SEECCM III
3rd South-East European Conference on Computational Mechanics-
an ECCOMAS and IACM Special Interest Conference
M. Papadrakakis, M. Kojic, I. Tuncer (eds.)
Kos Island, Greece, 12–14 June 2013

COMPUTATIONAL SIMULATION OF CROSS ROLL STRAIGHTENING

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Keywords: Cross roll straightening, FEM, plastic bending.

Abstract. *The paper deals with numerical analysis of the process of cross roll straightening of circular bars in a seven-roll straightening machine. In this machine, initially curved bar rotates along its axis as it progresses through laterally staggered rolls, being loaded by a fluctuating bending moment beyond its elastic limit. To simulate the process efficiently, special program was developed, based on a beam-type finite element, Euler scheme of material flow along the straightened bar and nonlinear iterative solution of the elasto plastic material behavior. Based on the input data, process characteristics like roller loading, product deflection, curvature and plasticization can be quickly obtained. With reliable solution of the direct problem, optimal intermeshing of rollers for given input data can be found in an iterative process. The paper describes main features of the algorithm and examples of its application.*

1 INTRODUCTION

In the process of cross roll straightening, initially curved circular bar rotates along its axis as it progresses through laterally staggered rolls, being loaded by a fluctuating bending moment beyond its elastic limit (Fig. 1). Resulting redistribution of residual stress is aimed at minimization of both curvature and residual stress. The principal problem is to choose optimal roll intermeshing strategy to minimize residual stress and curvature for given input parameters - initial bar curvature, its diameter, yield stress and material hardening.

In previous years such strategies were based mainly on empirical experience combined with elementary analytical approaches [1]. With the advent of the Finite Element Method, more complex computational models can be created and many phenomena of the cross roll straightening are being solved. Nevertheless, there are still limitations to apply the FEM for straightening process in the industrial practice due to its capacity and time demands [2]. This is the reason to use simpler and quick computational models. Generally they are based on the integration of the curvature of the leveled product [3]-[5].

In this paper we suggest a reversed procedure, starting from the suggested roll staggering. Fast algorithm is then used to evaluate curvatures along the leveled product, bending moments, roll loadings, together with full stress/strain history in each material point, residual stress distribution and final curvature. The program in MATLAB is based on FEM using a simple beam element with Euler description of material flow through the leveling machine. With fast and reliable solution of the problem, optimal setting of the leveling rolls can be found in an iterative process. In the paper we shall present suggested algorithm and our experience with its stability and general effectiveness.

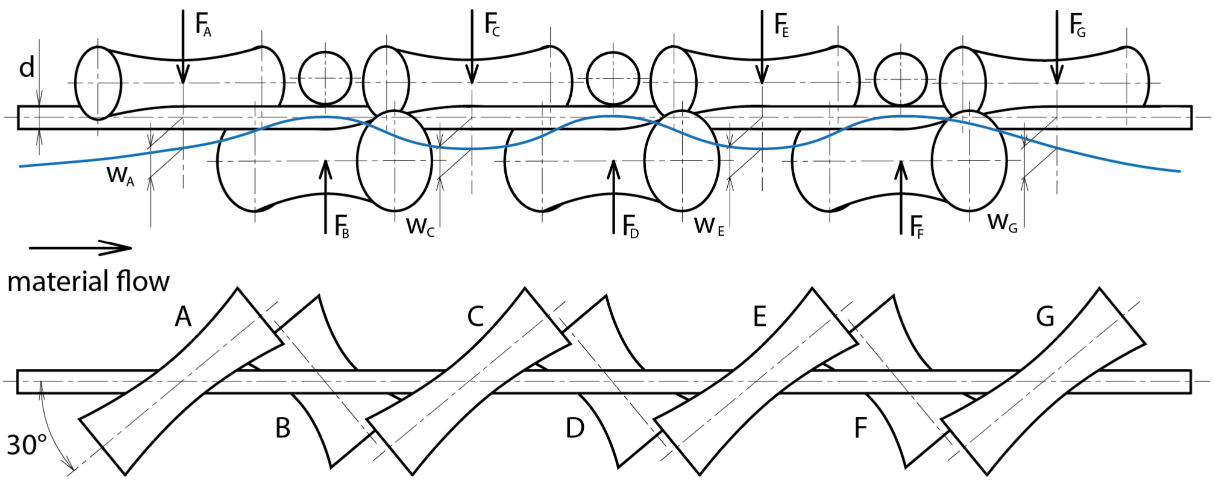


Figure 1: Schematic representation of the leveling process.

2 GENERAL ASSUMPTIONS OF THE PROCESS SIMULATION

In Fig. 1 we show schematic representation of the 7-roller cross roll leveling machine. Material of the bar is moving through the machine from the left side, rotating along its longitudinal axis on rollers which are skewed by 30 degrees. The three bottom supporting rollers are the driving rollers, vertically fixed, whereas the four top rollers are adjustable to obtain optimal bending to straighten the product.

The algorithm is based on several basic assumptions:

1. The bar deflection, slope and curvature can be described by bending theory of beams with one dimensional state of stress.
2. Simple point contacts with fixed pitch exist between the rollers and the bar.

3. Stationary situation with constant value of input curvature of the bar is supposed.
4. Material model is characterized by bilinear σ–ε curve with linear elastic and linear plastic hardening part, and kinematic hardening rule.

Input parameters are represented by the bar diameter, modulus of elasticity E, yield stress σ_y, hardening E_T, input curvature and by vertical intermeshing of the adjustable rollers. Output parameters are the deflection, slope and curvature along the bar, distribution of bending moments, shear forces and roller reactions and distribution of axial stress, elastic, plastic and total strain in any cross section along the beam, including residual stress and curvature at the end (Figs. 4, 5).

3 BASIC EQUATIONS AND SOLUTION ALGORITHM

The algorithm is based on iterative solution of a linearized equation

$$\mathbf{K}_{T,i-1} \cdot \Delta\mathbf{U}_i = \mathbf{R}_{i-1}, \tag{1}$$

$$\mathbf{U}_i = \Delta\mathbf{U}_i + \mathbf{U}_{i-1}, \tag{2}$$

where $\mathbf{K_T}$ is global tangential stiffness matrix composed of 120 two-node FE beam elements (see Fig. 2, ref. [6]) with two degrees of freedom, displacement and slope, in each node. $\mathbf{R}$ is a matrix of residual nodal shear forces and bending moments, $\mathbf{U}$ global matrix of nodal displacements and slopes. The beam element according to Fig. 2 has four degrees of freedom in the matrix $\boldsymbol{\delta}$

$$\boldsymbol{\delta} = \begin{bmatrix} w_1 \\ w_1' \\ w_2 \\ w_2' \end{bmatrix} \text{ and the element stiffness matrix } \mathbf{k} = \frac{E \cdot J}{L^3} \cdot \begin{bmatrix} 12 & 6 \cdot L & -12 & 6 \cdot L \\ 6 \cdot L & 4 \cdot L^2 & -6 \cdot L & 2 \cdot L^2 \\ -12 & -6 \cdot L & 12 & -6 \cdot L \\ 6 \cdot L & 2 \cdot L^2 & -6 \cdot L & 4 \cdot L^2 \end{bmatrix} \tag{3}$$

where E is the elastic modulus, J the area moment of inertia and L the element length.

Figure 2: Beam element.

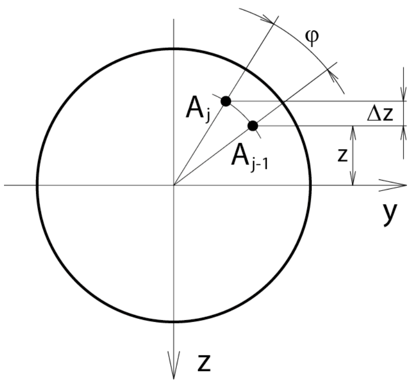


Figure 3: Cross section of the bar.

During every iteration, correction for nonlinear material behavior is realized. It is based on the computation of curvature in each element,

$$w'' = \mathbf{B} \cdot \boldsymbol{\delta} \tag{4}$$

where $\boldsymbol{\delta}$ is obtained for each element from actual displacements $\mathbf{U_i}$, and **B** is the curvature approximation matrix [6]

$$\mathbf{B} = \left[-\frac{6}{L^2} + \frac{12 \cdot x}{L^3}, \quad -\frac{4}{L} + \frac{6 \cdot x}{L^2}, \quad \frac{6}{L^2} - \frac{12 \cdot x}{L^3}, \quad -\frac{2}{L} + \frac{6 \cdot x}{L^2} \right]. \tag{6}$$

To simulate the movement of the bar through the leveling machine, Euler-type scheme is adopted. The material then moves through the beam elements, which have fixed positions in space. Development of the plastic deformation linked with the history of stress distribution over the bar cross section is always tracked from the first node on the left side of the beam in the loop over j-index from j = 2 to 121, until the last node is reached. First, the curvature increment between two subsequent nodes is evaluated

$$\Delta w''_j = w''_j - w''_{j-1}. \tag{6}$$

Next, the strain increment in any point A of the cross section, caused by axial displacement is obtained from

$$\Delta \varepsilon_{as} = \Delta w''_j . z , \tag{7}$$

and the strain increment caused by rotation

$$\Delta \varepsilon_r = w''_j . \Delta z . \tag{8}$$

In eqs. (7) and (8), z is the distance of each point of the cross section from the neutral axis of bending and Δz the change of this distance caused by rotation between the points *j-1* and *j*, as can be seen in Fig. 3.

Total strain increment is

$$\Delta \varepsilon = \Delta \varepsilon_{as} + \Delta \varepsilon_r \tag{9}$$

and testing stress

$$\sigma_j = \sigma_{j-1} + E . \Delta \varepsilon \tag{10}$$

where σ_{j-1} is the stress distribution over the cross section in the previous nodal point. For the first node, the initial stress distribution connected with the initial curvature of the bar is taken into account. Similarly, the state in the last node for converged solution then corresponds to residual stress and curvature of the beam leaving the leveling machine.

Correction of the testing stress according to plastic behavior of material together with correct distribution of elastic and plastic component of total strain is realized by algorithm published elsewhere [6], [7]. Typical distribution of stress over the cross section can be seen in Fig. 4.

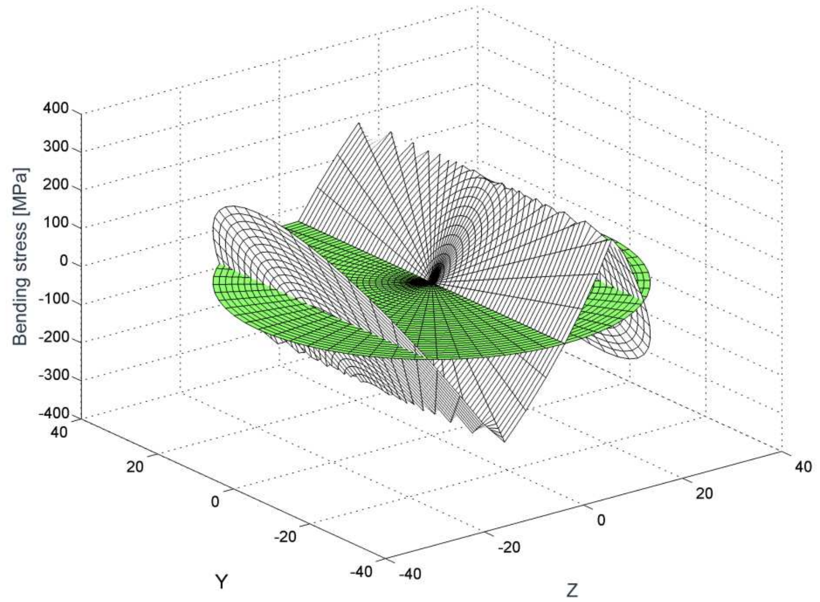
Nonlinear distribution of stress according to Fig. 4 results in correction of bending moment, which is modified according to

$$M_m = \iint \sigma(z) \cdot z \, dS , \tag{11}$$

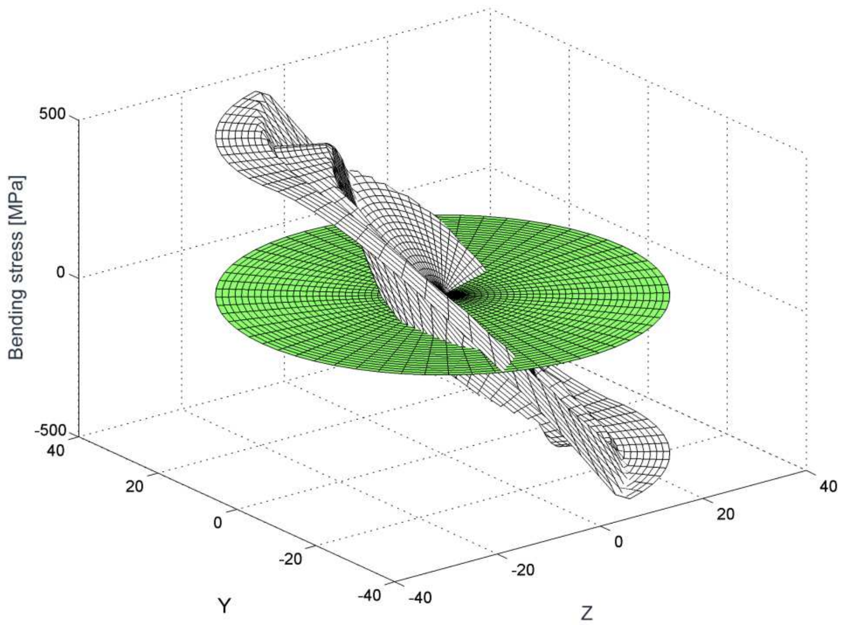
where *z* is the vertical coordinate and *S* the cross section area. From the modified moment, equivalent nodal loading matrix **f** is easily computed for each element

$$\mathbf{f} = \int_0^L \mathbf{B}(x) \cdot M_m(x) \cdot \mathrm{d}\, x\,, \tag{12}$$

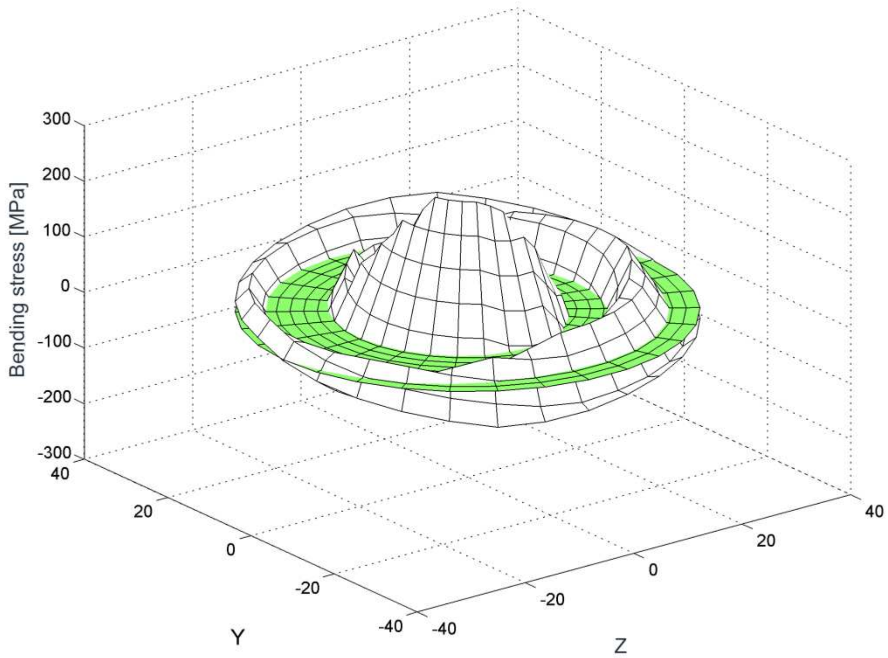
where **B**(x) is the curvature approximation matrix according to Eq.(5), L is the element length and $M_m(x)$ is a linear approximation of the modified bending moment along the finite element, obtained from the values in nodal points. Global matrix of equivalent nodal loads $\mathbf{F}_i$ is then obtained by contributions from all finite elements and matrix of residual loads for the next iteration is $\mathbf{R}_i = -\mathbf{F}_i$.



a) initial state



b) intermediate state at roll D



c) residual stress after leveling

Figure 4: Distribution of elastic plastic bending stress σ.

In case of growing plastic strain, i.e. for active plastic loading, also the stiffness matrix must be modified. It is realized by changing the beam flexural rigidity according to

$$(EJ)_m = \iint E_m(z) \cdot z^2 \, dS \text{ , where} \tag{13}$$

$$E_m = E \cdot \left(1 - \frac{E}{E+H}\right) \text{ and } H = \frac{E \cdot E_T}{E - E_T} . \tag{14}$$

E, E_T is the modulus of elasticity and tangential hardening modulus, respectively – see [7]. Modified flexural rigidity according to Eq. (13) enters the stiffness matrix (3) of each plasticized element. It results in a new tangential stiffness matrix $\mathbf{K}_{Ti}$ prepared for the next iteration.

Finally, the convergence criteria are checked and the procedure is either stopped or returned back to Eq.1 with iteration number *i* increased by one.

4 PROGRAM VERIFICATION

The algorithm presented above was programmed in MATLAB and verified by specific tests. Its performance was compared with full time-consuming FE analysis and with simple analytical models of our industrial partner with acceptable results. It can be illustrated by the following testing example: Circular cross section bar with diameter of 70 mm is moved through the leveling machine with subsequent intermeshing of adjustable rollers: 0, 12, 10 and 0 mm. Material is characterized by yield stress of 500 MPa and no hardening. In Fig. 5 we show the deflection, slope, curvature, bending moment, shear force and maximal bending stress along the length of the leveled bar. Fig. 4c) shows the distribution of residual stress over the cross section of the bar after leaving the machine. Maximal value of residual stress after straightening is 240 MPa. Initial radius of curvature 10 m was straightened to final value of 182 m. Loading of leveling rollers A-G (Fig. 1) is 16.5 kN, 60.9 kN, 101.1 kN, 111.6 kN, 95.5 kN, 55.0 kN and 14.4kN.

The results correspond to detailed FEM analysis realized by ANSYS, the solution procedure is stable and very fast in comparison to multipurpose FEM package. Presented example was solved in 60 iterations with total running time 8 min on a standard PC. This performance, together with user friendly interface makes our program an ideal tool for optimization of the leveling process.

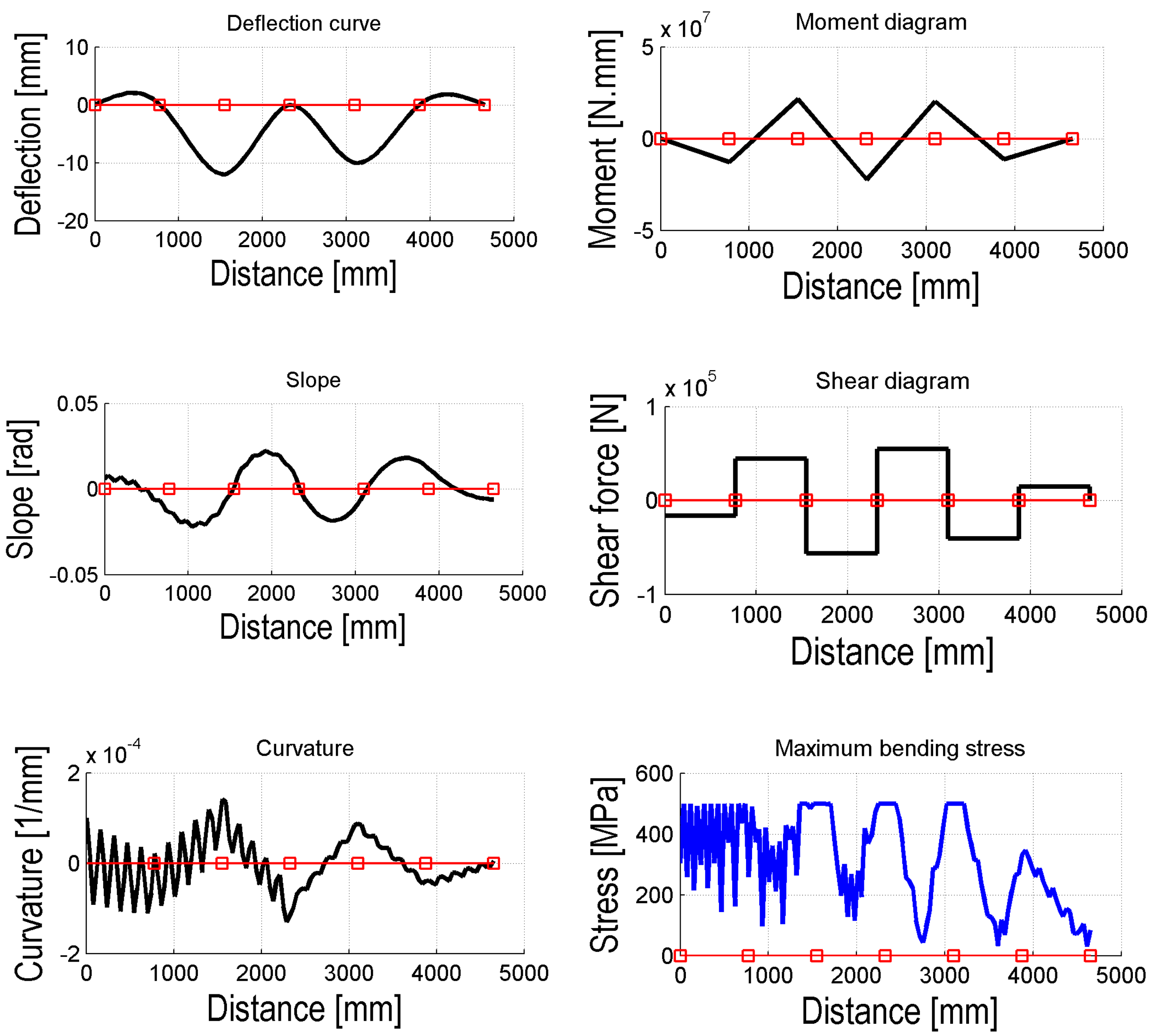


Figure 5: Results of the testing example: deflection, slope, curvature, bending moment, shear force and maximal bending stress along the leveled bar.

5 CONCLUSIONS

User friendly and fast program for direct solution of cross roll leveling process of circular bars was developed and tested. The algorithm is based on simple FE beam element with Euler scheme material flow and nonlinear iterative solution of the final equations using Newton-Raphson scheme. It was created with the aim to gain a user friendly and fast tool for analysis of practical industrial problems, applicable for engineering optimization of leveling schemes. Modular structure of the program is prepared to enhance its applicability to other similar processes like plate leveling, tensile leveling of thin sheets, cross roll straightening of tubes, etc. Some improvements are being prepared also in precise evaluation of position of the contact point between the rollers and product. Other improvements should include the influence of shear force to product deflection or better modelling of material. Especially the cyclic hardening/softening of material can have a substantial influence on the results. This will be the main direction of further development with strong accent to practical industrial applicability of the results.

ACKNOWLEDGEMENT

Financial help of the grant projects GA101/09/1630 and European Regional Development Fund project CZ.1.05/2.1.00/01.0002 is gratefully acknowledged.

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