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SIMPLIFIED METHOD TO ESTIMATE J DEVELOPMENT AND APPLICATION

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ABSTRACT

The J_s method is a simplified rule to calculate J with two handbooks giving the stress intensity factor and the limit stress and the material stress strain curve.
The development, an application and a comparison with finite element calculation are presented.

1.INTRODUCTION

Increasing employment is being made of the methods for estimating the risks of failure due to flaws by using elastic-plastic fracture mechanics. This can lead to examining, in particular, fatigue propagation and stability as proposed, for example, in appendix ZG of the RCC-M [1] for some of the components of nuclear reactors.
These analyses use, in particular, the J criterion. There are, at present, two simplified methods of estimating J, one in Appendix A16 of the French code RCC-MR [2], and the other in the English R6 rule [3].
This study was carried out as part of a cooperative program, with the *Institut de Protection et de Sûreté Nucléaire* of the CEA.

2.SIMPLIFIED METHOD FOR CALCULATING J (J_S METHOD)

2.1.General principles

We are interested here in the method for calculating J for a cracked structure. This value is, for example, compared to the toughness JIC of the material in order to predict the initiation of fracture on imposition of a monotonic load. The initiation condition is thus written:
$J = J_{IC}$
J is calculated by a simplified method denoted as Js and used in the option 2 of the R6 rule [3]. This method uses:
- the tensile strength stress-strain curve
- an equation for the limit load
- an equation giving the stress intensity factor.

This method is proposed in appendix A16 of the RCC-MR [2].

2.2.Review of the theory for calculating J

Since the work of Rice [4], practical methods for calculating J have been developed by the EPRI [5] and the R6 rule [3] in order to apply elastic-plastic fracture mechanics to cracked components in an industrial environment.
Whe linear fracture mechanic is valid, we have the elastic J (noted J_e) given by the equation : $J_e = K_I^2 / E$

where - E is Young's modulus, with:
- $E^* = E$ for plane stresses,
- $E^* = E / (1 - \nu^2)$ for plane deformations (ν is Poisson's ratio)

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, this equation no longer holds. This means that 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.
There is an extensive literature on practical methods for calculating J. It must be acknowledged that the most astute method was established by Ainsworth [7], then developed by Roche [8]. This method has made it possible to realize what the experimentalists had noticed long ago, that under an imposed load, J is proportional to the ratio of the actual deformation to the elastic deformation in the specimens. This is simply expressed by the equation: $J/Je = \epsilon/\epsilon_e$
The deformation considered is, in fact, calculated using the measurement of the C O D (crack opening displacement) value characteristic of the cracked specimen.
To establish his method for calculating J, Ainsworth introduced the reference stress, which by using the tensile stress-strain curve for the material makes it possible to determine the deformation employed in the above equation. An approximation that is pessimistic, but much easier to calculate than the reference stress, is deduced from limit analysis of the cracked structure. As for K_I, there is now an hanbdoock which gives limit loads and stresses for an ensemble of mechanical configurations [9].
This method was taken to revise the R6 rule [3].
The present version of this document proposes various methods for calculating which are, in fact, only different presentations or simplifications of Ainsworth's method. There are now numerous validations of this rule [10]. These consider a large number both of materials and configurations.
Finally, the most practical equation for carrying out the developments required is taken from the R6 rule: $J = Je \cdot [\epsilon_{ref} / \epsilon_e) + \varphi]$
Let us note, that with respect to the equation given above, the term φ has been added, which consists simply of introducing a correction for the small plastic zone : $\varphi = 0.5(\sigma_{ref} / Re)^2 \cdot (\epsilon_e / \epsilon_{ref})$
In these equations ; σ_{ref} is the reference stress ; ϵ_{ref} is the corresponding reference deformation in the tensile stress-strain curve of the material ; ϵ_e is the elastic strain corresponding to σ_{ref} : $\epsilon_e = \sigma_{ref} / E$
where E is Young's modulus
Je is the value of J calculated elastically for the load correspondig to σ_{ref} ; Re is the yield stress corresponding to a 0.2 % plastic deformation.
A practical interpretation of this equation can be had by stating that to calculate J, we can calculate Je, which we must, subsequently, amend by a correction term : $A = (\epsilon_{ref}/\epsilon_e) + \varphi$, which depends only the tensile stress-strain curve of the material. This is written as :$J = Je \cdot A$.
In other words, the calculation of J can be done by an elastic calculation of Je on condition that the result is revised using the plasticity correction term A (which is obviously greater than 1).
It is this method, designated the Js method, which is given in appendix A16 of the RCC-MR [2].

3.APPLICATION TO SPECIFIC CASES

3.1.CALCULATION OF Js

Specification of the problem

To illustrate the procedure for calculating Js, 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 all the section far from the notch (Figure 1).
The material is A48 steel at a temperature of 300 ° C where the tensile stress-strain curve used is that of the RCC-MR A3 12S [2].

Application of J_s method

The evaluation of each of the terms used in the J_s method is illustrated below.
The calculation of 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 form factor dependent on the configuration and on the definition of σ_N [11].
The limit load or the limit stress (taken here as equal to the reference stress) is, in general, given by a formula of the type : $\sigma_{ref} = F_2 \sigma_N$; where $F_2 = b / (b - a)$
With the tensile stress-strain curve of the material used (Figure 2), the plastic correction curve giving A as a function of the reference stress is shown in Figure 3. The correction Az has also been plotted in this figure.
When the reference stress is well below the elastic limit, A = 1. For a stress equal to twice this value, the correction is of the order of 20, therefore, J real is 20 times greater than the Je elastic.
Elastic J (noted J_e) and plastic J_s (noted J_s) calculted by the J_s method are shown in Figure 4.

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

The results calculated with the Js method are compared with those obtained by an elastic-plastic calculation of J by the finite-element technique using the method $G(\Theta)$ [12] established in the CASTEM 2000 calculation code [13].
The mesh and the limiting conditions considered are recalled in Figure 5. The tensile stress-strain curve used is that in Figure 2.
The comparison is shown, as a function of the nominal stress in Figure 6. The value of J calculated by the finite-element technique increases more slowly than that by the Js method. The values of Js can overestimate the value of J calculated by the finite-element technique by a factor of 4. The effect of the horizontal plateau in the tensile stress-strain curve is again found.
Outside of this zone, the agreement between the two methods is satisfactory.

4.ANALOGY WITH THE R6 RULE

We have, also, determined the tensile stress-strain curve which would, in this specific case, bring the Js curve into coincidence with the universal R6 curve. This tensile stress-strain curve is shown in Figure 7 and compared with that of the material considered, in being careful to choose the same Young's modulus and the same yield stress. The normalized values (σ/Re, ϵ/ϵ_e) of the universal tensile stress-strain curve are given for each point in Table 1. This is below the curve for the material except at the end of the plastic plateau. It has a shape which does not conform with the curve for the material.

5.CONCLUSIONS

A simplified method for estimating J (Js method) has been presented. This makes use of equations giving K_I, limit loads and the tensile stress-strain curve of the material.
This Js method is given in appendix A16 of the RCC-MR nuclear construction code.
For a specific case, the comparison of the value of J obtained with an elastic-plastic calculation by the finite-elements technique shows that the values of Js thus estimated are reasonably pessimistic .

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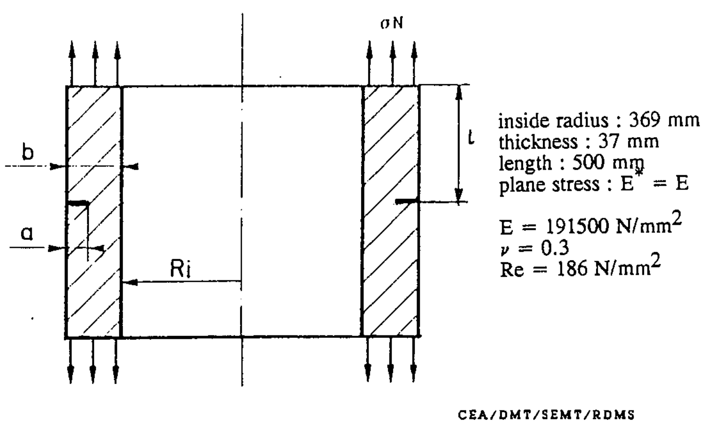


Figure 1

STRESS - STRAIN CURVE
A48 steel temperature 300 deg.C
Characteristics 125 A3 RCC-MR

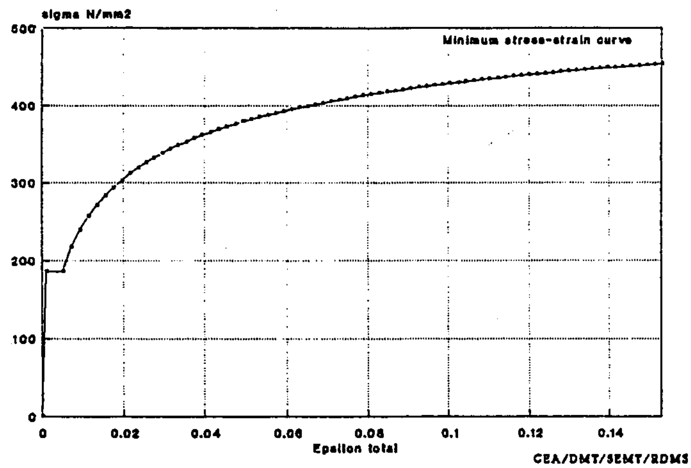


Figure 2

A + (epsref / epse) + phi
imposed loading

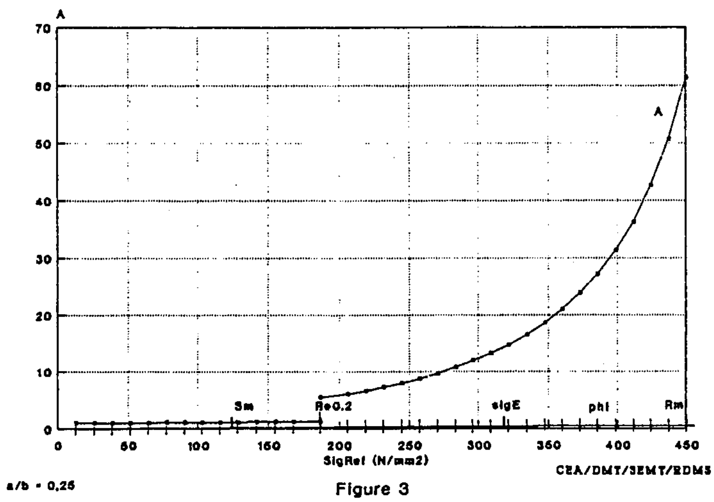


Figure 3

Js et Je
Imposed loading

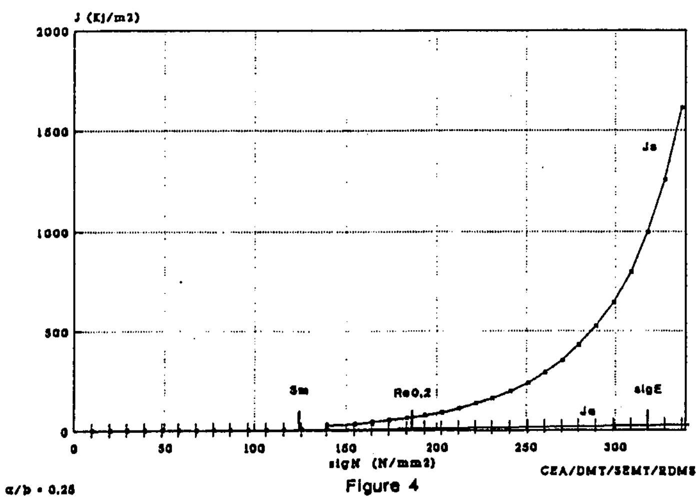
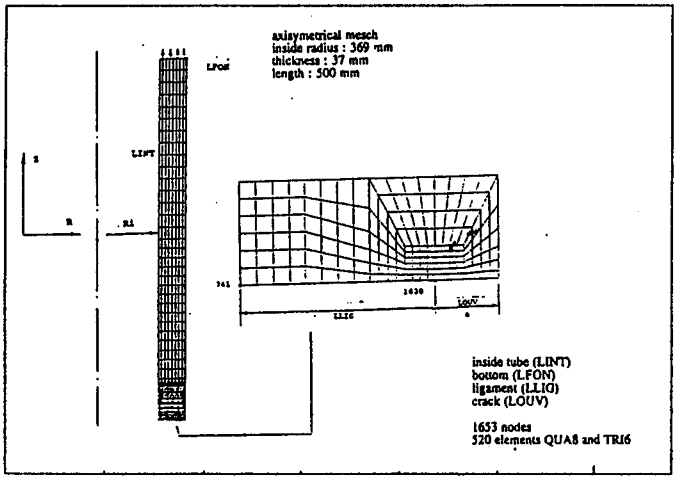


Figure 4



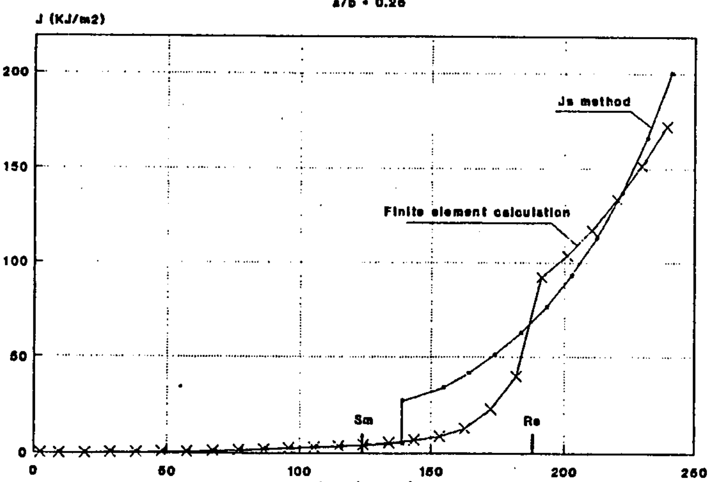
CEA/DMT/SEMT/RDMS

Figure 5

IMPOSED LOADING COMPARISON J

finite-element calculation and Js method

a/b = 0.26



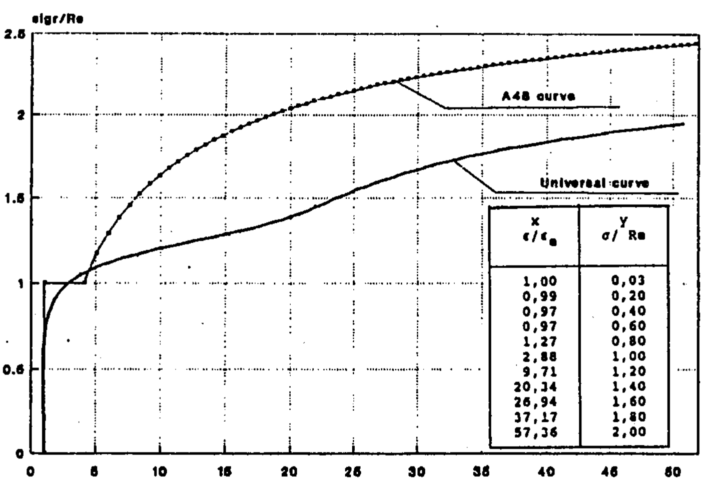
CEA/DMT/SEMT/RDMS

Figure 6

COMPARISON STRESS-STRAIN CURVES

Normalized curves

Universal and A48



x ϵ/ϵ_e	y $\sigma/$ Re
1,00	0,03
0,99	0,20
0,97	0,40
0,97	0,60
1,27	0,80
2,88	1,00
9,71	1,20
20,34	1,40
26,94	1,60
37,17	1,80
57,36	2,00

CEA/DMT/SEMT/RDMS

Figure 8