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3D computation of cracked elbows

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ABSTRACT : The major rules for piping flaw evaluation are derived from simple geometries like plates and cylinders.The engineering methods used up to now have been validated in situations where plasticity is confined. During the past five years, many flaw evaluations considered more complex situations like elbows, tees or nozzles. To improve the engineering methods to be used in this field we have done 3D computations of cracked elbows to have an accurate evaluation of elastic and plastic J .

Two 3D cracked models of PWR primary loop elbows in cast stainless steel are presented. The first contains a longitudinal semi-circular surface crack.The flaw of the second model is orientated at 45° with respect to the crown generating line of the elbow. These models are submitted to complex loading like pressure and bending moments. Stress analysis is done in a wide range of plasticity extension and helps us to understand the behaviour of cracks in such complex components.

The main objective here is to discuss the validity of actual engineering method KJ (using R6/3 option 2 - K_r,L_r relationship). An accurate definition of the reference load (defining L_r) is extremely important to have a good plasticity correction. Different relationships are applied to the two models. The comparison of the finite element results to the simplified methods values leads to some recommendations in the use of such methods for the flaw evaluation of complex piping cracked components.

1. INTRODUCTION

In the last years the needs in terms of accuracy in the flaw evaluation for steel components of nuclear industry are more and more important. Due to the high level of the loadings under faulted condition and the margins required, it is impossible to verify always the elastic or small scale yielding hypothesis. The non linear behaviour of the strain hardening materials must be taken into account in the J estimation schemes.

Even if it is possible now to complete available 3D elasto-plastic analyses of cracked bodies to evaluate J, we need validated simplified methods to do parametric defect assessment studies. Most of these methods are based on the plasticity correction of the elastic Stress Intensity Factors (SIF). But often the size of plastic zone has to be very limited. What occurs when the limit load is reached or overstepped ? Some, as the R6/3 option 2 approach [1], uses the reference stress techniques.

In this paper we try to show how the finite element analysis of two cracked elbows under pressure and bending moment helps us to understand better the behaviour of the cracked structure and to improve the definition of the main parameters of the simplified methods.

2. GEOMETRY OF ELBOWS - MATERIAL - LOADING

2.1 *Geometry*

Two elbows of the main primary system of a french PWR have been meshed :

¤ *Model A* : the first one [2],is representated figure 1; the caracteristic parameters are : angle of 90°, inner radius Ri = 380 mm, thickness e = 62.5 mm, bending radius Rb = 1354 mm; the crack centered on the middle section is a longitudinal external half circular flaw with depth : a = c = 20 mm

¤ *Model B* : the second one [3] (figure 2) has the same caracteristics excepteed the angle which is equal to 40°; moreover, the outlet nozzle of the steam generator is added to this last model. The flaw has the same dimensions as in model A but is orientated at 45° with respect to the connection line of the nozzle with the elbow.

2.2 Material

¤ *Model A* is all in austeno-ferritic steel : Young's Modulus : E = 172 000 MPa, Yield stress : $\sigma_y = 163$ MPa and $\nu = 0.3$.

¤ *Model B* is composed by a nozzle in ferritic steel : Young's Modulus : E = 187 500 MPa, Yield stress : $\sigma_y = 235$ MPa and $\nu = 0.3$, the elbow is also in austenoferritic steel : Young's Modulus : E = 174 700 MPa, Yield stress : $\sigma_y = 163$ MPa and $\nu = 0.3$

2.3 Loading

¤ *Model A* is submitted to pressure (15.5 MPa) and to in plane bending (up to 600 t.m).

¤ *Model B* : the nozzle is embedded and we superpose to the pressure(15.5 MPa), in plane (My = 31 t.m) , out of plane (Mx = 391 t.m) bending and torsion (Mz = -165 t.m). All the moments are applied at the end of a straight pipe in extension of the elbow.

3. GLOBAL BEHAVIOUR AND FRACTURE MECHANICS RESULTS

3.1 Global behaviour

¤ *Model A* : The flaw treated here modifies neither the global behaviour nor the limit load of the elbow. The normal section containing the crack plastifies by ovalization. The global plastic zone encroaches on the plastic strain field around the crack tip. That means that the overall deformation mechanism drives the opening of the crack wich is amplified in case of large plastic strains. We can suggest, as it is written in [4], that the reference load, defined from the moment - ovalization curve, as the load above which the non linear part of the displacement overcomes the linear one, will be the most important parameter governing the plasticity correction of J.

The shape of the crack (c/a =1) and the bending (shell) stresses can explain the fact that the bottom of the crack is less loaded than the edge at the free surface.

We can also note the influence of pressure which modifies the triaxiality of the stresses and has consequences on the load displacement curve. The reference load is reached at a higher level of moment.

¤ *Model B* : In this case there are two plastic zones which grow :

a. one near the crack location, where membrane stresses prevail and

b. one near the middle section of the elbow submitted to a strong ovalization generating bendind stresses. In consideration of the type of loading the shear stresses are here not negligible.

As before the presence of the defect does not modify the global behaviour of the structure.

3.2 Fracture mechanics results of the Finite Element analysis

The elastic and plastic values of J have been computed along the crack front by the "Theta" method [5]. From J, we compute Kj as below :

$Kj = (J * E)^{1/2}$ at the edge of the crack (plain stress conditions)

$Kj = (J * E/(1-v^2))^{1/2}$ at the bottom of the crack (plain strain conditions)

¤ *Model A* : For the loading considered here,mode I prevails. We present here the elastic and plastic S. I. F. for the bottom and the edge of the crack at different steps of the loading :

	edge		bottom	
$Mpa*m^{1/2}$	KI	Kj	KI	Kj
P= 15.5 MPa	15.4	17.6	15.2	16.0
M=500 t.m	49.1	117.4	24.5	83.3
M + P	64.5	82.5	39.7	69.0

These values shows the effect of pressure, particularly in plastified regions, which changes the triaxiality of the stresses. Obviously in elasticity we can add :

$$KI\ (M+P) = KI\ (M) + KI\ (P)$$

but in plasticity $Kj\ (M+P) < Kj\ (M) + Kj\ (P)$.

Figure 3 shows that this is true only when plasticity begins to be significant. The difference between the values at the bottom and at the edge is due to the bending moment generating the ovalization, and to the shape of the flaw.

¤ *Model B* : The orientation of the flaw and the three moments induce mode I , II and III. The way we compute the energy release rate G takes into account the three modes; so Ke (elastic) and Kj represent the global S.I.F.. We give it only at the last step of loading (P=15.5 MPa, Mx=391 t.m, My=31 t.m, Mz=-165 t.m) :

	edge		bottom	
	Ke	Kj	Ke	Kj
$MPa*m^{1/2}$	28.84	50.55	28.02	45.53

In comparison with the results for the model A, the values here are less important for the following reasons : the loading is globally lower (|M| = 423 t.m), the thikness is greater near the flaw and the angle of the elbow is smaller. The difference exists already on the elastic solution and subsists in the plastic regime because we have not the same limit load and not the same plasicity mechanism near the crack. We can see with this example that the way the non linear behaviour is reached has a great importance on the amplification of J due to plasticity.

4. APPLICATION OF ENGINEERING METHOD AND REFERENCE LOAD

4.1 Engineering method

The method proposed here is devided in two steps : the Ke factor is obtained by the classical influence functions for longitudinal cracks in cylinders [6] and the plasticity correction is made using R6 option 2 diagram (Kr = f (Lr) where Lr = σe / $Q\sigma y$; KJ = Ke/ Kr) [1] and the stress classification proposed in reference [7] . An application of this method "MS" to the model A is given in [8]. The consevatism of the proposed estimation scheme has been confirmed for the edge of the crack and the recommendation was made not to neglect the bending stresses due to ovalization. This last point and the choice of an accurate limit load (moment) as defined in [4] and obtained by the 3D computation are taken into account in the first new method "ML". We have also made an application of the method "MS" but taking into account in the σe computation the complete stress tensor "NM"

4.2 Application

¤ *Model A* : the comparison between simplified methods and finite element estimation are made for the two type of loading : bending moment and bending moment + pressure. On the figures 4 and 5 the results, Kj, are presented for the edge (a) and bottom (b) of the crack. The conservatism (15%) is less important than at the edge (60%). The difference is more important when the pressure is present (80%).

¤ *Model B* : here the comparison at the bottom and at the edge of the crack with the method "MS" let appear a great difference we can divide in three steps :

kJ/ m^2	J "MS"	J 'mixed modes'	J 'Je (F.E.)'	J 'F.E.'
bottom	69.6	43.2	31.6	10.8
edge	93.9	52.0	37.0	14.6

The first step is due to the linear addition of KI, KII, KIII in the method "MS" (35% on Ke). The second comes from the approximation made with the influence function (15% on Ke). The last one (60%) is the consequence of the choice of Lr formula. In this case the accurate limit load is greater than the estimated one.

5. CONCLUSION

The comparison between the results of the 3D Finite Element non-linear Analysis of cracked elbows allows us to give some recommendations. First, the methods based on R6 option 2 procedure can give a good prediction of J if the plasticity correction is made on a value of Je as accuate as possible. In particular the presence of mixed modes is difficult to be taken into account. Secondly, we need a good knowledge of the phenomenon involved in the plasticity failure mechanism of the structure to use as well as possible the reference load approach. For example when we have multiple loadings the triaxiality of the stresses must take place in the definition of the limit load. Finally it is confirmed that the bending stresses due to the ovalization cannot be neglected as secondary stresses. It is necessary to be careful on these points to have a better idea of the validity domain of such simplified methods applied to complex structures.

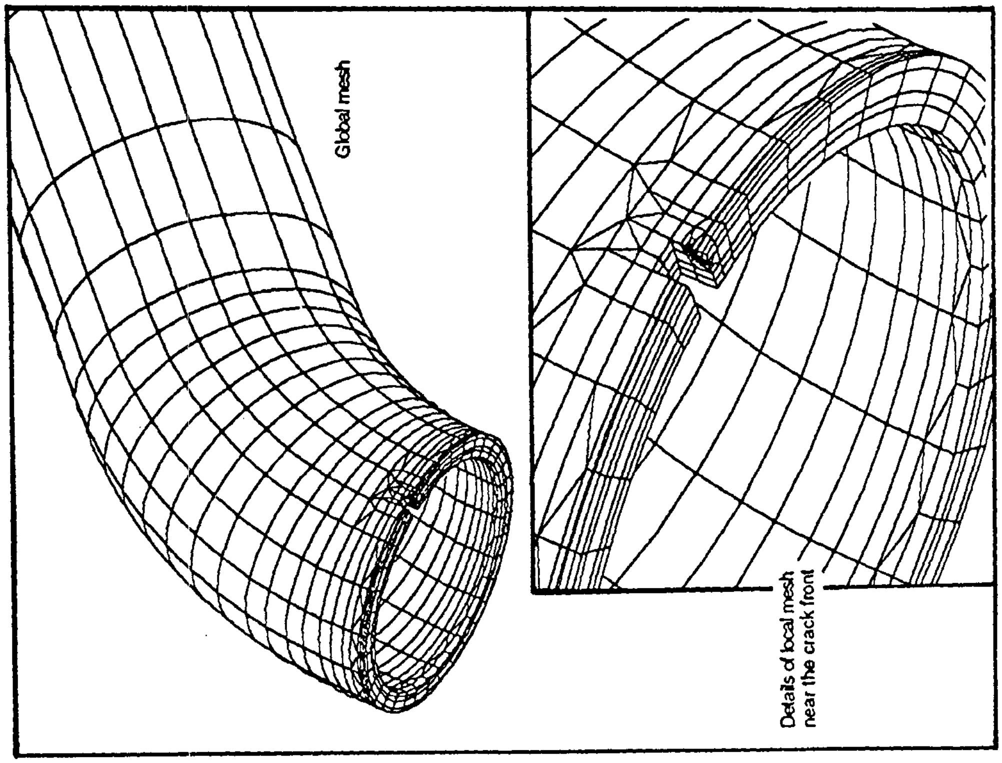

Figure 1 : Finite element mesh - model A

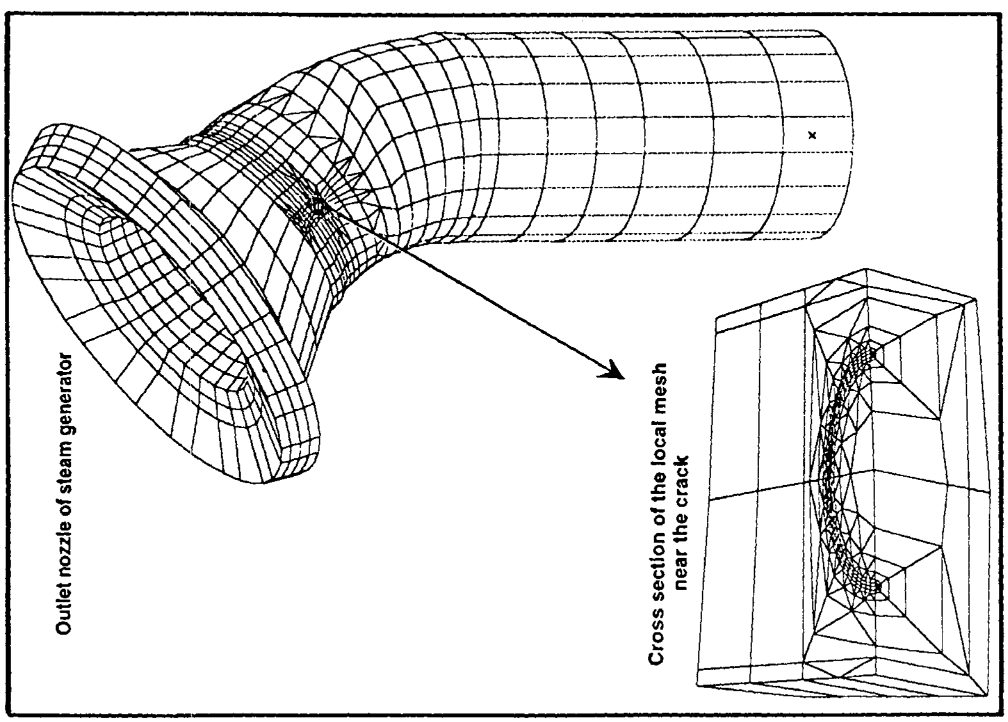

Figure 2 : Finite element mesh - model B

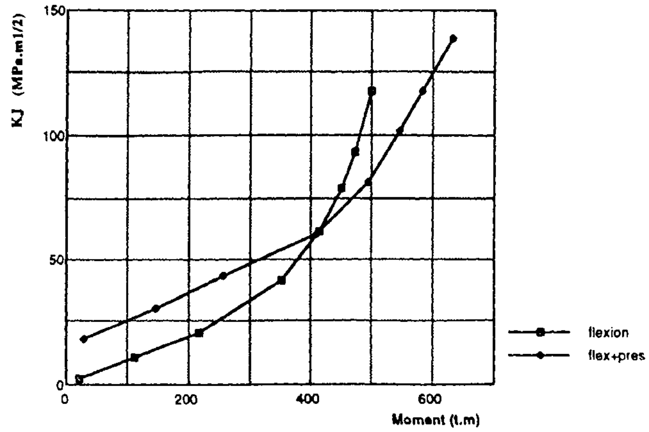

Figure 3 : Influence of pressure on J value - model A

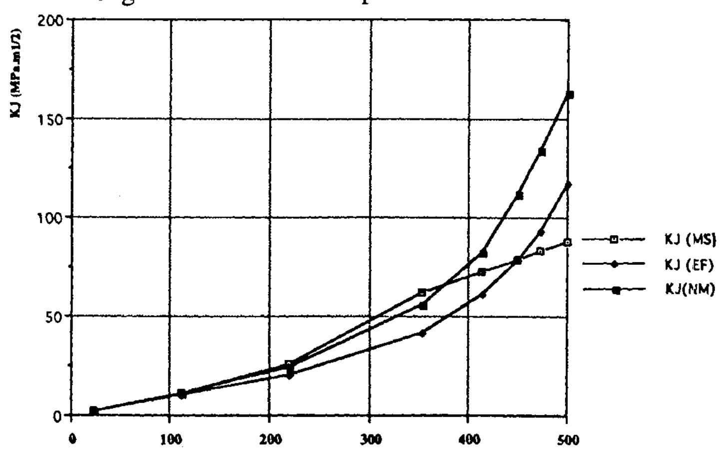

Figure 4.a : Comparison between simplified and finite element methods for bending load -model A - Edge

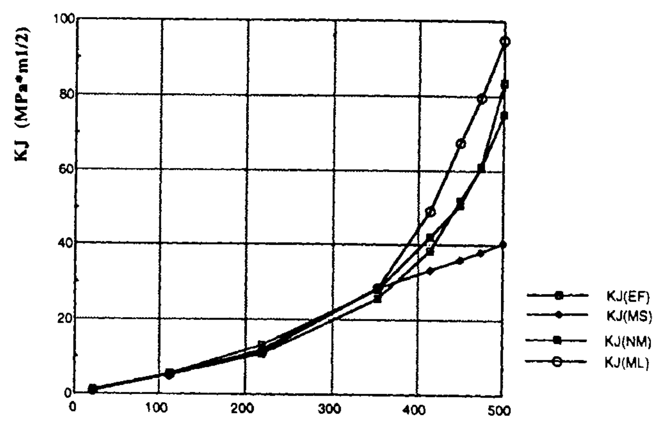

Figure 4.b : Comparison between simplified and finite element methods for bending load -model A - Bottom

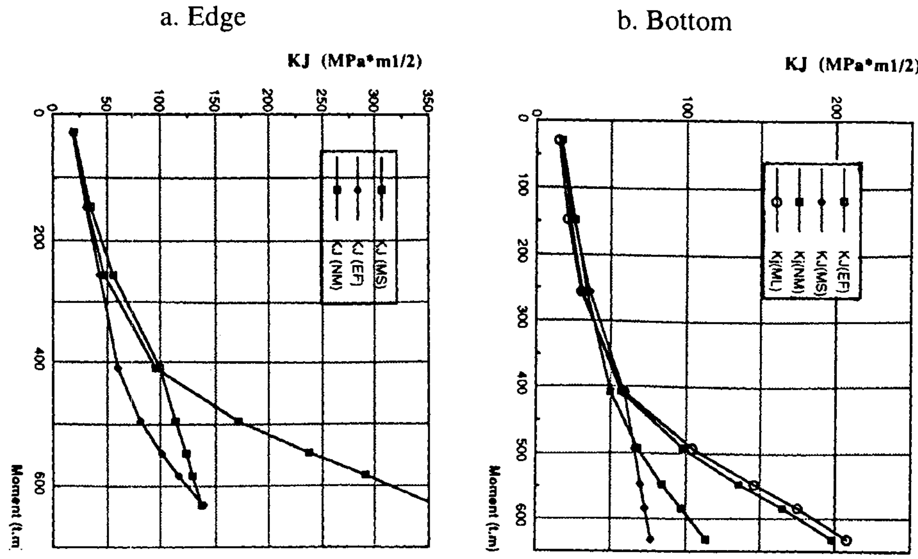

Figure 5 : Comparison between simplified and finite element methods for constant pressure and bending load -model A

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