Mechanical analysis of an auxiliary piping elbow

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ABSTRACT

This study was undertaken following the through-wall cracking of a safety injection line elbow (Bugey PWR Unit 3, November 11, 1983). Its objective is to evaluate the stress distribution in the elbow, under the various loadings applied to the pipe, in order to explain the cracking. These loadings are modelized using in situ carried measurements and conclusions from the laboratory survey (global pipe displacements, thermal stratification of the internal fluid ...). A finite element stress analysis (by piping and 3D computer codes) allowed us to compare the various effects of these loadings on the elbow cracking. This work has contributed to the improvement in the reliability of this piping in complement of the modifications which are carried out in operating plants to prevent these defects.

1 INTRODUCTION

At the time of a in service inspection, in french Bugey PWR Unit 3 (November 1983), an incident was discovered : a leak on a safety injection line (in the weld between a straight part and an elbow) was flowing out. This line was very quickly repaired, and on-site measurements as well as a metallurgical survey were decided (by the "Groupe des Laboratoires, EDF). The observations had shown that it was dealt with a stress corrosion cracking (due to an accidental pollution during the plant started operation) and fatigue growth. A large number of very small surface cracks were found near a water level marking, on the inner surface ([1]). In order to understand the appearance of these cracks, a structural analysis of the incriminated elbow was conducted by the Departement "Mécanique et Modèles Numériques" of EDF.
A three-dimensional finite element analysis of the elbow, using a piping computation (beam-type pipe code POUX, which is developed at EDF) of the whole line, was performed.
The actually applied loadings are modelized according to results from measurements and expertise conclusions. There are two steps :
- only mechanical loadings :
  . global displacements (coming from the primary piping),
  . contacts with the whip restraints,
  . uniform dilatation in sections due to the temperature field.

- the same mechanical loadings and fluid thermal stratification assumption. This paper will present only the results of the 3D elbow analysis, the global behaviour of the line giving the mechanical loadings of our 3D-model.

2 MODELIZATION AND CALCULATIONS

2.1 Discretization of the structure

The figure 1 shows the geometry of the line (thickness : e = 18 mm ; mean radius : r = 75.1 mm, curvature radius of the elbow : R = 220 mm). The characteristic parameter of the elbow is : $eR/r^2 = 0.702$. The figures 2 and 3 show the 3D idealized part, with a detail of the elbow. The finite elements used are hexaedrons and pentaedrons (20 and 15 nodes, with incomplete quadratic displacement field, from the computer code ASKA-PERMAS). The straight parts have a sufficient length in order to attenuate the ovalization created in the elbow. The mesh size is composed of 1270 elements and 8324 nodes.

2.2 Discretization of the loadings

- Loadings from the piping : since it is modelized by beams, it provides a system of 3 forces and 3 moments (bending and torsion) (cf. Navier-Bernoulli kinematic assumptions). These 6 terms are elementary loading cases ; the contact with the whip restraint is idealized by a normal distributed thrust. We take into account the internal pressure (15.5 MPa), with the tensile axial force corresponding to the closed end condition (see figure 4).
- Thermal stratification : the temperatures of the outer surface, in the horizontal straight part, from the on-site measurements are : on the top : 240°C, and on the bottom : 100°C (see figure 5). This phenomena occurs during few days, jointly with a pressurization of 5 MPa. The pressure reaches 15.5 MPa at the end of this process : the check valve opens and the temperature field is homogeneized about 250°C. The stratified level is chosen corresponding to the water level marking which was discovered by the metallurgical survey. The heat exchanges between fluids and wall are modelized by a linear correspondance with exchange coefficients (natural convection in the fluid).

2.3 Piping calculations

a Case without thermal stratification

We assume an averaged temperature in the sections of the pipe (that involves only dilatations). With the mechanical loadings, which are applied on the pipe (global displacements, contacts with the whip restraints), we obtain the loadings of the 3D modelized elbow : forces, moments, thrust from the whip restraint.

b Case with thermal stratification

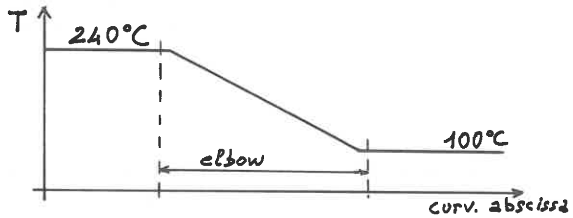
Its influence in the straight horizontal part of the line, which is idealized by beams, is analysed by equivalent dilatation and curvature. In order to determine these values, a simple 3D calculation, with thermal stratification on a straight pipe, was carried out.

2.4 3D modelized part calculations

(a) Case without stratification
The behaviour of the steel (Z2CND1712-02 or A376TP316) is assumed to be isotropic linear thermoelastic :

Temperature T (° C)	100°C	250°C	323°C
Young's modules E (MPa)	195000.	183800.	178000.
Thermal expansion ratio α (1/°C)	$1.682.10^{-5}$	$1.745.10^{-5}$	$1.77.10^{-5}$
Poisson's ratio ν	0.3		

The temperature distribution along the pipe is indicated in the following figure :



(b) Case with stratification
A thermal study is performed, and provides the distribution of the temperature field in the wall. The thermal characteristics are the following :
- heat transfers : hot fluid : T_c = 240°C, h_c = 1200 W/m2.°C
  cold fluid : T_f = 100°C, h_f = 1700 W/m2.°C
  ambiant air : T_a = 30°C, h_a = 11 W/m2.°C
- thermal conductivity : (in the steel) : λ = 17 W/m.°C

In the horizontal straight part, far from the elbow, we have a plane problem, which is solved using our 2D computer code ALIBABA. In the elbow, we need a 3D modelization, using ASKA-PERMAS code.
Then this temperature field is introduced in the thermomechanical calculation, with the other various loadings.

2.5 Performing of the calculations

These are carried out with ASKA-PERMAS (3D problems) on the CRAY 1 computer and with ALIBABA and POUX codes (which are developed at EDF) on IBM 3090.

3 RESULTS

3.1 Case without stratification

(a) Comparison of the elbow compliances
The usual method consists of applying the generalized forces provided by a beam-type calculation (using the flexibility factors applied to the elbow stiffness, given by design codes ASME-RCCM) to the 3D modelized elbow. Its validity is proved here by a comparison between the compliances S in both of these modelizations.

$$\underbrace{\delta}_{\substack{\text{3 displacements} \\ \text{3 rotations}}} = \underbrace{S}_{\substack{\text{compliance} \\ \text{(6 x 6 matrix)}}} \cdot \underbrace{F}_{\substack{\text{loads} \\ \text{(3 forces, 3 moments)}}}$$

The difference between the terms of the matrix S, according to two modelizations, goes from 0.5 % to 19 % (19 % for the term of coupling torsion - out of plane bending), the beam-type piping model is, on average, 5 % flexibler than the 3D model. We conclude that the results of the piping calculation may be used directly.

b) Three-dimensional aspects

- We analyse the stress distribution in the elbow by distinguishing between the "global" stresses, coming from piping calculation, which are in equilibrium with the generalized applied forces, and "local" stresses, caused by the redistributions in the elbow, which represent an ovalization and warping ot the sections. Local stresses may reach values of 100 % of global stresses, i.e. an intensity factor 2. The design rules ASME-RCCM for the elbow (1rst class) provide similar values. The figure 6 presents an example of this amplification. It appears that it attenuates in the straight parts quickly, like the sections ovalization. The attenuating length corresponds here to the value : $l_a = 1.5\sqrt{r^3/e} = 220$ mm : the ovalization amplitude is reduced to 2 % of its maximal value.
- It appears that the pressure has a little opening effect on the elbow.
- The loadings provided from the piping calculation give the following stress values at the cracking zones (note the increasing effect of contact with the whip restraint !).

• longitudinal crack (extrados)
hoop stress

without whip restraint	with whip restraint
115 MPa	240 MPa

• circonferential crack (intrados) : we have a compression, due to the turning off of the elbow by the thrust from the whip restraint (value : 187 kN). This latest unexpected result required the next analysis with a thermal stratification assumption.

3.2 Case with thermal stratification

a) thermal calculation :

- Horizontal straight part : the figure 7 shows the temperature profiles provided by the 2D computation. It appears that the outer side temperature are very close to these of the fluids (checking of the initial assumptions).
- Elbow : we note the strenght of the temperature gradient at the stratified level (about 10°C/mm) : see figure 8 .

b) Thermo-mechanical calculation :

- To evaluate the kinematic parameters for the beam mdel (dilatation ε, curvature γ) in the stratified horizontal straight part of the line, we use an energetic averaging method on the 3D deformation due to the stratification.

The simplest method consists, however, of an averaging on the temperature field in the section :

$T^{\circ}_{moy} = \frac{1}{S}\int_S T\, dS = 203°C$; $\nabla T^{\circ}_{moy} = \frac{1}{I}\int_S y.T\, ds = 631°C/m$. Then we obtain :

$\varepsilon^{\circ} = \alpha . T^{\circ}_{moy} = 3.496 . 10^{-3}$; $\gamma^{\circ} = \alpha . \nabla T^{\circ}_{moy} = 1.086.10^{2}\ m^{-1}$, i.e. a curvature radius R_{C_0} of 92.1 m.

The second method consists of an energetic averaging on the strain field caused by the stratification ; it provides :

$\varepsilon_1 = \frac{1}{S}\int_S \varepsilon^{**}_{3D}\, ds$; $\gamma_1 = \frac{1}{I}\int_S y. \varepsilon^{**}_{3D}\, dS$, i.e. :

$\varepsilon_1 = 3.46.10^{-3}$, $\gamma_1 = 1.33.10^{-2}\ m^{-1} \Leftrightarrow R_{C1} = 1/\gamma_1 = 75.1$ m ; namely :

$T^{\circ}_{moy} = \varepsilon_1/\alpha = 201°C$; $\nabla T_{moy} = \gamma_1/\alpha = 774°C/m$ ($\alpha \approx 1.72.10^{-5}°C/m$)

We note that although the averaged dilatations ε are close, the temperature gradient ∇T°_{moy} appears wrong.

- The crossing through the stratified level causes a high perturbation on the hoop and axial stresses : we obtain jumps about 200 MPa, which alternates quickly on each side. This perturbation is due to the variations of the gradient ∇T and corresponds to an alternate through-wall bending. (Fig.9) An analytical study has shown that a thermal shock may cause a very localized 3D stress peak ([2]). Using a fine analysis, none of these 3D stress peaks was observed in our situation. In spite of its relative coarseness, the 3D discretization used here appears efficient.
Assuming a strafied level fluctuation (due to a thermohydraulic gravity wave propagating in the straight horizontal part of the pipe : length : 2.40 m), we obtain a frequency about 0.13 Hz, i.e. 80000 cycles per week. Superimposing these cycles with other fluctuations at lower frequency and of higher amplitude (thermohydraulical oscillator between the various primary piping lines), we may expect a fatigue cracking and thermal striping at the inner surface, like it was observed during the metallurgical expertise.
- Adding with the loadings from the line : a contact with the whip restraint appears, but a smaller thrust, 107 kN instead of 187 kN. The stresses values are the following :

	Averaged value	localized jumps
crack extrados, hoop stress	110 MPa	$\Delta\sigma$ = 220 MPa
crack intrados, axial stress	20 MPa	$\Delta\sigma$ = 220 MPa

4 CONCLUSIONS

4.1 With regard to the stress distribution in this safety injection line elbow, which supports these various thermomechanical loadings, we have shown that :

- contacts with the whip restraints are very penalizing for the stress levels, namely for the extrados crack (σ^t = 240 MPa) ;
- the thermal stratification hot water-cold water, which we have modelized, provides high localized stress jumps, crossing the stratified level (where it was cracked) : about 200 MPa. The thermohydraulical behaviour of this stratification causes cycles which explains the fatigue cracking.

4.2 Nevertheless, this method of analysis appears laborious. The results depends too much on the choice of many parameters (stratified level, thermal transfer factors ...). Instead, we might determine the stress perturbation, caused by stratifications, ising a localized analysis, vithout considering the whole structure. Then it will be added to the other classical global loadings. Moreover, it is easier to vary independently these parameters.

ACKNOWLEDGEMENTS
The authors gratefully acknowledge the help of Mrs POULIQUEN (EDF) for the piping calculations, and also Mrs CANAT.

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[2] Taheri S. - 1987. Local effects on thin elastic shell due to thermal and mechanical loadings. SMIRT 9 BN 1/6.

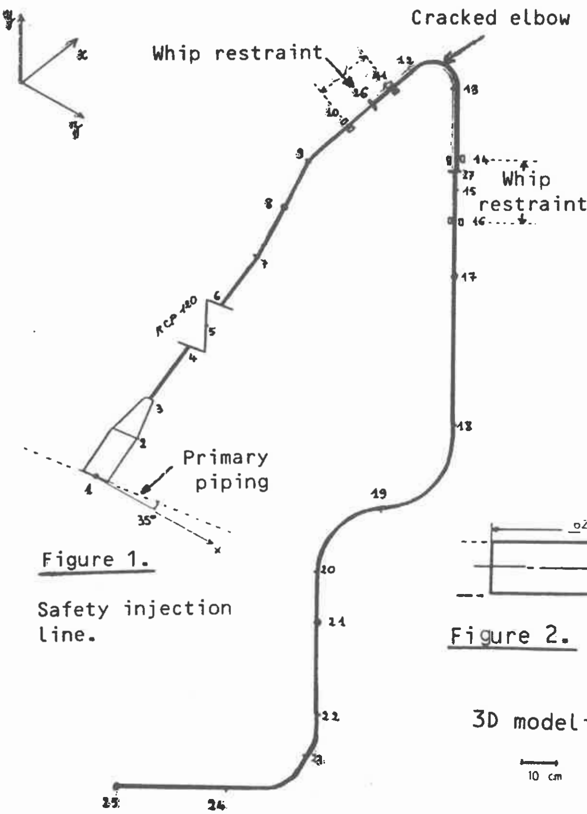

Figure 1.

Safety injection line.

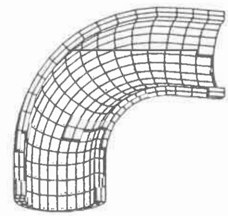
Figure 3.

3D elbow mesh.

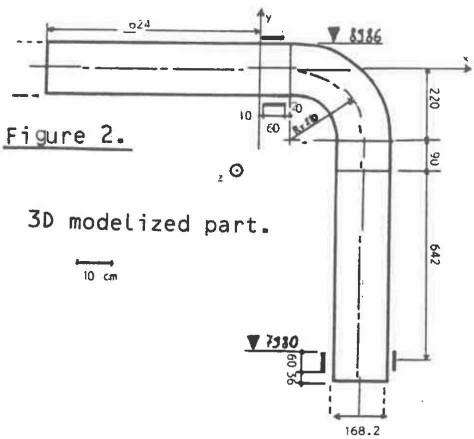

Figure 2.

3D modelized part.

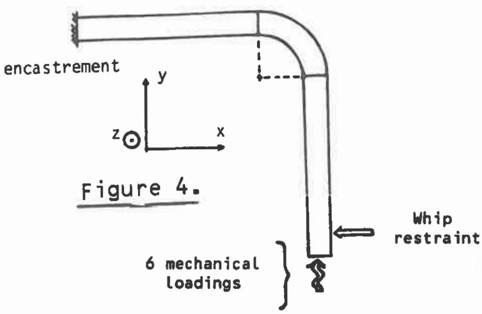

Figure 4.

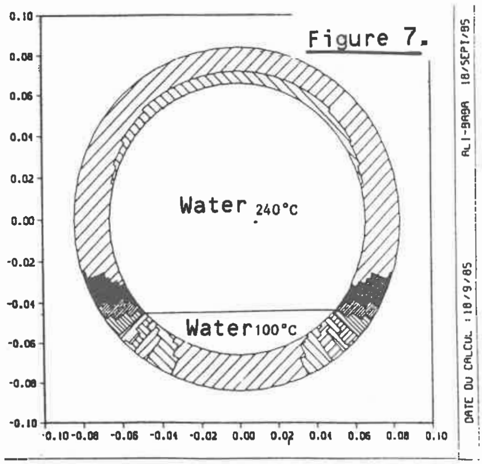

Figure 7.

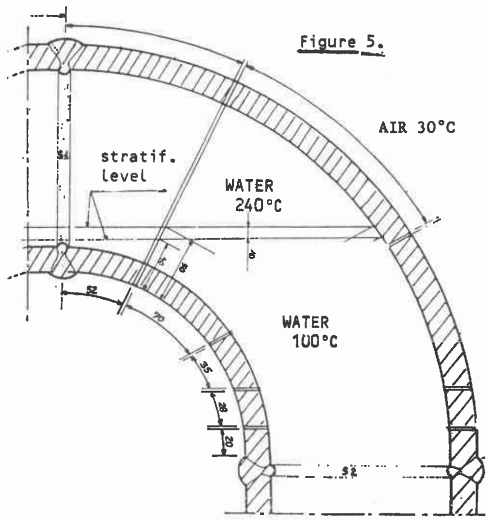

Figure 5.

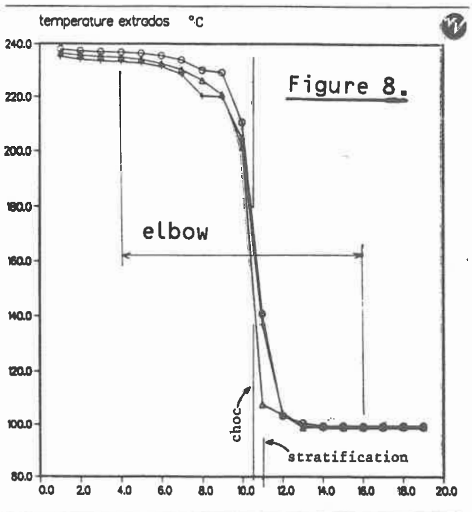

Figure 8.

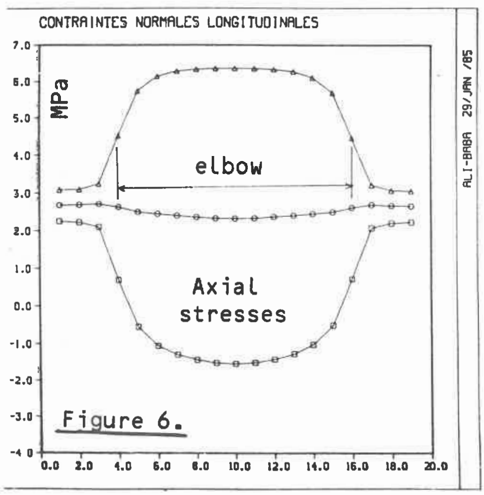

Figure 6.

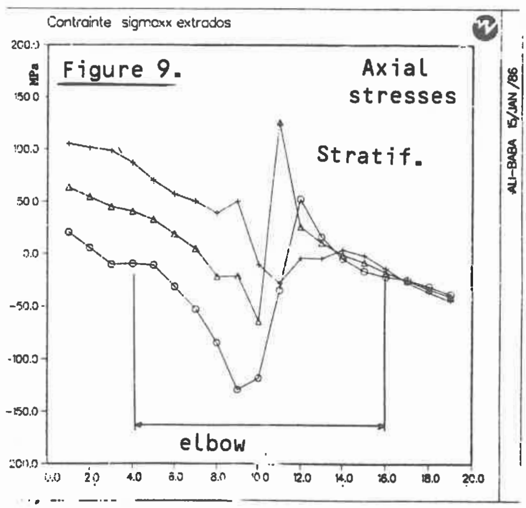

Figure 9.