Steam Generator Tube Plugging FEM Analysis

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1 ABSTRACT

A mechanical steam generator tube plugging system was introduced to Loviisa nuclear power plant in 2005. Interest was raised concerning the loads imposed by the new plugging system to the steam generator tubes and the collector. The effect of operational conditions to the plug contact behavior and the tube inner diameter deviation effect were also issues that had to be addressed. The decision to use finite element (FE) modeling as part of plugging system validation process was made.

The constructed FE model was a one quarter model using symmetry boundary conditions which included mechanical plug, steam generator tube and part of the collector. The choice to use explicit time integration to solve problem was evident due to the fact that mechanical plugging event involves highly plastic deformations and drastically changing contact conditions. The quasi static assumption enabled the use of mass scaling to increase the explicit time integration method stable time increment so that the problem was solvable within decent CPU time.

In order to validate FE model the associated training block was used for strain gauge measurements in the plugging concept validation process. Strain gauge measurements provided information of the collector deformation in the vicinity of the plugged tube.

2 INTRODUCTION

Heat exchanger tubes within a steam generator (shown in Figure 1) may develop leaks in long term operation. This will result in risk that secondary circuit is exposed to possible contamination by the primary water. Subsequently these tubes may have to be plugged.

A mechanical steam generator tube plugging system was introduced to Loviisa nuclear power plant in year 2005. The mechanical plug is a cylindrical device that is mounted inside the collector tube of the steam generator with help of expander. In Figure 2 is presented the main dimensions of the mechanical plug and an illustrative scheme of the mounting process.

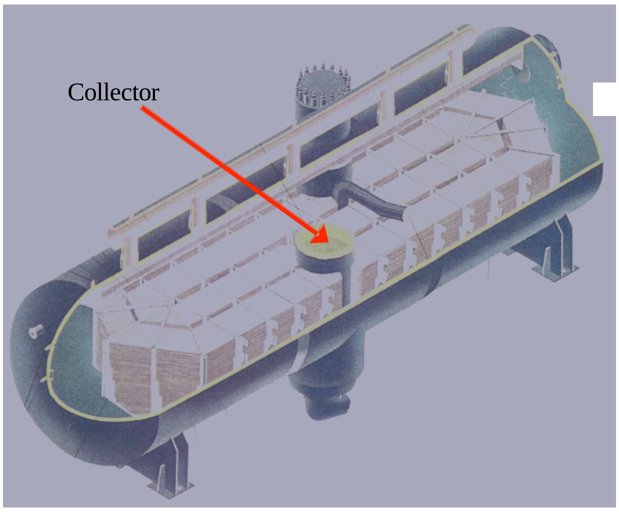

Figure 1. The steam generator.

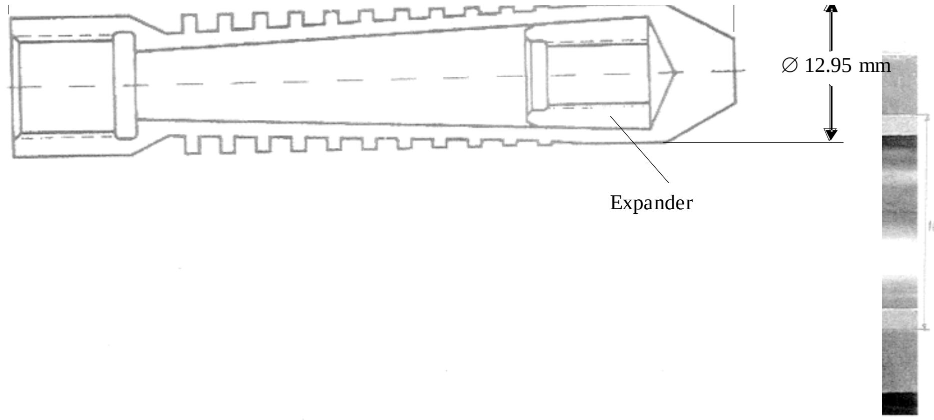

Figure 2. The main dimensions of the plug and the mounting of the plug.

Mechanical plugs have been installed large numbers since 1980. Earlier versions of these mechanical plugs suffered from primary water stress corrosion cracking (PWSCC). The most significant occurrence of PWSCC happened in February 1989 at North Anna Unit 1. In this incident, circumferential PWSCC occurred nearly through wall all around the circumference of the plug. The remaining ligament broke during a plant transient and the tip of the plug propelled up the tube until it hit the U -bend, which it penetrated. This caused a significant primary-to-secondary-side leak [Shah et al., 1993].

Since that incident plug design is developed and material type used for the plug is nowadays well PWSCC tolerable Inconel 690.

An interest was raised concerning the loads imposed by the new plugging system to the steam generator tubes and the collector. The effect of operational conditions to the plug contact behaviour and the tube inner diameter deviation effect were also issues that had to be addressed. The decision to use finite element (FE) modelling as part of plugging system validation process was made.

3 FE -MODELLING

The constructed FE model, shown in Figure 3, was a one quarter model using symmetry boundary conditions which included mechanical plug, steam generator tube and part of the collector. The software used for the modelling was ABAQUS-6.6 [2007].

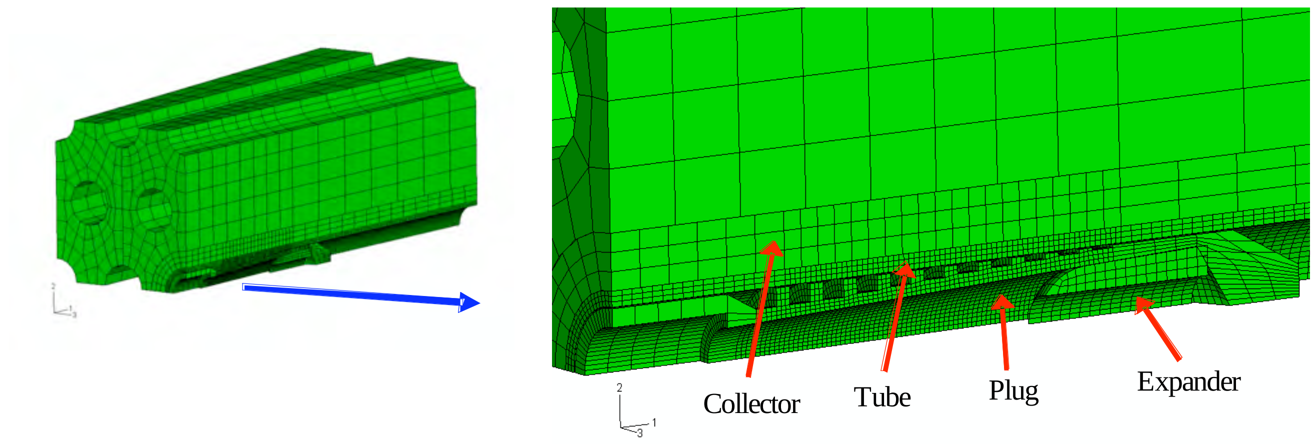

Figure 3. The FE -model. The model consists of 27 272 nodes and 18 989 solid elements.

The material properties used for the collector and the tube parts of the model are typical O8X18H10T austenitic steel properties that are found in Loviisa plant steam generator material specifications. The Inconel 690 alloy mechanical material properties used for the plug part of the model was derived from the material test performed to the test specimens that were cut form a real plug. The uniaxial tests were performed at room temperature and at elevated 350 ℃ temperature. The true stress-strain relation used to model the Inconel 690 alloy is shown in Figure 4.

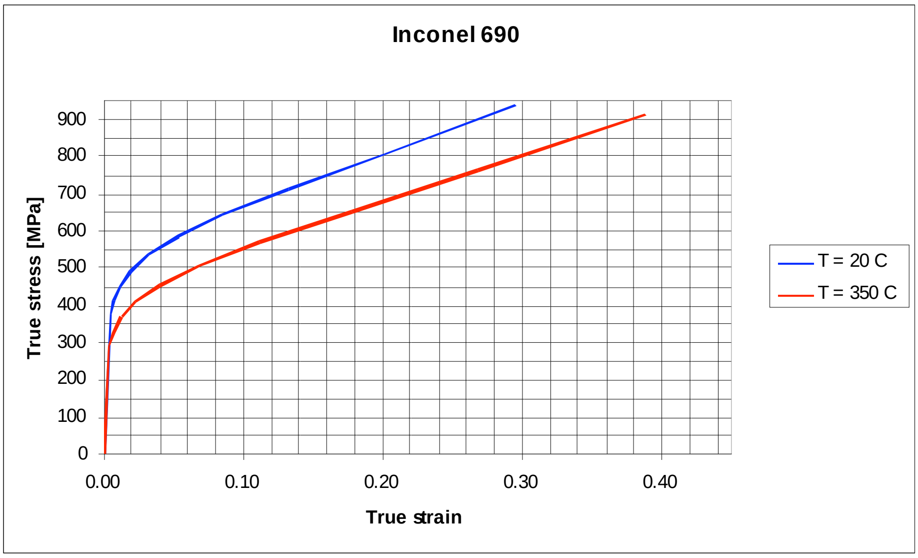

Figure 4. Inconel 690 alloy true stress-strain relation for the plug at temperatures 20 ℃ and 350 ℃.

The choice to use explicit time integration to solve problem was evident due to the fact that mechanical plugging event involves highly plastic deformations and drastically changing contact conditions. Similar to Wang et al. [2006] who have used successfully ABAQUS/Explicit and mass scaling to model quasi-static hot rolling process, the quasi-static assumption enabled the use of mass scaling. In mass scaling the material density is increased. This additional mass increases the numerical stable time increment of the explicit time integration method and computing can be done faster. The mass scaling is done in such extend that the kinetic energy of the model stays much lower compared to the strain of energy of the model.

The load history for the simulation was constructed in such way that the loadings were applied "slowly" and when the loading reached its maximum value the loading was kept at constant value for a while. The pseudo-time history constructed for the simulation is presented in Table 1.

Table 1. Pseudo-time history for the simulation.

Time span	Description
0s → 10s	Expander pulling force is ramped linearly to the maximum value of 1/4×37355 N
10s → 13s	Expander pulling force remains at constant value of 1/4×37355 N
13s → 14s	Expander pulling force is ramped linearly to zero
14s → 15s	Expander pulling force remains at zero value
15s → 23s	Internal over pressure of the collector is ramped linearly to the value of 12.3 MPa
23s → 25s	Internal over pressure of the collector remains at constant value of 12.3 MPa
25s → 33s	Temperature raises linearly to the value of 330 °C, pressure remains at value 12.3 MPa
33s → 35s	Temperature and pressure have constant values of 330 °C and 12.3 MPa, respectively (these values are consider to be the operational conditions in this study)

As an example to show that the kinetic energy of the simulation remains small (quasi-static assumption), the energies of a typical simulation is presented in Figure 5.

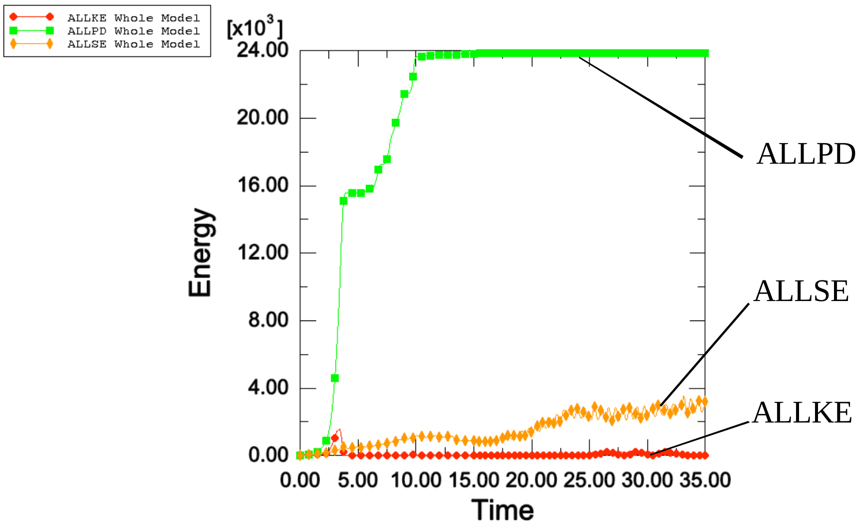

Figure 5. Whole model energies. ALLKE is the kinetic energy, ALLPD is the plastic dissipation and ALLSE is the strain energy.

In order to asses the effect of steam generator tube inner diameter deviation to the contact forces of the plug, the simulation was carried out for three variants of the model. The first variant of the model had tube inner diameter (Din) of 13.2 mm, the second variant had tube inner diameter of 13.5 mm and the third one had Din = 13.8 mm.

4 STRAIN GAUGE MEASUREMENTS

FE -analysis model was verified against the strain gauge measurements which where conducted in year 2005 during receiving tests of the plugging system. The test article, shown in Figure 6, was a cylindrical section block from a real VVER-440 steam generator collector. The section thickness (direction of the tubes) was 116 mm and the inside diameter of the test article tubes ranged from 13.5 mm to 13.7 mm.

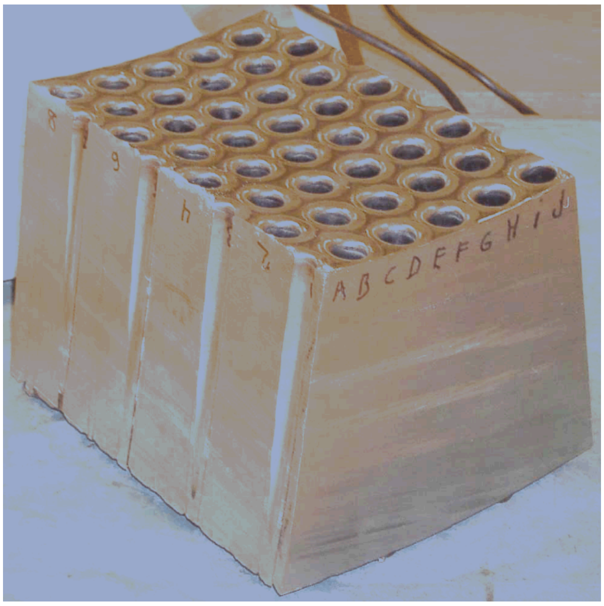

Figure 6. The test article used for strain gauge measurements.

Strain gauge measurements were done around the plugged tube and inside the adjacent tube at the nominal depth of 32 mm from the surface.

5 FE -RESULTS COMPARED TO THE MEASUREMENTS

From the measurements the data from the expander movement versus expander pulling force was also available. The comparison with measurement and FE -result is done in Figure 7. The plugged tube had inner diameter of 13.5 mm.

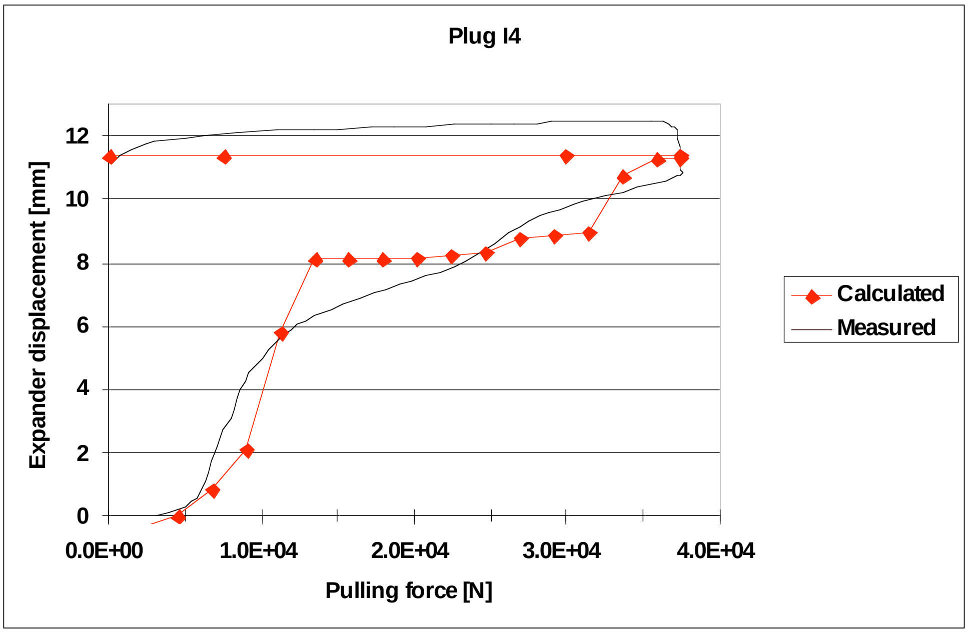

Figure 7. Expander movement versus expander pulling force.

In Figure 8 is presented Mises stress of the collector tube adjacent to the plugged tube. The measurement was taken from the nominal depth of 32 mm from the surface. The FE -results were taken from four different depths.

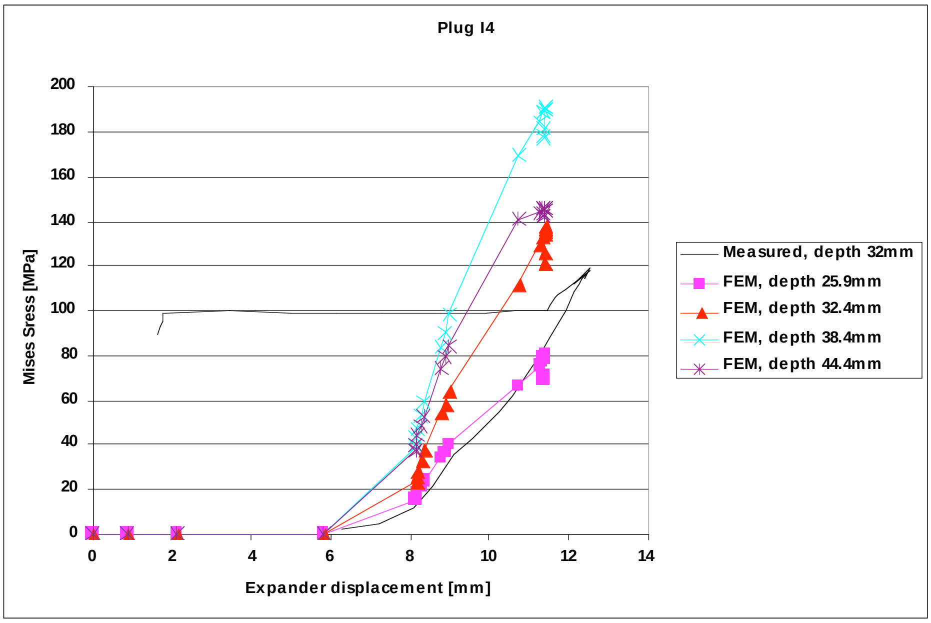

Figure 8. Mises stress observed from tube adjacent to the plugged tube.

As an example of the deformation and the stress state of the plug, deformed shape and Mises stress contours are illustrated in Figure 9.

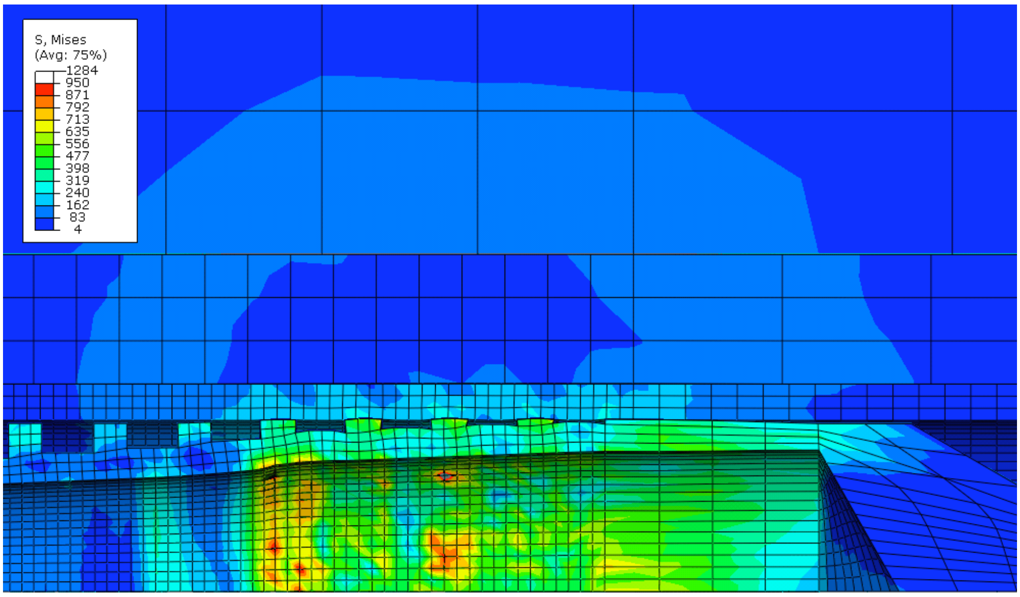

Figure 9. Deformed shape and Mises stress contours (MPa, true stress) of model with Din = 13.2 mm. Temperature is 330 ℃ and collector over pressure is 12.3 MPa. The expander is removed from the view and the deformation is in real scale.

6 CONTACT FORCES

In order to evaluate contact forces between plug and collector the ribs of the plug were numbered in the manner that can be seen in Figure 10. In the Figure 11 is presented the average contact pressure results for different loading stages for the tube with inner diameter of 13.8 mm. Similar examinations were conducted for tubes with Din = 13.2 mm and Din = 13.5 mm. The rib average contact pressures for each rib were calculated from the ABAQUS nodal output entity CPRESS.

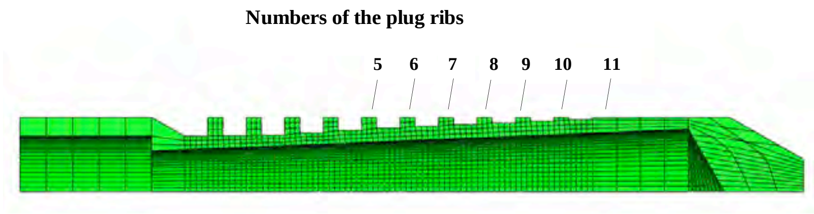

Figure 10. The plug rib numbering.

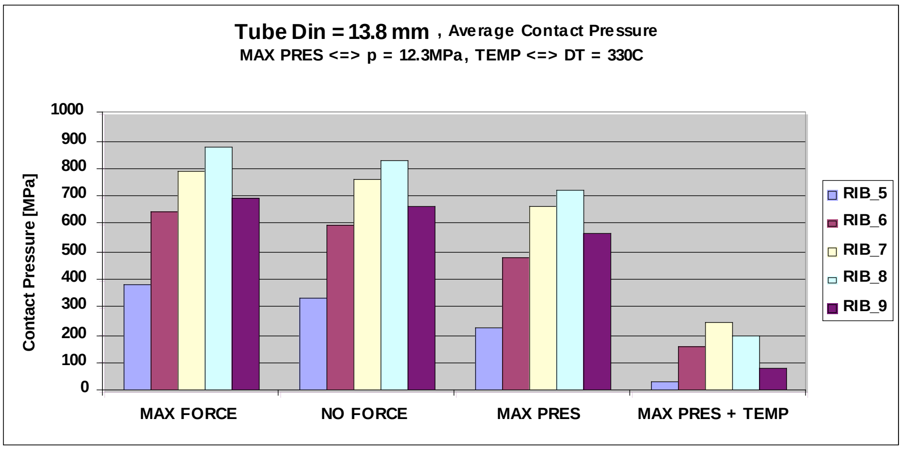

Figure 11. Average rib contact pressure at different loading stages. Tube inner diameter was 13.8 mm. Loading stages are: MAX FORCE = maximum expander pulling force applied, NO FORCE = pulling force removed, MAX PRES = maximum collector over pressure applied and MAX PRES + TEMP = both maximum over pressure and temperature applied (operational conditions).

From the individual rib average pressures the total contact resultant force of the plug can be calculated as follows:

$$R_c = \sum_i A_i p_i \text{ , where} \tag{1}$$

R_c is the contact resultant force, index i is the rib number, A_i is the top surface area of the rib i and p_i is the average contact pressure of the rib i.

Equation 1 was applied for each of the collector tube inner diameter model (Din=13.2 mm, Din=13.5 mm and Din=13.8 mm) and the results are presented in Figure 12.

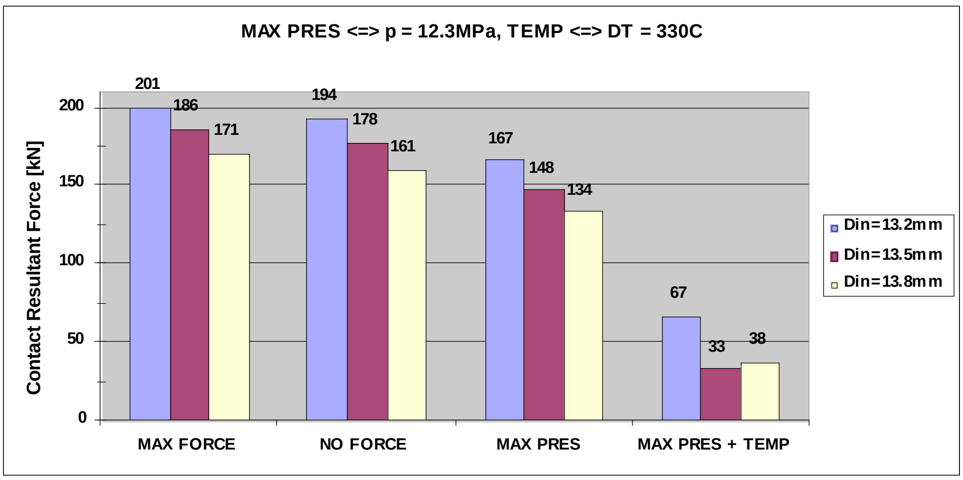

Figure 12. Contact resultant forces at different loading stages for different inner diameter tubes.

The pressure difference over the plug that is needed to move the plug can be estimated based on the results of the Figure 12. If the fact that the ribs are causing denting to the collector tube is ignored, then the condition for the plug movement is:

$$\Delta p = \mu R_c/(\pi \mathrm{Din}^2/4), \quad \text{where} \tag{2}$$

Δp is the pressure difference over the plug, μ is the friction factor, R_c is the contact resultant force and Din is the collector tube inner diameter.

In Table 2 is estimated (using equation 1) the pressure difference over the plug that is needed to move the plug, assuming $\mu = 0.1$. The contact resultant force R_c is taken from loading stage MAX PRES + TEMP (operational conditions).

Table 2. Pressure difference needed to move the plug. $\mu = 0.1$.

Din [mm]	**Δp [Mpa]**
13.2	49
13.5	23
13.8	25

7 CONCLUSIONS

Compared to measurements FE -model gave fairly good results. When comparing the FE -model stress results (Figure 8) to the measurement it should be noted that the nominal strain gauge measuring depth of 32mm may deviate a couple of millimetres and the circumferential position of the gauge doesn't match exactly to the FE model result point. In Figure 8 the maximum measured expander displacement seems to be larger then FE -model predicts. This is due the fact that the measured expander displacement includes the deformation of the pulling device.

In the contact force study it can be seen that the collector over pressure doesn't have large effect on the contact forces. On the other hand, temperature increase diminishes drastically the contact forces. For the operational conditions, the collector tube inner diameter effects to the contact forces in the way that the contact force for the smallest tube inner diameter (Din = 13.2mm) was about twice the value that were obtained for Din=13.5mm and Din=13.8mm. Tube inner diameter Din=13.5mm and Din=13.8mm contact force results were almost the same for the same for this loading stage.

The estimation for the pressure difference needed over the plug to move the plug at operational conditions is in this study ≥ 230 bar.

REFERENCES

ABAQUS version 6-6, 2007. Users documentation, Simulia Inc., Dassault Systèmes.

Shah V. N. and MacDonald P. E., 1993, Aging and Life extension of Major Light Water Reactor Components, Elsevier, USA, p. 317-321.

Wang M., Yang H., Sun Z., Guo L., OU X., 2006, Dynamic explicit FE modeling of hot ring rolling process, Transactions of Nonferrous Metals Society of China 16, p. 1274-1280.