Computation of Stresses in French Steam Generator Tubes

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ABSTRACT

For different programs on steam-generator tube integrity like leak-before-break or probabilistic evaluations, we need a complete and detailed estimation of the stresses in tube/tubesheet region in order to apply a stress corrosion cracking model.

After a quick description of the french rolling process, this paper presents the different computations that we have performed on 900 MW and 1300 MW steam generator tubes in nominal situation on an axisymetrical model. These are compared with the different experimental results available today. They are in a reasonnable agreement.

We intend to use this type of model on some degraded situations and we are developping some more simple models to perform parametrical studies. A refined model taking into account the effect of the different rolls on the stress levels is also under development.

1 INTRODUCTION

Some of the French PWR steam generator contains Inconel 600 tubes that are sensible to different types of damage [1], and principally the stress corrosion cracking in primary environment. This phenomenon has been the cause of 80 % of the tube plugging in EDF plants.

One of the major difficulty to analyse the damage in the transition zone is the determination of the stress field regarding all the history of the tube and specifically during the rolling process.

Recently, we discovered in some plants, an abnormal amount of sludge on the secondary side of the tubesheet. This sludge was very hard and could restrain the tube with a complete modification of the stress field. Some changes in crack susceptibility from longitudinal direction to circumonferential direction, lead to an important safety issue.

For these different reasons, EDF decide to refine his leak before break approach of steam generator tubes [2] and to perform a complete probabilistic approach of the damage of steam generator tubes [3].

2 THE FRENCH ROLLING PROCESS

All the french steam generator tubes have been expanded by rolling (figure 1) over the entire thickness of the tube sheet (DI), completed by an additionnal rolling (DAM) to reduce the stresses on the outer wall of the tube.

The main parameters of these two phases rolling process are presented on table 1.

3 STRESS COMPUTATION FOR NOMINAL SITUATION

The inservice stresses are the results of :

- residual stresses of the manufacturing process,
- residual stresses of the rolling process,
- permanent stresses of fitting between the different tube support plate,
- pressure and temperature stresses during operation,
- in some cases, denting stresses.

Different program has been done to determine experimentally the stress profile along the different steps of the process [4, 5].

In this presentation, we only discuss the stress profile of the residual stresses corresponding to the rolling process.

We have used a bidimensionnal mesh of around 8000 degrees of freedom (figure 2), with a complete elastoplastic simulation of the process by finite element method using contact hypothesis between the Inconel tube and the A508 tubesheet and between the tube and the rollers.

The plastic behaviour of the materials is supposed isotropic and the tubesheet is modelled using elastic equivalent properties for Young modulus and Poisson factor : E^* and ν^* (far from the tube).

The table 2 presents the different material properties used in the computation. The computations are done with INCA computer code from CASTEM system developped by CEA.

To analyse the results and compare with experimental results, 5 steps are used :

1. First contact tube - tubesheet,

2. DI at maximum displacement,

3. DI final,

4. DAM at maximum displacement,

5. DI + DAM final,

but a very refined time history model is necessary to obtain some realistic results that are very sensible to the load history.

Some results are presented in table 3 and figures 3 to 6, comparing the analytical results with experimental results.

The residual stresses are lower for the 1300 MW process than the 900 MW process.

The second phase of the rolling process (DAM) decreases the stress in the outer wall but increases the stresses in the inner wall. The maximum stresses are obtained closed to the end of the contact between tube and tubesheet.

In our computation, the longitudinal stresses are greater than the circumferential stresses, that is not in accordance with test results. It is due to the fact that our bidimensionnal model is too severe for the longitudinal stresses at the end of the rolls. The circumferential stresses are reasonnably estimated but longitudinal stresses are overestimated, that is consistant with the comparison of the profiles (figure 7).

However, the model can give some interesting qualitative results on the different phases of the process and is usable to analyse the effect of different hypothesis on the process.

But this type of analysis need more developments to become a reference method to develop more simple methods to perform a large parametric study for probabilistic approaches [3]. Two types of developments are in progress :

- study of the non-axisymetrical load effects on the plastic deformation of the tube,

- identification process solving inverse problem using profile measurements.

4 SLUDGE EFFECT ON ROLLING RESIDUAL STRESSES

After the discover of shrinking of some tubes in different plants, we decide to analyse the consequences of hard sludge of different height, using numerical and experimental studies.

The amplitude of the shrinking analysed can reach 0.5 mm on the radius with different sludge height (up to 6.5 mm). The mechanical sludge effect is a parabolic displacement from the secondary side tubesheet.

To analyse the effect of the sludge on the stress level, we have to define 3 different zones in the transition tube - tube sheet (figure 8) :

- zone 1 : inside the tube-sheet

- zone 2 : in the sludge zone

- zone 3 : above the sludge zone.

The main results are :

- increase of axial stress τ_z for internal wall in zone 2 and external wall in zones 1 and 3,

- decrease of τ_z for internal wall in zone 1,

- compressive stresses (axial and circumferential) external wall in zone 2,

- decrease of circumonferential τ_c for internal and external wall in zone 1,

- for internal wall in zone 3, τ_c and τ_z decrease if the height of the sludge increases,

- τ_z greater than τ_c.

All these results confirm that the sludge is in favor of the circumferential cracking of the tube in the primary side.
To end the analysis, we try to simulate the cleaning of the tubesheet to obtain the tendancy of the operation on the stress level in the transition zone. The comparison have been done with the end of the nominal process. The sludge effect completed by the cleaning of the tubesheet :

- τ_z decrease in zone 1,

- τ_z increase in zone 3, external wall,

- τ_c decrease in zone 1 and τ_c greater than τ_z for the initial wall.

For the stress corrosion cracking under PWR water point of view, the cleaning can be a powerfull operation in term of residual stresses in the rolled transition zone and decrease significantly the tendancy for circumferential cracking.

5 CONCLUSIONS

Axisymetric elastoplastic computations of residual stresses in the rolled transition zone is not completly solved. However, this large study show that very interesting qualitative result can be obtained and the influence of different parameter can be anlaysed with this type of tool like : geometry effect, material properties effect or shrinking effect of sludge.

The comparison of the nominal french process (DI + DAM) with the experimental results is reasonnable, but not completly good, especially a surestimation of the axial stresses is given by direct computation at the top of the rolling process.

The sludge effect simulation confirms the tendancy to increase the risk of circumferential crack with shrinking. It gives us some idea of the acceptable shrinking of approximatively 0.06 mm on the radius and the more severe height of the sludge approximatively 3.5 mm. The cleaning of the tube sheet is benefitial and gives back a tendancy of longitudinal cracking, but some slight increase of the stresses on the outer wall for initial shrinking greater than 0.1 mm on the radius has to be surveyed.

The development of computation of stresses in the rolled transition zone of steam generator tubes is always going on in France to take into account some non-axisymetrical effects, to develop a simplify approach for parametrical studies and to determine the total stress field in this zone of the steam generator.

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PLANT TYPE	900 MW	1300 MW
ROLLING TOOL	1243 (no smoothed)	1231 (smoothed)
d	- 3 mm	- 3,3 mm
D	15,25 mm	17,3 mm
External tube diameter	22,26 mm	19,05 mm
thickness	1,28 mm	1,09 mm
initial gap	0,18 mm	0,21 mm

d : distance between the end of the rolling process and the secondary side tube-sheet.
D : distance between the end of the two phases of rolling.

TABLE 1 : GEOMETRY OF THE 900 MW AND 1300 MW STEAM GENERATOR ROLLING PROCESS

MATERIAL PROPERTIES		900 MW	1300 MW
ROLLS	E	220 000 MPa	220 000 MPa
	ν	0,3	0,3
TUBE	E	218 230 MPa	220 000 MPa
	E_T	5 820 MPa	3 300 MPa
	ν	0,3	0,3
	Sy	480 MPa	336 MPa
TUBE-SHEET	E	206 160 MPa	200 000 MPa
	E_T	5 280 MPa	2 140 MPa
	ν	0,3	0,3
	Sy	440 MPa	476 MPa
	E^*	59 365 MPa	82 530 MPa
	ν^*	0,41	0,3

TABLE 2 : MATERIAL PROPERTIES USED IN COMPUTATION

INTERNAL WALL		DI FINAL	DI + DAM FINAL
900	τC	250 MPa	350 MPa
	τz	375 MPa	475 MPa
1300	τC	200 MPa	250 MPa
	τz	275 MPa	400 MPa

τC : circumferential stress τz : longitudinal stress

TABLE 3 : RESIDUAL STRESSES ON THE INTERNAL WALL OF THE TUBE

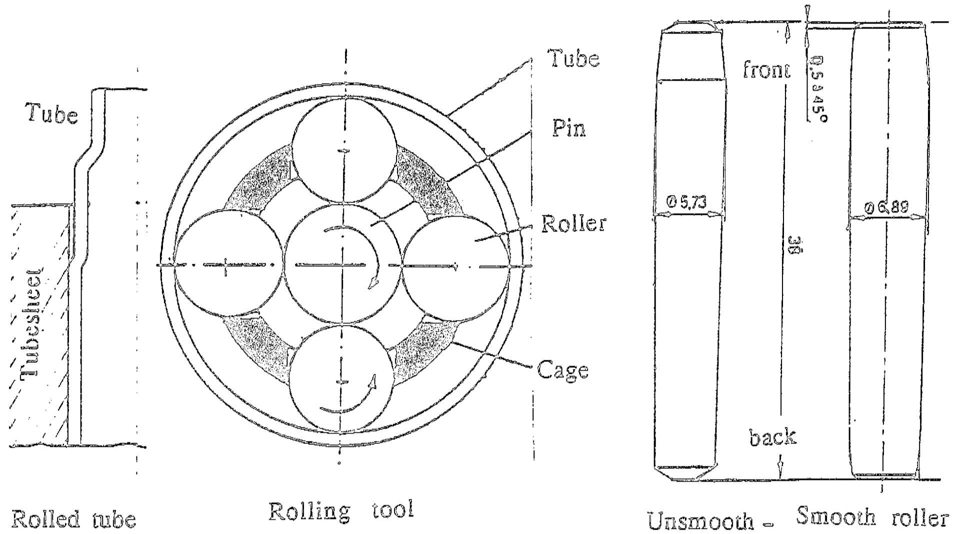

Figure 1 : Rolling proceeding

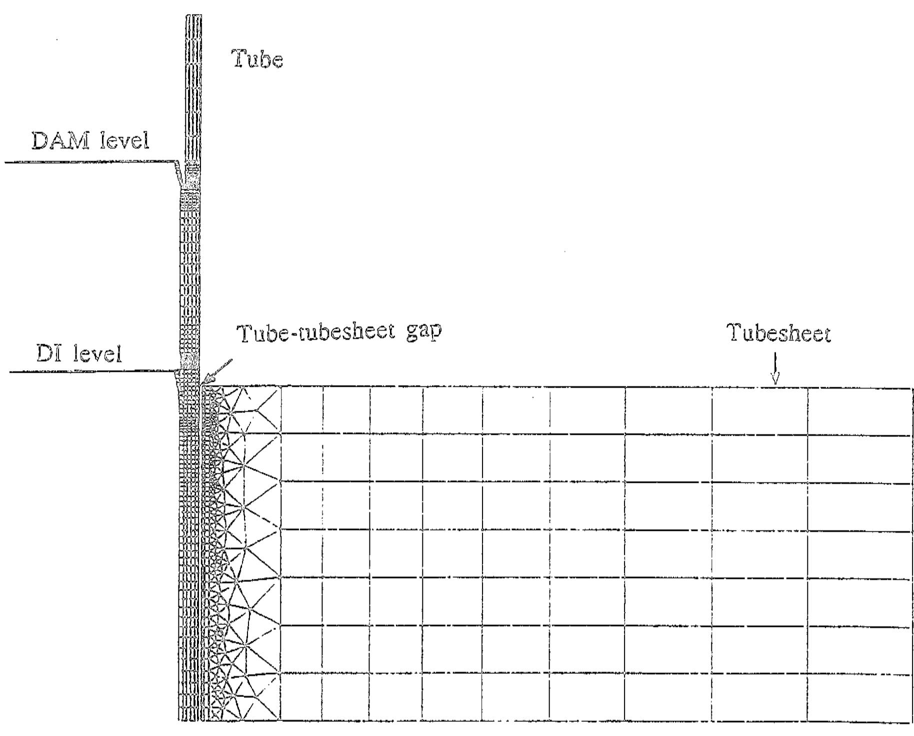

Figure 2 : Tube - tubesheet - rolls mesh

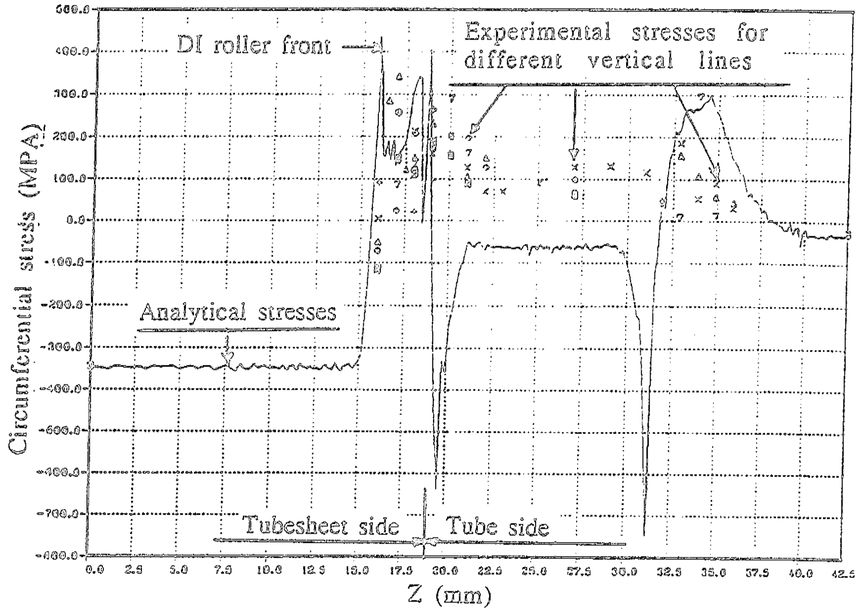

Figure 3 : Analytical versus experimental results 900 M
Internal wall - Circumferential stress

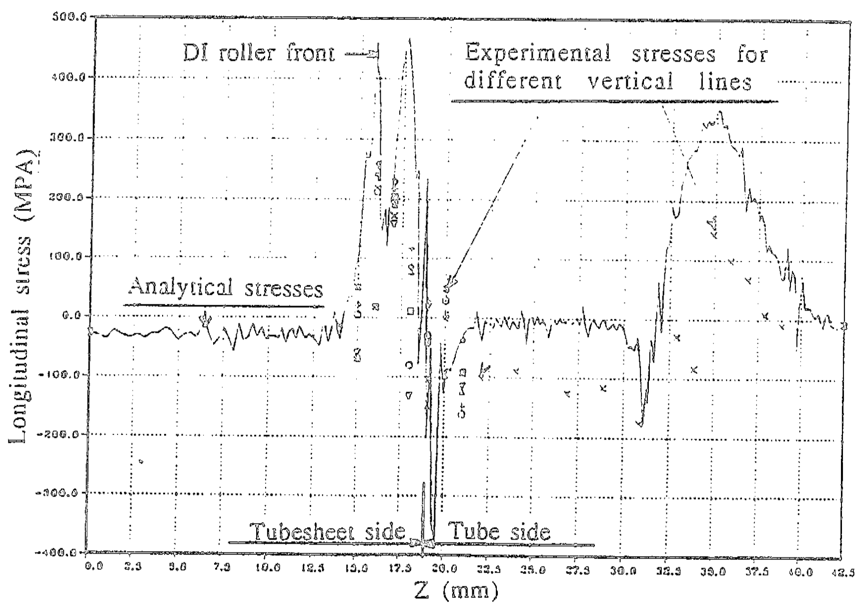

Figure 4 : Analytical versus experimental results 900 M
Internal wall - Axial stress

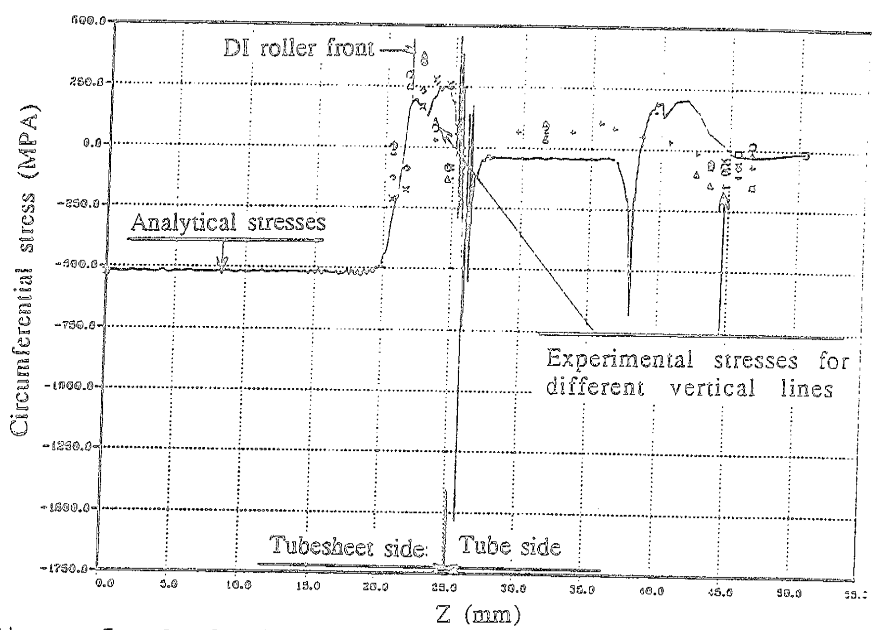

Figure 5 : Analytical versus experimental results 1300
Internal wall - Circumferential stress

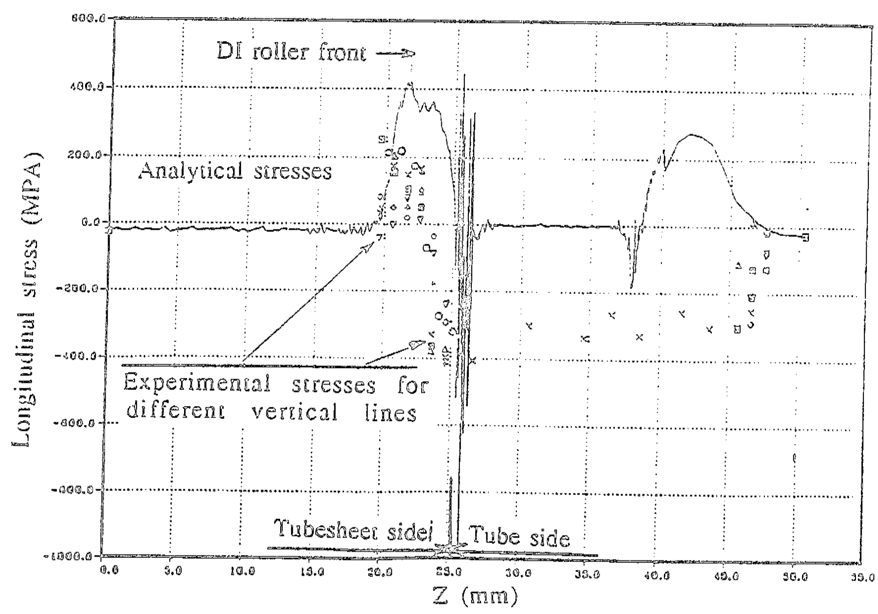

Figure 6 : Analytical versus experimental results 1300 MW
Internal wall - Axial stress

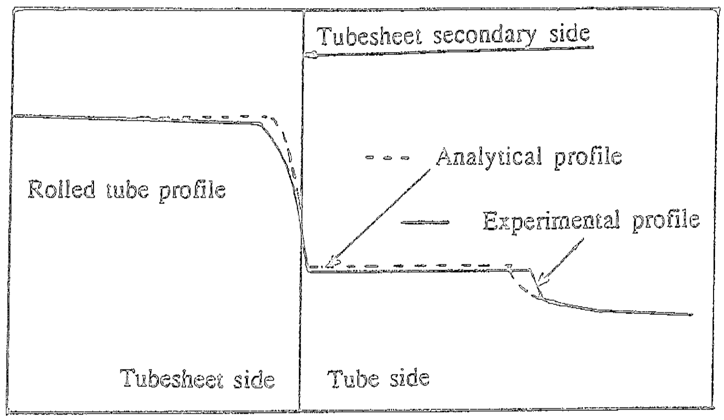

Figure 7 : Analytical versus experimental profiles

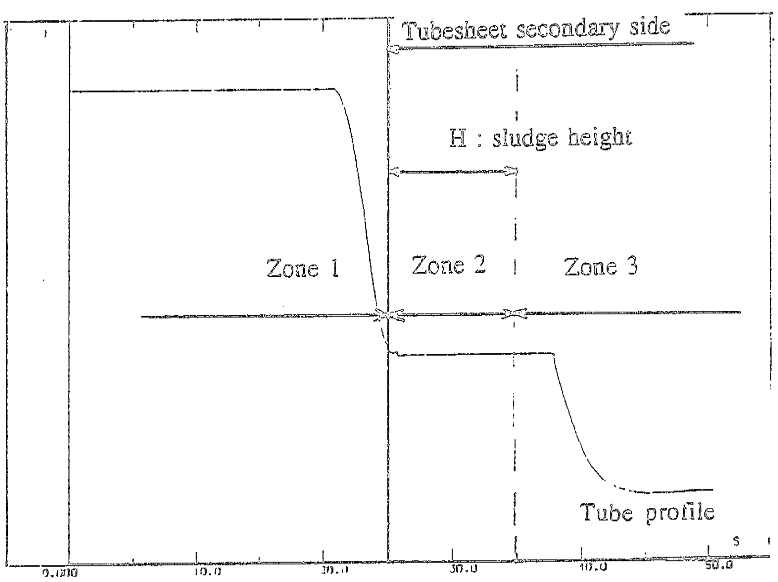

Figure 8 : Sludge zones near the tube sheet.