Finite Element Calculation and Direct X-Ray Diffraction Measurement of Residual Stresses Induced by an Hydraulic Expansion in Steam Generator Tubes During the Sleeving Process

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1. INTRODUCTION

When installing an internal sleeve to repair a steam generator tube, it is usual to expand the sleeve locally by means of an internal pressure, in order to put it into contact with the tube before welding. This process induces residual stresses in the parent tube, near the end of the contact zone, even if the residual bulging is very small. This study is aimed at assessing the residual stresses as a function of that bulging and of the respective mechanical properties of the materials. An analytical approach based on finite element calculations and an experimental one by X-ray diffraction have been used to evaluate the residual stresses.

2. ANALYTICAL EVALUATION OF THE RESIDUAL STRESSES

2.1. Material properties

In order to account for possible variations of materials properties, 3 combinations of stress-strain curves are analysed :

. mean strength (YS = 350 MPa) for both tube and sleeve
. mean strength (YS = 350 MPa) for tube and high (YS = 510 MPa) for sleeve
. high strength (YS = 510 MPa) for tube and mean (YS = 350 MPa) for sleeve.

The stress-strain curves used to represent both the tube and the sleeve plastic behavior are derived from tension tests on inconel tubes. They are illustrated in Figure 1.

2.2. Model

The calculations are carried out by means of the ANSYS program (version 4.3). A uniform pressure is applied inside the sleeve which, in turn, pushes into the inner face of tube after some plastic deformation.

Preliminary calculations over a full model of the expansion zone show that if the pressurization zone extends over at least 4 to 5 diameters, the central part is not influenced by the unexpanded extremities and behalves like 2 concentric tube sections with internal pressure. No residual stresses appear there, except when the tube yield strength is higher than the sleeve one, in which case a residual contact pressure remains. These preliminary calculations show also that large residual stresses appear near the transition zone between expanded and unexpanded regions.

A more refined model is used to compute the residual stresses in the transition zone. This extends only over 3.6 diameters, what has been checked to be sufficient to avoid boundary effects in the zone of interest. Considering the amount of plastic strain involved in the expansion process (up to 10 % in the sleeve), a Newton-Raphson method of integration is used. Although the model is axisymmetric, 3D triangular shell elements are used as the curent version of ANSYS does not allow the selected method of integration with axisymmetric elements. A small sector of both tubes has thus been modelized as shown on Fig. 2. Cylindrical boundary conditions have been introduced along each of the two end generating lines of both tubes.

Corresponding nodes of the two tubes are connected by means of gap/contact elements. Some bias has been given to the node interdistance in order to shorten the length of the elements in the zone of interest and, by this way, increase the accuracy of the results.

2.3. Calculation process

The calculation is performed as a succession of static load increments : the pressure applied on the sleeve is increased by steps until the contact between sleeve and tube is reached; the pressure is still further increased until a given amount of permanent strain in the central region of the tube is obtained. The pressure is then reduced down to zero giving the residual stresses in the structure. This process is repeated for several values of permanent strain in the central region in order to obtain the residual stresses distribution as a function of the applied pressure or of the residual bulging.

2.4. Results

We will first consider the case where both the sleeve and the parent tube have the same elastic limit. Figure 3 is typical of the obtained radial residual displacement. The bulging in the transition zone is larger than the one calculated in the middle (infinite cylinder behaviour). Residual axial and tangential stresses on the inside and outside surface of the parent tube are shown in figure 4 where large peaks are observed in the transition zone.

The figure 5 summarizes the results obtained, the most important beeing :

- the bulging of the tube is larger in the transitions than in the central part, especially for small bulges. It may even occur that the transitions deform plastically while the central region still behave elastically.
- the residual stresses increase rapidly with the applied pressure (or the residual bulging) to reach an asymptotic value which is nearly 50 % of the yield strength for the tangential direction and 75 % for the axial one.
- the highest residual stresses are compressive on the outside surface of the parent tube and tensile inside.
- a residual radial gap, although very small, remains between tube and sleeve, after the pressure relaxation.

The case of a "strong" sleeve with a "normal" tube leads to the same conclusions as above, provided that the residual stresses are expressed as ratios of the yield strength rather than as absolute values.

In the case where the yield stength of the sleeve is significantly smaller than the one of the tube, a residual contact pressure exists between sleeve and tube after expansion. In this case, a residual stress is observed even in the central region of application of the hydraulic pressure. This stress is however much smaller (nearly 10 % of yield strength) than what is obtained in the transition region. The other conclusions hereabove concerning the residual stresses are still valid. The only significant difference is that the pressure increment between the value at the contact and the one where the shelf region is reached is slightly larger in this case.

3. EXPERIMENTAL STRESS MEASUREMENT

3.1. Description of tests

Tests were carried out on about 20 specimens. They consisted in measuring along axial lines the tube OD and sleeve ID by means of a comparator, and the residual stresses by means of X-rays. Specimens are prepared by inserting a 3/4" tube section into 7/8" tube and applying an internal presure of about 1000 bar (14000 psi) over a length of about 100 mm (4"). This pressure is such that the residual bulging in the central zone remains very small (< 0.3 %). Both tube and sleeve are sufficiently long to avoid any effect of extremities.

The tube material is Inconel 600 MA and arises from 3 batches. All three have rather low mechanical properties (YS = 290 - 300 MPa; UTS = 660 - 700 MPa). The sleeve material is Inconel 690 heat treated, with YS in the range 330 - 360 MPa and UTS 670 - 730 MPa.

3.2. X-Rays Measurements

A diffractometer capable of registering back-reflected X-ray diffractions patterns is used. Stress calculations are based on the X-ray elasticity parameters and the Kröner model [1] is used.

Through the points from the plotting of the $2\ \theta_{\phi\psi}$ values versus $\sin^2\psi$, an ellipse curve has been drawn an the splitting of the positive and negative values was taken in this case as a measure of the geometrica error rather than one of the shear stress. No reversing of the ψ -positive and ψ -negative branches has been noticed in our measurements, what gives a good confidence in the validity of results.

The measurement conditions have been optimalized to determine the residual stresses.

Equipment : SET-X Elphyse
Target : MN $K\alpha$
$K\beta$ filter : C_r
X-ray generator : 20 kV, 3.8 mA
Collimator : coarse ϕ spot 2 mm
Angles range : PHI (1 ϕ) : 0
PSI (15 ψ) : 39.2, 35.8, 32.2, 28.6, 24.5, 19.8, 13.8, 0,
-9.7, -17.0, -22.2, -26.6, -30.5, -34.1, -37.5
2 θ region : 157,72° ± 10° (256 channels, first channel acquisition : 25, last channel acquisition : 229)
Counting time : 60 sec.
Young modulus : 214000 MPa
Poisson coef. : 0.30
hkl : 311
Coefficient of anisotropy : 1.60

3.3. Results

Both internal (inside sleeve) and external (outside tube) diameter measurements show systematically a uniform expansion, except in the transition zones where a small overexpansion appears. Figure 6 shows a typical measurement of OD bulging. For a radial bulging of 0.020mm (about 0.2 %) in the central part, the bulging at transition is 0.035 mm. This result corresponds very well to the prediction of the analysis.

Opposite to the reproducibility of these diameter measurements, the surface residual stresses determined by X-rays exhibit a large variability coming from the manufacturing process (grinding, polishing, ...). At the outer surface of the tube, a thin layer (< 100 µ) is characterized by high variable residual stresses in both axial and circumferential directions which is not homogeneous in depth, a high level of microdeformation and a small grains structure. This cold worked thin layer presents a higher yield strength than the bulk material which may reach about 750 MPa [2]. In the practice, the response of this thin layer will be different from the inconel 600 bulk material during mechanical sollicitations. In the F.E. theoretical calculation, this external thin layer has not been taken into account. Consequently, this surface effect prevents a precise comparison with calculated residual stresses. However, most transition zones show rapid variations of stresses, with an amplitude of the same order of magnitude as the calculated ones, i.e., a large fraction of about 3/4 of the base material yield strength. Figure 7 shows an example of measurement of the longitudinal stress along an axial line. In that case, the base line of surface residual stresses is low and measured stresses compare fairly well to calculated ones.

As the inner face of the tube is nearly free of machining surface stresses, it is expected that the correspondance between calculated and actual stresses would be much better. However, the surface cleaning before sleeving (by honing) could also introduce cold working. But this point is not possible to check by X-rays without cutting the tube and changing the residual stresses.

4. CONCLUSIONS

The hydraulic expansion used when sleeving steam generator tubes induces significant residual stresses, as well axially as circumferentially, in the transition zones between expanded and non expanded regions. Figure 5 summarizes the results obtained : the calculated peak stresses reach about 50 % of the yield strength in tangential direction and 75 % in the axial one. Analysis predicts an overbulging of about 0.040 mm in the transition and this is confirmed by measurements. Experimental determination of the residual stresses by X-ray diffraction is impaired by the presence at the surface of a thin cold worked layer in the as received tube which shows variable mechanical properties and residual stresses and which interfers with the expansion effects. However measurements confirms the presence of significant additional stresses in transitions.

REFERENCE

1. E. KRONER
   Zeitschrift für Physik, 151 (1958) p. 504 - 518
2. Paul S. PREVEY : Conference Proceedings of the American Society for Metals.
   Edited by William B. YOUNG, 1987, p. 11.

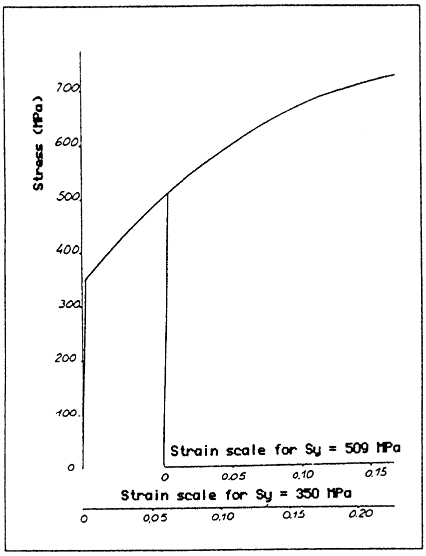

Fig. 1 - Stress strain curve used in the calculations

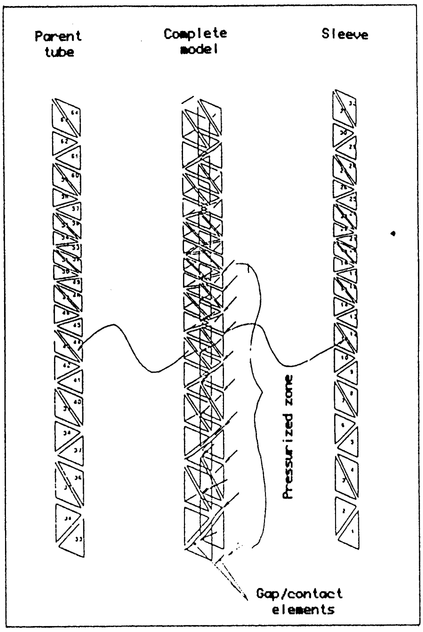

Fig. 2 - Perspective of the finite element model

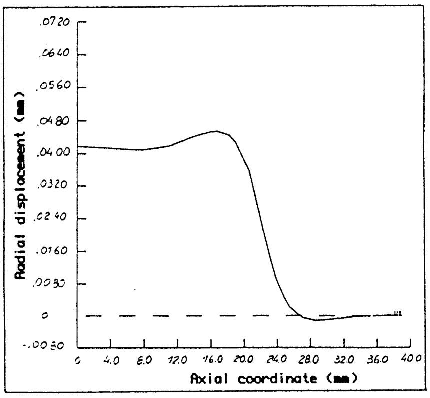

Fig. 3 - Residual radial bulging in the SG tube

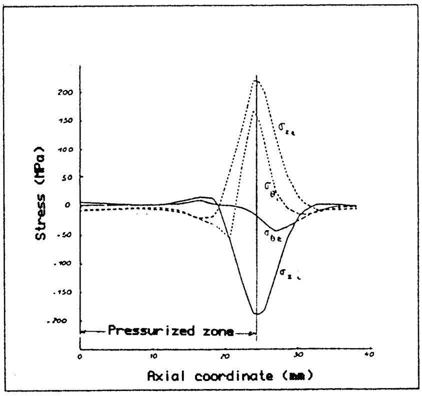

Fig. 4 - Residual stress distribution in the SG tube

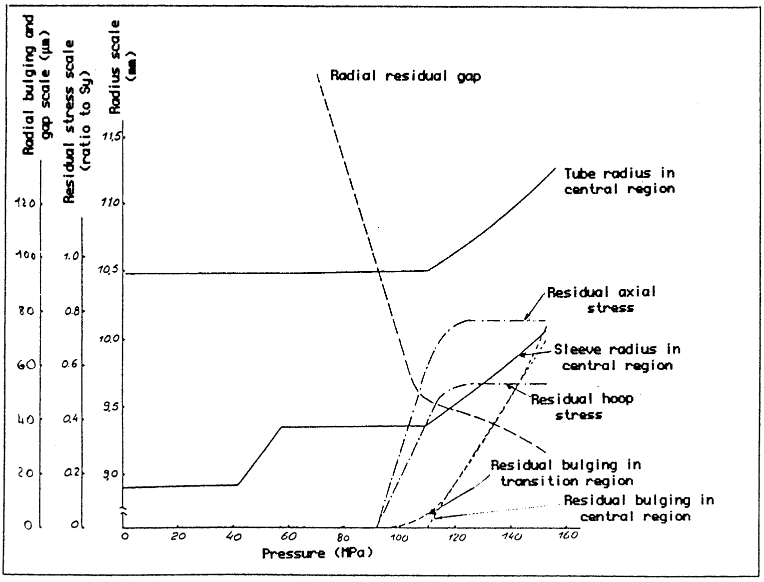

Fig. 5 - Evolution of the main parameters with the maximum applied pressure

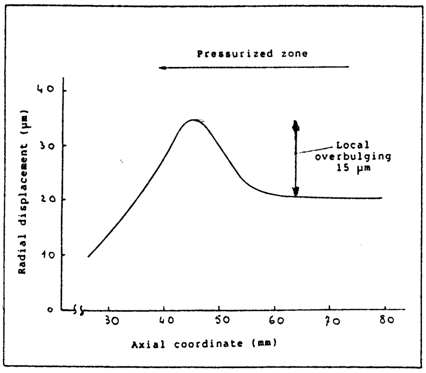

Fig. 6 - Measured axial profile of the radial displacement showing local overbulging in the transition zone

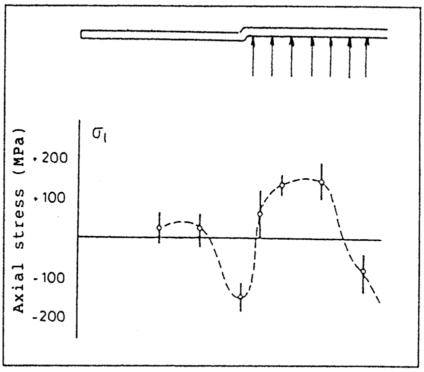

Fig. 7 - Typical measured axial stress distribution at the tube outer side in the transition region