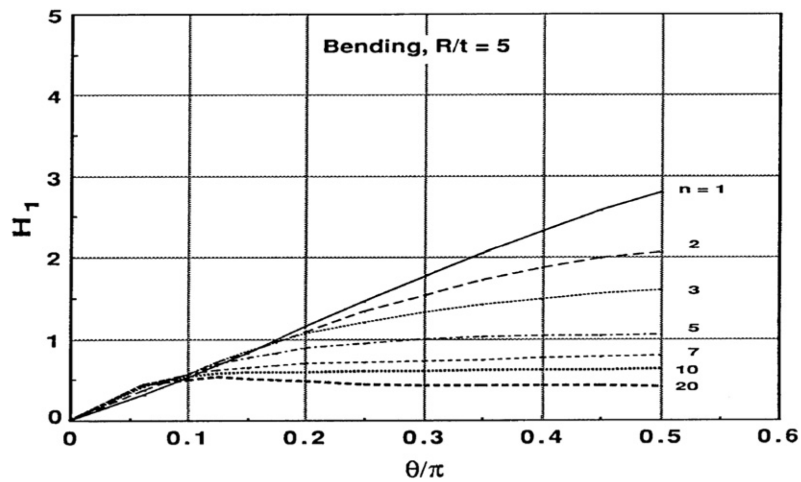


Fig. 4. Example of parametric curves for n and θ/π to obtain the value of factor H1, considering the rate $R/t = 5$ − EPRI manual (Zahoor, 1989).

will correspond to the deviations encountered in the executed tests and experiments.

(d) 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 in that manual, for pipes submitted to pure bending or axial load, containing through-wall circumferential cracks, are $0.0625 \le \theta/\pi \le 0.5$ (crack length) and $5 \le R/t \le 20$ (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 that manual (see example at Fig. 4) gives a rather good indication of the possibility to perform eventual extrapolations of greater magnitude with adequate accuracy.

(e) 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.

(f) 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.

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

During the implementation of the calculation routines using the electronic data sheet software *MS-EXCEL*, there were 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 (Jong, 2004).

7. Conclusions

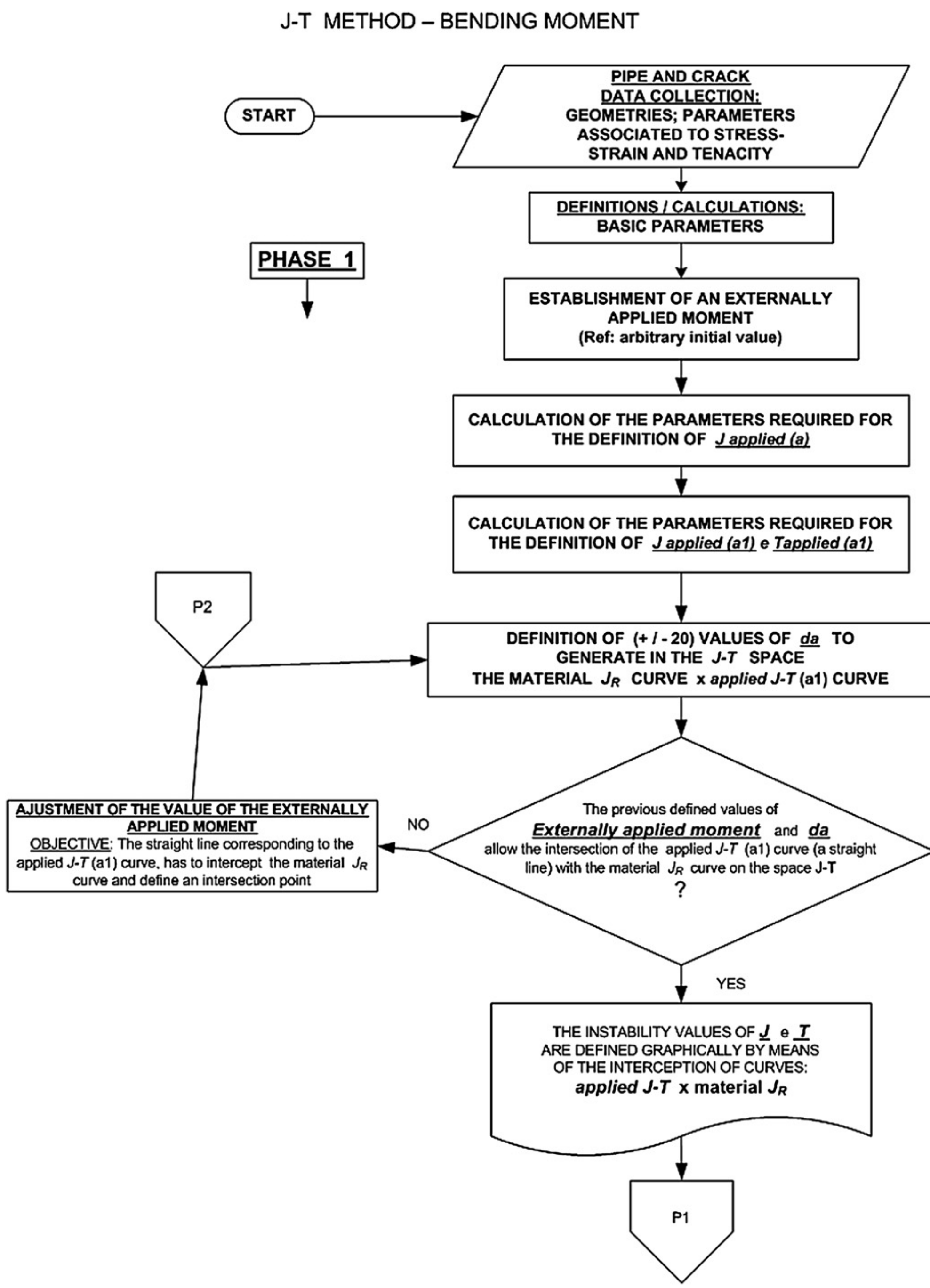
The predictions made with the application of J–T and DPFAD led to maximum bending moments with values close (some conservative and others non-conservative) to those obtained from the experiments. The results obtained with the R6 method (which in this work was applied considering a generic failure curve that takes into account a great variety of materials) presented less agreement. This method showed to be of easier application.

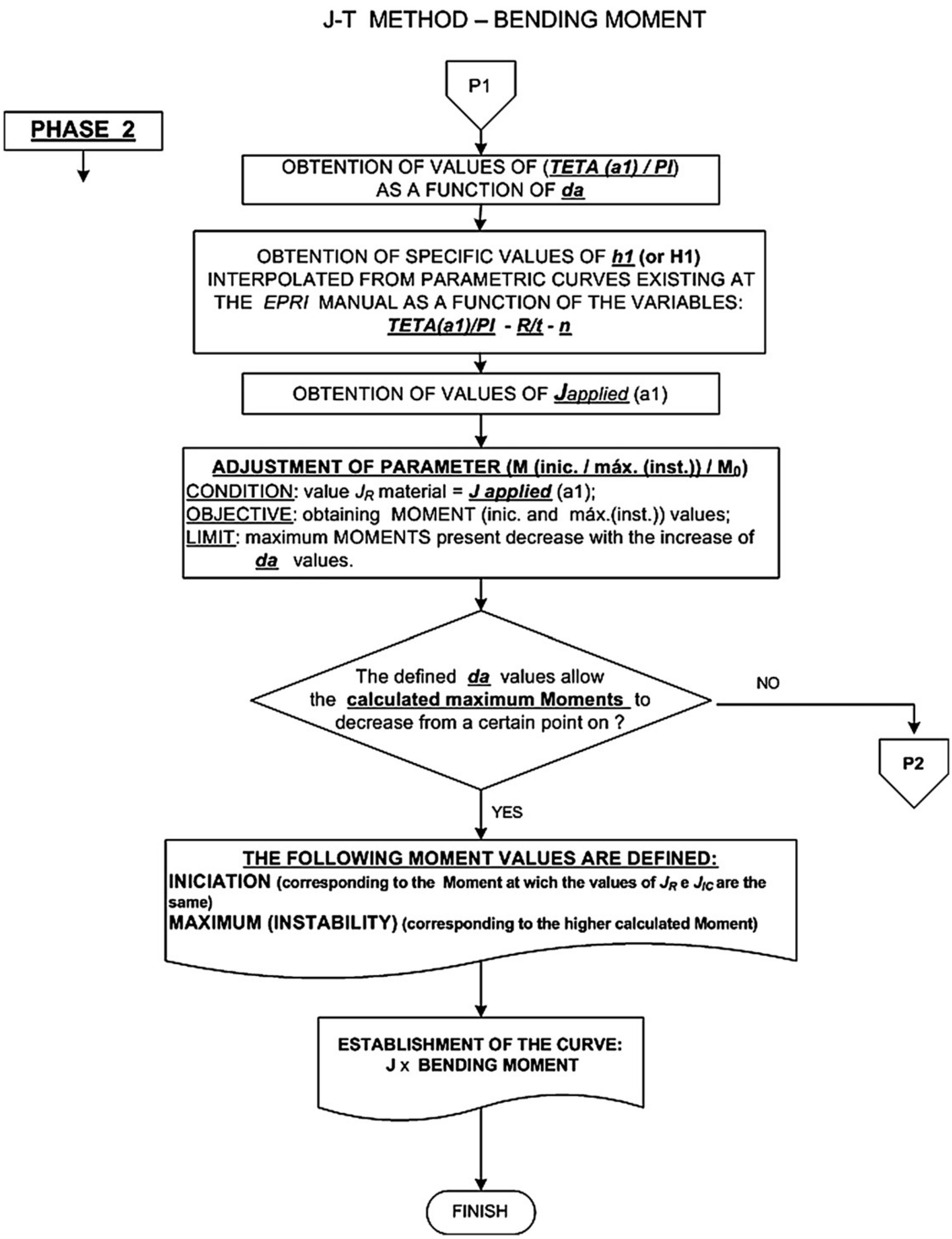
Based on the obtained deviation margins, it can be concluded that three methods can be used for the prediction of collapse of similar piping in terms of materials, geometry and type of loading. The considered cracked piping cases demonstrated that the calculation routines presented consistent results 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. Several recommendations were given regarding the consideration of the material properties, required parameters, pipe and crack geometry for the execution of piping analysis. Also, some important aspects, related to the computational implementation of the described methods, were pointed out.

Appendix 1

This appendix presents, for each one of the methods used in this work, the computation routine flowchart, references and formulas, and the graphical results obtained for one of the cases described in Table 1 (CASE 4111-5 − Austenitic Pipe SA-358 type 316).


J-T METHOD – BENDING MOMENT
START
PIPE AND CRACK DATA COLLECTION: GEOMETRIES; PARAMETERS ASSOCIATED TO STRESS-STRAIN AND TENACITY
DEFINITIONS / CALCULATIONS: BASIC PARAMETERS
PHASE 1
ESTABLISHMENT OF AN EXTERNALLY APPLIED MOMENT (Ref: arbitrary initial value)
CALCULATION OF THE PARAMETERS REQUIRED FOR THE DEFINITION OF J applied (a)
CALCULATION OF THE PARAMETERS REQUIRED FOR THE DEFINITION OF J applied (a1) e Tapplied (a1)
P2
DEFINITION OF (+ / - 20) VALUES OF da TO GENERATE IN THE J-T SPACE THE MATERIAL J_R CURVE x applied J-T (a1) CURVE
AJUSTMENT OF THE VALUE OF THE EXTERNALLY APPLIED MOMENT
OBJECTIVE: The straight line corresponding to the applied J-T (a1) curve, has to intercept the material J_R curve and define an intersection point
NO
The previous defined values of Externally applied moment and da allow the intersection of the applied J-T (a1) curve (a straight line) with the material J_R curve on the space J-T ?
NO
YES
THE INSTABILITY VALUES OF J e T ARE DEFINED GRAPHICALLY BY MEANS OF THE INTERCEPTION OF CURVES: applied J-T x material J_R
P1


J-T METHOD – BENDING MOMENT
PHASE 2
P1
OBTENTION OF VALUES OF (TETA (a1) / PI) AS A FUNCTION OF da
OBTENTION OF SPECIFIC VALUES OF h1 (or H1) INTERPOLATED FROM PARAMETRIC CURVES EXISTING AT THE EPRI MANUAL AS A FUNCTION OF THE VARIABLES: TETA(a1)/PI - R/t - n
OBTENTION OF VALUES OF Japplied (a1)
ADJUSTMENT OF PARAMETER (M (inic. / máx. (inst.)) / M0)
CONDITION: value JR material = J applied (a1);
OBJECTIVE: obtaining MOMENT (inic. and máx.(inst.)) values;
LIMIT: maximum MOMENTS present decrease with the increase of da values.
The defined da values allow the calculated maximum Moments to decrease from a certain point on ?
NO
P2
YES
THE FOLLOWING MOMENT VALUES ARE DEFINED:
INICIATION (corresponding to the Moment at wich the values of JR e JIC are the same)
MAXIMUM (INSTABILITY) (corresponding to the higher calculated Moment)
ESTABLISHMENT OF THE CURVE: J x BENDING MOMENT
FINISH

J-T METHOD - BENDING MOMENT	
References	**PIPE AND CRACK DATA** External Diameter; Thickness (t); $\theta(\text{rad})/\pi$ σ_0 ; σ_{UTS} ; σ_{FS} ; E; α; n; ε_0 J_{IC}; C; m.
Ref: 1 e 2	**BASIC PARAMETERS** R_{medium}; R/t ; Beta ; A
PHASE 1	**GRAPHICAL DEFINITION OF THE RESULTS (CURVES J_R e JT)**
Ref: 1 e 2	**REQUIRED PARAMETERS FOR THE DEFINITION OF** **J apl. (a)** M = Externally constant applied Moment (higher than the instability moment obtained experimentally). The value (M) to be adopted is the one when it is possible to achieve an intersection point between the J_R curve of the material and the straight line defined by Japplied .
	$J_{apl}(a) = J_{el.}(aef., M) + J_{pl.}(a, M, n)$ $J_{el}(aef.,M) = f_b \times \left(M^2 / R_m{}^3 t^2 E\right)$ $f_b = \frac{\theta(aef.)}{\pi} . \left\{1 + A.\left[4,5967.\left(\frac{\theta(aef.)}{\pi}\right)^{1,5} + 2,6422.\left(\frac{\theta(aef.)}{\pi}\right)^{4,24}\right]\right\}^2$ $\theta(aef.) = \theta(a).\left\{1 + \left\{\frac{\left[\left(\frac{F_b{}^2}{\beta}\right).\left(\frac{(n-1)}{(n+1)}\right).\left(\frac{\sigma_b}{\sigma_0}\right)^2\right]}{\left[1 + \left(\frac{M}{M_0}\right)^2\right]}\right\}\right\}$ $F_b = \left\{1 + A\left[4,5967\left(\frac{\theta(a)}{\pi}\right)^{1,5} + 2,6422\left(\frac{\theta(a)}{\pi}\right)^{4,24}\right]\right\}$ $\sigma_b = \frac{M}{\pi R_m{}^2 t}$ $M_0(a) = 4\sigma_0 R_m{}^2 t\left(\cos\frac{\theta(a)}{2} - 0,5\sin\theta(a)\right)$ $J_{pl.}(a,M,n) = \alpha\sigma_0\varepsilon_0\pi R_m\left(1 - \frac{\theta(a)}{\pi}\right)^2 h1\left(\frac{M}{M_0}\right)^{n+1}$ The parameter "θ" is a function of da; therefore, of a1 = a+da

<table>
<tr><td>Ref: 1 e 2</td><td>

REQUIRED PARAMETERS FOR THE DEFINITION OF
J applied (a1) e Tapplied (a1)

M = Externally constant applied Moment. The value (M) to be adopted is the one when that possibitates the achievement, in the J-T space, of an intersection point between the material J_R and the the applied J (a1) curve (a straight line), that has as origin the coordenates (0;0) on the J-T space (graphic).

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$$da = 0{,}005.\left(R_m\,\theta\left(a\right)\right)$$

$$a1 = a + da$$

To obtain the J applied (a1) parameter, substitute the variable a by the variable a1, on the refered formulas for the calculation of J applied (a) .

(dJ/dA) = (Japplied(a) - Japplied(a1)) / da

$$T\,appl.\ (a1) = \frac{\left(\frac{dJ}{da}\right).E}{\left(\sigma_{FS}\right)^2}$$

</td></tr>
<tr><td>Ref: 2</td><td>

MATERIAL J_R curve

$$JR_{mat.} = C.\left(da\right)^m$$

</td></tr>
<tr><td>PHASE 2</td><td>

NUMERICAL VERIFICATION OF THE RESULTS

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<tr><td>Ref: 1 e 2</td><td>

REQUIRED PARAMETERS FOR THE DEFINITION OF
J applied (a1)

M = Bending Moments variable with a1, applied in a arbitrary way, to obtain the Initiation Moment and the Maximum (Instability) Bending Moment.

To obtain the J applied (a1) parameter, substitute the variable a by the variable a1, on the refered formulas for the calculation of J applied (a) .

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References

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1- ZAHOOR, A. - Ductile Fracture Handbook Vol.1, Report EPRI NP-6301-D, 1989
2- ROBERT CLOUD & ASSOCIATES, INC. - ETCNSP LBB COURSE USP, July 1992

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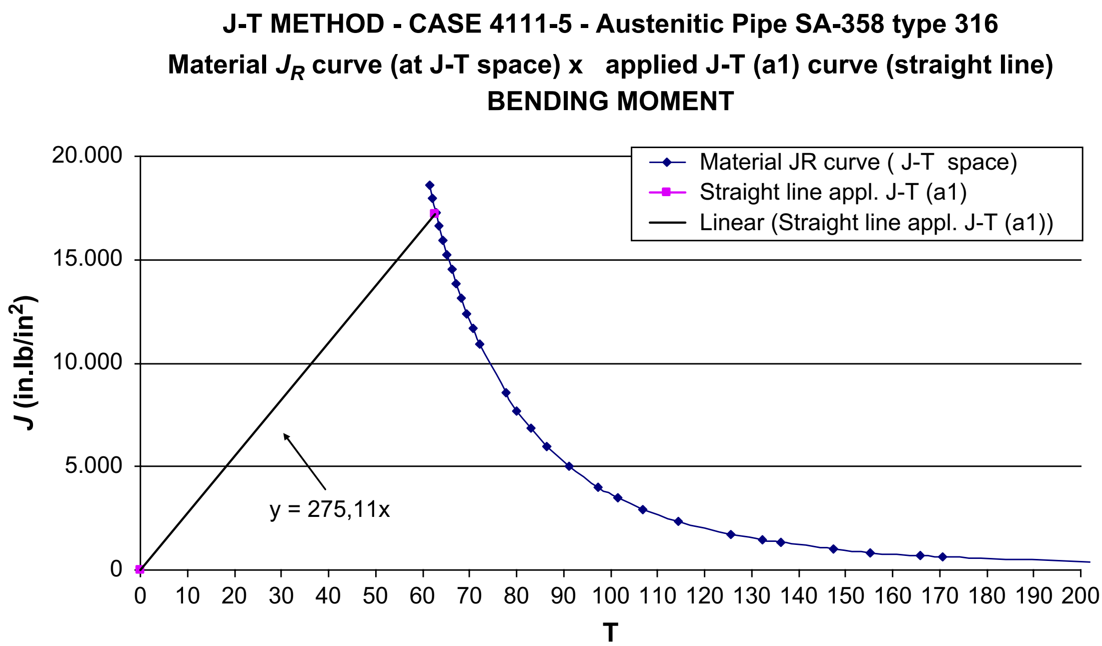
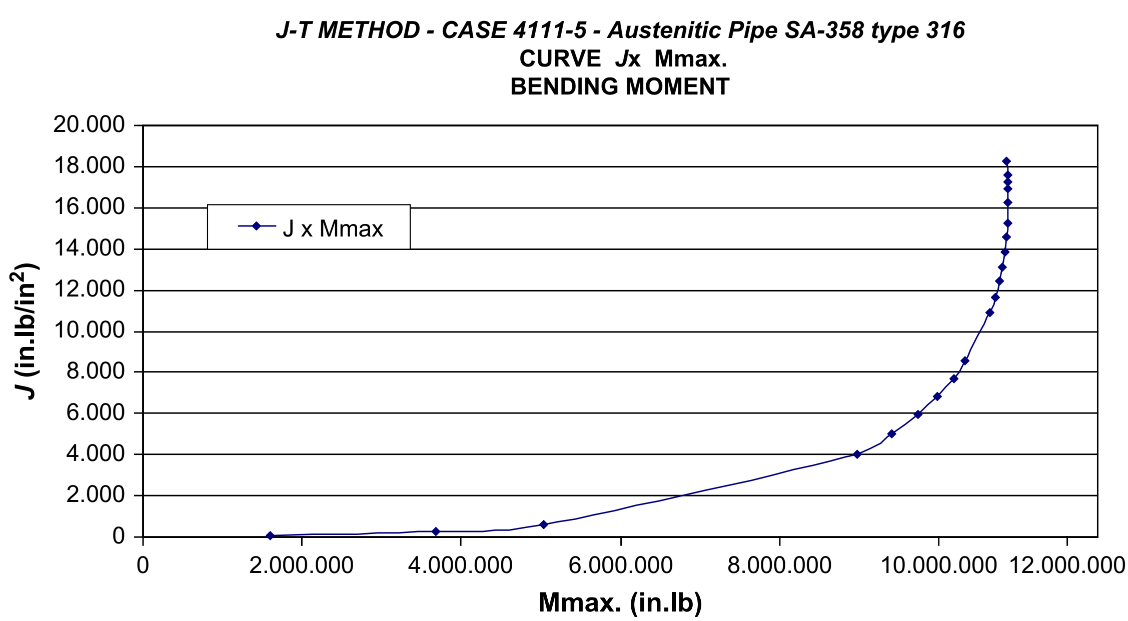
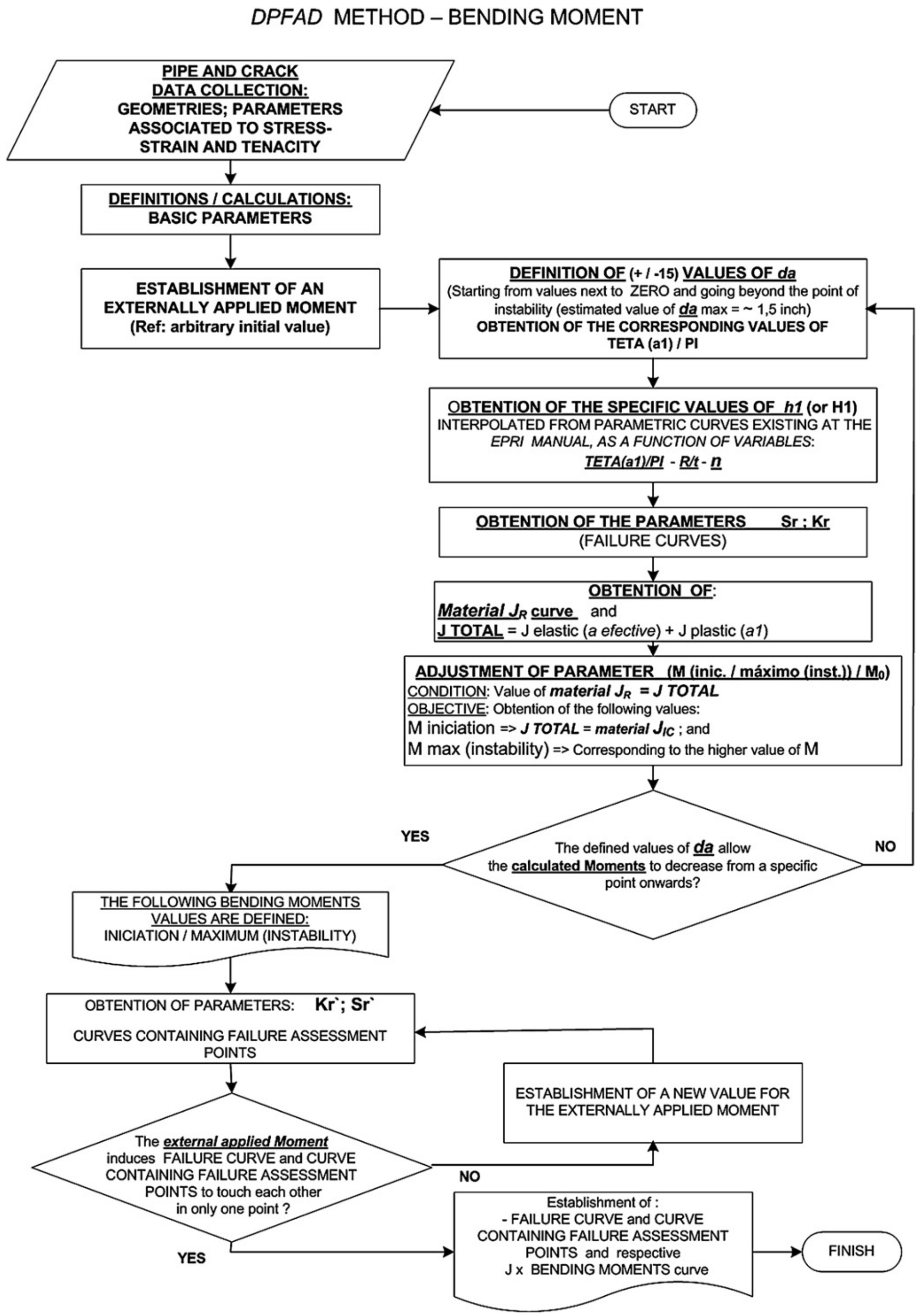

J-T METHOD - CASE 4111-5 - Austenitic Pipe SA-358 type 316
Material JR curve (at J-T space) x applied J-T (a1) curve (straight line)
BENDING MOMENT
Material JR curve (J-T space)
Straight line appl. J-T (a1)
Linear (Straight line appl. J-T (a1))
y = 275,11x
J (in.lb/in2)
T
20.000
15.000
10.000
5.000
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200


J-T METHOD - CASE 4111-5 - Austenitic Pipe SA-358 type 316
CURVE Jx Mmax.
BENDING MOMENT
J x Mmax
J (in.lb/in2)
Mmax. (in.lb)
20.000
18.000
16.000
14.000
12.000
10.000
8.000
6.000
4.000
2.000
0
0 2.000.000 4.000.000 6.000.000 8.000.000 10.000.000 12.000.000


DPFAD METHOD – BENDING MOMENT
PIPE AND CRACK DATA COLLECTION: GEOMETRIES; PARAMETERS ASSOCIATED TO STRESS-STRAIN AND TENACITY
START
DEFINITIONS / CALCULATIONS: BASIC PARAMETERS
ESTABLISHMENT OF AN EXTERNALLY APPLIED MOMENT (Ref: arbitrary initial value)
DEFINITION OF (+ / -15) VALUES OF da (Starting from values next to ZERO and going beyond the point of instability (estimated value of da max = ~ 1,5 inch) OBTENTION OF THE CORRESPONDING VALUES OF TETA (a1) / PI
OBTENTION OF THE SPECIFIC VALUES OF h1 (or H1) INTERPOLATED FROM PARAMETRIC CURVES EXISTING AT THE EPRI MANUAL, AS A FUNCTION OF VARIABLES: TETA(a1)/PI - R/t - n
OBTENTION OF THE PARAMETERS Sr ; Kr (FAILURE CURVES)
OBTENTION OF: Material J_R curve and J TOTAL = J elastic (a efective) + J plastic (a1)
ADJUSTMENT OF PARAMETER (M (inic. / máximo (inst.)) / M_0)
CONDITION: Value of material J_R = J TOTAL
OBJECTIVE: Obtention of the following values:
M iniciation => J TOTAL = material J_IC ; and
M max (instability) => Corresponding to the higher value of M
YES
The defined values of da allow the calculated Moments to decrease from a specific point onwards?
NO
THE FOLLOWING BENDING MOMENTS VALUES ARE DEFINED: INICIATION / MAXIMUM (INSTABILITY)
OBTENTION OF PARAMETERS: Kr`; Sr`
CURVES CONTAINING FAILURE ASSESSMENT POINTS
ESTABLISHMENT OF A NEW VALUE FOR THE EXTERNALLY APPLIED MOMENT
The external applied Moment induces FAILURE CURVE and CURVE CONTAINING FAILURE ASSESSMENT POINTS to touch each other in only one point ?
NO
YES
Establishment of : - FAILURE CURVE and CURVE CONTAINING FAILURE ASSESSMENT POINTS and respective J x BENDING MOMENTS curve
FINISH

DPFAD METHOD - BENDING MOMENT	
References	**PIPE AND CRACK DATA**
	External Diameter; Thickness (t)
	$\theta(\mathrm{rad})/\pi$ σ_{YS}; σ_{UTS}; σ_{FS}; E; α; n; ε_0
	J_{IC}; C; m. $\sigma_0 = \sigma_{YS}$
Ref.: 1	**BASIC PARAMETERS**
	R_{medium}; R/t; Beta
	A ; Sr max.
	FAILURE CURVE
Ref.: 2	**OBTENTION OF THE PARAMETERS Kr and Sr**
	M(a1) = M = Bending Moments variable with a1, applied in a arbitrary way, in order to obtain the Initiation Moment and the Maximum (Instability) Bending Moment.
	$Sr(a1) = \frac{M(a1)}{M_0(a1)}$ Sr varies from ZERO to the maximum defined limit
	$M_0(a1) = 4\sigma_0 R_m^2 t\left(\cos\frac{\theta(a1)}{2} - 0{,}5\sin\theta(a1)\right)$
	The parameter "θ" is a function of da; therefore, of a1 = a+da
	$Kr = \left\{\frac{J_{el.}(a1,M)}{\left[J_{el}(a_{ef.},M) + J_{plast.}(a1,M,n)\right]}\right\}^{0,5}$
	$J_{el}(a_1, M) = f_b \times \left(M^2 / R_m^3 t^2 E\right)$
	$f_b = \left[\frac{\theta(a1)}{\pi}\right]\left\{1 + A\left[4{,}5967\left(\frac{\theta(a_1)}{\pi}\right)^{1,5} + 2{,}6422\left(\frac{\theta(a_1)}{\pi}\right)^{4,24}\right]\right\}^2$
	$J_{el}(a_{ef.},M) = f_b \times \left(M^2 / R_m^3 t^2 E\right)$
	$f_b = \frac{\theta(aef.)}{\pi}.\left\{1 + A.\left[4{,}5967.\left(\frac{\theta(aef.)}{\pi}\right)^{1,5} + 2{,}6422.\left(\frac{\theta(aef.)}{\pi}\right)^{4,24}\right]\right\}^2$
	$\theta(aef.) = \theta(a1).\left\{1 + \left\{\frac{\left(\frac{F_b^2}{\beta}\right).\left(\frac{(n-1)}{(n+1)}\right).\left(\frac{\sigma_b(a1)}{\sigma_0}\right)}{\left[1 + \left(\frac{M}{M_0}\right)^2\right]}\right\}\right\}$

	$F_b = \left\{1 + A\left[4{,}5967\left(\frac{\theta(a_1)}{\pi}\right)^{1,5} + 2{,}6422\left(\frac{\theta(a_1)}{\pi}\right)^{4,24}\right]\right\}$ $\sigma_b(a1) = \frac{M(a1)}{\pi R_m^{2} t}$ $J_{pl}(a1,M,n) = \alpha\sigma_0\varepsilon_0\pi R_m\left(1-\frac{\theta(a1)}{\pi}\right)^2 h1\left(\frac{M}{M_0}\right)^{n+1}$
CURVES : material J_R and total J applied	
Ref.: 2	$JR_{mat.} = C.(da)^m$ **total $J_{applied} = J_{elastic}(aef,M) + J\ plastic\ (a1,M,n)$**
CURVE CONTAINING FAILURE ASSESSMENT POINTS	
Ref.: 2	**OBTENTION OF PARAMETERS Sr'** **(M = Constant external applied Bending Moment)**
	$Sr`(a1) = \frac{M}{M_0(a1)}$
	OBTENTION OF PARAMETERS Kr' **(M = Constant external applied Bending Moment)**
	$Kr`(a1) = \left[\frac{J_{el.}(a1)}{JR(da)}\right]^{0,5}$ $J_{el}(a_1,M) = f_b \times \left(M^2 / R_m^{3} t^2 E\right)$ $f_b = \left[\frac{\theta(a1)}{\pi}\right](F_b)^2$ $F_b = \left\{1 + A\left[4{,}5967\left(\frac{\theta(a_1)}{\pi}\right)^{1,5} + 2{,}6422\left(\frac{\theta(a_1)}{\pi}\right)^{4,24}\right]\right\}$

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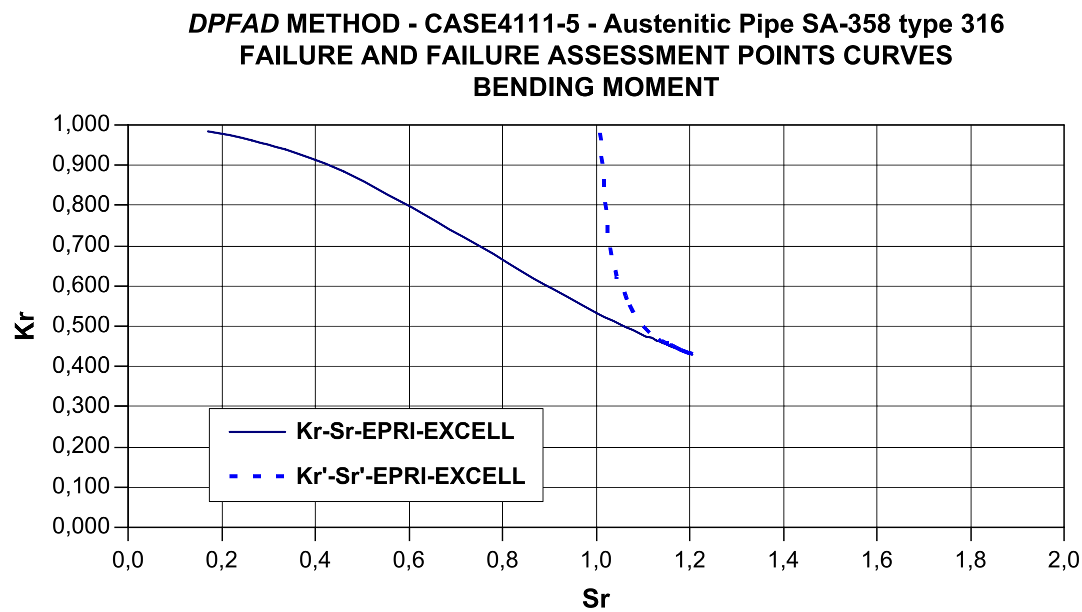
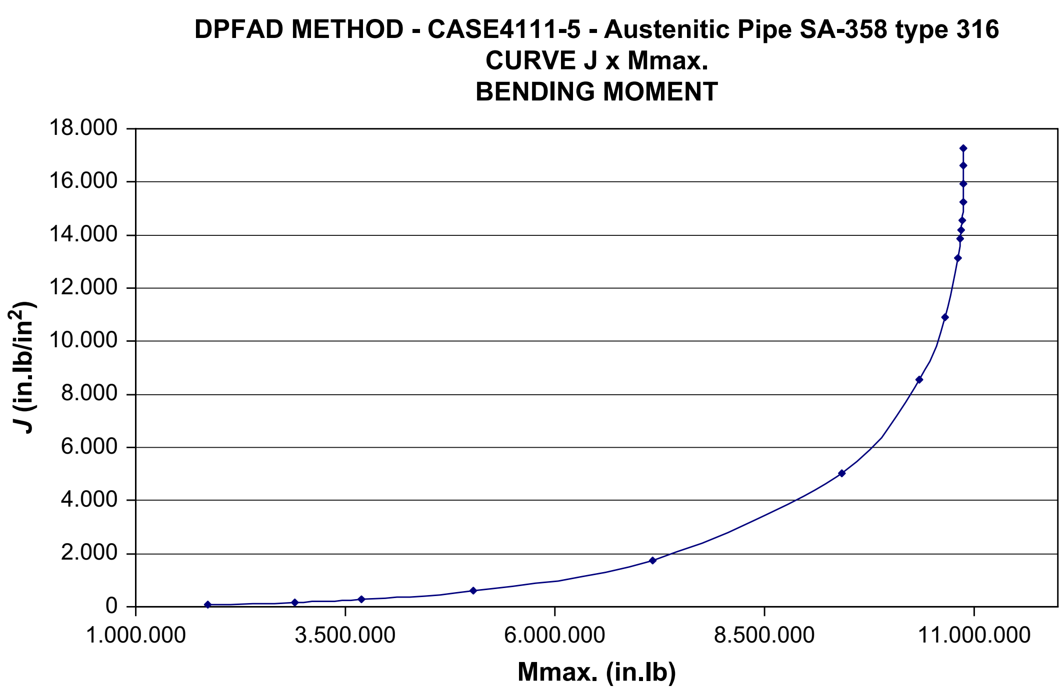
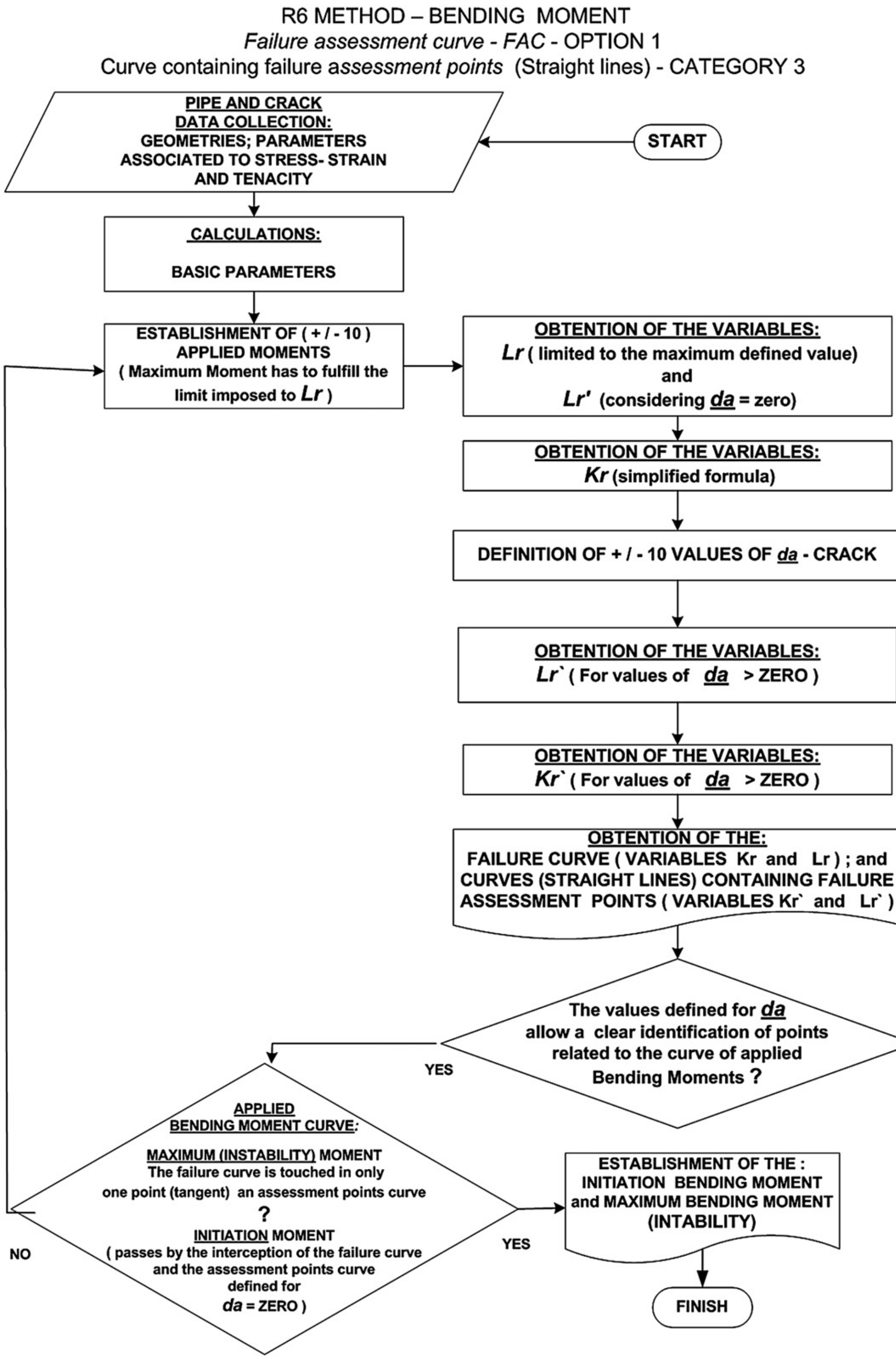
2- BLOOM, J. M. - Deformation Plasticity Failure Assessment Diagram Approach, NUREG CP-0075 / CSNI REPORT 84-97, 1984


DPFAD METHOD - CASE4111-5 - Austenitic Pipe SA-358 type 316
FAILURE AND FAILURE ASSESSMENT POINTS CURVES
BENDING MOMENT
Kr
Sr
1,000
0,900
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
0,0
0,2
0,4
0,6
0,8
1,0
1,2
1,4
1,6
1,8
2,0
Kr-Sr-EPRI-EXCELL
Kr'-Sr'-EPRI-EXCELL


DPFAD METHOD - CASE4111-5 - Austenitic Pipe SA-358 type 316
CURVE J x Mmax.
BENDING MOMENT
J (in.lb/in2)
Mmax. (in.lb)
18.000
16.000
14.000
12.000
10.000
8.000
6.000
4.000
2.000
0
1.000.000
3.500.000
6.000.000
8.500.000
11.000.000


R6 METHOD – BENDING MOMENT
Failure assessment curve - FAC - OPTION 1
Curve containing failure assessment points (Straight lines) - CATEGORY 3
START
PIPE AND CRACK DATA COLLECTION: GEOMETRIES; PARAMETERS ASSOCIATED TO STRESS- STRAIN AND TENACITY
CALCULATIONS: BASIC PARAMETERS
ESTABLISHMENT OF (+ / - 10) APPLIED MOMENTS (Maximum Moment has to fulfill the limit imposed to Lr)
OBTENTION OF THE VARIABLES: Lr (limited to the maximum defined value) and Lr' (considering da = zero)
OBTENTION OF THE VARIABLES: Kr (simplified formula)
DEFINITION OF + / - 10 VALUES OF da - CRACK
OBTENTION OF THE VARIABLES: Lr` (For values of da > ZERO)
OBTENTION OF THE VARIABLES: Kr` (For values of da > ZERO)
OBTENTION OF THE: FAILURE CURVE (VARIABLES Kr and Lr) ; and CURVES (STRAIGHT LINES) CONTAINING FAILURE ASSESSMENT POINTS (VARIABLES Kr` and Lr`)
The values defined for da allow a clear identification of points related to the curve of applied Bending Moments ?
YES
NO
APPLIED BENDING MOMENT CURVE:
MAXIMUM (INSTABILITY) MOMENT
The failure curve is touched in only one point (tangent) an assessment points curve
?
INITIATION MOMENT
(passes by the interception of the failure curve and the assessment points curve defined for da = ZERO)
NO
YES
ESTABLISHMENT OF THE : INITIATION BENDING MOMENT and MAXIMUM BENDING MOMENT (INTABILITY)
FINISH

R6 METHOD - BENDING MOMENT	
Failure assessment curve - FAC **OPTION 1 (Ref.: 2)** **Curve containing failure assessment points (straight lines)** **CATEGORY 3 (Ref.: 1 e 2)**	
References	**PIPE AND CRACK DATA** **External Diameter; Thickness (t);** $\theta(\ rad\ )/\ \pi$ $\sigma_0; \sigma_{UTS}; \sigma_{FS}; E; \alpha; n; \varepsilon_0$ $\sigma_{YS} = \sigma_0$ J_{IC}; C; m.
Ref.: 1, 2 e 3	**BASIC PARAMETERS** R_{medium}; R/t; a_0; A; Lr max.
Ref.: 2	**OBTENTION OF VARIABLES Lr and Lr\` for da = ZERO** For da = ZERO we have Lr = Lr\` $Lr' = M \Big/ 4\sigma_{YS} R_m^2 t\left(\cos\frac{\theta}{2} - 0{,}5\sin\theta\right)$ M = External Bending Moments applied in a arbitrary way.
Ref.: 2	**OBTENTION OF VARIABLES Kr (simplified formula)** $Kr = (1 - 0{,}14Lr^2)[0{,}3 + 0{,}7\exp(-0{,}65Lr^6)]$ for Lr < = Lr max. Kr = ZERO, for Lr > = Lr max.
Ref.: 2	**OBTENTION OF VARIABLES Lr' for da > ZERO** $Lr' = M \Big/ 4\sigma_{YS} R_m^2 t\left(\cos\frac{\theta}{2} - \frac{\sin\theta}{2}\right)$ The parameter "θ" is a function of da; therefore, of a1 = a+da M = External Bending Moments applied in a arbitrary way.
Ref.: 1 ; 2 e 3	**OBTENTION OF VARIABLES Kr' for da > ZERO** Kr\` = K_I elastic (a+da) / K material (da) $Kr' = M\left\{1 + A\left[4{,}5967\left(\theta/\pi\right)^{1,5} + 2{,}6422\left(\theta/\pi\right)^{4,24}\right]\right\}(\pi R_m \theta)^{0,5} \Big/ \pi R_m^2 t (J_{mat} E)^{0,5}$

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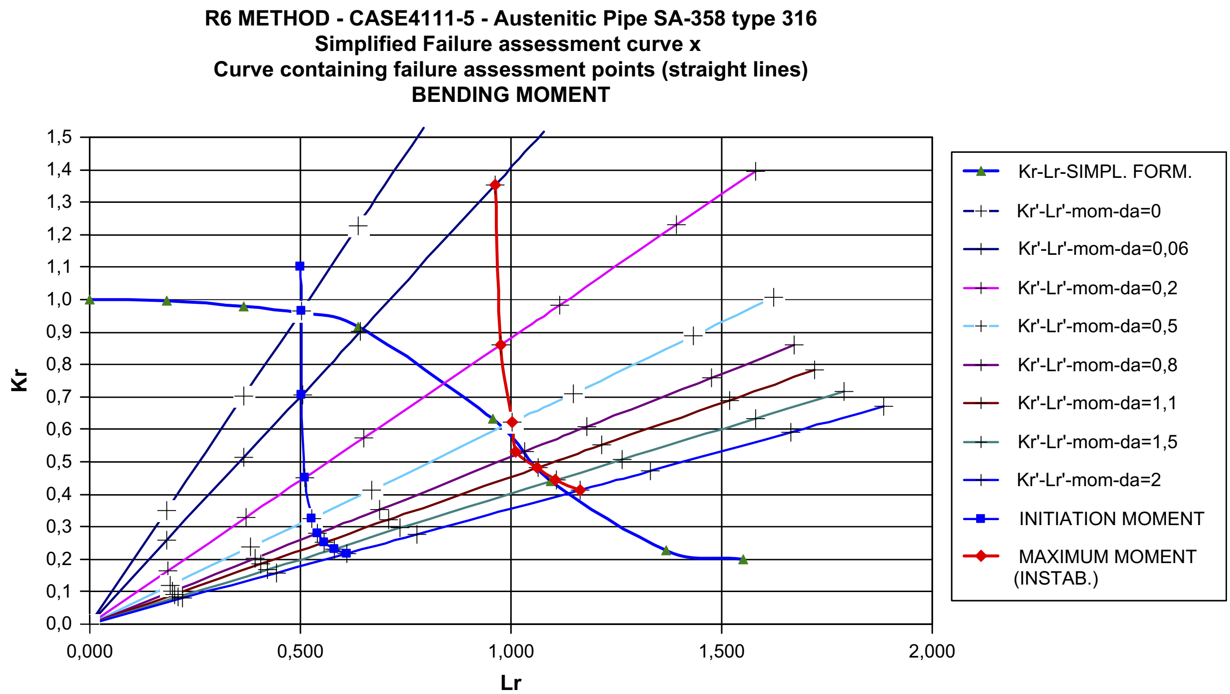

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