19th International Conference
ENGINEERING MECHANICS 2013
Svratka, Czech Republic, May 13 – 16, 2013

ON ADVANCE IN LEVELING PROCESS OF LONG PRODUCTS

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Abstract: *This paper deals with advance in numerical simulation of leveling process of long products. The main task is useful setting of roller leveling machine to minimize residual curvature of a particular curved product. The problem is solved by program, using software MATLAB and fast algorithm which is based on the Finite Element Method (FEM) and its fundamental equation is set up. The curved material passes through laterally offset rollers with repeated elasto-plastic bending respecting the Eulerian approach. This results in convenient redistribution of residual stress which brings down the curvature of the product. The solution of this problem is complicated by high inherent nonlinearity and instability or sensitivity caused by cyclic plasticity of considered material. The problem is solved and useful setting is found by iterative process, based on input measured geometrical data and given material characteristics.*

Keywords: ***leveling, FEM, elasto-plastic bending, residual stress.***

1. Introduction

Current requirements of industry call for more accurate operations and efficient technologies. Nowadays, there are high demands by engineers, designers or technologists in one side and by consumers or customers in the other. Because of previous facts and continuous development of manufacturing technology the emphasis is placed on quality of used materials and semiproducts. One of the most important features of quality of long products can be its curvature. In a lot of manufacturing operations there is necessity of using straight bars so we use roller leveling machines.

The leveling process is based on the elasto-plastic bending, as discussed in Petruska et al. (2012), Sebek (2012) and others, which is repeated on every roller. In our case we are talking about seven rollers (Fig. 1) but there is commonly used nine or eleven rollers and for thin materials up to twenty one rollers. The elasto-plastic bending provides redistribution of initial residual stress which brings down curvature of long product. The aim of our analysis of leveling process is to determine and examine how to set positions of rollers to decrease curvature of long product at possible minimum by convenient redistribution of residual stress using cyclic plasticity of considered material.

The solving process of this problem is highly unstable and sensitive due to its inherent nonlinearity caused by elasto-plastic bending and therefore cyclic plasticity of material (Nastran & Kuzman, 2003 and Mutrux et al., 2011). Because of that fact the usage of iterative algorithm is obvious. It is necessary to obtain satisfactory convergence using advanced solvers of nonlinear problem as discussed further.

Historically, one of the first algorithms for solving the problem of long products' leveling are based on empirical and theoretical knowledge of materials processing technology field like Tokunaga (1961) and others. Later, there is a significant approach with development of computational technology along with the use of FEM. There are a lot of simple and quick analyses in one hand but due to increasing computer power more complicated models are used as in Schleinzer & Fischer (2001), Biempica et al. (2009), Zhao et al. (2011), Li et al. (1999) or Wu et al. (2000) in terms

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of solving algorithms, used material models, more complicated geometry and involving other effects and impacts in the other. There are many computational models formulated as analytic forming model by Doege et al. (2002) or like Liu et al. (2012) and Nastran & Kuzman (2002) which are all generally based on the integration of long product's curvature at each roller where the curvature is known.

In this paper are published advances and verification of new model for fast leveling process analysis (Petruska et al., 2012). Verification of our results is performed on the basis of results published by Nastran & Kuzman (2002). Whole developed algorithm starting from the intermeshing of each roller position is described in detail. Next, deflection, slope, curvature, bending moment and output residual stress are computed by the algorithm based on input measured geometrical data and given material characteristics of curved long product. The algorithm and its subroutines are programed using software MATLAB. At the end of our paper we present some improvements which are being prepared.

2. Applied algorithm of numerical simulation in detail

In our case long products are supposed. Another assumption is considering uniaxial state of stress. We work with seven roller leveling machine (Fig. 1) where each of top rollers is individually adjustable and all bottom rollers are fixed.

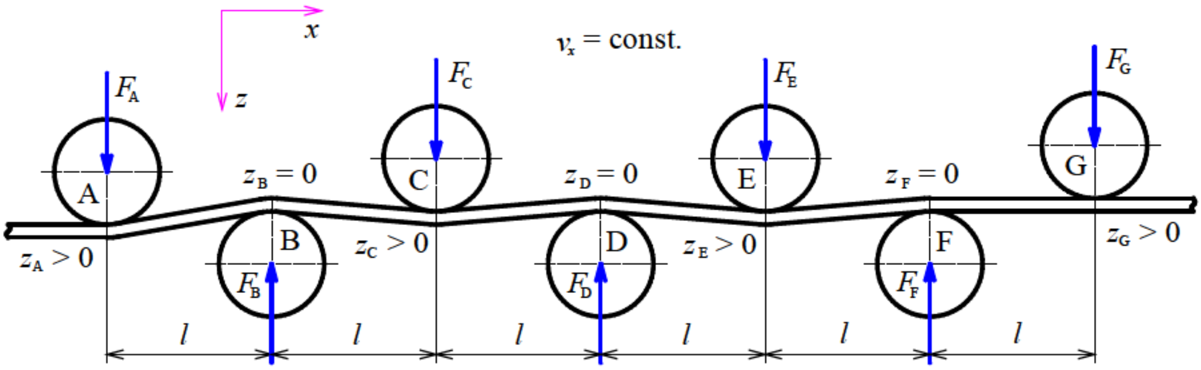

Fig. 1: Scheme of leveling machine in working process (Petruska, 2012 and Sebek, 2012)

As mentioned earlier, inputs for solving the problem of leveling process are measured geometrical data of curved material and its mechanical characteristics. Measured geometrical data are information about shape and cross section's dimensions. We are considering circular cross section long product so we don't take into account the length dimension of leveled material but only diameter. There is just the condition of minimal length because of design dimensions of the leveling machine. Required mechanical characteristics are E, E_T and σ_k which are Young's modulus, tangential hardening modulus and yield stress, respectively. For cyclic plasticity we use the kinematic hardening rule respecting Bauschinger effect which is necessary prerequisite (Schleinzer, 2001).

The main idea of presented algorithm is based on iterative solution of fundamental nonlinear equation of the FEM at Eq. (1) by the Newton-Raphson method. Issues concerning the convergence are discussed in Sebek (2012). In Eq. (1), index i represents iteration number and $\mathbf{R}_{i-1}$ matrix of residual nodal forces, which is equal minus global equivalent nodal forces matrix, thus $\mathbf{R}_{i-1} = -\,\mathbf{F}_{i-1}$.

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

The global increment matrix of nodal displacements and slopes is obtained by Eq. (2). At first iteration, $\mathbf{U}_0$ equals zero. The bar is loaded by prescribed displacements from adjustable rollers, only a point contact with fixed pitch l (Fig. 1) is supposed between the bar and rollers.

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

First of all, the bar is meshed between the first roller (A) and the last one (G) by beam finite elements with their element stiffness matrices, according Eq. (3), where j is index of each node, L is length of each element and $(E \cdot J)_{j,i}$ is beam flexural rigidity, where J is the area moment of inertia.

Global tangential stiffness matrix $\mathbf{K}_{T,i-1}$ is done by folding and adding all element stiffness matrices so the square matrix is formed.

$$\mathbf{k}_{j,i} = \frac{(E \cdot J)_{j,i}}{L^3} \cdot \begin{bmatrix} 12 & 6 \cdot L & -12 & 6 \cdot L \\ 6 \cdot L & 4 \cdot L^2 & -6 \cdot L & 2 \cdot L^2 \\ -12 & -6 \cdot L & 12 & -6 \cdot L \\ 6 \cdot L & 2 \cdot L^2 & -6 \cdot L & 4 \cdot L^2 \end{bmatrix} \tag{3}$$

After solving Eq. (1) we can determine curvatures in all nodes by Eq. (4).

$$w''_{j,i} = \mathbf{B}_{j,i}(x_j) \cdot \boldsymbol{\delta}_{j,i} \tag{4}$$

In the previous equation stands out $\mathbf{B}_{j,i}(x_j)$ as curvature approximation matrix which is estimated by Eq. (5) where x_j is longitudinal coordinate of each element.

$$\mathbf{B}_{j,i}(x_j) = \left[-\frac{6}{L^2} + \frac{12}{L^3} \cdot x_j \quad -\frac{4}{L} + \frac{6}{L^2} \cdot x_j \quad \frac{6}{L^2} - \frac{12}{L^3} \cdot x_j \quad -\frac{2}{L} + \frac{6}{L^2} \cdot x_j \right]^{\mathrm{T}} \tag{5}$$

There is also $\boldsymbol{\delta}_{j,i}$ matrix described by Eq. (6). It has four degrees of freedom and contains displacements and slopes of each element. Thus, each element has two nodes.

$$\boldsymbol{\delta}_{j,i} = \left[w_{j,i} \quad w'_{j,i} \quad w_{j+1,i} \quad w'_{j+1,i} \right]^{\mathrm{T}} \tag{6}$$

Now we can estimate curvature increments in all nodes by following Eq. (7).

$$\Delta w''_{j,i} = w''_{j,i} - w''_{j-1,i} \tag{7}$$

Next, the strain and stress distribution is identified with considering the Eulerian approach when material flows through beam elements which are fixed in the space along the leveling machine. Total strain increment is defined by Eq. (8) for every layer which the cross section is cut into (Fig. 2) where z is vertical coordinate and d is diameter of the bar. Then, the stress is calculated by Eq. (9). An initial distribution of these values can be concerned with initial curvature of the bar.

$$\Delta \varepsilon_{j,i}^{move}(z) = \Delta w''_{j,i} \cdot z \tag{8}$$

$$\sigma_{j,i}(z) = \sigma_{j,i-1} + E \cdot \Delta \varepsilon_{j,i}^{move} \tag{9}$$

There is a condition tested whether the actual yield stress is reached in every layer respecting kinematic hardening rule and loading history. If the condition is positive, the stress in Eq. (9) and actual yield stress has to be modified. Then, modified stress distribution is illustrated at Fig. 2. Next, we can estimate an elastic and plastic component of the total strain, see Owen & Hinton (1980).

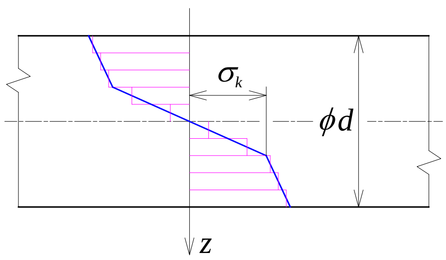

Fig. 2: Illustration of imaginary cutting the cross section into layers and stress distribution (Sebek, 2012)

By stress distribution according to the one at Fig. 2, where plastic deformations occurred, we can estimate modified bending moment with Eq. (10) where ψ represents the cross section.

$$M_{j,i}(x_j) = \iint_{\psi} \sigma_{j,i}(z) \cdot z \cdot \mathrm{d}S \tag{10}$$

Now we shall form new global matrix of equivalent nodal forces using element equivalent nodal forces matrices at Eq. (11).

$$\mathbf{f}_j = \int_0^L \mathbf{B}_j(x_j) \cdot M_j(x_j) \cdot \mathrm{d}\, x_j \tag{11}$$

Due to plastic deformations we have to compute modified element stiffness matrices by Eq. (3) with modified beam flexural rigidity $(E \cdot J)_{j,i}$ using Eqs. (12) – (14) in every layer where the actual yield stress has been reached with respecting the kinematic hardening rule and loading history. When the previous condition is negative we put E_m in Eq. (13) equal E (Owen & Hinton, 1980).

$$H = \frac{E \cdot E_T}{E - E_T} \tag{12}$$

$$E_m(z) = E \cdot \left(1 - \frac{E}{E + H}\right) \tag{13}$$

$$(E \cdot J)_{j,i} = \iint_{\psi} E_m(z) \cdot z^2 \cdot \mathrm{d}S \tag{14}$$

Variable H in Eq. (12) is the hardening parameter. After that procedure, we can complete new global stiffness matrix for next iteration if there was any.

At the end of each iteration, convergence criteria are tested. They are based on global matrix of displacements and slopes by Eq. (15), global matrix of residual nodal forces by Eq. (16) or both. In Eqs. (15) and (16) symbols θ_u and θ_f are required deformation and force tolerances, respectively.

$$\frac{\|\mathbf{U}_i - \mathbf{U}_{i-1}\|}{\|\mathbf{U}_i\|} \leq \theta_u \tag{15}$$

$$\frac{\|\mathbf{R}_i\|}{\|\mathbf{F}_i^{react}\|} \leq \theta_f \tag{16}$$

The denominator of a fraction in Eq. (16) represents the sum of reaction forces inferred by the intermeshing of rollers, that is the interaction between rollers and leveled material.

Finally, if convergence criteria are satisfied, the procedure is stopped. In the opposite case the iteration number is increased by one and the procedure is returned back to Eq. (1) and repeated.

Previous procedure corresponds to the one where only longitudinal move is included. The algorithm can be easily modified for considering the rotation of bar around its axis as well. It can be done by involving strain increment at Eq. (17) caused by rotation. Then, total strain increment is a sum of the strain increment caused by translation in Eq. (8) and rotation.

$$\Delta\varepsilon_{j,i}^{rot} = w''_{j,i} \cdot \Delta z \tag{17}$$

Increment of z coordinate caused by rotation in Eq. (17) is illustrated in Fig. 3.

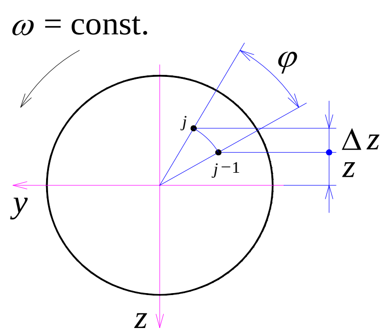

Fig. 3: Dimensioned circular cross section for cross roll straightening

There is an example of residual stress after cross roll straightening in Fig. 4.

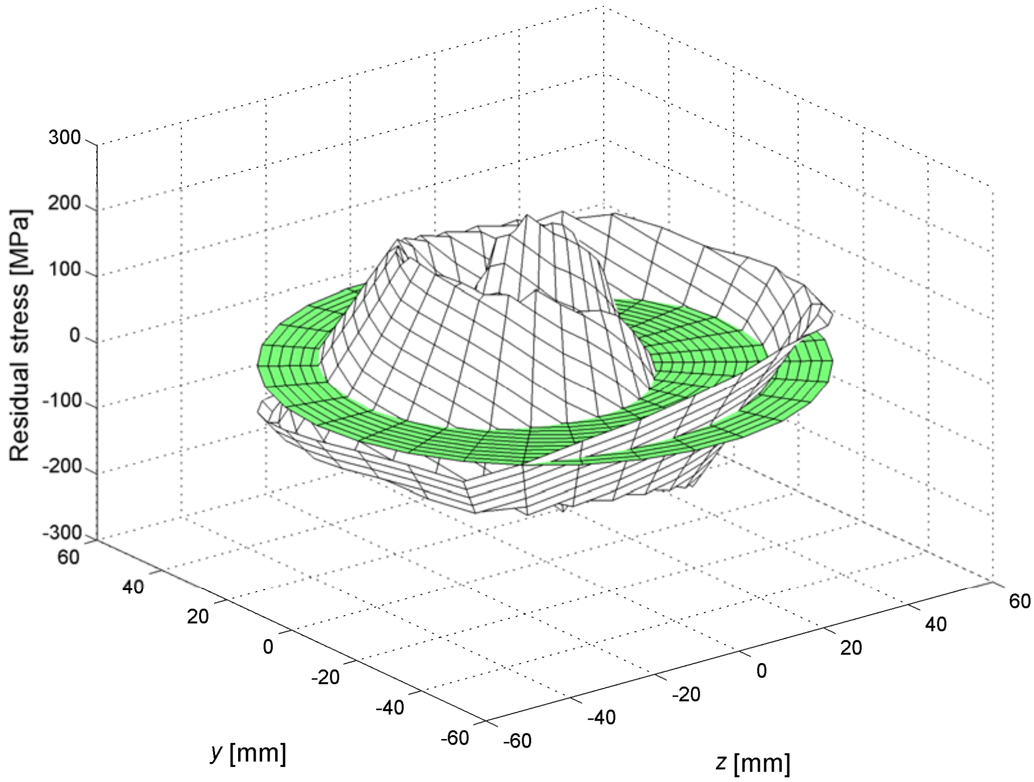

Fig. 4: Distribution of residual stress after leveling process

We are developing and debugging algorithm considering rotation of the bar which enables the simulation of cross roll straightening. More details will be presented in the future.

3. Verification example

For verification of our algorithm we used results published in Nastran & Kuzman (2002) where the seven roller leveling machine is also used. In this case we are considering the leveling without rotation of the bar. There is a different design of leveling machine as shown at Fig. 5 in Nastran & Kuzman (2002). In this case rollers A, C, E and G are fixed and rollers B, D and F are individually vertically adjustable. Nevertheless, we easily modified our program so it agrees with the one in Nastran & Kuzman (2002).

Values used in a computation:

- diameter 2.1 mm
- yield stress 530 MPa
- Young's modulus 210000 MPa
- initial curvature $2.5 \cdot 10^{-3}$ mm^{-1}
- intermesh of roller B 0.4 mm
- intermesh of roller D 0.3 mm
- intermesh of roller F 0.2 mm
- pitch 25 mm

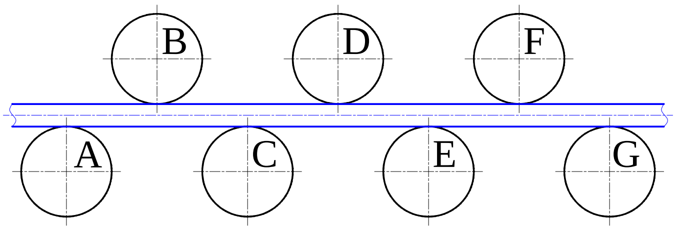

Fig. 5: Illustrative scheme of leveling machine used in verification (Nastran & Kuzman, 2002)

Analyzed variables along the bar length are depicted in following Figs. 6 – 13. Deflection, slope, curvature and bending moment from our program and from Nastran & Kuzman (2002) are compared in these figures. We are even able to compute the progress of shear force during leveling process along the curved bar as shown in Fig. 14.

We can note that progress of variables in dependence to distance of moving leveled bar corresponds to progresses in Nastran & Kuzman (2002) with satisfactory matching. But they cannot be identically the same because of using a bit different material model by Nastran & Kuzman (2002) when the yield stress is not constant during leveling process due to cyclic softening. We do not involve this fact in our program as well as hardening and parameter which determines the smoothness of the transition from the elastic to plastic region. So that is why we used the value of 530 MPa for yield stress instead of 560 MPa as in Nastran & Kuzman (2002) because of cyclic softening.

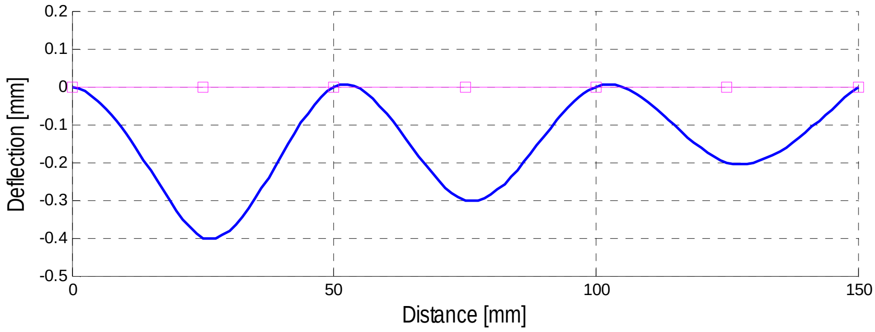

Fig. 6: Progress of deflection due to intermesh of rollers by our program

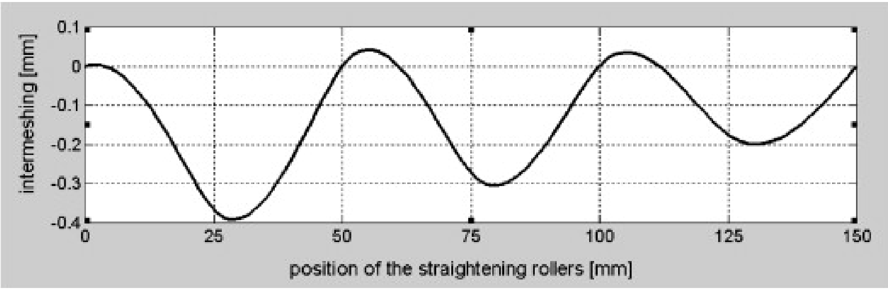

Fig. 7: Progress of deflection due to intermesh of rollers (Nastran & Kuzman, 2002)

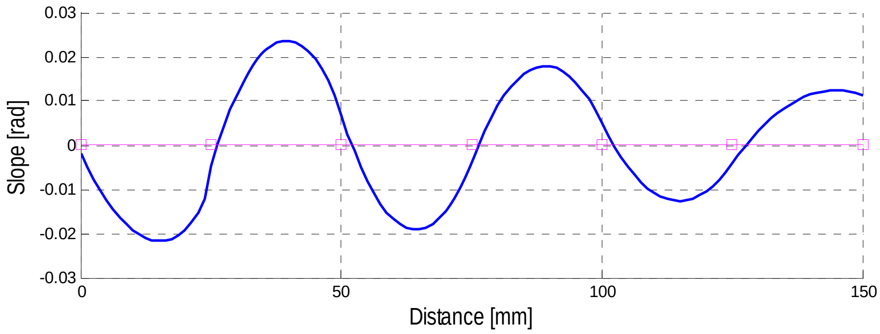

Fig. 8: Progress of slope by our program

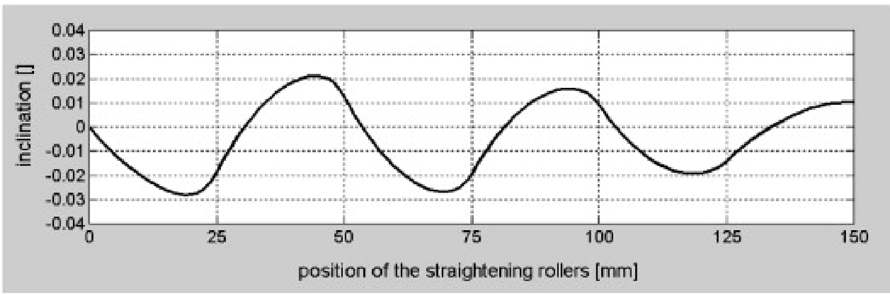

Fig. 9: Progress of slope (Nastran & Kuzman, 2002)

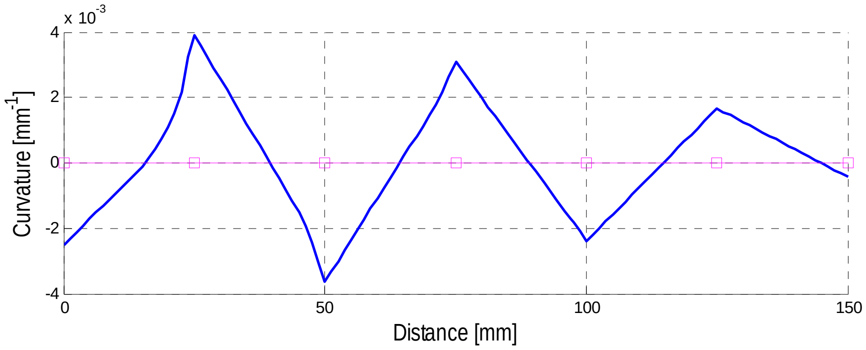

Fig. 10: Progress of curvature by our program

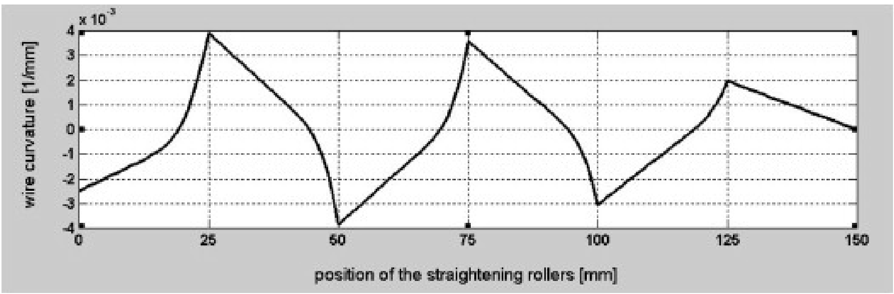

Fig. 11: Progress of curvature (Nastran & Kuzman, 2002)

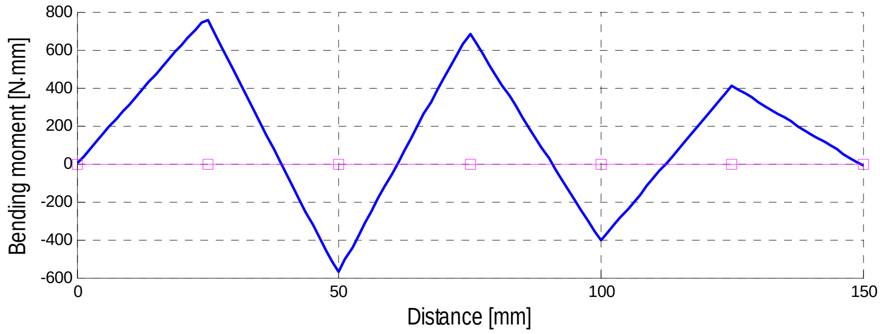

Fig. 12: Progress of bending moment by our program

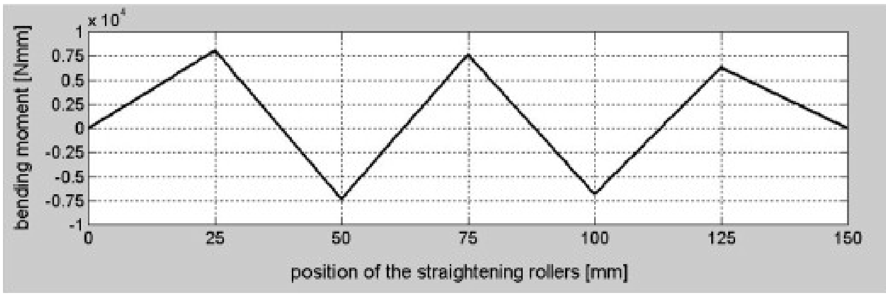

Fig. 13: Progress of bending moment (Nastran & Kuzman, 2002)

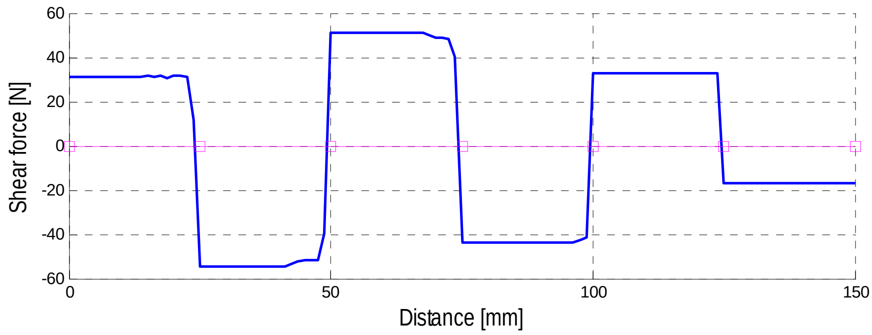

Fig. 14: Progress of shear force along the leveled bar by our program

4. Conclusions

The user friendly program with fast algorithm for solving the leveling process of long products has been developed. The principle of the algorithm is based on FEM and its fundamental equation respecting Newton-Raphson method for solving nonlinear problems. There are beam elements used with considering the Eulerian approach when material moves through leveling machine. Whole algorithm of the suggested program is described in detail. Verification example is shown as well.

The modular structure of presented program allows enlargement of another subroutines such as the one involving rotation of the bar around its axis, plate and tensile leveling, cross roll leveling of tubes, etc. The principal idea when considering rotation of the bar, i.e. cross roll straightening, is presented as well and it is being prepared.

Other improvements can be included as well as more precise material model especially of cyclic hardening or softening, an influence of shear force to deflection of leveled product or location of contact point between rollers and moving material during leveling process and rate of its effect.

Our tendencies are strongly aimed to practical applicability of results in an industrial field and further progress and advances will be presented in a future.

Acknowledgement

Financial help of the grant projects FSI-J-13-2020 and European Regional Development Fund project CZ.1.05/2.1.00/01.0002 is gratefully acknowledged.

References

Petruska, J., Navrat, T. & Sebek, F. (2012) A New Model for Fast Analysis of Leveling Process. *Advance Materials Research*, 586, pp. 389-393.

Nastran, M. & Kuzman, K. (2003) Some comments on cold forming process stability analysis. *Journal of Materials Processing Technology*, 133, pp. 166-173.

Sebek, F. (2012) *Computational analysis of leveling of square cross section rods.* Master's thesis. Brno University of Technology, Brno.

Mutrux, A., Berisha, B. & Hora, P. (2011) Prediction of cyclic softening in a medium carbon steel during cross roll straightening. *Journal of Materials Processing Technology*, 211, pp. 1448-1456.

Tokunaga, H. (1961) On the Rolled Straightener. *Japan Society of Mechanical Engineers*, 4, 15, pp. 605-611.

Schleinzer, G. & Fischer, F. D. (2001) Residual stress formation during the roller straightening of railway rails. *International Journal of Mechanical Sciences*, 43, pp. 2281-2295.

Biempica, C. B., Díaz, J. J. C., Nieto, P. J. G. & Sánchez, I. P. (2009) Nonlinear analysis of residual stresses in a rail manufacturing process by FEM. *Applied Mathematical Modeling*, 33, pp. 34-53.

Zhao, Y., Guo, D. & Hu, F. (2011) Finite element simulation of web falling during heavy rail roller straightening. *Procedia Earth and Planetary Science*, 2, pp. 44-49.

Li, K. Y., Chen, C. K. & Yang, S. C. (1999) Profile determination of a tube-straightening roller by envelope theory. *Journal of Materials Processing Technology*, 94, pp. 157-166.

Wu, B. J., Chan, L. C., Lee, T. C. & Ao, L. W. (2000) A study on the precision modeling of the bars produced in two cross-roll straightening. *Journal of Materials Processing Technology*, 99, pp. 202-206.

Doege, E., Menz, R. & Huinink, S. (2002) Analysis of the levelling process based upon an analytic forming model. *Manufacturing Technology*, 51, 1, pp. 191-194.

Liu, Z., Wang, Y. & Yan, X. (2012) A new model for the plate leveling process based on curvature integration method. *International Journal of Mechanical Sciences*, 54, 1, pp. 213-224.

Nastran, M. & Kuzman, K. (2002) Stabilization of mechanical properties of the wire by roller straightening. *Journal of Materials Processing Technology*, 125-126, pp. 711-719.

Owen, D. R. J. & Hinton, E. (1980) *Finite Elements in Plasticity.* Pineridge Press, Swansea.