DEFECT ASSESSMENT PROCEDURE BASED ON A SIMPLIFIED METHOD TO ESTIMATE J

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In the nuclear industry, it is more and more usual to perform fracture assessment on defective structures made of ductile material with the help of elastoplastic fracture mechanics relying on the parameter J. Several engineering methods were recently proposed in the literature (EPRI, R6) to calculate this parameter. These results were used to develop a practical method (Js method) in the appendix A16 of the French RCC-MR construction code for fast breeder reactors which simply gives J as a function of elastically calculated Je and a plastic correction factor . This method is used in order to evaluate the margins against crack initiation and crack instability.
This paper reviews the development of this method. Results on representative cracked pipes calculated by the Js method are compared with experimental and elastic plastic finite elements solutions .

INTRODUCTION

In the nuclear industry, it is more and more usual to perform fracture assessment on defective structures made of ductile material with the help of elastoplastic fracture mechanics relying on the parameter J. Several engineering methods were recently proposed in the literature (EPRI [1], R6 [2]) to calculate this parameter.

These results were used to develop a practical procedure noted Js method which simply gives J as a function of elastically calculated Je and a plastic correction factor. This method has been introduced in the appendix A16 [3] of the French RCC-MR [4] construction code for fast breeder reactors in particular in order to evaluate the margins against crack initiation and crack instability.

The present paper reviews the A16 defect assessment procedure in particular to avoid plastic collapse and crack instability. This assessment procedure is examined through two simple but representative examples using the simplified estimation of J which is compared with finite element analyses and experimental estimates of J.

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A16 DEFECT ASSESSMENT PROCEDURES

Plastic collapse and crack instability on a structure containing a defect of initial size a_o must be avoided according A16 defect assessment procedures.

Plastic collapse

In order to avoid **plastic collapse**, the primary stresses in the cracked geometry should not exceed the usual limits specified by construction code for the non defective structure according to the level A, C or D of criteria. For example, if the limit analysis is used, the characteristic stress $S_o = (C/C_L)/R_L$ should not exceed the following values :

- level A : $S_o \leq S_m$
- level C : $S_o \leq \mathrm{Min}\{1.35S_m, S_y\}$
- level D : $S_o \leq \mathrm{Min}\{2.4S_m, 0.7S_u\}$

where C is the specified load, C_L the limit load for the cracked geometry obtained for an elastic perfectly plastic material with a yield strength R_L. S_m, S_y, S_u : allowable stress, yield strength and ultimate strength of the material.

Crack instability

The specified loading (C) shall not exceed the loading that induces the crack instability (C_{inst}). That instability loading is deduced from the conditions which signify (Fig.1) tangency between the J_R material curve and the J curve of the defective structure : $J = J_R$ and $dJ/da = dJ_R/da$.

This procedure takes into account the strain hardening capacity of some materials as austenitic steels and their ability to accomodate significant stable crack growth. A conservative value can be obtained considering only crack initiation which is avoided if $J \leq J_{IC}$.

BACKGROUND TO THE Js METHOD (SIMPLIFIED METHOD TO CALCULATE J)

To apply A16 procedures, J parameter must be calculated for the specified load C applied to the structure containing a defect of size a. Since the work of Rice [5], practical methods for calculating J have been developed by the EPRI [1] and the R6 rule [2] in order to apply elastic-plastic fracture mechanics to cracked components in an industrial environment.

In the limit of the linear fracture mechanic, the calculated value of J (noted J_e) is related to the stress intensity factor K_I by the equation : $J_e = K_I^2 / E^*$, where E^* is Young's modulus, E, divided by $(1 - \nu^2)$, where ν is Poisson's ratio, in plane strain ; $E^* = E$ in plane stress.

When plastic deformations appear but remain small, correction methods for the calculation of K_I are proposed. They consist, for example, of increasing the crack size along the length of the plastic zone formed at the crack tip [6].

When the plastic deformations are greater and extend over the cracked component, the criterion K_I can no longer be applied even with this correction. It no longer has any physical significance. It is then necessary to make use of elastic-plastic fracture mechanics to estimate J.

It must be acknowledged that the most practical method was first established by Ainsworth [7] and then developed by Roche [8]. As noted by the experimentalists, this method expresses that, under load controlled, J is proportional to the ratio of the strain in the structure to the elastic strain : $J/J_e = \epsilon/\epsilon_e$.

Ainsworth [7] introduced the reference stress which, by using the tensile stress-strain curve, makes it possible to determine the strain in the structure. A conservative estimation of the reference stress is deduced from limit analysis of the structure containing the defect. As for K_I, there is now an handbook which gives limit loads for a lot of mechanical configurations [9]. There are now numerous validations of this procedure [10,11] considering a large number of materials and configurations.

Finally, as proposed in A16 procedures, the simplified estimation J_s of J is defined by :

$$J_s = J_e . K_J \qquad \text{with} \quad K_J = [\,\psi + \epsilon_{ref}/(\sigma_{ref}/E)] \geq 1$$

- σ_{ref} is the reference stress.
- ϵ_{ref} is the reference strain obtained from the uniaxial tensile stress-strain curve of the material at the stress level σ_{ref}.
- J_e is the elastic calculated value of J for the load corresponding to σ_{ref}.
- the first term $\psi = 0.5(\sigma_{ref})^2/[(\sigma_{ref})^2 + (S_y)^2]$ is a plasticity correction term introduced for the small plastic zone.
- S_y is the yield stress corresponding to a 0.2 % plastic strain.
- $K_J = [\,\psi + \epsilon_{ref}/(\sigma_{ref}/E)]$ is the correction factor, obviously greater than 1, determined with the tensile stress-strain curve of the material.

and needs:

* the tensile stress-strain curve of the material
* the limit load formula
* the stress intensity factor formula.

APPLICATION TO A PIPE UNDER TENSION

To illustrate the procedure for calculating J_s, we have chosen a configuration representative of piping with an external circumferential crack subjected to an axial force, which produces a nominal axial stress σN in the section far from the notch (Fig.2).
The material is a A48 ferritic steel at a temperature of 300°C where the tensile stress-strain curve used is that of the RCC-MR A3.12S [3].

Application of Js method

The evaluation of each of the terms used in the J_s method is illustrated below :

- the stress intensity factor K_I is given by a formula of the type $K_I = F_1 . \sigma_N \sqrt{\pi a}$, where F_1 is a geometrical factor dependent on the geometry and on the definition of σ_N [12]. Then $J_e = K_I^2/E$ can be calculated.
- the limit load or the limit stress (taken here as equal to the reference stress) is obtained by the formula $\sigma_{ref} = F_2\ \sigma_N$ where $F_2 = h / (h - a)$
- the tensile stress-strain curve of the material is shown in Fig.3.

The curve giving the plastic correction $K_J = [\ \psi + \epsilon_{ref}/(\sigma_{ref}/E)]$ as a function of the nominal axial stress σ_N is shown in Fig.4. When σ_N is well below the elastic limit, $K_J = 1$. For a stress σ_N equal to this value, the correction is of the order of 8, therefore J_s is 8 times greater than J_e elastic.

Comparison of Js with J obtained by the finite-element technique

The tensile stress-strain curve used is that shown in Fig.3. The results calculated by the Js method are compared (Fig.5) with those obtained by an elastic-plastic calculation of J by the CASTEM 2000 finite-element code [13] using the $G(\theta)$ method [14].
Below the yield stress, J finite-element solutions agree well with those obtained by the simplified J_s method. Due to the horizontal plateau in the ferritic stress-strain curve, the values obtained by the simplified Js method can overestimate in this zone the J finite element solutions by a factor of 4. Outside of this zone, the agreement between the two methods is good but with a slightly non conservatism around $J_{0,2}$ value.

APPLICATION TO A PIPE UNDER BENDING

To illustrate by an other example the procedure for calculating Js and also to evaluate the possibility of a stable crack growth after the initiation, the case of a pipe with an external circumferential crack subjected to bending moment M is presented (Fig.6). This test has been performed at CEA and has been used as benchmark for the IPIRG programme [15].

The material is a 316SS steel at room temperature ; the tensile stress-strain curve is shown in Fig.7 and the J_R-Δa curve of the material is shown in Fig.8.

Application of Js method

The stress intensity factor $K_I = Fb.\sigma_M.(\pi.r_m.\beta)^{1/2}$ where $Fb = 1+A.[4,5967(\beta/\pi)^{1,5}+2,6422(\beta/\pi)^{4,24}]$ and $M = \sigma_M \pi r_m^2 h$, the reference stress $\sigma_{ref} = (\sigma_M.\pi/4)/(\cos 0.5\beta - 0,5\sin\beta)$ are given in the Zahoor's handbook [16]. The elastic value $J_e = K_I^2/E$ and, using the tensile stress-strain curve of the material, the plastic correction factor $K_J = [\,\psi + \epsilon_{ref}/(\sigma_{ref}/E)]$ can then be calculated.

As proposed generally and detailed for example in appendix A16 of the RCC-MR, it is possible to evaluate the stable propagation after initiation by using the J_R-Δa of the material. This propagation is stable only if the two following conditions are satisfied :

$$J_R(\Delta a) = J(a_o+\Delta a) \quad (1) \qquad \text{and} \qquad dJ(a_o+\Delta a)/da = dJ_R(\Delta a)/da \quad (2)$$

To perform this analysis, one way is to calculate by the J_s method the curves giving the values of J for constant loading and draw them in a diagram containing the J_R-Δa curve of the material adjusted at the initial size of the crack (a_o) (Fig.1). The point of instability is the point of tangency between one J curve in the pipe and the J_R-Δa of the material (equation 2).

As a matter of fact, it is not necessary to calculate the complete set of J curves in the pipe for different values of the moment M. A more practical way to determine the instability load is to notice that the J value of the cracked pipe must follow the J_R-Δa curve of the material (equation 1) and to determine for each value of Δa that values of σ_{ref} and ϵ_{ref} (these two values are linked by the tensile stress strain curve) which satisfy $J_R(\Delta a) = J(a_o+\Delta a)$. For that value of Δa, the value of the applied moment can be determined from the equation $M = \sigma_{ref}(4r_m^2h)/(\cos 0.5\beta - 0,5\sin\beta)$. By this way, it is possible to calculate directly the path of the "real" resisting moment and to obtain the maximal (instability) value of the moment.

Comparison of calculated and experimental moments of instability

The results calculated by the Js method are compared with those obtained by an elastic-plastic calculation of J by the CASTEM 2000 finite-element code [13] using the $G(\theta)$ method [14] or by using the area delimited by experimental relation between the bending moment and the rotation (Fig.9 and 10). In the elastic regime, the two methods gives the same results which signifies a correct value of K_I ; where plasticity appears, the maximum value of the bending moment derived from the Js method is 20% lower than the experimental maximum moment due to the choice of the reference stress.

CONCLUSIONS

A simplified method for estimating J (Js method) has been presented which can be used where the K_I formula, the limit load formula and the tensile stress-strain curve of the material are available.

This Js formulation, given in appendix A16 of the RCC-MR nuclear construction code, makes easy instability estimation using the J_R-Δa curve of the material.

The applications shown that it gives a reasonnable agreement for such a simplified method which can be implemented on a personal computer.

SYMBOLS USED

a :	defect size
a_o :	initial defect size
C :	applied load
C_L :	limit load of the defective structure
E* :	$E/(1 - \nu^2)$ in plane strain ; E in plane stress.
h :	pipe wall thickness
J :	parameter J of the defective structure
J_e :	elastic evaluation of the parameter J
J_s :	simplified evaluation of J
J_{IC}:	material resistance parameter at initiation
J_R :	material resistance parameter
K_J :	plastic correction factor on J_e
M :	applied bending moment
R_L :	yield strength of the elastic perfectly plastic material.
r_m :	pipe mean radius
S_m :	allowable stress
S_y :	yield strength
S_u :	ultimate strength
β :	crack half angle
Δa :	crack growth
ϵ :	strain

ϵ_e : elastic strain
ϵ_{ref} : reference strain
ν : Poisson's ratio
σ_{ref}: reference stress
σ_N : applied nominal axial stress
σ_M : applied nominal bending stress
ψ : plasticity correction term for small scale yielding

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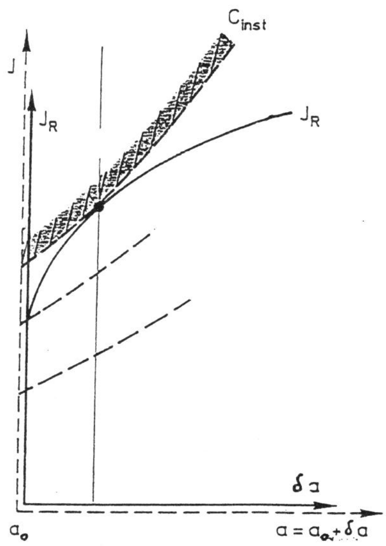
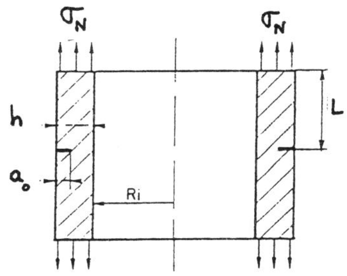


Fig.1 : Determination of instability by tangency method



h = 37 mm   Ri = 369 mm

$a_o/h = 0.25$ L = 500 mm

$E^* = E = 191500\ N/mm^2$

$\nu = 0.3$ $Sy = 186\ N/mm^2$

Fig.2 : Pipe under tension

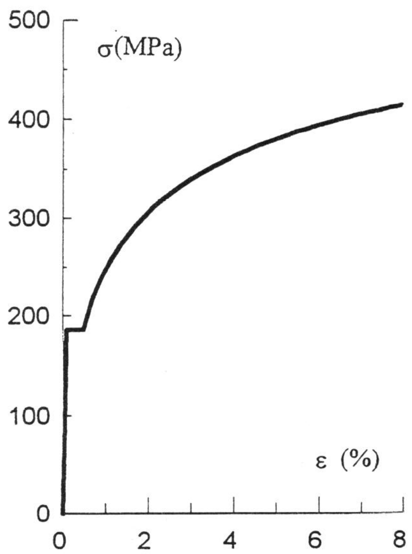


Fig.3 : A48 ferritic stress strain curve.

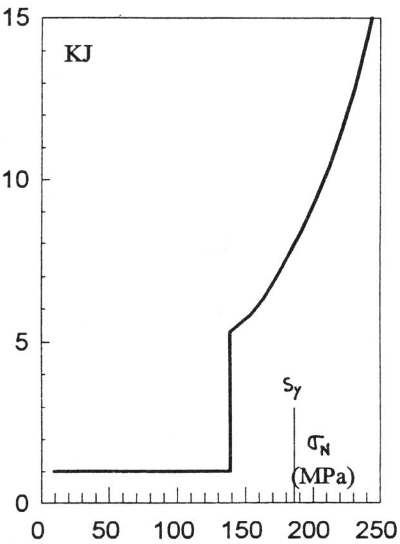


Fig.4 : Plastic correction factor KJ (Pipe under tension).

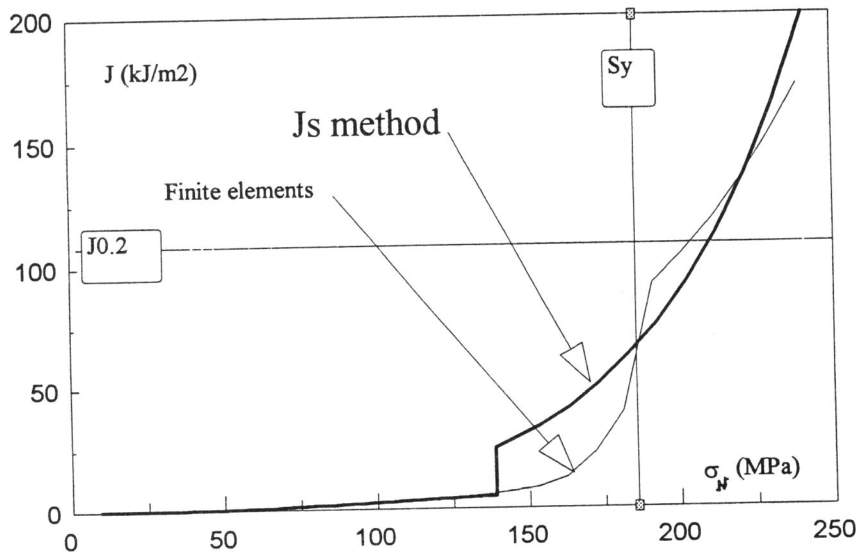
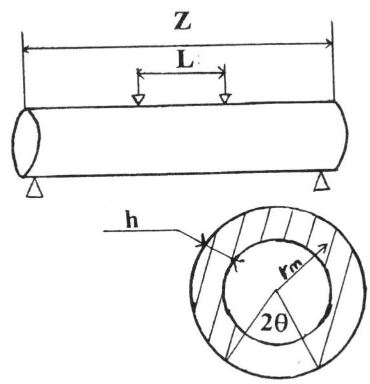


Fig.5 : Comparison between Js method and J obtained by finite element method for pipe under tension.



r_m = 48.5 mm
h = 8.41 mm
2θ = 120 deg.
Z = 1.9 m
L = 1.1 m

Fig.6 : Pipe under bending

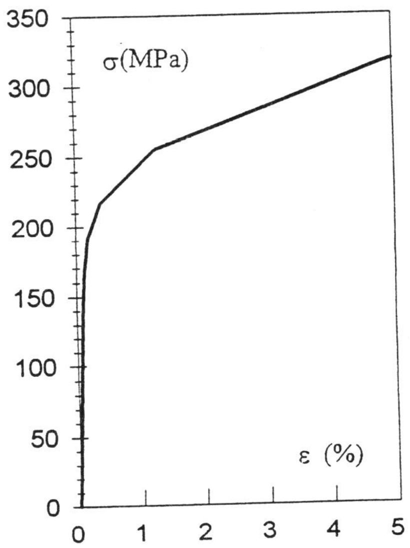


Fig.7 : 316SS stress strain curve

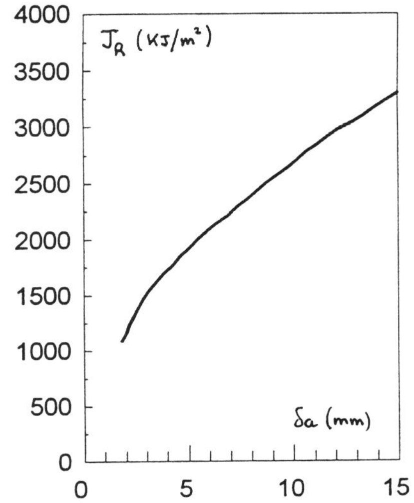


Fig.8 : 316SS JR-δa curve.

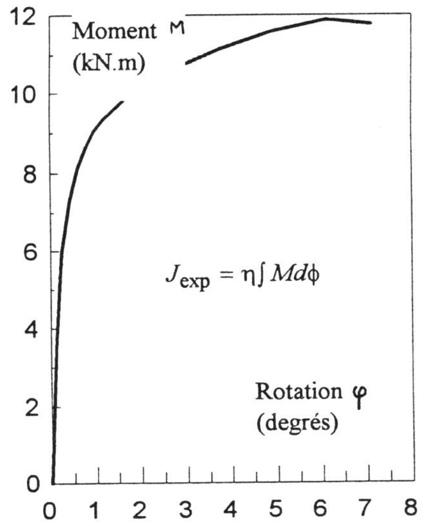


Fig.9 : Determination of Jexp using experimental curve $M=f(\varphi)$.

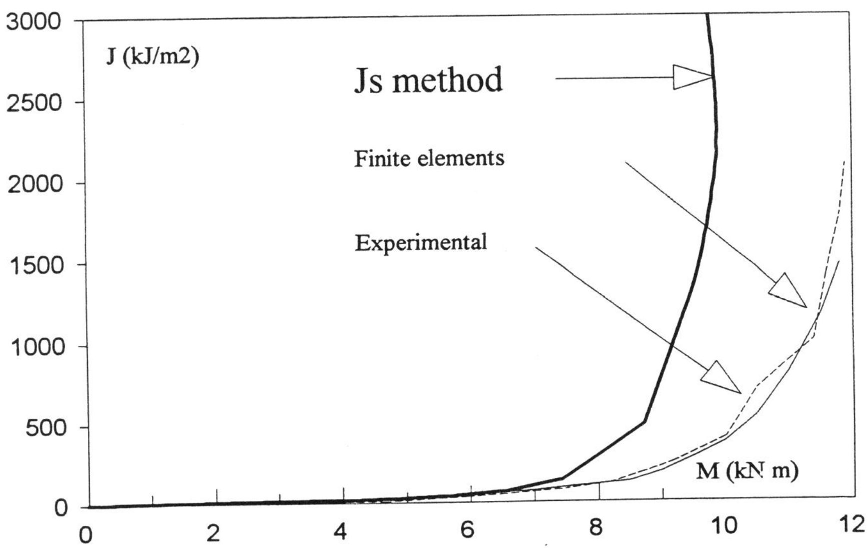


Fig.10 : Comparison between Js method and J obtained by finite element method or by experimental determination for pipe under bending.