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DESCRIPTION AND APPLICATION OF KJ RULE TO CRACKED CAST ELBOW INTEGRITY ANALYSIS

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I. INTRODUCTION.

Safety analyses of austeno-ferritic cast elbows degraded by thermal aging phenomenon, with postulated cracks initiated by shrinkage cavities, have to be performed under normal, emergency, and faulted conditions. For this last condition, under lOCA or SLB mechanical loads, we may have to demonstrate the stability of the crack after a small ductile tearing. To perform this analysis, we need:

- the J-Δa curve of the aged material,

- and the J_{app} value, in function of the crack depth, for the selected load.

This paper is focused on this second point. Usually, in conditions of small scale yielding, methods based on plastic zone correction are appropriate and allow to obtain a safe approximation of J_{app}:

$$J_{app} = K_{cp}^{2} / E'$$

We note that this approach is very simple and very productive when a large number of crack configurations must be analysed.

For large loadings or crack depths, yielding spreads through the ligament and the previous method is no longer applicable. A more adjusted method has to be developed.

II. BASES OF THE METHODOLOGY TO COMPUTE J_{app}.

This simplified method is based on the R6 revision 3 rule developed by the CEGB, ref. [1]. With the option 3, if we have computed the value of J_e and J_{ep} for a given crack with a finite element code under the same loading, we obtain the value of K_R with the following relation:

$$K_R = (J_e / J_{ep})^{1/2}$$

Such values of J_e and J_{ep} were computed in ref. [2] for four longitudinal cracks (a/t = 0.25 and 0.5 , 2c/a = 3 - 4 - 6) in a vessel loaded by pressure.

We have plotted in figure 1, these values of K_R in function of L_R, ratio of the applied load to the limit load of the cracked component:

$$L_R = C/C_L$$

Now, we compare this four curves with the option 2 Failure Assessment Line (FAL) proposed by Ainsworth ref. [1], and given by the following relation:

$$K_R = [E\varepsilon_{ref}/\sigma_{ref} + L_R^2/2(1 + L_R)]^{-1/2}$$

In this relation, σ_{ref} is the nominal stress applied in the uncracked section of the component and ε_{ref} is the corresponding strain obtained on the material tensile curve. In the case of a simple structure loaded in tension, the previous expression of L_R becomes a simple function of σ_{ref}:

$$L_R = \sigma_{ref}/ Q\sigma_y$$

with : σ_y: yield stress Q: weakening factor of the crack.

We note in figure 1 that option 2 FAL is below the four option 3 FAL corresponding to the four cracks; this means that option 2 gives a greater amount of plasticity correction and then a greater value of J_{app}, particulary for the deepest crack.

Then, if we can compute the value of J_e using stress intensity factor handbook or influence function technique, and if an expression for Q is known, a conservative value of J can be obtained by using K_R computed with the R6 F.A.L. rev. 3 option 2 and the following relation:

$$K_J = K_I / K_R \qquad \text{and} \qquad J_{app} = K_J^2/ E'$$

Note that this relation is similar to the plastic zone correction one in small scale yielding conditions. Computation of K_I and K_R in function of the crack depth a, allows to obtain the curve $J_{app} = f(a)$ and to perform the crack stability analysis by comparison with the J-R curve.

In the case of more complex structures as cracked pipes or elbows, loaded with pressure and bending moment, if the value of K_I is not very difficult to compute, the value of L_R is more difficult to obtain. First, we have elastic membrane and bending stresses in the analysed section, which may be of primary or secondary nature and may relax for a certain value of stress; secondly, the limit load is different for a longitudinal crack or a circumferential crack. In this second case, this relation may be complex under pressure plus bending loads.

II. EXPRESSION FOR A LONGITUDINAL SURFACE CRACK IN A PIPE AND IN AN ELBOW.

For a longitudinal crack in a pressurized pipe, the method to compute L_R described in the previous paragraph is applied by neglecting the bending stress due to pressure. The shape factor Q comes from a local limit load expression proposed and qualified on a large number of tests by the Battelle Colombus Lab.:

$$Q = \frac{A_o - A}{A_o - A/M}$$

with: $A_o = 2a(c+t)$ $A = \pi ac$ and $M = (1 + 1.61c^2/Rt)^{1/2}$

In this case, the membrane stress comes from pressure and is always primary by nature, then, there is no reason to relax this stress.

For longitudinal crack in an elbow, there are bending circumferential stresses due to the ovalisation of the elbow under in plane bending moment in addition to the pressure LAME stress. In order to understand the behavior of a crack under these combined stresses in plastic regime, FRAMATOME has undertaken the following study.

We have selected the geometry of a nuclear primary piping, see figure 2, (R_i = 367 mm, t = 63 mm) with a longitudinal internal crack of infinite length, which allows a 2-D plane strain simulation. Three crack depths were analysed:

$$a/t = 0.1 - 0.25 - 0.5$$

The pipe is loaded first to the nominal pressure: P = 15.5 MPa, then by diametral displacement until 4 to 6 mm, which gives the bending circumferential stress. Both elastic and elasto-plastic computations of J were performed with a typical austeno-ferritic stress strain curve (σ_y = 120 MPa , α = 2.15 n = 5).

From the J_e and J_{ep} results of the three cracks, we can plote the F.A.L. option 3, as for the results in figure 1, in function of membrane plus bending stress, figure 3. We observe, for the smaller crack, that the value of K_R decrease always, when the value of membrane plus bending stress increase.

But for the two largest cracks, the values of K_R decrease until a characteristic value of stress, then increase afterwards. The growth of J, plotted in function of the applied elastic stresses, presents a parabolic shape at the beginning but changes drastically and becomes smaller after this characteristic stress, as shown in figure 4. A relaxation phenomenon, which limits the growth of J, is activated when the circumferential stress reachs this caracteristic value.

In order to precise this value, we have plotted K_R in function of an equivalent stress divided by the shape factor: σ_e/Q. This equivalent stress σ_e is obtained from the solution of the limit load of a cantilever beam, of the same thickness of the pipe, with the same crack depth, under tension plus bending loads. We obtain the well know parabolic limit curve, in function of σ_{mL} and σ_{bL}, respectively values of membrane and bending stresses at limit conditions:

$$\sigma_{bL}/1.5Q\sigma_y + (\sigma_{mL}/Q\sigma_y)^2 = 1$$

The solution of this equation with respect to $Q\sigma_y$, gives the equivalent stress σ_e.

$$\sigma_e = \sigma_b/3 + [(\sigma_b/3)^2 + \sigma_m{}^2]^{1/2}$$

The results are shown on the figure 5. For the quarter thickness crack, we observe that K_R reaches its minimum value when σ_e/Q is close to the yield stress. In this case, the maximum membrane primary stress, corresponding to the nominal pressure, divided by Q: σ_m/Q = 108 MPa, is also close to the yield stress: 120 MPa.

For the half thickness crack, we reach the minimum of K_R for σ_e/Q = 167 MPa. At nominal pressure without displacement, σ_m/Q = 170 MPa. That means, obviously, we have not relaxation of the primary stress when σ_m is greater than σ_y. We note that K_R increases when the ovalisation is applied afterwards: the added bending stress is fully relaxed. For the shorter crack, the relaxation of the bending stress is not clearly shown. The plasticity is not only confined in the ligament but spread everywhere in the pipe due to the stiffness of the crack section.

Based on these results, the following rule has been proposed to compute L_R for longitudinal deep crack (> t/4):

$$L_R = \sigma_e / Q\sigma_y$$

with: if $\sigma_e \geq \sigma_y$ and $\sigma_m < \sigma_y$ then $\sigma_e = \sigma_y$

if $\sigma_m > \sigma_y$ then $\sigma_e = \sigma_m$

This rule is represented by the two horizontal lines (with arrows) in figure 5, starting from: $\sigma_e/Q = \sigma_y$ for the t/4 crack and $\sigma_m/Q = \sigma_y$ for the deepest crack. These two curves will give a greater plasticity correction than the elastoplastic computation, and then a conservative value of J is computed.

IV. EXPRESSION FOR A CIRCUMFERENTIAL CRACK IN A PIPE AND IN AN ELBOW.

For circumferential crack in a pipe loaded under pressure plus bending, the stress distribution is more complicated: added to the pressure end effect are the membrane stress in the shell due to the bending moment: σ_m^{mt}, plus the bending stress in the thickness due to this bending moment: σ_b^{mt} , which is small in the case of a pipe, but which may be important in the case of an elbow with a small curvature. The most convenient relation is the KANNINEN one, ref. [3], proposed for a pipe under pressure and bending:

$$L_R = M/M_L \quad \text{with} \quad M = \sigma_m^{mt} \pi R^2 t$$

and $M_L = 4\,\sigma_y R^2 t\,(\cos\beta - 0.5a/t.\ \sin\gamma)$ γ: half crack angle

with $\beta = a\gamma/2t + \pi\sigma_m^{p}/2\sigma_y$ σ_m^{p}: pressure membrane stress

But this relation gives $L_R = 0$ with pressure and without bending moment. The EPRI relation ref.[4], has been derived to correct this discrepancy and gives, in this case, the exact value of pressure limit load.
The formulation proposed in the K_J rule, for circumferential crack, is based on this second formulation:

$$L_R = M/AM_L' \qquad M_L' = M_L(\sigma_m^{p} = 0)$$

with: $$A = -\beta' + [\beta'(2 + \beta')]^{1/2}$$

and: $$\beta' = 0.5[\sigma_m^{mt} R F_L / 2\sigma_m^{p} M_L']^2$$

F_L: limit load in tension, $F_L = 2\sigma_y Rt\,[\pi - a\gamma/t - 2\arcsin((a/2t)\sin\gamma)]$

Note, firstly, that the pressure end effect on the limit load is not in the KANNINEN expression of M_L but in the term A; secondly, the shape factor of the crack section is different from the one proposed for the longitudinal crack: it corresponds in this case to a global shape factor of the full section of the pipe.

The expression of L_R becomes:

$$L_R = \frac{\sigma_e^{mt}}{\frac{4}{\pi}\sigma_y \left[\cos\frac{a\gamma}{t2} - \frac{1a}{2t}\sin\gamma\right]\left[-\beta' + (\beta'(2+\beta'))^{1/2}\right]}$$

with: $\sigma_e^{mt} = \sigma_b^{mt}/3 + [(\sigma_b^{mt}/3)^2 + \sigma_m^{mt2}]^{1/2}$

For high longitudinal stress, relaxation phenomenons may likely take place, but for safety analysis and due to the lack of qualification, no rule of relaxation are retained for circumferential crack.

Qualification of this approach is shown on figure 6. Elasto-plastic computation of an internal circumferential surface crack in a pipe under pressure (P = 20 MPa) plus bending moment (M = 250 10^4mN), ref. [5], were performed. The geometry is the following:

R_m = 300 mm t = 60 mm a/t = 0.5 a/c = 0.4

Results of K_R computed with option 3, in function of L_R, with the previous formulation, are compared with the option 2 FAL. We note the good correlation between these two FAL, and then the good prevision of J_{app} using this formulation of L_R associated with the option 2 FAL.

V. CONCLUSIONS.

A simplified rule was developed to compute J applied to surface cracks in pipes and elbows. The reference stress for computing L_R combines the membrane and bending stresses in an expression derived from the limit load of a beam under bending and tension. In the case of circumferential crack under pressure plus bending, the EPRI relation was used.
For longitudinal crack, the model takes into account the relaxation of the bending ovalisation stress.
A large number of elasto-plastic computations were performed to develop and qualify these models. Further works are underway to improve the circumferential crack model applied to an elbow with three dimensional computations.

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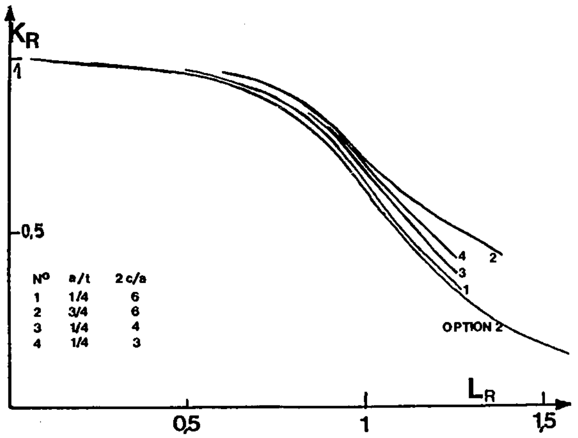

Figure 1: FAD option 3 of the 4 cracks and comparaison with FAD option 2.

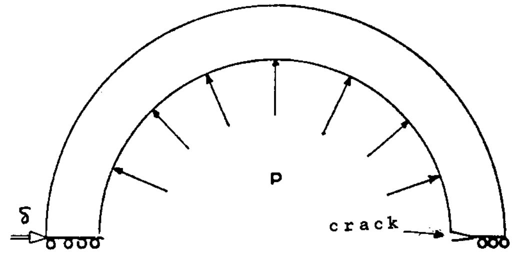

Figure 2: 2-D cracked pipe model.

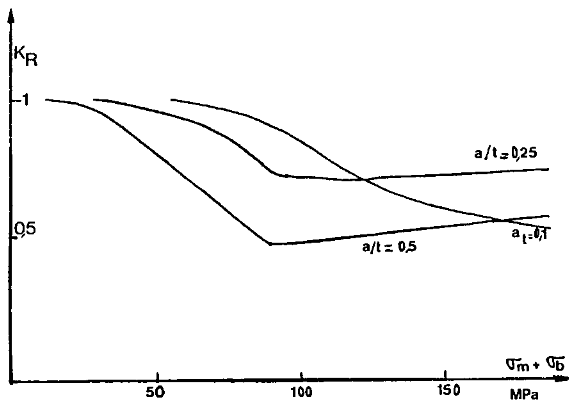

Figure 3: Kr in function of the elastic stress $\sigma_m + \sigma_b$ for the 3 cracks.

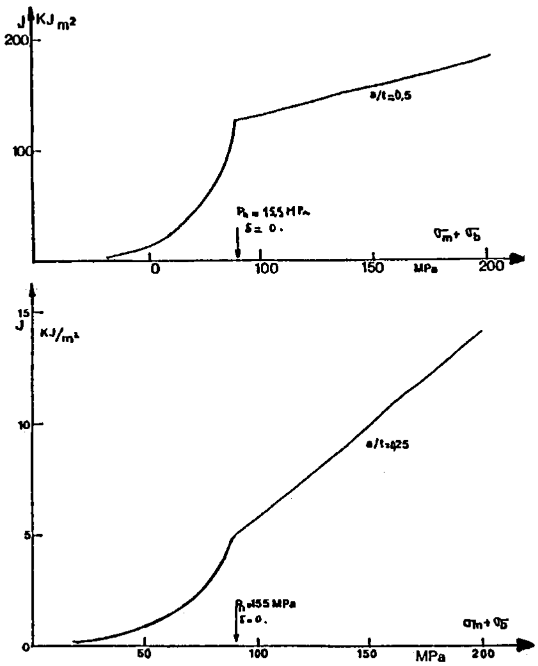

Figure 4: J values computed with SYSTUS for the 2 deepest cracks.

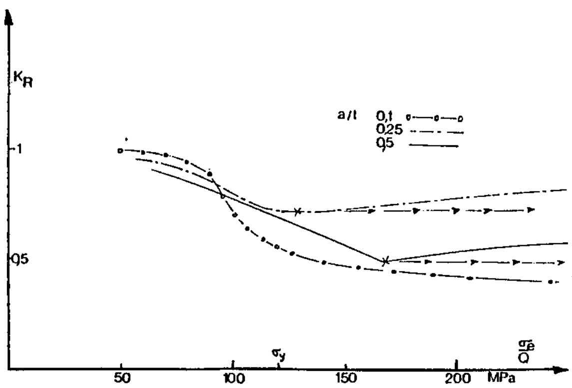

Figure 5: Kr in function of σ_e/Q for the 3 cracks.

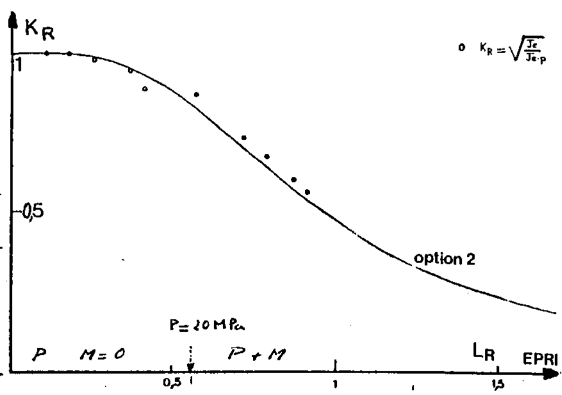

Figure 6: FAD option 2 and $\sqrt{J_e / J_{e-p}}$ computed with CASTEM code.