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Axisymetrical modelling of operating stresses in 900 MWe steam generator rolled tubes

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ABSTRACT

Mechanical loads induced first by roll-expansion process, then by pressure and thermal effects during operating time, sometimes lead to phenomenon of stress induced corrosion cracking in steam generator tubes. The aim of this work is to determine the operating after rolling process in steam generator tubes, in order to enhance the knowledge of the stress state in the nocivity analysis of such cracks. We also quantify the effects of certain mechanical parameters. The originality of the 2D axisymmetrical model proposed here lies in the simulation of the complete tube-plate and in the modelling of the tube-plate orthotropy. The study deals with the case of the 900 MWe steam generators and the results are compared to those given by previous similar studies on the 1300 MWe steam generators.

1. PREPARATION OF THE MODEL [1]

The first step of this study consists in preparing a 2D axisymmetrical basic model for a tube and the tube-plate, taking the orthotropy of the tube-plate into account [2], [3] (the elementary cell has the squaresymmetry). As a matter of fact, the homogenized behaviour of the tube-plate is plane orthotropic in the 0° and 45° directions (cf. figure 1),

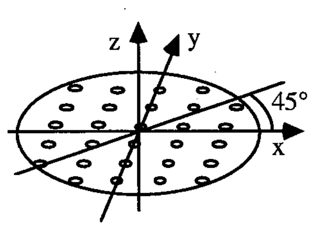

Figure 1 : The tube-plate.

judging by the following values of the equivalent overall plane and antiplane elastic moduli (cf. table 1) :

Direction	E*/E	ν*	Ez*/E	Gz*/E
0°	0.5079	0.2099	0.7015	0.4149
45°	0.3556	0.4468	0.7015	0.4149
Without holes (homogeneous case)	1	0.3	1	0.7692

Table 1 : Equivalent elastic moduli in the 0° and 45° directions.

The tube-plate containing several thousands of holes is modelled by a 2D axisymmetrical model divided into three areas (cf. figure 2) :

- area 1, composed of steel 16MND5 with an isotropic elastic plastic behaviour (isotropic strain hardening with the Von Mises criterion), the radius of which (R_1) being identified so that the residual displacements obtained are equal to the experimentally observed ones : $u_r = 0.22$ mm. This area takes the local geometry into account.
- area 2 : as the homogeneized behaviour of the tube-plate is plane and isoclinal in the third direction, we determine a transversal isotropic behaviour for the tube-plate by identifying for area 2 the elastic homogenized characteristics.
- area 3 simulates the far stiffness of the tube-plate with an equivalent elastic behaviour.

The tube is made of Inconel 600 described by an elastic plastic behaviour (isotropic strain hardening with the Von Mises criterion).

Geometrical parameters are :
- thickness of the tube : e = 1.27 mm,
- average radius : $R_m = 10.475$ mm,
- clearance tube/plate : J = 0.19 mm.

The edges of each area are characterized by :
- $R_1 = 18$ mm
- $R_2 = 100$ mm
- $R_2 + \delta = 110$ mm.

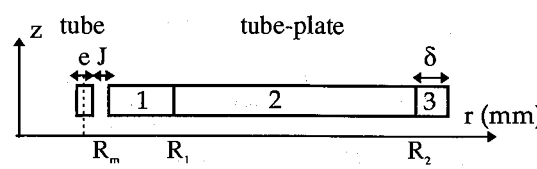

Figure 2 : 2D axisymmetrical basic model.

The axisymmetrical elastic moduli of the plate are determined for each area, from homogenized values (cf. table 1), through analytical methods and identifications from plane stress (x,y) calculations (cf. table 2) :

Area	1	2	3
E (MPa)	200 000	83 900	613 376
ν	0.3	0.3678	0.3678

Table 2 : Axisymmetrical elastic moduli for area 1, 2 and 3.

This 2D axisymmetrical basic model will, once extended (cf. section 2), allow us to perform roll-expansion simulations.

2. ROLL-EXPANSION CALCULATION [4]

Rolling and kiss-rolling are simulated with rollers, the action of which is modelled by frictionless contact conditions between the rollers and the tube and between the tube the plate. The calculation is displacement driven and is adjusted by comparison with the expected residual displacements (u_r = 0.22 mm for rolling and 0.10 mm for kiss-rolling).

The loading path consists in a sequence of major rolling steps :

1. contact with a first roller : in the lower part of the tube, to recover the clearance between the tube and the tube-plate,
2. full depth rolling, followed by
3. residual rolling (removal of the tool) : to generate a residual pressure at the tube/plate interface, ensuring pull-out strength,
4. kiss-rolling, followed again by
5. residual kiss-rolling (removal of the tool) : above this zone, a second roller applies a pressure load to reduce the tube bending residual stresses.

The 2D axisymmetrical basic model prepared before is extended along z and the two rollers are meshed (cf. figure 3) :

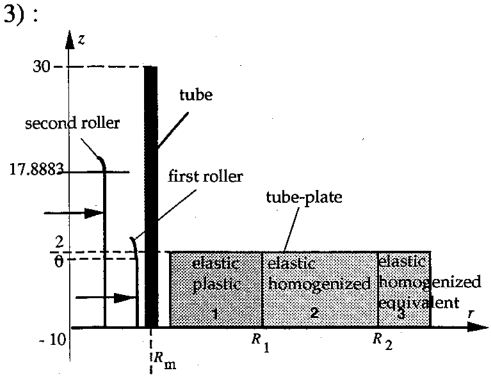

Figure 3 : 2D axisymmetrical model.

The axial and circumferential stresses generated in the tube can be decomposed into the summation of [5] :

- shell bending waves (global effect) along z (wave length : $3\sqrt{R_m e}$ in elasticity), of opposite sign on the external or internal surface for the axial stress, located :
  - around the edge of the tube/plate interface,
  - around the last contact point between the kiss-rolling roller and the tube.

- three-dimensional peak stresses (local effect) along z (wave length : e), located :
  - near the point (z = 17.8883) of the kiss-rolling roller, on the internal surface,
  - on the edge of the tube/plate interface, on the external surface.

The interesting effect of kiss-rolling is to have the sign of the shell bending wave change : at the end of the process, we obtain compression axial stresses on the external surface of the tube, near the edge of the tube/plate interface, reducing the corrosion risk by the secondary water.

The axial and circumferential stresses (cf. figure 4) obtained numerically and experimentally are compared, in the case of the 900 MWe steam generator and also in the case of the 1300 MWe one.

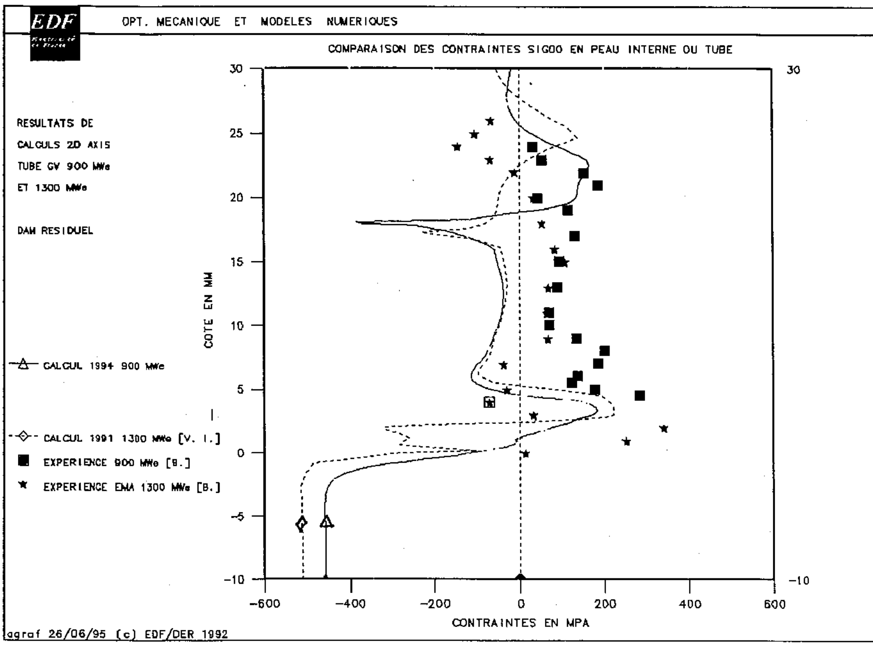

Figure 4 : Comparison of the circumferential stresses s_{qq} on the internal surface of the tube, after residual kiss-rolling.

The reduction of the thickness of the tube (2%) is less than the experimental value (4%). The residual pressure at the interface (-48 MPa) is similar to the values obtained from the previous experimental and numerical studies (-40 MPa) [6], [7].

This refined model and a sample model used in previous studies [6] give the same results for a standard rolling (corresponding to a residual displacement of 0.22 mm) but not for a non-standard rolling (corresponding to an excessive residual displacement of 0.45 mm) ; in that case, the refined model is stiffer than the mock-up.

The stress state obtained through the rolling and kiss-rolling simulation is used as an initial stress state when computing the operating stresses under pressure and thermal loads, as shown in section 3.

3. OPERATING STRESS CALCULATION [8]

The operating stresses under pressure and thermal loads computed after the rolling and kiss-rolling simulation (considered as an initial stress state) are compared to a previous approach where the rolling stresses and the operating stresses (calculated without initial stress condition) were simply added together in spite of non linearities.

We consider the case of a tube located in the hot leg, in a current area, 750 mm far from the axis of the steam generator. We assume that there is some athermal mud fitting the interstice between the tube and the plate.

P_P, P_S, T_P and T_S represent respectively the pression or the temperature on the primary or the secondary side.

Heat exchange coefficients are :

- on the primary side : $H_P = 36000$ W/m²/°C
- on the secondary side :
  - with the plate $H_{Spl} = 13000$ W/m²/°C
  - with the tube : $H_{Stu} = 13000$ W/m²/°C.

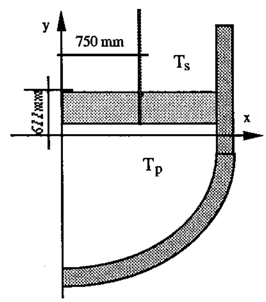

Figure 5 : position of the tube in the steam generator.

New loads are also taken into account :

- end-closed effect σ_{zz},
- equivalent tube-plate traction σ_{rr}, coming from the global stress state of the steam generator,
- a loading path applied at the end of the rolling process, consisting in :
  - hydrostatic tests,
  - heating,
  - power increase.

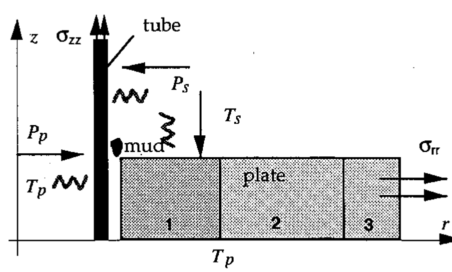

Figure 6 : Loads.

The thermal homogenized behaviour of the tube-plate is taken into account.

We observe that the approach with the simple summation does not always give the same results for the stresses on the tube. The results are different :

- for the compression peak of :
  - the circumferential stress $\sigma_{\theta\theta}$ on the internal surface of the tube (cf. figure 7),
  - the axial stress σ_{zz} on the external surface of the tube.
- in the lower part of the tube, at the tube/plate interface, for the circumferential stress $\sigma_{\theta\theta}$ on the internal surface of the tube (cf. figure 7).

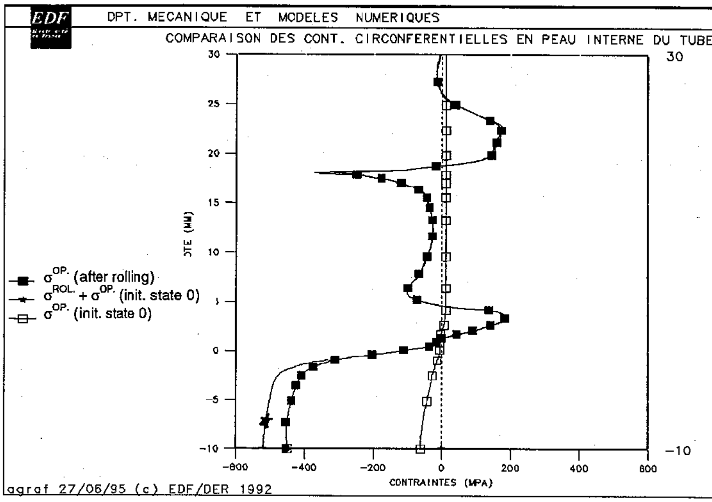

Figure 7 : Comparison of the operating circumferential stresses $\sigma_{\theta\theta}$ on the internal surface of the tube.

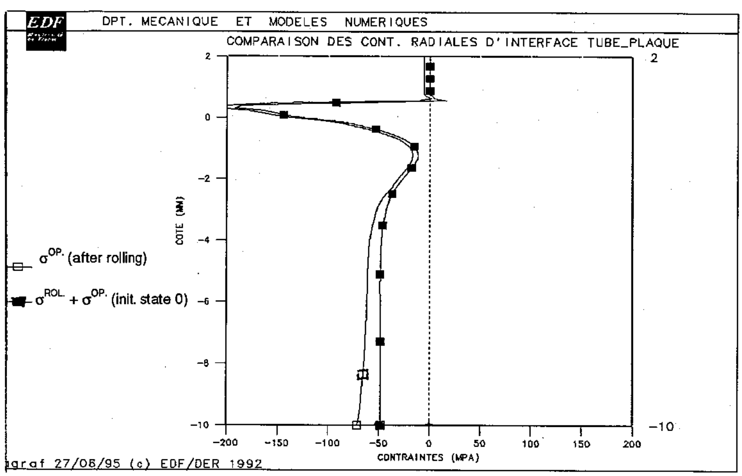

Figure 8 : Residual pressure at the tube/plate interface.

The residual pressure at the interface is equal to -48 MPa at the end of the simulation of rolling and kiss-rolling and to -70 MPa at the end of the power ascension (cf. figure 8).

4. SENSITIVITY ANALYSIS

We quantify the effects on the rolling stresses of :

- the yield stress : when the yield stress decreases from 330 MPa to 300 MPa, the circumferential stress decreases by 25%,
- the modelling of hardening (kinematic instead of isotropic) : residual stresses decrease,
- the value of the initial gap between the tube and the plate : if the gap increases, stresses increase by 10%,
- the value of the residual displacement : for a non-standard residual displacement of 0.45 mm instead of 0.22 mm, stresses increase so that the Von Mises stresses reach 800 MPa.

We also analyse the effects on the operating stresses of :

- the position of the tube (cold leg ; closer to the axis of the steam generator)
- the presence of mud on the plate or the presence of mud fitting the interstice between the tube and the plate.

The table 3 summarizes the main results obtained by this sensibility analysis :

Case	Leg	Distance of the tube from the axis of the steam generator	Presence of athermal mud	Conclusion
0	Hot	750 mm	in the interstice between the tube and the plate	Reference solution.
1	Hot	750 mm	<u>no</u>	Weak increase of the stresses near the interstice.
2	Hot	<u>400 mm</u>	no	Not sensitive, far away from the edges and center.
3	<u>Cold</u>	750 mm	no	Important reduction of the stresses at the bottom of the tube (T_p decreases by 40°C at the end of the cycle).
4	Hot	750 mm	<u>on the plate (50 mm)</u>	Increase of the stresses on the internal surface of the tube and decrease on the external one.

Table 3 : Results of the analysis study.

In the end, we also determine the 3D effects on the rolling stresses of the cycling (10 cycles of the rollers) on a 2D plane stress model. This study gives better results in comparison with the experimental results : the residual pressure is -37 MPa compared to -40 MPa and the reduction of the thickness of the tube (4%) is closer to the experimental one.

5. CONCLUSION

For the first time, the operating stresses under pressure and thermal loads have been computed after the rolling and kiss-rolling simulation, considered as an initial stress state ; the previous approach where the rolling stresses and the operating stresses (calculated without initial stress condition) were simply added together in spite of non linearities gave different results.

The results of the main study and of the sensitivity analysis will later be included in a probabilistic study about the maintenance of steam generator tubes.

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