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NUMERICAL SIMULATION OF FLATNESS DEFECTS: APPLICATION TO ROLLING PROCESS

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Abstract: In this paper we present a new numerical technique to model the buckling phenomena under residual stresses induced by rolling process. This technique consists in coupling two finite element models: the first one consists in a three dimensional model based on 8-node tri-linear hexahedron which is used to model the three dimensional behaviour of the sheet in the roll bite; the second model is based on a shell formulation well adapted to large displacements and rotations, it will be used to compute buckling of the strip out of the roll bite. We propose to couple these two models by using Arlequin method.

Keywords: Rolling, Residual stresses, Buckling, Arlequin Method, Asymptotic Numerical Method

1. Introduction

Flatness defects are among the major problems encountered in strip rolling. Their direct origin is out-of-bite stress gradients resulting in buckling in the compressive stress areas. The most important flatness defects are “edge-waves” and “center-waves” buckles. These waves are the result of buckling due to self-equilibrating longitudinal residual stresses with a compressive longitudinal membrane force state in the middle of the strip (“center buckles”) or in the edge zones (“edge buckles”), respectively. During the rolling process, the buckling waves are usually suppressed by global traction. Thus, in some cases, the sheet may appear more or less flat, or even perfectly flat on the rolling line. Nevertheless we can still talk about flatness defects, insofar as there may be residual stresses in the sheet. This is why the post-bite stress profile is called “latent flatness defects”. If defects are only latent, the stress field computed beyond the bite by a 3D finite element model (FEM) should be correct. One can find in the literature three ways to model rolling, depending on the manner to account for flatness defects. The first way is based on 3D FEM that generally do not permit to capture buckling effects; they can only predict latent defects. Other models permit to account for buckling in an uncoupled approach: the 3D model yields residual stresses that are further included as the starting part of a buckling analysis. Last, few FEM are able to model rolling and buckling in a coupled manner. Several publications have been focused on uncoupled approaches. Counhaye [5] was the first to propose a coupling model of

rolling process and buckling phenomena. The model is based on a stress-relaxation algorithm applied only in the out-of-bite areas. They added an additional term to the elastic/plastic strain rate decomposition which represents the local shortening of a material segment when it becomes wavy due to buckling. Abdelkhalek et al. [6] used a different approach for coupling 3D FEM and Asymptotic Numerical Method (ANM) using a shell formulation. In this approach, a full 3D model of rolling is computed; the post-bite stress field obtained is introduced in the shell formulation where a buckling analysis under residual stresses is performed. The new distribution of the stress field obtained by buckling is considered as a new boundary condition for the 3D FEM. These computations are repeated until convergence.

In the present work, we propose a new approach to simulate rolling process taking into account buckling phenomena. A simplified model is used which consists in coupling a 3D continuum model and a shell model using Arlequin method. The buckling is due to residual stresses which are introduced in the 3D model and propagated in the shell model during the simulation.

2. Formulation

We propose an algorithm which consists in coupling 3D FEM and shell model by Arlequin method. So the idea is to combine these two models in the same finite element simulation that we solve by ANM. In the three dimensional part, we consider small strain and residual stresses which come from a full model taking into account the elastoplastic law adapted to rolling.

$$\begin{cases} \int_{\Omega_{3D}} \sigma : \delta \varepsilon d\Omega - \lambda P_{ext} (\delta u^{3D}) = 0 \\ \sigma = D : \varepsilon + \lambda_{res} \sigma^{res} \end{cases} \quad (1)$$

where ε and $\delta \varepsilon$ are respectively the strain and the virtual strain tensors. P_{ext} corresponds to the energy density due to external load, which is calibrated by a load parameter λ ; σ and σ^{res} are respectively the Cauchy stress tensor and the residual stress. We use small strain in this part of the model since we assume that the sheet in upstream of the roll mill is flat. But progressively, the 3D model will transmit the residual stresses to the shell model. Thus only the shell model will buckle during the simulation.

Finally in the shell part, we consider a geometrically nonlinear model. This shell model, proposed by Büchter et al. [7], avoids locking by incorporating an additional parameter describing the shell thickness variation. It is distinguished from classical shell models that are usually based on degenerated constitutive relations, since the present formulation uses the unmodified and complete three-dimensional constitutive law.

$$\left\{ \begin{array}{l} \int_{\Omega_{shell}} {}^t S : \left[\gamma^l (\delta u^{shell}) + 2\gamma^{nl} (u^{shell}, \delta u^{shell}) \right] d\Omega = \lambda P_{ext} (\delta u^{shell}) \\ \int_{\Omega_{shell}} {}^t S : \delta \tilde{\gamma} d\Omega = 0 \\ S = D : \left[\gamma^l (u^{shell}) + \gamma^{nl} (u^{shell}, u^{shell}) + \tilde{\gamma} \right] + \lambda_{res} S^{res} \end{array} \right. \quad (2)$$

The total Green-Lagrange strain tensor is decomposed into the compatible strain $\gamma^n = \gamma^l + \gamma^{nl}$ and an additional assumed strain term $\tilde{\gamma}$. Stress tensor is the second Piola-Kirchhoff stress S and S^{res} the residual stress.

3. Arlequin coupling

The Arlequin method allows to couple two different mechanical states through reliable coupling operators as well as consistent energy distribution between the two coupling zones (see Fig. 1).

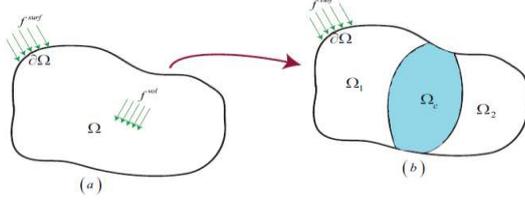


Figure 1: The Arlequin method in a general mechanical problem; A general mechanical problem (a) becomes a superposed domains Ω_1 and Ω_2 , that intersect in the gluing zone Ω_c .

The central point of the model is the coupling operator which is selected by analogy with the deformation energy of the shell. Otherwise the coupling area varies during the rolling process. In this paper, we limit ourselves to the H^1 coupling, and hence

$$c(\mu, u) = \int_{\Omega} \mu u + \gamma^l(\mu) : D : \gamma^l(u) d\Omega \quad (3)$$

We denote respectively u and μ the displacement and the Lagrange multiplier fields.

The integration domain is three-dimensional and the Lagrange multiplier is discretized using shell kinematic. We note that the integration points and interpolation, for Lagrange multiplier, are not necessarily the same as for the shell domain.

In addition we introduce weighting functions in order to share the energy between the two models in the coupling area. These weighting functions are used respectively for strain energy and for work induced by external forces. They satisfy the following relations :

$$\left\{ \begin{array}{l} \alpha^{3D} + \alpha^{shell} = 1 \quad \text{in } \Omega_c \\ \alpha^{3D} = 1 \quad \text{in } \Omega_{3D} \setminus \Omega_c \\ \alpha^{shell} = 1 \quad \text{in } \Omega_{shell} \setminus \Omega_c \end{array} \right. \quad (4)$$

Find the global displacement field in the domain Ω is therefore to weight the displacement u^{3D} and u^{shell} respectively in the domains Ω_1 and Ω_2 .

By introducing the weighting functions in equations 1 and 2, the Arlequin method allows us to write the following variational form :

$$\left\{ \begin{array}{l} \int_{\Omega_{3D}} \alpha^{3D} {}^t \sigma : \delta \varepsilon d\Omega + c(\mu, \delta u^{3D}) = \lambda P_{ext} (\alpha^{3D} \delta u^{3D}) \\ \int_{\Omega_{shell}} \alpha^{shell} {}^t S : \left[\gamma^l (\delta u^{shell}) + 2\gamma^{nl} (u^{shell}, \delta u^{shell}) \right] d\Omega - \\ c(\mu, \delta u^{shell}) = \lambda P_{ext} (\alpha^{shell} \delta u^{shell}) \\ c(\delta \mu, u^{3D} - u^{shell}) = 0 \\ \int_{\Omega_{shell}} \alpha^{shell} {}^t S : \delta \tilde{\gamma} d\Omega = 0 \\ \sigma = D : \varepsilon + \lambda_{res} \sigma^{res} \\ S = D : \left[\gamma^l (u^{shell}) + \gamma^{nl} (u^{shell}, u^{shell}) + \tilde{\gamma} \right] + \lambda_{res} S^{res} \end{array} \right. \quad (5)$$

4. Asymptotic numerical method

ANM is a technique for solving nonlinear equations based on the Taylor expansion to high order [3]. The technique consists in transforming a given nonlinear problem into a sequence of linear ones to be solved successively, leading to a numerical representation of the solution in the form of power series truncated at relatively high orders. Compared to iterative methods, ANM allows significant reduction of computation time since only one decomposition of the stiffness matrix is used to describe a large part of the solution branch. Thus, the procedure allows developing the unknown variables of the problem in the form of power series with respect to a path parameter "a" (see [1, 3] for more details).

5. Results

The presented test case concerns flatness defects generated by a rolling process. The procedure we proposed is non-iterative coupling: (i) first a rolling calculation (LAM3) allows us to provide residual stresses, (ii) to compute flatness defects, a second calculation using the coupling code 3D/shell/Arlequin is then performed considering residual stresses resulting from the previous calculation.

The results are compared with Counhaye's [5] and Abdelkhalek's [6] models and with experimental measurements.

Note that Counhaye's model is a modification of rolling code LAM3 which only relax membrane stresses in compression zones but the model is limited for the representation of flatness defects in the sheet.

Moreover, the procedure proposed by Abdelkhalek is based on an iterative coupling between the rolling code LAM3 and a thin shell code. It is also able to relax the excessive stresses and predicts flatness defects of various shapes. But compared to our new procedure, it has some limitations. Firstly, it's too complicated; the first iteration is a complete rolling calculation, the following describes only the downstream domain of the structure. Secondly, the transfer of the data between subdomains is not really standard. In particular, clamped boundary condition which is used on the shell model side of the bite is not very convincing.

We apply the proposed model to a rolling case described in Table 1, which refers to the rolling pass, the last stand of a tinplate sheet mill with very low thickness.

Let us call the method proposed in this work, Kpogan's model.

Table 1. Characteristics of investigated rolling pass

Strip width	855 mm
Strip thickness (strip crown)	0.355 mm (4.81%)
Exit thickness	0.252 mm
Rolling speed	22 m/s
Front tension	100 MPa
Back tension	170 MPa
Type of mill	4-high
diameter WR	555 mm
diameter BUR	1300 mm
Length WR	1400 mm
Length BUR	1295 mm
WR crown	0.0322%
BUR crown	No crown
Fraction law	Coulomb: $\tau = 0.03 \times \sigma_n$
Young's modulus	$E = 210$ GPa
Poisson's ration	$\nu = 0.3$

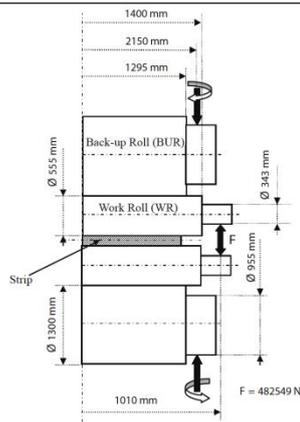


Figure (2) shows the post-buckled state of the sheet. As Counhaye's model is limited to represent flatness defects, we compare the post-buckled state of the sheet with Abdelkhalek's model. Figures (2.a) and (2.b) show respectively the results of Kpogan and Abdelkhalek's model. We obtain, as Abdelkhalek's model, longitudinal folds near the roll mill.

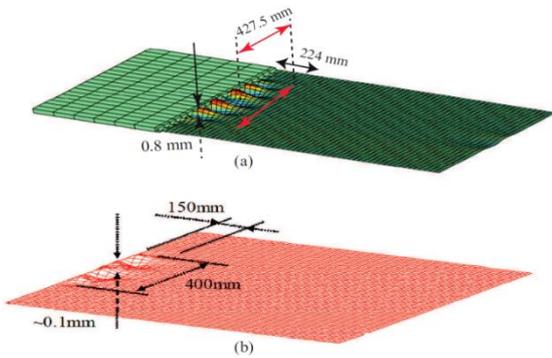


Figure 2. Vertical displacement of the sheet buckled under residual stresses ; Figure (a) : Kpogan's model ; Figure (b) : Abdelkhalek's model

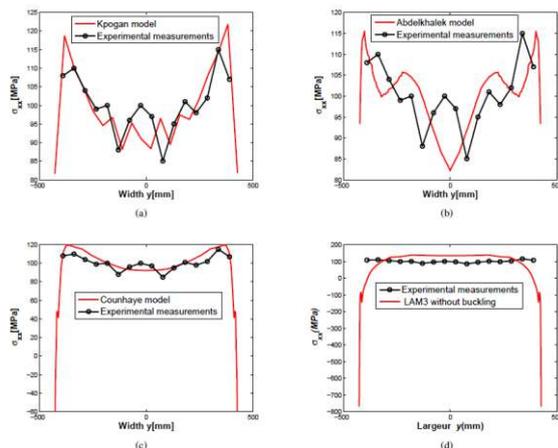


Figure 3. Comparisons of results with reference models ; Figure (a) : Kpogan's model; Figure (b) : Abdelkhalek's model ; Figure (c) : Counhaye's model ; Figure (d) : LAM3 code without buckling

Figure (3) illustrates σ_{xx} profiles for Kpogan, Abdelkhalek and Counhaye's models. Figure 15a shows the results obtained with Kpogan's model. We notice that with Kpogan's model, the stresses are relaxed and they are close

to the experimental measurements. Compared to the results of Abdelkhalek (Fig. 15b) and Counhaye's (Fig. 15c) models, Kpogan's model gives results much closer to the experiment.

6. Conclusion

We have proposed in this study a numerical model which consists in coupling Arlequin and asymptotic numerical methods to simulate flatness defects observed in rolling process. Our attention was focused on very thin sheets where these phenomena are often observed. Note that in thin sheet rolling, we need tri-dimensional model to compute correctly the deformations in the bite and a shell model far from the rolls to compute buckling modes. It is not obvious for a unique model to capture all these phenomena. Both models are coupled by using Arlequin method. This method allows us to model the entire structure while distinguishing upstream and downstream domain of the sheet.

We performed an industrial rolling test case taking into account complex residual stresses obtained by the rolling code LAM3. The results were compared with experimental data. The model we proposed gives satisfactory results. It predicts the relaxed stresses after buckling and shows the corresponding flatness defects.

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