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J SIMPLIFIED ASSESSMENT FOR CRACKED PIPES AND ELBOWS IN THE RSE-M CODE

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ABSTRACT

RSE-M Code provides rules and requirements for in-service inspection of French Pressurized Water Reactor power plant components. Non mandatory guidance is given in the Code for defect assessment in a wide range of configurations: surface cracked pipes and elbows under pressure, moment and thermal loading. The Code provides influence coefficients to calculate stress intensity factors in pipes and elbows containing semi-elliptical surface defects (circumferential or longitudinal). The J assessment method is based on the reference stress concept with two options for reference loads evaluation: "CEP elastic plastic stress" and "CLC modified limit load".

This paper presents an overview of all the formulations and namely the case of pipe-to elbow junctions. The paper provides also a description of the very large data base of 2D and 3D J elastic-plastic finite element calculations performed to establish and validate the formulations. Finally an applicability domain of the methods is given ensuring a conservative prediction of J.

Keywords: Codes & Standards, defect assessment, engineering method, J estimation scheme

1. NOMENCLATURE

L_{tran}	Length of the thickness transition
r_i	Inside radius of pipe or elbow
r_e	Outside radius of pipe or elbow
r_m	Mean radius of pipe or elbow
r_{mb}	Mean radius of pipe (thick side of tapered transition)
R_c	Radius of curvature of elbow
t	Pipe wall thickness

$t(\varphi)$ Elbow variable wall thickness (intrados reinforcement)
t_b Pipe wall thickness (thick side of tapered transition)
λ Elbow parameter : $\lambda = \frac{tR_c}{r_m^2}$
ψ_c Bend angle of elbow
ψ_1 Slope of the tapered transition
a Depth of a surface crack
c Half-crack length
β Half-crack angle
φ Crack azimuth on elbow
X Position of the crack in a tapered transition
E Young's modulus
ν Poisson's ratio
S_y Yield stress (at 0.2%)
M_1 Torsion moment
M_2 In-plane bending moment
M_3 Out-of-plane bending moment
P Pressure
K_I Mode I stress intensity factor
J_{el} Elastic value of J
J Elastic-plastic value of J

Other symbols are defined in the body of the text.

2. INTRODUCTION

The RSE-M Code (RSE-M, 2000) provides rules and requirements for in-service inspection of French Pressurized Water Reactor power plant components. Its scope is close to the scope of Division 1 in Section XI of ASME B & PV Code (ASME, 1998), except that concrete components and metallic liners are not included. Appendices 5.3 and 5.4 of the Code give non mandatory guidance for analytical evaluation of flaws, i.e. fracture mechanics analyses based on simplified methods. The J assessment method for mechanical loading is based on the reference stress concept with two options for reference load evaluation : "CEP elastic plastic stress" and "CLC modified limit load". For thermal and combined loading, an analytical method is also available but it will not be described here (see Le Delliou, 2004).

This paper presents an overview of all the formulations for mechanical loading and namely the case of pipe-to elbow junctions. The paper provides also a description of the very large data base of 2D and 3D J elastic-plastic finite element calculations performed to establish and validate the formulations. Finally an applicability domain of the methods is given ensuring a conservative prediction of J.

3. PIPING CONFIGURATIONS COVERED

EDF, FRAMATOME and CEA have developed simplified methods to calculate the J integral for surface cracks in 5 typical piping configurations :

a) Circumferential surface crack in a straight pipe

Figure 1 shows a circumferential semi-elliptical crack at the outside surface of a pipe. The crack angle β is defined by : $\beta = \frac{c}{r_e}$ ($\beta = \frac{c}{r_i}$ if the crack is on the inside surface). The mechanical loading can be a combination of pressure, in-plane bending moment M_2 and torsion moment M_1.

b) Circumferential surface crack in a tapered transition

Figure 2 shows an axisymmetrical crack at the inside surface of a tapered transition. The crack is located in the thin side of the transition, at a distance X (≥ 0) from the thickness transition. The mechanical loading can be a combination of pressure, in-plane bending moment M_2 and torsion moment M_1.

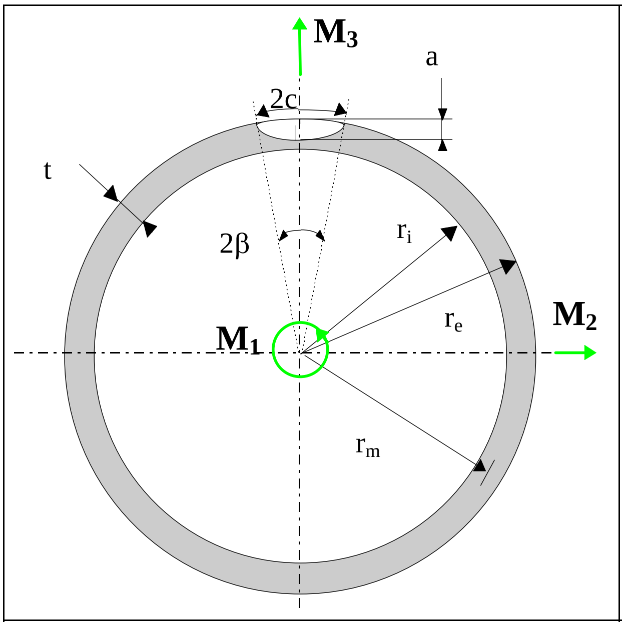

Figure 1 - A circumferential semi-elliptical crack in a straight pipe

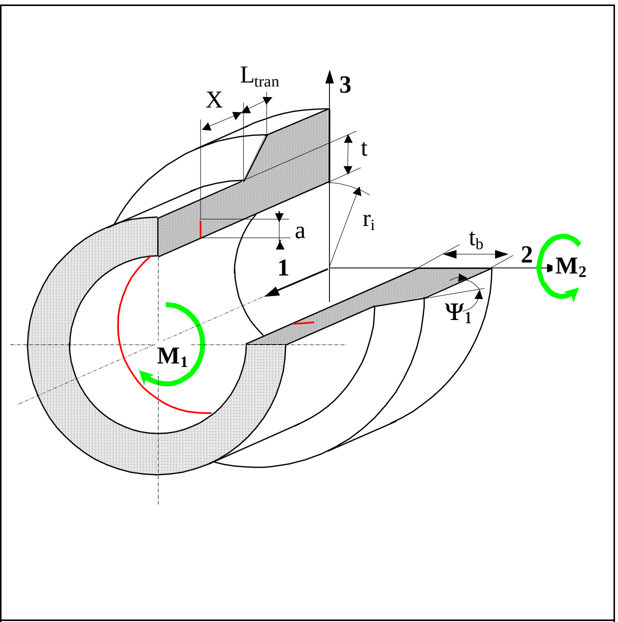

Figure 2 - An axisymmetrical crack at the inside surface of a tapered transition

c) Longitudinal surface crack in a straight pipe

Figure 3 shows a longitudinal semi-elliptical crack at the inside surface of a pipe. The mechanical loading can be a combination of pressure, in-plane bending moment M_2 and torsion moment M_1.

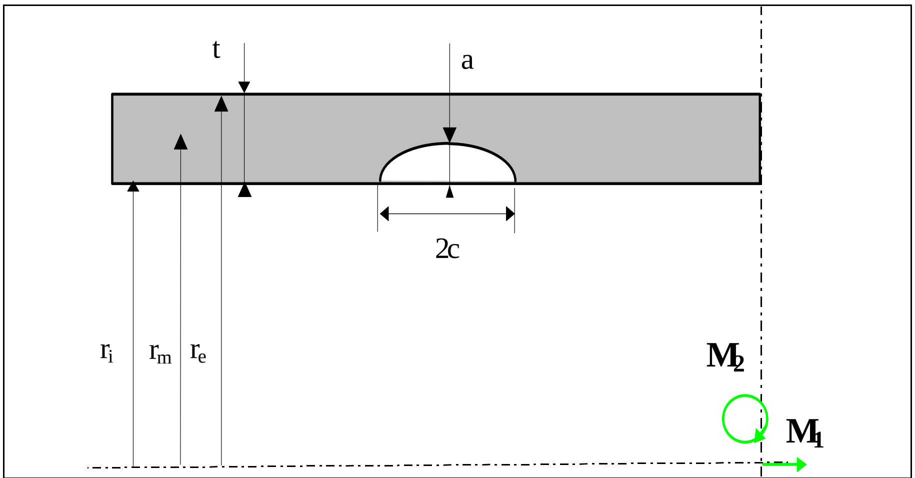

Figure 3 - A longitudinal semi-elliptical crack in a straight pipe

d) Longitudinal surface crack at the mid-section of an elbow

Figure 4 shows a longitudinal semi-elliptical crack at the outside surface of an elbow. The crack must be located in the elbow mid-section and in one of these three positions : intrados (φ = -90°), extrados (φ = 90°) or crown (φ = 0°). The crack angle β is defined by : $\beta = \frac{c}{r_m}$. The mechanical loading can be a combination of pressure, in-plane bending moment M_2, out-of-plane bending moment M_3 and torsion moment M_1.

The components of moment are those existing in the mid-section of the elbow. They can be calculated from those existing at the elbow end as shown in figure 4 by the relations :

$$M_1 = M_1^0 \cos\left(\frac{\psi_c}{2}\right) - M_3^0 \sin\left(\frac{\psi_c}{2}\right)$$

$$M_2 = M_2^0$$

$$M_3 = M_1^0 \sin\left(\frac{\psi_c}{2}\right) + M_3^0 \cos\left(\frac{\psi_c}{2}\right)$$

e) Circumferential surface crack at a pipe-elbow junction

Figure 5 shows a circumferential semi-elliptical crack at the junction between a straight pipe and an elbow. The crack angle β is defined by : $\beta = \frac{c}{r_m}$. The mechanical loading can be a combination of pressure, in-plane bending moment M_2, out-of-plane bending moment M_3 and torsion moment M_1. The components of moment M_1 an M_3 are those existing in the mid-section of the elbow. They can be calculated from those existing at the elbow entrance with the same formulas as for case d).

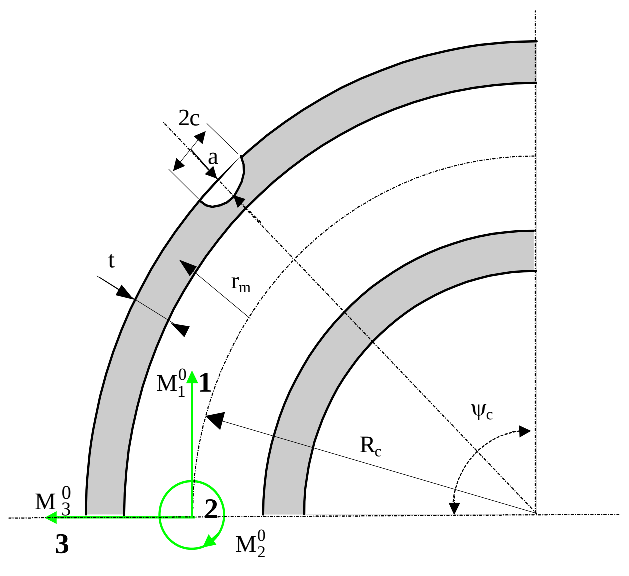

Figure 4 - A longitudinal semi-elliptical crack in the mid-section of an elbow at the extrados (φ = 90°)

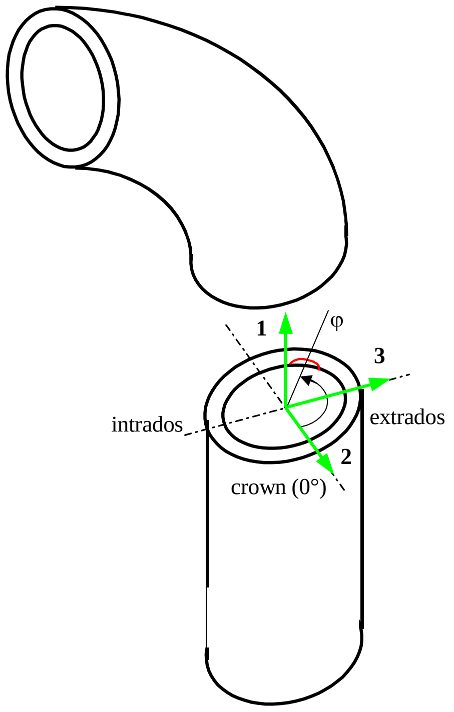

Figure 5 - A circumferential semi-elliptical crack in a pipe-elbow junction

4. PRESENTATION OF THE J-ESTIMATION SCHEME

4.1 Background

CEA, Framatome ANP and EDF have developed a simplified method to calculate the J integral in cracked piping components subjected to mechanical loading. The estimation of the elastic-plastic parameter J (called J_S) is based on a plastic correction of the elastic value of J (called J_{el}), using the reference stress technique as established by Ainsworth (1984) for the R6 procedure (Milne, 1988) :

$$J_s = J_{el}\left[\frac{E\varepsilon_{ref}}{\sigma_{ref}} + \psi\right] \quad (1)$$

where :

- $J_{el} = \frac{K_I^2}{E*}$ with $E* = \frac{E}{1-\nu^2}$
- $\sigma_{ref} = L_r S_y$
- ε_{ref} is the strain corresponding to the stress $\sigma_{ref} = L_r S_y$ on the true stress - true strain curve of the material (same approach as Option 2 of the R6 rule)
- ψ is the plastic zone correction.

The reference stress, σ_{ref}, can be determined by two options named respectively “Modified Limit Load option” (CLC) and “Elastic-Plastic Stress option” (CEP).

Equations for cases a) to d) have already been fully presented in previous papers (Lacire, 2001, Lacire, 2002, Le Delliou, 2003) and will not be recalled here. Only case e) will be presented hereafter for both options.

4.2 CEP option for a circumferential surface crack at a pipe-elbow junction

Since plasticity can cause redistribution of elastic stresses, two equivalent elastic and plastic stresses, named respectively σ_{eqel} and σ_{eqpl}, are determined from the stress components in the elbow wall :

$$[\sigma_{eqel}]^2 = [s'_{1m}]^2 + \sigma_{2m}^2 - s'_{1m}\sigma_{2m} + 4\sigma_{12}^2 \quad (2)$$

$$[\sigma_{eqpl}]^2 = s_{1m}^2 + \sigma_{2m}^2 - s_{1m}\sigma_{2m} + 4\sigma_{12}^2 \quad (3)$$

where :

- $s_{1m} = \sigma_{1m} + \frac{g}{f_{pl}}\sigma_{gb}$ is the plastic total axial membrane stress,
- $s'_{1m} = 1.5 * \sigma_{1m} + \frac{1}{f_{el}}\sigma_{gb}$ is the elastic total axial membrane stress,
- σ_{1m} and σ_{2m} are respectively the axial and circumferential membrane stresses due to the pressure,
- σ_{gb} is the axial membrane stress due to the bending moment,
- σ_{12} is the shear stress due to the torsion moment,
- g is a coefficient taking into account the effect of plasticity,
- f_{el} and f_{pl} are coefficients taking into account the presence of the crack

The expressions used to calculate the stress components σ_{1m}, σ_{2m}, σ_{gb} and σ_{12} from the loads P, M_1^0, M_2^0 and M_3^0, as well as the expressions of the coefficients g, f_{el} and f_{pl} are given in Tables 1 and 2, depending on the crack shape (semi-elliptical or axisymmetrical) and location (inner or outer surface). It should be noted that the moments have to be taken in the pipe-elbow junction.

The reference stress σ_{ref} is deduced from these elastic and plastic equivalent stresses. Its corresponds, on the material stress-strain curve, to the strain ε_{ref} expressed by the following relation, as illustrated on figure 6 :

$$\varepsilon_{ref} = \varepsilon_{el}(\sigma_{eqel}) + \varepsilon_{pl}(\sigma_{eqpl})$$

where :

- $\varepsilon_{el} = \sigma_{eqel}/E$ is the elastic strain associated to σ_{eqel},
- ε_{pl} is the plastic strain associated to σ_{eqpl}.

Finally, an estimate of the elastic-plastic J-integral is obtained from equation (1) doing $\psi = 0$ (no plastic zone correction).

Additional information can be found in (Marie, 2003).

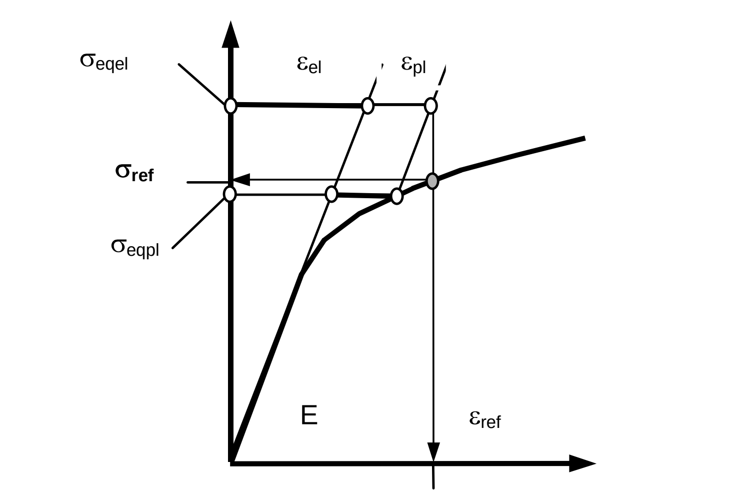

Figure 6 – CEP option : reference stress evaluation

4.3 CLC option for a circumferential surface crack at a pipe-elbow junction

For this case, the equation used to calculate L_r for a pressure combined with the moments M_1 (torsion), M_2 (in-plane) and M_3 (out of-plane) is :

$$L_r = \sqrt{\left[\gamma^2 \frac{m}{q_m \mu_{em} \mu_t}\right]^2 + \left[\frac{pC_{1c}}{\mu_{ep}}\right]^2 + \left[\frac{m_1}{q_n \mu_{en}}\right]^2} + (1-\gamma^2)\left(\frac{m}{q_m \mu_{em} \mu_t}\right) \quad (4)$$

where p, m_1, and m are non-dimensional loading :

$$p = \frac{\sqrt{3}}{2}\frac{Pr_m}{tS_y} \qquad m_1 = \frac{\sqrt{3}}{2}\frac{M_1}{\pi r_m^2 tS_y} \qquad m = \frac{\sqrt{\left(\frac{M_2}{\mu_{g2}}\right)^2 + \left(\frac{M_3}{\mu_{g3}}\right)^2}}{4r_m^2 tS_y} \quad (5)$$

and q_m, q_n, μ_{em}, μ_{en}, μ_{ep}, μ_t, C_{1c}, γ, μ_{g2} and μ_{g3} are coefficients depending only on geometrical parameters. These coefficients are given in Table 3. The moments M_1, M_2 and M_3 have to be taken in the elbow mid-section.

When there exists a bending moment ($m > 0$), a correction is requested to avoid non-conservative results at the onset of plastification ($L_r < 1$). This correction needs the calculation of the parameter L_r^* :

$$L_r^* = \sqrt{\gamma^4 m^{*2} + m_1^2 + p^2} + (1-\gamma^2)m^* \quad \text{where} \quad m^* = 0.28(1+\lambda)q_m\sqrt{1-\left(\frac{m_1}{q_n}\right)^2 - p^2} \quad (6)$$

Then K_r is calculated from L_r by :

$$K_r = \left[\frac{E\varepsilon_{ref}}{L_r S_y} + \frac{1}{2} \frac{L_r^2}{L_r^2 + 1} \right]^{-\frac{1}{2}} \quad (7)$$

where ε_{ref} is the strain corresponding to the stress $\sigma_{ref} = L_r S_y$ on the true stress - true strain curve of the material (same approach as Option 2 of the R6 rule).

When m > 0 and $L_r^* < L_r < 1$ a corrected value of K_r is calculated by a linear interpolation between $K_r\left(L_r^*\right)$ and $K_r\left(L_r = 1\right)$:

$$K_r = K_r\left(L_r^*\right) + \frac{K_r\left(L_r = 1\right) - K_r\left(L_r^*\right)}{1 - L_r^*}\left(L_r - L_r^*\right) \quad (8)$$

Figure 7 shows the principle of the correction :

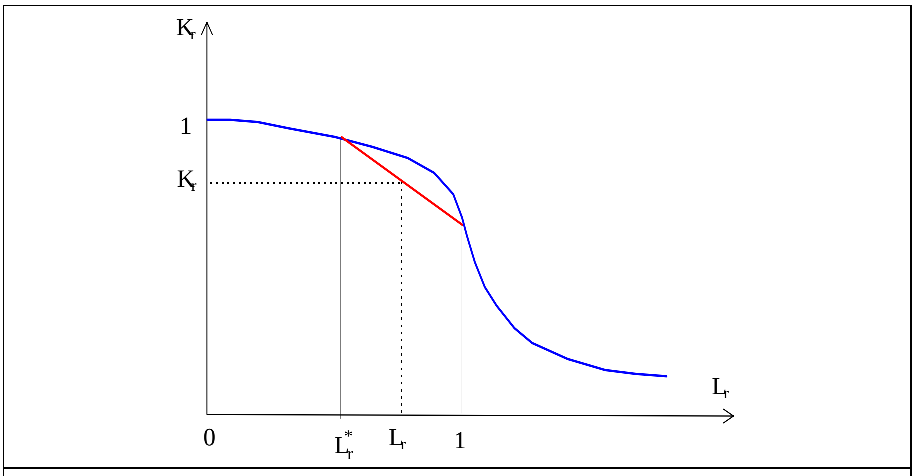

Figure 7 – CLC option : correction of K_r in the transition regime between confined plasticity and generalized plasticity in bending

Finally, an estimate of the elastic-plastic J-integral is obtained by :

$$J = \frac{J_e}{K_r^2}$$ where J_e is the elastic value of J

Additional information can be found in (Michel, 2003).

5. DESCRIPTION OF THE VALIDATION PROGRAM

5.1 Finite element database

A set of elastic-plastic calculations on configurations representative of nuclear power plant piping has been established and constitutes the reference database used to develop and validate the analytical method. About 200 FE calculations of J performed by CEA and EDF using 2 FE codes (CASTEM2000 from the CEA and Code_Aster from EDF) are available for the configuration (case e) presented in this paper.

To elaborate a comprehensive finite element database, including semi-elliptical and axisymmetrical defects, the following parameters were investigated :

- relative pipe wall thickness (t/r_m = 1/5 or 1/10),
- elbow parameter ($0.2 \le \lambda \le 0.8$),
- elbow angle ($45° \le \psi_c \le 180°$)
- crack location (inside or outside surface),
- crack azimut (angle φ),
- relative crack depth (a/t = 1/8 ; 1/4 ; 1/2),
- crack aspect ratio (a/c = 1/3 for most cases),

- tensile curve (Ramberg-Osgood fit with n = 6 or 8, 316 stainless steel, carbon steel with a plateau). The Ramberg-Osgood fit uses the equation :

$$\varepsilon = \frac{\sigma}{E}\left[1+\alpha\left(\frac{\sigma}{\sigma_0}\right)^{n-1}\right]$$ with E = 174700 MPa, α = 1 and σ_0 = 163 MPa,

- type of loading.

5.1 Application of the method on examples

Three examples of application are presented here, whose characteristics are given in Table 4. The stress-strain curve used is the Ramberg-Osgood one described previously, with n = 6. In the FE calculation with combined loading (pressure and moments), the pressure is applied first, then it is held constant and the moments are applied proportionally. For the application of the analytical method, the elastic value of J comes from the FE calculation, in order to avoid inaccuracies due to the analytical evaluation of J_{el}. To characterize the overall load level due to combined loading, a parameter called L_{r_nom} is defined by the formula :

$$L_{r\_nom} = \sqrt{m^2 + [pC_{1c}]^2 + [m_1]^2} \tag{9}$$

where p, m_1, and m are non-dimensional loading defined by equation (5).

For the three examples, Fig. 8, 10 and 12 show the evolution of J at the deepest point of the crack as a function of L_{r_nom}, whereas Fig. 9, 11 and 13 show the evolution of the relative difference on J between the estimate J_S and the FE result (J_{EF}). This difference was calculated by the formula :

$$Diff\_J(\%) = 100\,\frac{J_S - J_{EF}}{J_{EF}} \tag{10}$$

This type of analysis was conducted on the whole database, in order to determine an overall trend on the accuracy of the analytical method. The under-conservatisms are limited to 20 % but the over-conservatisms can be high (more than 100 % for high levels of loading).

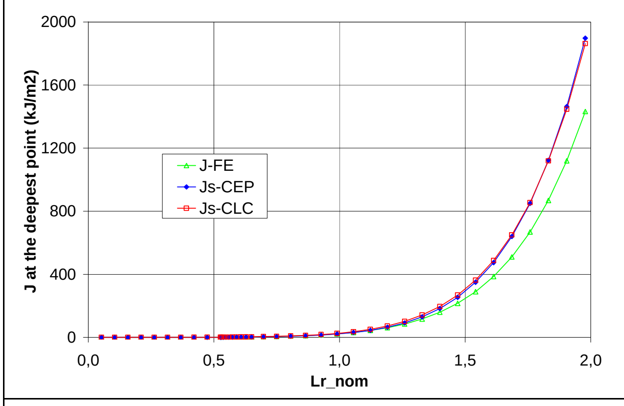

Figure 8 - case 1 : J at the deepest point

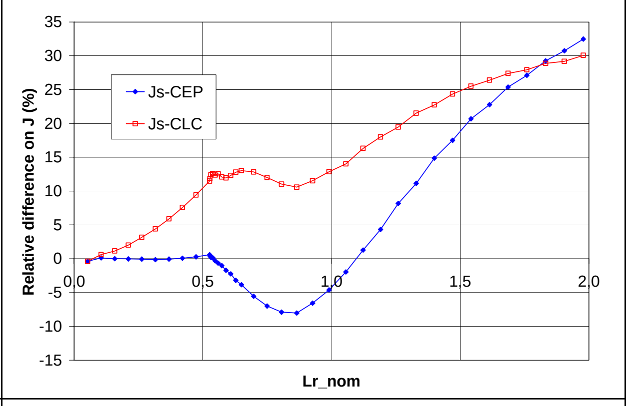

Figure 9 – case 1 : relative difference on J

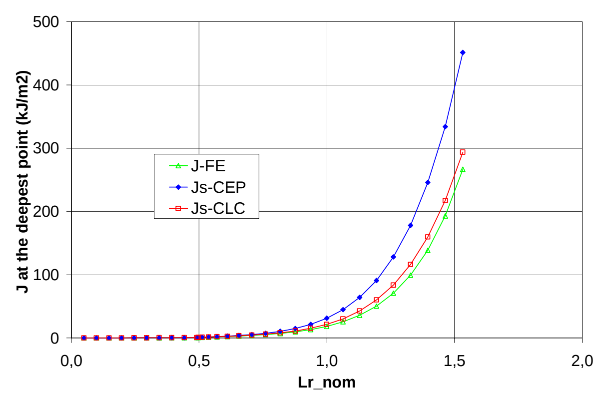

Figure 10 - case 2 : J at the deepest point

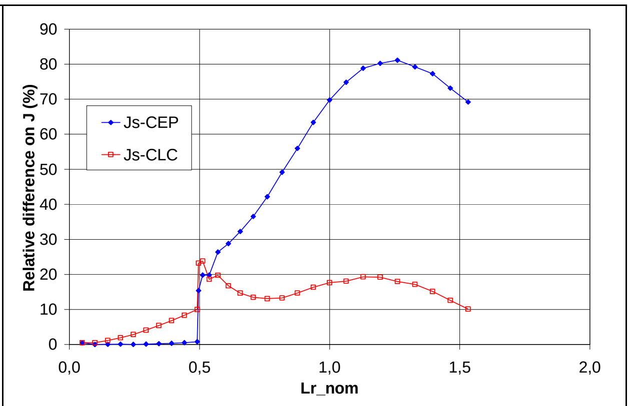

Figure 11 – case 2 : relative difference on J

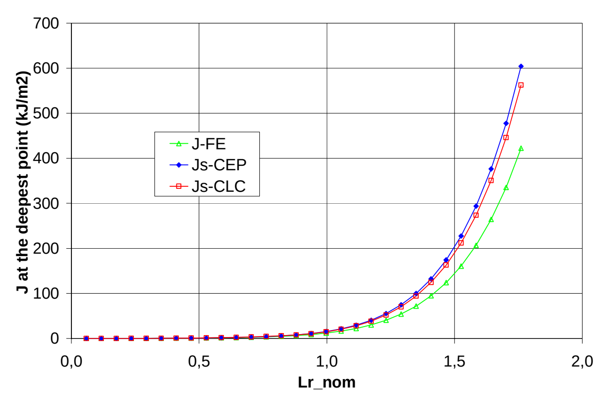

Figure 12 - case 3 : J at the deepest point

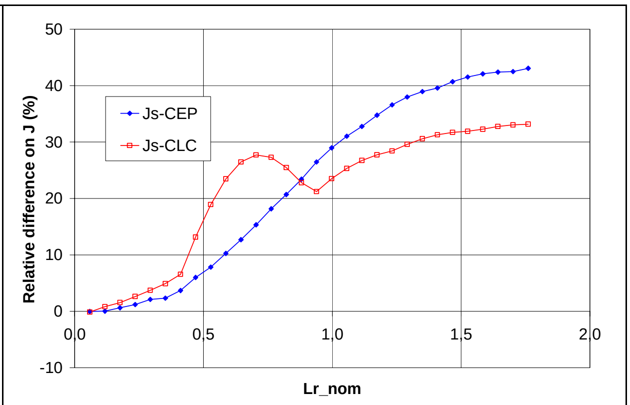

Figure 13 – case 3 : relative difference on J

6. APPLICABILITY DOMAIN

For the configuration presented in this paper (pipe-to elbow junction), the CLC and CEP options are applicable to elbows with $r_m / t \geq 3$, $0.2 \leq \lambda \leq 1$ and $45° \leq \psi_c \leq 180°$. Regarding the crack size and shape, the conditions are as follows :

- if $\frac{1}{3} \leq \frac{a}{c} \leq 1$ then $\frac{a}{t} \leq \frac{1}{2}$
- if $0 \leq \frac{a}{c} \leq \frac{1}{3}$ then $\frac{a}{t} \leq \frac{1}{4}$

7. CONCLUSIONS

The RSE-M Code provides rules and requirements for in-service inspection of French Pressurized Water Reactor power plant components. Its scope is close to the scope of Division 1 in Section XI of ASME.

Appendix 5.4 of the Code gives non mandatory guidance for analytical evaluation of flaws, i.e. fracture mechanics analyses based on simplified methods, including evaluation of elastic stresses, stress intensity factors and the J-integral.

J-estimation schemes have been developed to calculate the J integral in a pipe or an elbow containing a surface crack, submitted to mechanical or thermal loading :

- circumferential crack in a straight pipe (included in the 2000 Addenda) or a tapered transition,
- longitudinal crack in a straight pipe,
- circumferential crack at the junction between a straight pipe and an elbow,
- longitudinal crack in the mid-section of an elbow.

These methods will be included in the next Code Addenda, to appear in 2005.

In this paper, the case of a circumferential crack at a pipe-to elbow junction submitted to mechanical loading was developed. An outline of the validation work was shown and the range of application was specified.

Work is on-going on the development of a J-estimation scheme for cracks in welds, to take benefit of the mismatch between the tensile properties of the weld material and those of the base material.

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Table 1 - Circumferential inner surface crack at a pipe-elbow junction. Coefficients for the CEP option.

Stress component or coefficient	Semi-elliptical inner surface crack	Axisymmetrical inner surface crack
σ_{1m}	$\frac{Pr_m}{2t}\cdot\frac{t}{t(\varphi)}\cdot\frac{1}{q_p}\cdot\left(1+\frac{1}{z}\right)$ where $q_p=\left(1-\frac{a}{t(\varphi)}\right)+\frac{a}{t(\varphi)}\cdot\frac{1}{1+\frac{c}{\sqrt{r_m a}}}$ and $z=1+\frac{Pr_m}{2t(\varphi)}\cdot\frac{2\pi r_m^2 t}{\left\|M_1^0\right\|}$	$\frac{Pr_m}{2t}\cdot\frac{t}{t(\varphi)}\cdot\frac{1}{q_p}$ where $q_p=\left(1-\frac{a}{t(\varphi)}\right)$
σ_{2m}	$\frac{Pr_m}{t}\cdot\frac{t}{t(\varphi)}\cdot\frac{C_{1c}^*}{q_p}$ where $C_{1c}^*=\frac{(1.85R_c+1.35r_m\sin\varphi)}{2(R_c+r_m\sin\varphi)}$	$\frac{Pr_m}{t}\cdot\frac{t}{t(\varphi)}\cdot\frac{C_{1c}^*}{q_p}$ where $C_{1c}^*=1.085\frac{(1.85R_c-1.35r_m)}{2(R_c-r_m)}$
σ_{gb}	If y <0 : $\frac{\sqrt{(M_2^0)^2+(M_3^0)^2}}{\pi r_m^2 t}\cdot\frac{1}{\mu_g}\cdot(1-0.23y-0.0176y^2)$ If y >0 : $\frac{\sqrt{(M_2^0)^2+(M_3^0)^2}}{\pi r_m^2 t}\cdot\frac{1}{\mu_g}\cdot(1-0.32y-0.12y^2)$ where $y=\frac{-\left\|M_1^0\right\|}{\left\|M_2^0\right\|+\left\|M_3^0\right\|}\cdot SGN\left(\frac{M_1^0}{M_3^0}\right)$ If $\lambda\geq 0.5$: $\mu_g=Min(0.8\lambda^{0.6};1)\,Min\left(1;1.075-0.15\frac{\psi_c}{\pi}\right)$ If $\lambda<0.5$: $\mu_g=0.905\lambda^{0.78}\ Min\left(1;1.075-0.15\frac{\psi_c}{\pi}\right)$	
σ_{12}	$\frac{M_1^0}{2\pi r_m^2 t}\cdot\frac{1}{q_p}\cdot\frac{1}{0.8}$	
f_{el}	If y <0 : $\left[\cos\left(\frac{\beta}{2}\frac{a}{t}\right)-\frac{a}{2t}\sin\beta\right]\frac{1}{k}\left[1+0.23y-0.0176y^2\right]$ If y >0 : $\left[\cos\left(\frac{\beta}{2}\frac{a}{t}\right)-\frac{a}{2t}\sin\beta\right]\frac{1}{k}\left[1-0.32y-0.12y^2\right]$ where $\beta=\frac{c}{r_i}$ $k=Min[1;(-0.378\lambda^2+0.986\lambda+0.446)]$	If y <0 : $\left[1-\frac{a}{t}\right]\frac{1}{k}\left[1+0.23y-0.0176y^2\right]$ If y >0 : $\left[1-\frac{a}{t}\right]\frac{1}{k}\left[1-0.32y-0.12y^2\right]$ where $k=Min[1;(-0.378\lambda^2+0.986\lambda+0.446)]$
f_{pl}	$\left[\cos\left(\frac{\beta}{2}\frac{a}{t}\right)-\frac{a}{2t}\sin\beta\right]\frac{1}{k}$	$\left[1-\frac{a}{t}\right]\frac{1}{k}$
g	$\frac{\pi}{4}$	

Table 2 - Circumferential outer surface crack at a pipe-elbow junction. Coefficients for the CEP option.

Stress component or coefficient	Semi-elliptical outer surface crack	Axisymmetrical outer surface crack
σ_{1m}	$\frac{Pr_m}{2t} \cdot \frac{t}{t(\varphi)} \cdot \frac{1}{q_p} \cdot \frac{1}{0.95}$ where $q_p = \left(1 - \frac{a}{t(\varphi)}\right) + \frac{a}{t(\varphi)} \cdot \frac{1}{1 + \frac{c}{\sqrt{r_m a}}}$	$\frac{Pr_m}{2t} \cdot \frac{t}{t(\varphi)} \cdot \frac{1}{q_p}$ where $q_p = \left(1 - \frac{a}{t(\varphi)}\right)$
σ_{2m}	$\frac{Pr_m}{t} \cdot \frac{t}{t(\varphi)} \cdot \frac{C^*_{1c}}{q_p} \cdot \frac{1}{0.95}$ where $C^*_{1c} = \frac{(1.85R_c + 1.35r_m \sin\varphi)}{2(R_c + r_m \sin\varphi)}$	$\frac{Pr_m}{t} \cdot \frac{t}{t(\varphi)} \cdot \frac{C^*_{1c}}{q_p} \cdot \frac{1}{0.95}$ where $C^*_{1c} = \frac{(1.85R_c - 1.35r_m)}{2(R_c - r_m)}$
σ_{gb}	If y <0 : $\frac{\sqrt{(M_2^0)^2 + (M_3^0)^2}}{\pi r_m^2 t} \cdot \frac{1}{\mu_g} \cdot (1 - 0.3y - 0.1y^2)$ If y >0 : $\frac{\sqrt{(M_2^0)^2 + (M_3^0)^2}}{\pi r_m^2 t} \cdot \frac{1}{\mu_g} \cdot (1 + \mathrm{Max}[-0.25y - 0.6y^2; -0.37])$ where $y = \frac{-\lvert M_1^0 \rvert}{\lvert M_2^0 \rvert + \lvert M_3^0 \rvert} \cdot \mathrm{SGN}\left(\frac{M_1^0}{M_3^0}\right)$ and $\mu_g = \mathrm{Min}(0.8\lambda^{0.6}; 1)$	
σ_{12}	$\frac{M_1^0}{2\pi r_m^2 t} \cdot \frac{1}{q_p} \cdot \frac{1}{0.9}$	
f_{el}	$\left[\cos\left(\frac{\beta}{2}\frac{a}{t}\right) - \frac{a}{2t}\sin\beta\right]^{\frac{1}{k}}$ where $\beta = \frac{c}{r_e}$ $k = \mathrm{Min}\left[1; (-0.378\lambda^2 + 0.986\lambda + 0.446)\{1 - 0.31\,\mathrm{Max}[0; (\sin(1.74\varphi - 1.976))^{1.53}]\}\right]$	$\left[1 - \frac{a}{t}\right]^{\frac{1}{k}}$ where $k = \mathrm{Min}[1; -0.378\lambda^2 + 0.986\lambda + 0.446]$
f_{pl}	$f_{pl} = f_{el}$	
g	$\frac{\pi}{4}$	

Table 3 - Circumferential surface crack at a pipe-elbow junction. Coefficients for the CLC option.

Coefficient	$\beta < 2\pi \frac{a}{t}$	$\beta \geq 2\pi \frac{a}{t}$
C_{1c}	$0.5 + \frac{2R_c - r_m}{4(R_c - r_m)}$	
γ	0.8 (inner surface crack) 1 (outer surface crack)	
μ_{g2}	$1 + \left[\left(0.13 + 0.4383\psi_c - 0.07353\psi_c^2\right) \cdot \mathrm{Min}\left(0\,;\,0.62\lambda^2 + 0.31\lambda - 0.85\right)\right]$	
μ_{g3}	$1 + \left[\left(0.13 + 0.4383\psi_c - 0.07353\psi_c^2\right) \cdot \mathrm{Min}\left(0\,;\,1.2\lambda - 1.1\right)\right]$	
q_m	$\cos\left(\frac{\beta}{2}\frac{a}{t}\right) - \frac{1}{2}\frac{a}{t}\sin(\beta)$	$1 - \frac{a}{t}$
q_n	$1 - \frac{\beta}{\pi}\frac{a}{t} - \frac{2}{\pi}\arcsin\left[\frac{1}{2}\frac{a}{t}\sin(\beta)\right]$	$1 - \frac{a}{t}$
μ_{em}	$1 - 0.16\sqrt{\frac{a}{t}}$	1
μ_{en}	$0.92\ \mu_{em}$	
μ_{ep}	1 (inner surface crack) 0.9 (outer surface crack)	
μ_t	$1 + \frac{1}{2}\frac{a}{t}\frac{\beta}{\pi}$	$1 + \frac{1}{2}\frac{a}{t}$

Table 4 - Characteristics of the examples presented.

	r_m (mm)	t (mm)	R_c (mm)	ψ_c (°)	Crack location	a (mm)	c (mm)	φ (°)	Loading
Case 1	400	40	1200	90	inside	10	30	-147.9	P+M_2 : P up to 10 MPa M_2 up to 5000 kN.m
Case 2	400	40	2400	90	inside	10	30	3	P+M_1+M_3 : P up to 10 MPa M_1,M_3 up to 4000 kN.m
Case 3	400	40	2400	90	outside	10	30	141.4	M_2 up to 6000 kN.m