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Justification of J-integral calculations in the case of bimetallic junctions

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ABSTRACT :

The J-integral based theories may not be appropriate when applied to welded structures where residual stresses play an important role. This is the case for bimetallic junctions of PWR especially in the region of the interface where cracks are located. Indeed, the loading applied to the structure is very complex and the local loading may be non proportional. So, the J-integral may be path dependent, and then, irrelevant. In this paper, the usual conditions of J approach validity are firstly recalled, and secondly extended to admit regions of non proportional loading. The defined methodology is then applied to precise, in the case of bimetallic junctions, the loading conditions of J approach validity.

1. INTRODUCTION

The most commonly used approach in Fracture Mechanics is the « Global Approach » which consists in calculating the parameter « J » - defined as the Rice Integral - equal to « G », the energy released rate. Nevertheless, this approach is not always valid, and then other less usual approaches, such as the two parameters approach or the local approach, have to be used. Then, it is particularly important to make sure whether the J-integral approach is valid or not. In this paper, we study the case of some welded structures, the bimetallic junctions of PWR, where residual stresses play an important role. When a crack is created at the interface of the junction, non proportional loading can be observed, and the J approach may not be appropriate. So the aim of this paper is to define a methodology which can be used to determine, in this particular case, the loading conditions where J-integral based fracture theories are appropriate or not.

2. METHODOLOGY

2.1 *Usual conditions of J approach validity*

Usually, the J-integral based on Incremental Theory of Plasticity is considered valid, if proportional loading occurs everywhere in the structure. In this case, the values of J match with the values of J based on Deformation Theory of Plasticity. If we want to verify the proportional loading assumption, the following conditions have to be fulfilled, everywhere in the structure :

- (C1) : J-integral obtained from Incremental Theory of Plasticity is path independent.
- (C2) : this J is close to the J based on Deformation Theory of Plasticity.
- (C3) : the stress and stress fields obtained from the two theories are identical or close.

All these conditions are necessary. From (C1) to (C3) they are more and more restrictive. Let us make some comments about them :

Most authors are satisfied with condition (C1), which is not sufficient. Only one model is needed to represent the material behavior. So, other arguments must be taken into account to prove the J approach validity.

Condition (C2) is more restrictive than (C1), but is also not sufficient. Two models are needed to represent the material behavior. Compared to (C1), in addition, it involves the measure of a deviation with respect to proportional loading, using J-integral considerations. Although it is not strictly sufficient, we can admit that the J approach is almost surely valid when this condition is verified.

Condition (C3) is sufficient. Two models are needed, and the proportional loading must be verified everywhere. Nevertheless, the problem is that this condition is not very practical ! What to do with the possible deviations ? Shall we interpret them in global terms ?

Finally, it seems theoretically correct and practically acceptable to :

- verify condition (C2),
- check components of stress and strain fields obtained from the two theories.

We can then consider that the Incremental Theory of Plasticity (called hereafter « EP » like « Elasto-Plastic ») is representative of the real behavior of the structure considered, and that the Deformation Theory of Plasticity (called « ENL » because it is equivalent to « Non Linear Elasticity ») is only a way to verify the J approach validity.

2.2 *Extended conditions of J approach validity*

First of all, let us recall that the conditions (C1) (C2) or (C3) must be verified everywhere in the structure. That is a direct consequence of what we call the usual J approach validity conditions which involve proportional loading everywhere. This assumption is very restrictive. A significant progress can be made by extending the conditions using the following remarks :

- non proportional loading may be accepted in a very small area around crack tip. This remark cannot be justified from a theoretical point of view. But we can justify it from a practical point of view if we consider experimental results.

- non proportional loading may be accepted far from the crack tip, so long as it has no effect on the proportional loading in the crack tip region.

In short, the assumption of proportional loading everywhere is too strong and in fact not necessary. It is sufficient to verify that the loading is proportional in a large region around the crack tip. So, we will try to justify the J approach by searching a « crown shaped area », (called « C »), of proportional loading, around the crack tip, with an internal radius sufficiently small, and an external radius sufficiently large. For that, we will compare the result obtained from the model « EP » with the result obtained from the mixed model « CM » defined as follow :

- we assume Deformation Theory of Plasticity in C,
- we assume Incremental Theory of Plasticity out of C.

So, as mentioned above - in the previous paragraph - we will try to verify condition (C2) and we will check some components of stress and strain fields, but this time, only in a certain crown shaped area (C), and not everywhere. In the same way, the model (EP) will be representative of the real behavior of the material of the structure considered, and the mixed model « CM » will be only a way to verify the J approach validity.

3. APPLICATION TO BIMETALLIC JUNCTIONS

Bimetallic junctions are located between pipes made of austenitic steel, and the large components made of ferritic steel (reactor vessel, steam generator, primary coolant pump, pressurizer, ...) of the main primary system of PWR. Intergranular decohesions induce emergence of defects, considered as cracks, in the first layer of the buttering of these bimetallic junctions.

The difficulties are due to the bimaterial aspect on the one hand, and to the complexity of the loading applied to the structure on the other hand.

Firstly we present the statement of the problem, then we present the modelisation, the calculations, the results obtained, and we give some conclusions.

3.1 *Statement of the problem*

The bimetallic junction is represented by a bimetallic cylinder (see Fig. 1), with the following specifications :

- internal radius : Ri = 367.9 mm,
- thickness : e = 93.68 mm,
- length of the austenitic and ferritic part from each side of the junction : l = 500. mm,

- postulated crack : in the austenitic side, circumferential, located at 0.1 mm from the interface on the outer surface, depth : a = 8 mm.

Description of the two materials (at 300°C) :

	austenitic	ferritic
E(MPa)	176000	191500
ν	0.3	0.3
α(°C-1)	17.1E-6	13.06E-6
Sy(MPa)	245.	454.

The loading applied to the bimetallic junction can be described as follow :

- stress relieving heat treatment at 600°C,
- cooling at room temperature (20°C),
- introduction of the crack,
- heating from room temperature to operation temperature,
- mechanical loading due to pressure,
- mechanical loading due to the tensile load applied by the pipe.

The cooling at room temperature induces an important residual stresses state due to the difference between thermal expansion coefficient of each material [1,2]. So the crack is introduced in that residual stresses state. Then, in the region of the crack tip, the loading history may be non proportional and J-integral may be path dependent.

3.2 *Calculations*

We use a fine mesh (see Fig. 2), in the region of the interface and a very fine mesh in the region of the crack tip (4800 nodes, and quadratic elements). The smallest side of the elements located near the crack tip or near the interface is 0.025 mm long.

The calculations are made with the *Code_Aster* developed at EDF. Three models are considered for the material behavior [3] :

- (EP) : Incremental Theory of Plasticity,
- (ENL) : Deformation Theory of Plasticity,
- (CM) : mixed model, ENL on (C), EP out of (C), (C) being a crown shaped area.

The J-integral is calculated using the « THETA method » [4,5], which consists in calculating the energy released rate « G » as a domain integral. THETA is a vector field defined on this domain and represent the crack propagation velocity.

3.3 *Results obtained*

The main result (see Fig. 3), is the variation of G with respect to the loading F, for the 3 models. The values of G given for F<0 correspond to the crack introduction at 20°C. The values of G given for F=0 correspond to the heating from 20°C to 300°C. And then, we have the values of G corresponding to different values of the tensile load F>0.

For the model (EP) the values of G (G-EP), may be path dependent. They are represented on Fig. 3 by small squares. The corresponding curve is obtained by taking the mean value. For the model (ENL) and the model (CM), the values of G (G-ENL or G-CM), are path independent, to within 1%. We note that :

- if we consider residual stress loading, the G-ENL value is much higher than the G-EP value. Then, after heating the G-ENL value falls under the G-EP value. If we had considered the crack opening value, we would have obtained the same conclusion.

- when the tensile load is small (<100MPa), the G-EP values are path dependent, and the distance between G-ENL and the mean value of G-EP is important. The distance between G-CM and G-EP is smaller, but not negligible.

- when the load is bigger (>100MPa), the distance between G-EP and G-ENL remains significant, but on the other hand, the distance between G-EP and G-CM becomes small (<10%).

So, we are led to the following conclusions :

- according to (EP) and (ENL) comparison, it is clear that the loading is not proportional everywhere,

- according to (EP) and (CM) comparison, and if the tensile load is smaller than 100 Mpa, we have not been able to find an area (C) where G-EP and G-CM values are sufficiently close. So, the loading is not proportional, and then the J approach is not valid. Nevertheless, the J values, and the other values which can be used to estimate the crack nocivity (crack opening, stresses, strains, ...), are very low.

- according to (EP) and (CM) comparison, and if the tensile load is greater than 100 MPa, we can find an area (C) where G-EP and G-CM values are sufficiently close. If then we compare some local values of stress and strain fields, we can conclude that the loading is proportional in (C).

This study reveals that a non proportional loading in a zone far from the crack tip region, may have no effect on the J approach validity in that region. It is important to represent the real behavior of the material, corresponding to Incremental Theory of Plasticity. The Deformation Theory of Plasticity could be insufficiently representative of this behavior, but it could be useful to use it, as shown in this paper, to determine the loading conditions where J approach is appropriate or not.

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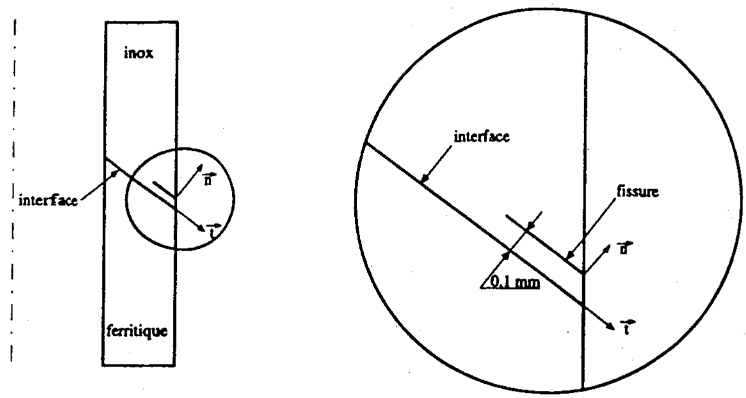

Figure1 : Scheme of the bimetallic junction

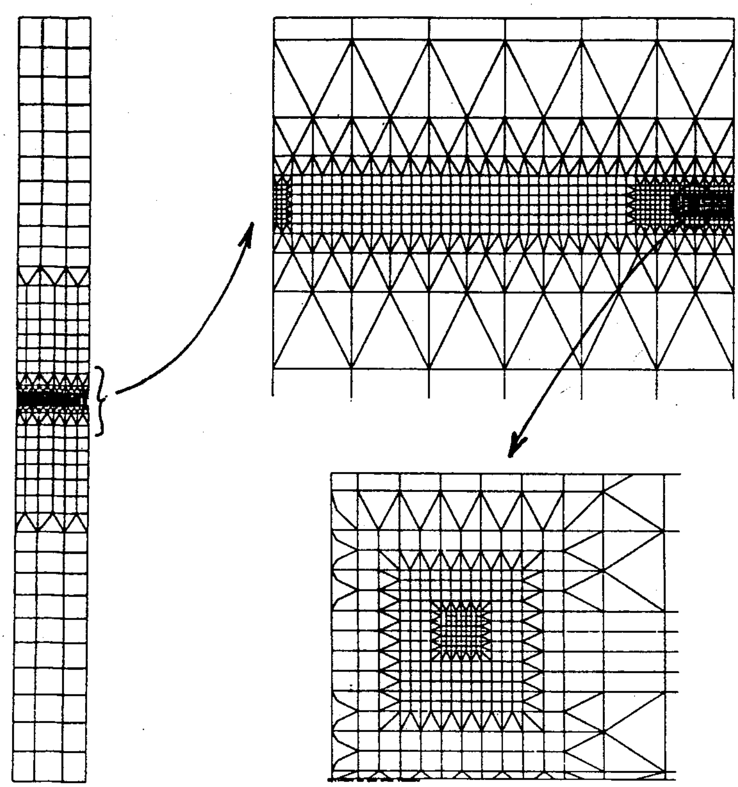

Figure 2 : Finite element model

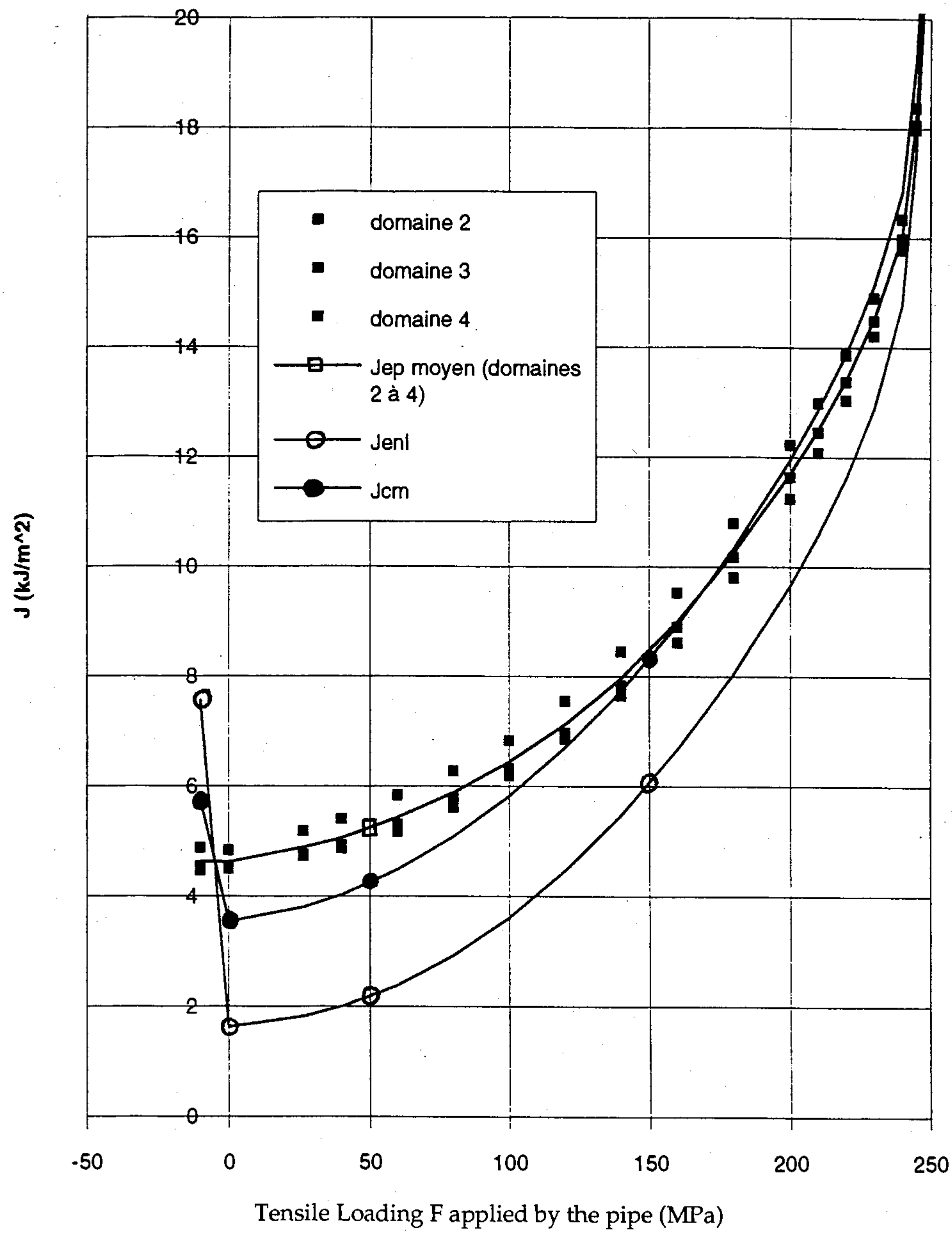

Figure 3 : Variation of G as a function of the loading F