SMiRT-12 / K. Kussmaul (Editor)

DG07/3

STRESS IDENTIFICATION IN STEAM GENERATOR TUBES FROM PROFILE MEASUREMENTS

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ABSTRACT

An identification method devoted to the determination of stresses in tubes, by means of profile measurements, provided by on site non-destructive evaluations, is presented here. From the only avalaible data (the radial displacement w on the inner wall), the computation of the strains, and consequently the stresses in the elastoplastic range, is made within the framework of the shell theory. For this purpose, we need to determine the associated curvature w'' : this step is an ill-posed problem, because of the lack of continuity with respect to the discrete data. This difficulty is overriden by means of an appropriate regularization procedure. The predictive ability of the method has been tested by comparison with direct simulations ; we present an industrial application.

1. INTRODUCTION

There are several situations in which the steam generator tubes are deformed : roll joining process at the tube plate level, denting... These phenomena are controlled periodically by in-service inspections of tubes. We are interested in the exploitation (if possible fast) of profile measurements, the use of which should permit to assess the stress level (namely maxima and their loci), avoiding any prior determination of the actual external loadings. A simple idea might consist in the using of the given radial displacement as a boundary condition in a finite element computation. Nevertheless, such method (moreover rather expensive) is very sensitive to the data : indeed there is no continuity of the result with respect to the data : a sinusoidal perturbation, of pulsation ω, is amplified by a factor generally greater than ω. Thus, we can't identify any stresses by that way.

The steam generator tube thinness and the measured data type (the radial displacement on the inner surface) makes us turn towards the use of a shell modelization. Besides, the shell model brings about a certain kind of natural regularization (Andrieux, 1992). We begin by the formulation of the basis model equations : displacement-strains relations in the framework of the shell theory, requirement of a regularized differentiation method to calculate the tube curvature from the displacement, stress determination, equilibrium conditions which furnish the unknown components. Due to the elastoplastic response of the constitutive material, we need the history of the successive displacements. At last, we describe some applications to real cases with the validation by reference to direct simulations.

2. FORMULATION

Strain characterization

The mechanical step of the stress identification consists in the determination of the strains in the whole tube from the displacement data, followed by the elastoplastic stress calculation. As we don't know the whole displacement vector field **u** $=(w,v,u)$ in r,θ,z coordinates (only the radial w component is measured), we have to use extra equilibrium conditions. Thus the knowledge of the axial displacement u is replaced by the fullfilment of the equilibrium equation on the axial stress resultant N_{zz}. This equation holds for each point z along the tube axis.

There are two simple cases, where the identification can be simply expressed : the purely axisymmetric one and the purely circumferential one. The model equations can be derived as the following :

Axisymmetrical case	Circumferential case
• shell kinematics :	
$u = (w(z), 0, u(z))$	$u = (w(\theta), v(\theta), u(z)= Kz)$
• membrane and curvature strain measures :	
$a_{\theta\theta}=\frac{w}{R}, \quad a_{zz}=u', \quad a_{z\theta}=0,$	$a_{\theta\theta}=\frac{w+v'}{R}, \quad a_{zz}=K, \quad a_{z\theta}=0,$
$k_{\theta\theta}=0, \quad k_{zz}=w'', \quad k_{z\theta}=0$	$k_{\theta\theta}=\frac{w''-v'}{R^2}, \quad k_{zz}=0, \quad k_{z\theta}=0$
• tridimensionnal strains :	
$\varepsilon_{\theta\theta}=\frac{w}{R},$	$\varepsilon_{\theta\theta}=\frac{1}{R}(w+v'-x_3\frac{w''-v'}{R}),$
$\varepsilon_{zz}=u'-x_3w'', \quad \varepsilon_{z\theta}=0$	$\varepsilon_{zz}=K, \quad \varepsilon_{z\theta}=0$

where $x_3=r-R \in\ ]-t/2,t/2[$ is the position through the thickness, R the tube mean radius, and ε_{rr} to be determined. These equations can be improved (in the case of moderately thick tubes) taking into account the true metric through the thickness.

In the above equations appear the data through w and w'' : we have to deal with the second derivative of the radial displacement. However, the w profile is given on a finite set of points on the tube axis or circumference. The consecutive numerical derivative computing is an ill-posed problem : no continuity of the computed second derivative with respect to the data is achieved. An arbitrary small data perturbation leads to large variations of the solution w'' : for instance if we perturb the data by a function like $\eta\sin\omega z$, the L^2 norm of the difference between the unperturbed and perturbed second derivative is amplified by a factor ω^2, highly increasing with the perturbation frequency (Andrieux, 1990). The unavoidable noise in the experimental measurement should makes the method unexploitable, without an appropriate treatment.

Thus we can't use directly a finite element mesh, with the prescribed displacement w on the inner wall of the tube. Using such a method to solve constitutive and equilibrium equations from the measured data, we should obtain unstable results.

Identification of the second derivative of the radial displacement

The w'' calculation lies on a Fourier series decomposition (FFT), after the w profile transformation into a periodic fonction for the axisymmetric case, adding a fitted polynomial. By differentiation, we obtain immediately a guess $\tilde{w}''$, which is an unstable approximant of the "true" value of w'' . Then, we compute a regularized value γ by simultaneous optimization of the distance between γ and $\tilde{w}''$ and the L^2 norm of the first derivative of γ. The relative weight of both terms is parametrized by a compromise factor α, determined by a non-linear equation $f(\alpha,\gamma,\eta) = 0$, (Groetsch, 1984 ; Engl, Bauer, 1985), depending on the solution γ and the previsible error η on the profile data, as well as the spatial discretization scale (see for more details Andrieux, 1990).

Stresses computation

We consider an elastoplastic constitutive relationship, with the Von Mises criterion, and an isotropic hardening. The plastic variables evolution law is discretized implicitely : the algorithm (of radial return type, see for instance Mialon, 1986) works with the increments Δw on the path of the radial displacement. Since several terms are unknown in the strains expression, we need an iterative procedure, to determine them. The $\Delta\varepsilon_{rr}$ component is obtained through the plane stress assumption, which can be improved by an estimation of the $\Delta\sigma_{rr}$ stress, through the radial equilibrium condition using $\Delta\sigma_{\theta\theta}$ (this modification leads to a better expression of the shell constitutive equations, see Voldoire, 1992). The $\Delta\varepsilon_{zz}$ component is computed by a secant iterative method, to satisfy the axial stress resultant equilibrium, for a known ΔF_z (in general 0) value :

$$\Delta F_z = \int_0^{2\pi} \Delta N_{zz}\, d\theta \equiv \int_0^{2\pi} \int_{-t/2}^{t/2} \Delta\sigma_{zz}\, dx_3\, d\theta$$

In the axisymmetric case, this equation is purely local in z : the algorithm surveys the set of z points, independently along the tube axis, at each of them it computes all the fields for a given number of x_3 positions in the thickness. Conversely, in the circumferential case, the axial equilibrium can be evaluated only after the whole circumference survey. Moreover, there are supplementary conditions : the circumferential stress resultant equilibrium, and the fields periodicity. So we have :

$$M^0 = \int_{-t/2}^{t/2} \Delta\sigma_{\theta\theta}\,(R+x_3)\, dx_3\,,\ \forall\,\theta \ ; \quad 0 = \int_0^{2\pi} \Delta v'(\theta)\, d\theta$$

where the constant M^0 have to be determined with the second condition. This makes the circumferential identification algorithm a little more complicated.

At each increment Δw, the iterative procedure is initialized by the elastic analytic solution. After convergence (which can be established for this algorithm), the state of stresses and internal plastic variable is kept. The radial equilibrium equation can be used to identify the actual loading pressure, which has been applied on the tube.

Profile reconstitution

In some situations, the only final profile measurement is available, and not the intermediate states. Nevertheless the loading path has a high influence on elastoplastic stress states : assuming a radial loading may not be sufficient (see next section). As it is usual for the inverse problems, an *a priori* information has to be provided. In particular, for the tubes rolling process transition zone analysis, we have developped a method of reconstitution of the intermediate profiles, from the knowledge of the final one, and several parameters, easy to collect, as the initial clearance between tube and plate... The intermediate profiles are then rebuilt with the help of elastic pressurized tube solutions (cf. Gamha,Voldoire, 1992). Previous numerical direct simulations (see for instance Maitournam *et al.*, 1993) are used to assess this methodology.

3. VALIDATION AND APPLICATIONS

The regularized second derivative computation method has been validated on analytical profiles, both "perfect" and noisy, like elastic solutions for a locally pressurized tube. Better results are obtained when the distribution of z points is regular, especially in the high curvature zones. The stress calculation algorithm has been tested with pure membrane elastoplastic solutions.

The first application consists in the comparison between direct simulation numerical results with the identified ones, on an industrial case : the roll expansion process of tubes in a plate. The Inconel tube main characteristics are :

Radius R	Thickness t	Elastic Moduli	Yield Stress	Hardening Modulus
8.98 mm	*1.09 mm*	*E=220000MPa, ν=0.30*	σ_y*=304 MPa*	*3000 MPa*

The loading path consists in a succession of rolling applied pressures : first in the lower part of the tube, to eliminate the clearance between tube and plate (here, about 0.21mm), and to generate residual pressure at the tube-plate interface, ensuring pull-out strength. Then, above this zone, a second roller applies a pressure, to reduce the tube bending residual stresses (improved roll-expansion). We compare in the figures 1. and 2. the residual axial and circumferential stresses, after the complete loading path. The reference values correspond to an axisymmetric 2D elastoplastic finite element computation (direct simulation). The computed radial displacements are used as data for the identification method. To illustrate the important role of the loading path , we have reported two kind of results : on the one hand, by a succession of five steps (representative of the path), on the other hand, with an unique step, between the initial straight tube and the final deformed one. As we can see, such a simplified analysis can't reproduce direct results, whereas the five steps identification is rather satisfactory. Certain discrepancies can be explained :

- the shell model is not able to represent the circumferential stresses in the attached tube part in the plate, owing to the bad estimation of the σ_{rr} stress, which is the higher stress during the rolling (but this unability is not very bothering in practical stress inspection) ;

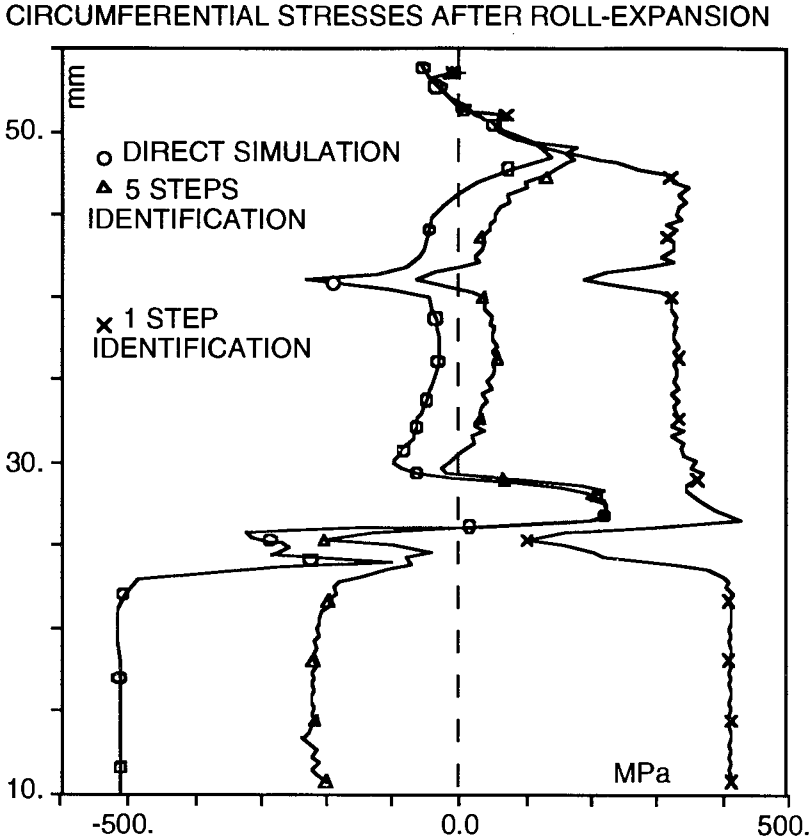

Figure 1. Residual roll-expansion $\sigma_{\theta\theta}$ stresses versus the position along the tube axis. Axisymmetric identification, compared with the direct simulation. Effect of the loading path on the identification.

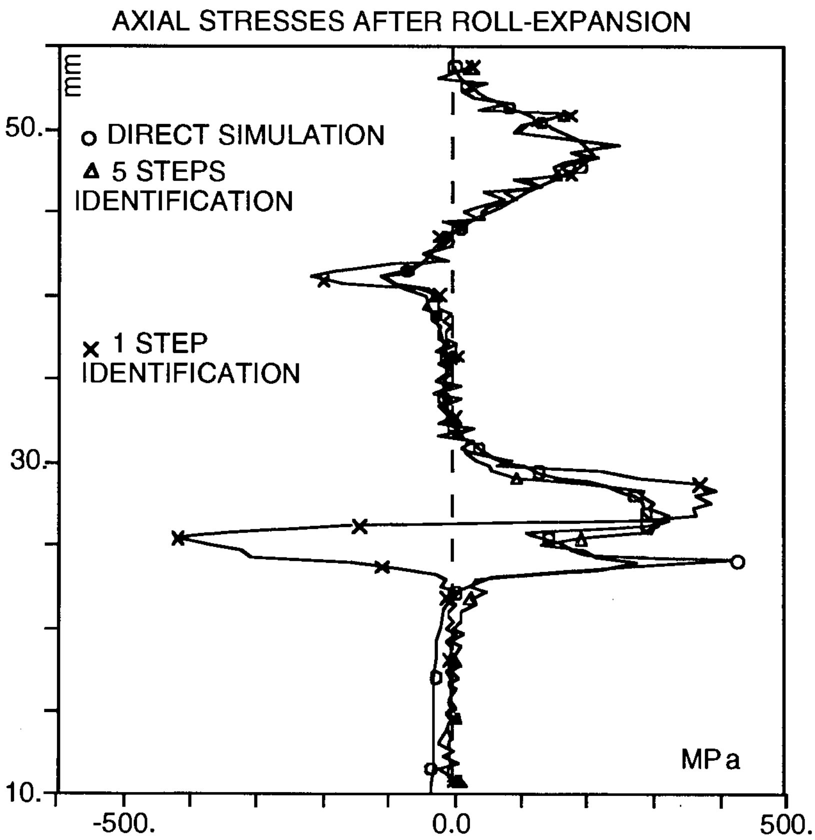

Figure 2. Residual roll-expansion σ_{zz} stresses versus the position along the tube axis. Axisymmetric identification, compared with the direct simulation. Effect of the loading path on the identification.

- it is not able to represent fully tridimensionnal effects, as the singularities, which can be observed at the rim of the contact zone between tool and tube, or plate and tube ;
- because of the unregularity of the spacing of the used z-points set, the second derivative identification causes little oscillations, visible on bending stresses.

In any case, we can conclude that the identification method is able to give good estimations of bending stresses maxima, and their loci. Other applications have us allowed to study the effect of the strain-stress curve on the identificated stresses, for a same profile, the effect of supplementary deformations on rolled tubes. The metric correction, appearing in the strain expressions (see section 2.), makes possible the extension to the analysis of moderately thick tubes, as for instance the vessel head adapters .

4. CONCLUSION

The method proposed here leads to a good alternative to the direct usual analysis of deformed tubes, the profile of which being measured by in-service inspections. The stresses assessment fits very well with direct numerical simulations, and supplies a worthwhile complement to other experimental methods, like for instance X-ray residual stresses determination. Several applications to the roll expansion process, denting, localized pushing of tubes, have given very satisfactory results, provided that we respect the loading history of the measured displacement, which is necessary owing to the material elastoplastic behaviour. Thus, we can identify bending stress maxima loci and values. The computer time cost is very low, to allow us to perform parametric studies, on the material characteristics, on the effect of the loading path..., and to consider an automatic treatment of the profiles, obtained by industrial inspections.

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