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Evaluation of ductile tearing in a cracked component with a simple method (Js)

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1. 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 have been developped in the past (EPRI, R6) 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 A16 rule developped jointly by CEA-EdF and Novatome for fast breeder reactors in particular in order to evaluate the loading at crack instability taking into account ductile tearing. The determination of initiation has already been presented (D.Moulin,1994).

This determination of the loading at crack instability is examined through two simple but representative examples using the simplified estimation of J. Predicted loadings at crack instability are compared with experimental results.

This study was carried out as a part of cooperative program with the Institut de Protection et de Sureté Nucléaire of the CEA.

2. BACKGROUND OF THE Js METHOD

Since the work of Rice [1968], practical methods for calculating J have been developed by EPRI [Kumar, 1981] and the R6 rule [Ainsworth, 1986] 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 Je) is related to the stress intensity factor K_I by the equation $J_e = K_I^2 / E^*$ where, in plane strain, E^* is the Young's modulus E divided by $(1-\nu^2)$ where ν is Poisson's ratio ($E^* = E$ in plane stress).

When plastic deformations appear but remain small, correction methods for the calculation of K_I increasing the crack size along the length of the plastic zone formed at the crack tip [Irwin, 1957] are proposed. But 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 is then necessary to make use of elastic-plastic fracture mechanics to estimate the strain energy release rate criterion J.

As noted by the experimentalists, J is proportional to the ratio of the strain (ε) in the structure to the elastic strain (ε_e) : $J / J_e = \varepsilon / \varepsilon_e$. The practical method taking into account this proportionality was first established by Ainsworth [1984] and then developed by Roche [1988]. Ainsworth introduced the reference stress which, by using the tensile stress strain curve, makes it possible to determine the strain (ε) in the structure. A conservative estimation of the reference stress is deduced from limit analysis of the structure containing defect. As for K_I, there is now an handbook which gives limit loads for a lot of mechanical configurations [Miller, 1988]. Numerous validations of this procedure [Milne, 1988] have been performed considering a large number of materials and structures containing defects. As proposed in A16 procedures [Drubay et al, 1993], the simplified estimation Js of J needs :

- the limit load formula to determine the reference stress σ_{ref} ,
- the tensile stress-strain curve of the material to determine the reference strain ε_{ref} corresponding to σ_{ref},
- the stress intensity factor formula K_I to determine $J_e = K_I^2 / E^*$.

The simplified estimation of J is then defined by :

$$J_s = J_e \cdot k_{JA16} \qquad \text{with} \qquad k_{JA16} = \left[\psi + \frac{E\varepsilon_{ref}}{\sigma_{ref}} \right]$$

- k_{JA16} is a correction factor greater or equal to 1,
- ψ is a plasticity correction term introduced for the small plastic zone.

3. PRACTICAL DETERMINATION OF THE LOADING AT INSTABILITY

Stability is determined by whether or not the applied loading produces forces tending to open the crack which exceeds the resistance of the material to this crack avancement. As proposed generally it is possible to evaluate the stable propagation after initiation by using the $J_R - \Delta a$ curve of the material. This propagation is stable only if the following two conditions are satisfied :

$$J_R(\Delta a) = J(a_o + \Delta a) \qquad \text{and} \qquad \frac{dJ(a_o + \Delta a)}{da} < \frac{dJ_R(\Delta a)}{da}$$

To perform this analysis, one way is to calculate the "fictitious" curves giving the values of J for constant loading and draw them in a diagram containing the $J_R - \Delta a$ curve of the material adjusted at the initial sizing of the crack a_o. The point of instability is the point where the $J_R - \Delta a$ curve of the material is tangent to one of the J curve of the structure.

As a matter of fact, it is not neccesary to calculate the complete set of J curves of the structure for different values of the applied loading. A more practical way to determine the instability load is to notice that the J value of the cracked structure follow the $J_R - \Delta a$ curve of the material an then 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 load is calculated and it is therefore possible to calculate directly the path of the "real" load and then to determine the maximal (instability) value of the load.

4. APPLICATION TO CRACKED PIPE UNDER BENDING

To illustrate the procedure for calculating the load of instability, we have chosen an experiment conducted at Battelle for the Nuclear Regulatory Commission's Short Cracks in Piping and Piping Welds Research Program [NRC,1991]. The test specimen - 711 mm outside diameter carbon steel pipe - contained an internal circumferential surface crack and was loaded at 288°C in four point bending with an internal pressure of 9.56 MPa (Fig.1). Stress- strain curve (Fig.2) and two J_R-Δa curves (Fig.3) have been used to determine the load at instability (maximum moment) following the procedure described above (Fig.4). Predicted values of the maximum moment (Fig.5) are about 95% of the experimental result despite the J_R curve used.

5. APPLICATION TO A CRACKED PLATE UNDER TENSION

The second example to illustrate the procedure for calculating the load of instability, is a test performed at AEA Technology [Sharples, 1990] on a 316 stainless steel plate under tensile loading with a semi-elliptical surface crack (Fig.6). Using the stress- strain curve (Fig.7) and the J_R-Δa curves (Fig.8) the load at instability (maximum moment) has been determined according to the procedure described above (Fig.9). Predicted value of the maximum loading (Fig.10) are about 90% of the experimental result.

6. CONCLUSIONS

A simplified method for estimating J (Js method) has been presented. This method can be u: where the K_I formula, the limit load formula and the tensile stress strain curve of the materia available.

Using this Js formulation, a simple numerical procedure has been proposed to estimate loading at instability taking into account the ductile tearing using the JR-Δa curve of material followed by the J value of the cracked structure.

Two examples show that it gives a reasonnable agreement with experimental results. T method has been implemented on a personal computer.

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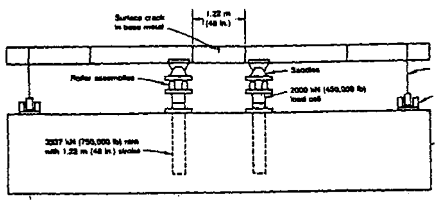

Figure 1 : Schematic of pipe in load frame(Test 1.2.3.16 Short Crack Program)

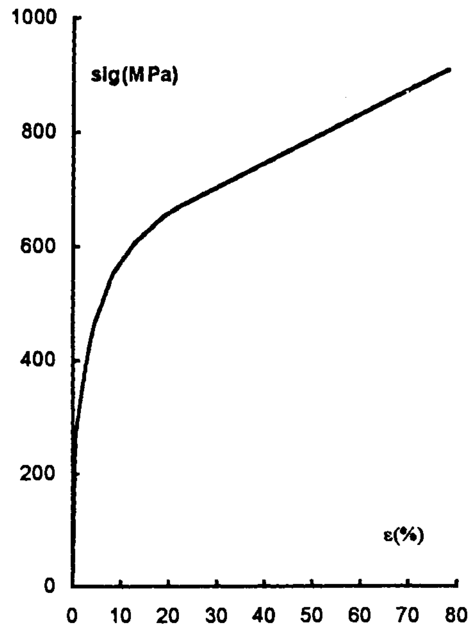

Figure 2 : Stress strain curve DP2 F26.5 at 288°C

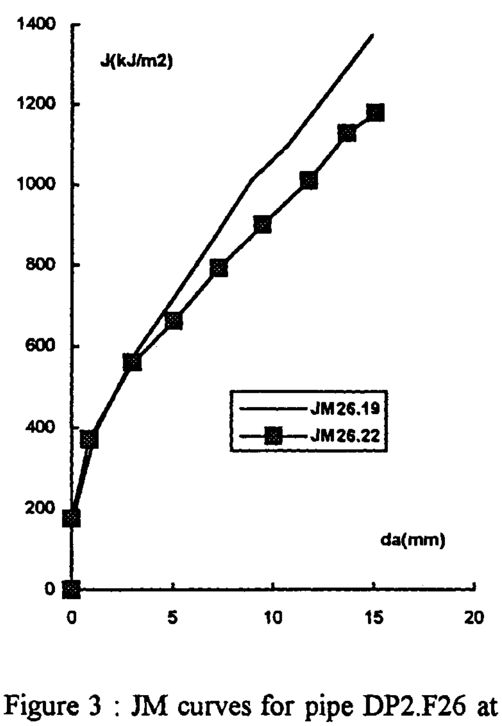

Figure 3 : JM curves for pipe DP2.F26 at 288°C

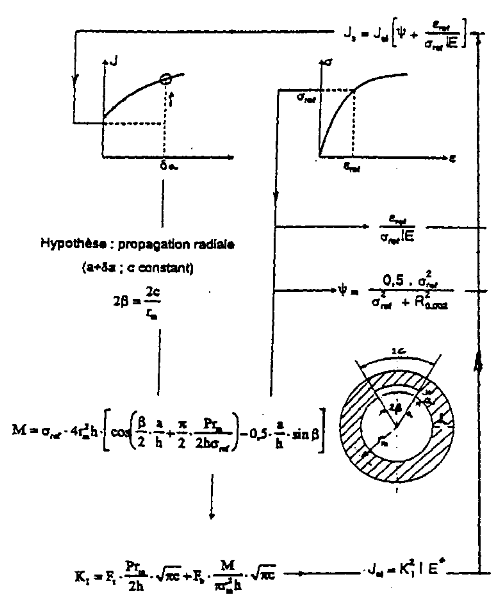

Figure 4 : Jsin flow chart for a cracked pipe under bending and internal pressure

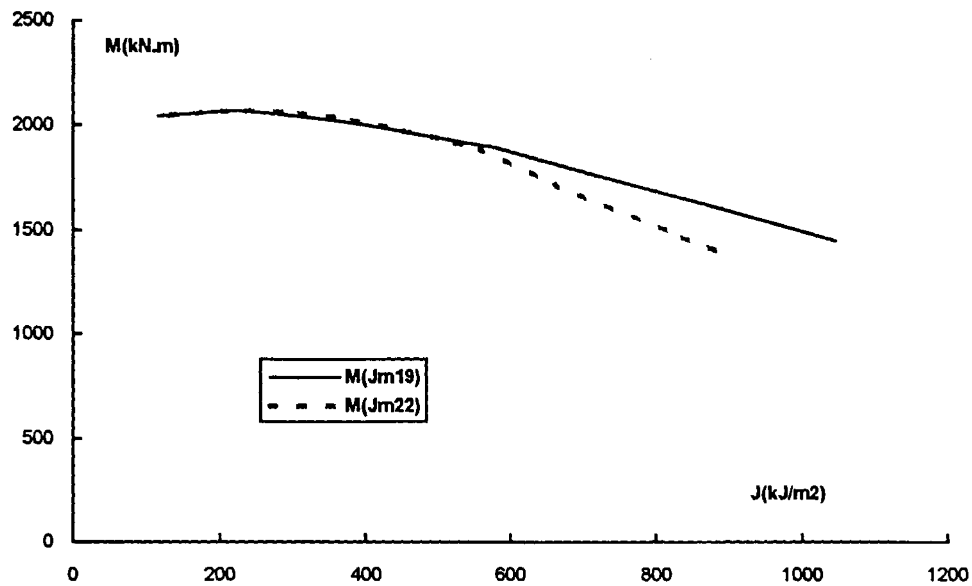

Figure 5 : Determination of the maximum moment for a pipe with an internal circumferential surface crack, loaded in four point bending with an internal pressure (Test 1.2.3.15 of Short cracks in piping and piping welds research program)

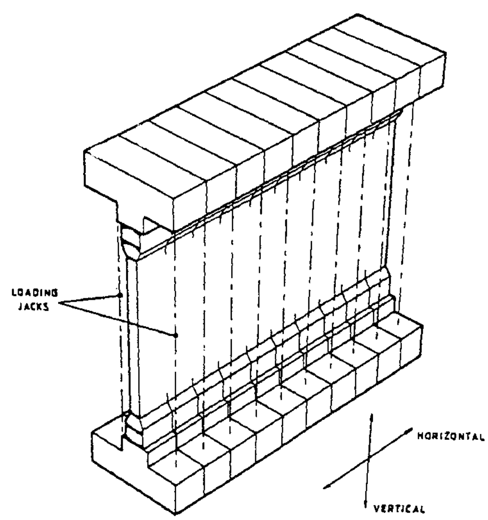

Figure 6 : Cracked plate under tension (AEA SSTP series)

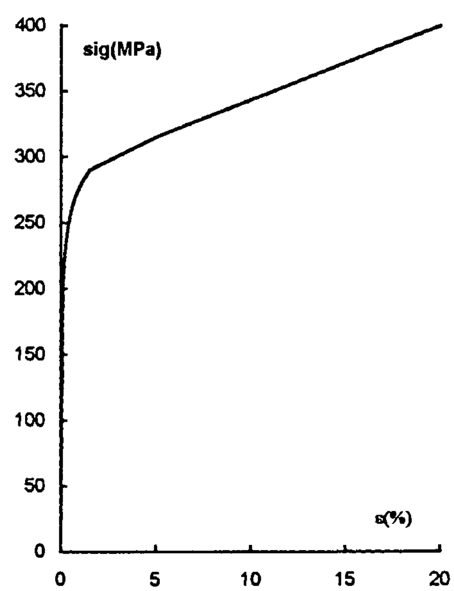

Figure 7 : 316L(N) stress strain curve at room temperature

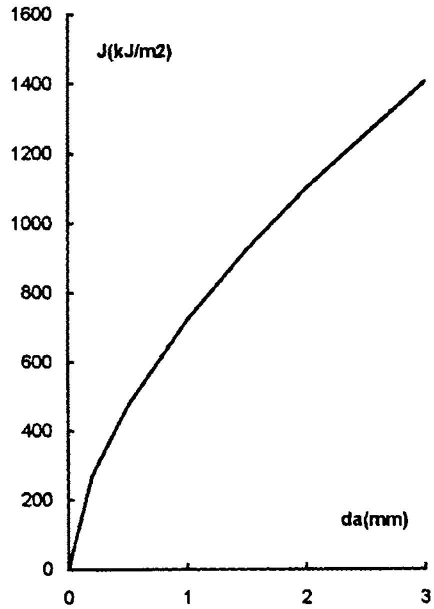

Figure 8 : J-da curve for 316L(N) at room temperature

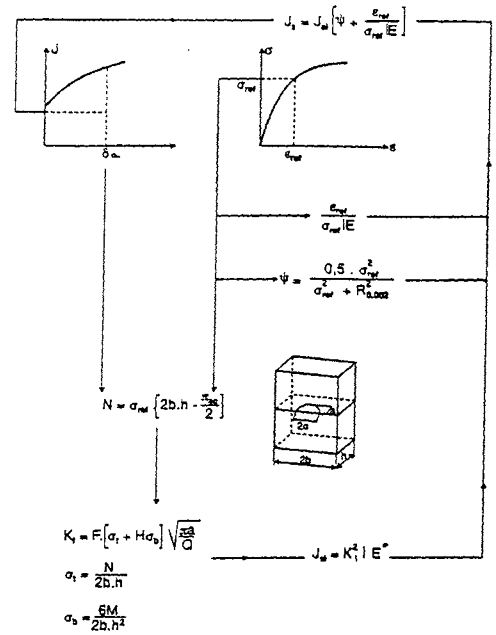

Figure 9 : Jsin flow chart for a cracked plate under tension

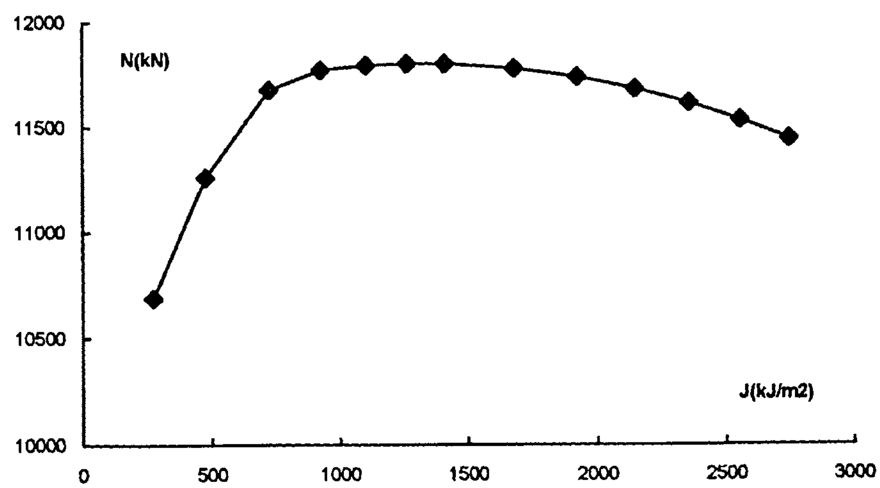

Figure 10 : Determination of the maximum force for a plate with an elliptical surface crack, loaded in tension at room temperature (test n°11 AEA SSTP series).