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Study on Mechanical Behavior of Thin-walled Member during Precision Straightening Process

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Abstract: This paper introduces the mechanical behavior of precise straightening thin-walled members systematically. As a result of its cross section characteristics of the thin-walled members, traditional straightening theory does not work well in the straightening process of this kind of metal bar stock. Considering the stress evolvement of section during the straightening process, a model was built to analysis the straightening process like thin-walled member with great section height. By making a thorough analysis of the straightening process, the section deformation law and the relationship between sectional distortion and straightening parameters has been mastered. An analytical model was built for macroscopic energetics parameters of the straightening process and the parameters was optimized based on this model. Then loading mode of thin-walled member straightening was discussed. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Straightening, Thin-walled member, sectional distortion, Stress analysis, Loading mode.

1. Introduction

With the rapid development of the construction, railway transportation, offshore exploration and bridge aviation industry, the thin-walled member has been popularized and applied in recent years as a new green material because of its superior performance in mechanical property and economic advantage. For the large gradient of stress-strain and temperature variation in the processes of metal forming, the exits of geometric imperfection and residual stress cannot be avoided in the product. So straightening is an important finishing step in the processes of metal forming, namely relieve residual stress and eliminate geometrical imperfection through repeated elastic-plastic reversely bending produced by special straightener [1]. Metal components straightening process has been studied and discussed by many scholars with methods of theoretical analysis and numerical calculation [2-8].

However, as a result of its special cross section characteristics, the mechanical and geometrical properties of thin-walled member are different from other members and traditional profiles. The main differences are as follows [9]:

(a) Because of its large section height, evolvement of the deformation and longitudinal residual stress produced by the former working procedures and straightening rolls have an important influence on its behavior during the straightening process, which is not taken into consideration in the traditional straightening theory.

(b) The thin-walled member is sensitive to loading mode specially, for its structure and poor performance of bearing transverse load. In addition, its technological requirements also differ from members with solid section. Therefore, the optimization of straightening parameters, such as bending deflection and straightening force, is particularly important. Meanwhile, in order to control the section stress and geometric shape during the straightening process, it must be done to find a reasonable path along which the straightening force is delivered on the section.

(c) On account of the complex cross-section mechanical properties of thin-walled structures, there must exist cross-section distortion caused by plastic deformation or instability during the straightening process, no matter how the load is applied, which affects the setting and control of the parameters during the straightening process.

Therefore, traditional straightening theory has great limitations when it is used to describe the mechanical behaviors of large-scale thin-walled structures during the straightening process. Considering the structure characteristics, this article makes a deep and systematic research of the mechanical behavior of thin-walled structures during straightening process and comes up with a complete set of precision straightening theory that works well with thin-walled member.

2. Stress Evolvement and its Influence

In essence, the roller straightening process is a repeated elastic-plastic bending process of the cross section, which is a typical inhomogeneous cross-section deformation state and results in macroscopic residual stress in the cross section [10]. During the process, new residual stress is generated while existing section stress is redistributed, so the next bending process would inherit the residual stress generated by the previous bending process which will give an impact on the anti-bending characteristics of the next bending process. For thin-walled members with larger section height, the impact of such an act on straightening process will be highly visible. Therefore, a cross-section elastic-plastic bending and straightening model for thin-walled structures should be established with the stress evolvement taken into consideration.

2.1. Solution of the Model

According to the residual stress superposition principle, the static equilibrium relationship and cross-section yielding conditions of basic elastic-plastic theory, numerical analysis of the n+1th elastic-plastic bending process of the cross section straightening can be achieved with the use of MATLAB software . The main process is as follows:

a) discretization of dimensionless cross-section stress distribution

Divide the height range from -1 to 1 into N sections and discrete stress which is continuously distributed in dimensionless cross section. The stress values $\sigma_{\Delta}^{(n+1)}$ of the section point is used for calculation and analysis instead of real stress continuously distributed in the section.

b) calculation of the stress in cross-section during bending loading

By calculating bending stress $\sigma_{w\Delta}^{(n+1)}$ of every section point according to curvature and superimposing the previous bending residual stress $\sigma_{c\Delta}^{(n)}$, we can achieve the stress values of the section point:

$$\sigma_{\Delta}^{(n+1)} = \sigma_{w\Delta}^{(n+1)} + \sigma_{c\Delta}^{(n)}$$

And then carry out the criteria for $\sigma_{\Delta}^{(n+1)}$:

if $\left|\sigma_{\Delta}^{(n+1)}\right| > \sigma_s$, then $\sigma_{\Delta}^{(n+1)} = \pm\sigma_s$.

if $\left|\sigma_{\Delta}^{(n+1)}\right| < \sigma_s$, then $\sigma_{\Delta}^{(n+1)} = \sigma_{w\Delta}^{(n+1)} + \sigma_{c\Delta}^{(n)}$.

c) calculation of the residual stress in cross-section after unloading plastic-bending ratio:

$$\overline{M}^{(n+1)} = \frac{6}{\sigma_s}\int_{-1}^{1}\sigma^{(n+1)} \cdot z \cdot \mathrm{d}z, \qquad (1)$$

rebounding stresses:

$$\sigma^{(n+1)'} = -\overline{M}^{(n+1)}\sigma_s z, \qquad (2)$$

residual stress:

$$\sigma_c^{(n+1)} = \sigma^{(n+1)} + \sigma^{(n+1)'}, \qquad (3)$$

After achieving the plastic-bending ratio and rebounding stresses according to (1) and (2) respectively, residual stress of the section point can be calculated with (3), namely

$$\sigma_{\Delta}^{(n+1)'} = -\overline{M}^{(n+1)}\sigma_s z$$

$$\sigma_{c\Delta}^{(n+1)} = \sigma_{\Delta}^{(n+1)} + \sigma_{\Delta}^{(n+1)'}$$

The logic block diagram of the numerical analysis for stress of single section point during the bending process is shown in Fig. 1. We have to run this program repeatedly for a roller straightening process during which the rolled stock would be bended reversely many times.

2.2. Stress Evolvement During the Straightening Process

Take example of the 8 roller straightening based on the principle of small deformation. Suppose that the maximum initial curvature of the dimensionless rectangular metal material C_{0max}=±3.5. With the numerical method discussed above, the parameter C_w of every bending process can be obtained under the condition of small deformation according to classical straightening theory, as shown in Table 1.

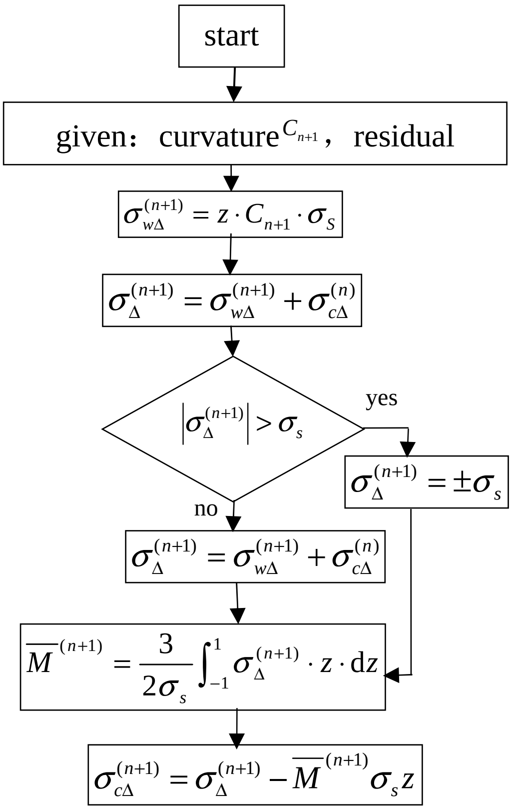
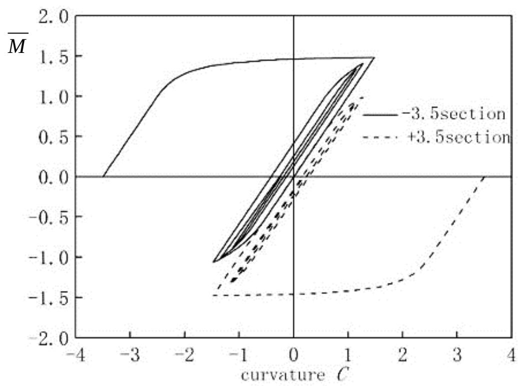


Fig. 1. Logic block diagram of the numerical analysis for elastic-plastic bending.

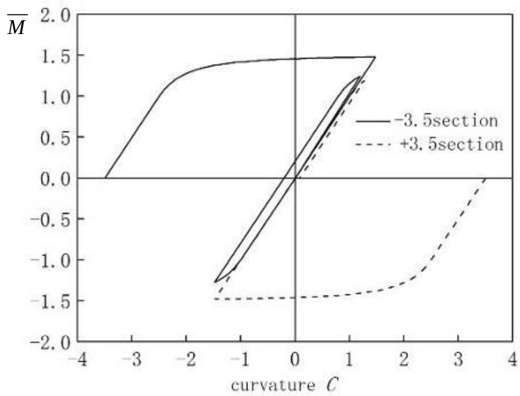
Table 1. Converse bending parameters of C_{0max}=±3.5 bar stock under small deformation straightening theory.

Number of roller	Reverse curvature C_w
1	0
2	1.4798
3	-1.4798
4	1.2717
5	-1.1908
6	1.1474
7	-1.1202

Compare the *M-C* curve of the stress evolvement model with that of the traditional straightening model, as shown in Fig. 2, it is easy to find that without taking the stress evolvement into consideration, the classic straightening model holds that the sections always have the same bending characteristics and the residual bending curvature tends to be the same and finally can be eliminated if bending parameters are set reasonably [1]. This can be seen as the *M-C* curve continuously tends to be convergent. However, the M-C curve of the stress evolvement model is not convergent because the sections have different bending characteristics as a result of the different stress evolvement history, which has an overall impact on the convergence of the *M-C* curve. Therefore, the behavior of the thin-walled members would have many great changes during the straightening process [11]. In addition, the model can be used to analysis the cross section residual stress of the bar stock, as shown in Fig. 3.



(a) Values of classic theory



(b) Numerical solution of new model.

Fig. 2. M-C curve of straightening

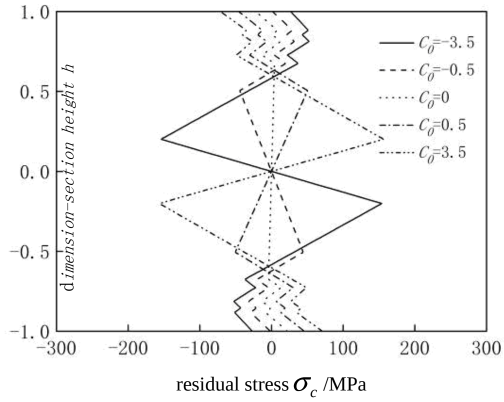


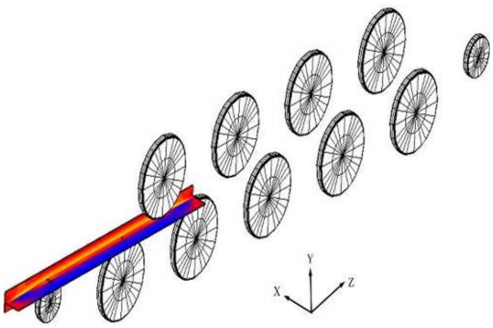
Fig. 3. Distribution of residual stress in sections with different initial curvatures of bar stock after straightening.

3. Simulation Analysis for the Mechanical Behavior of Member Straightening Process

The mechanical process of thin-walled member straightening is extremely complicated, involving many issues related to geometric and material nonlinearity, multi-point contact, and heredity of residual stress, section deformation and imperfection sensitivity. Numerical methods such as finite element method are used to analyze the mechanical behaviors of member during straightening process in this paper, because the exact analytical result can't be got through classical theoretical method.

3.1. Stress Evolution in the Straightening Process

Two dynamic finite element simulation models for thin-walled member straightening process of H-beam and brass tube (as shown in Fig. 4) are established respectively by using finite element analysis software, focusing on the introduction of the original geometric and physical imperfections, the processing method of geometric and multiple contact nonlinear in models, the friction description between the member and straightening rollers, the description and introduction of thermal-mechanical coupling characteristics.



(a) finite element simulation model of H-beam

(b) finite element simulation model of brass tube

Fig. 4. Finite element analysis model of the straightening process.

Taking variable roller spacing straightening with nine rollers for example, the equivalent stress evolution of the specific section site in H-beam straightening process is shown in Fig. 5. The simulation result shows that the equivalent stress in the section fillet changes smoothly during the straightening process, but the its values are quite high, and the equivalent stress in the web changes severely. The simulation also reveals the formation mechanism of plastic hardened zone at the root of web (as shown in Fig. 6).

Meanwhile, to research the heredity of the residual stress during H-beam straightening process, the residual thermal stress when cooling ends is introduced successfully to the multi-roller straightening model as the initial stress before straightening. The study found that the longitudinal stresses in most regions of the flange and web after straightening remain almost unchanged comparing with the values before straightening, but the roots of web are influenced severely by straightening process, the initial tensile stress before straightening changes to compressive stress whose stress gradient is very high. The stress heredity during traditional straightening is not conducive to improve the performance of the beam [12].

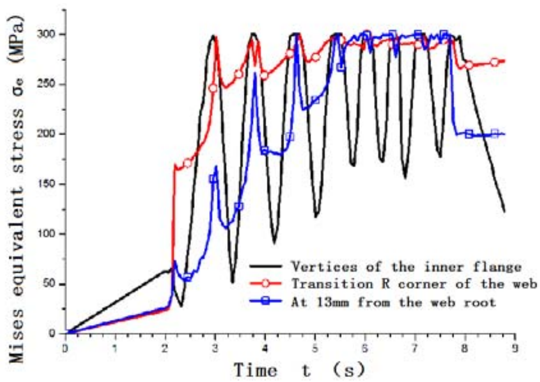


Fig. 5. The equivalent stress evolution in H-beam during straightening process.

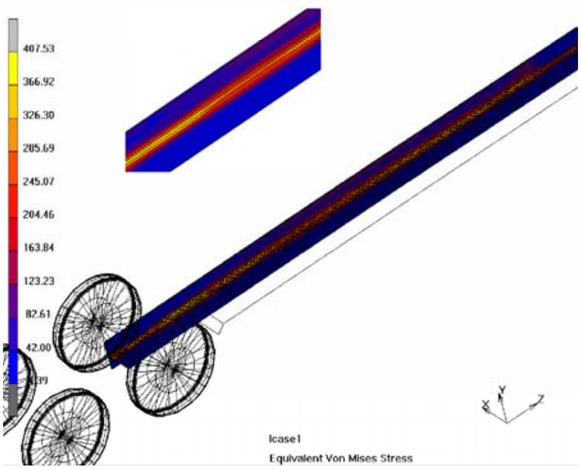


Fig. 6. The hardened zone produced in H-beam web.

In short, after the finite element analysis of H-beam and large-scale pipe, we have got more comprehensive understanding to thin-walled member straightening process. The evolution of stress and strain in the thin-walled member during straightening process has been grasped and some geometric and mechanical behaviors of thin-walled member in straightening process have been interpreted successfully.

3.2. Section Deformation Problem

The section deformation is the characteristic of thin-walled member in straightening process. The reason why the section deformation arises is that the lateral bearing capacity of thin-walled member section is weak. This kind of section deformation has an ignorable effect on the setting of straightening parameter.

By the finite element simulation, we have mastered the section deformation of H-beam and large-scale brass tube. The section deformation of H-beam is shown in Fig. 7. The main form of section deformation of H-beam appears as web falling. In this case, the actual bending deflection should be the sum of the theoretical one and the web falling.

The section deflection of H-beam in roller straightening is analyzed in theory by simplified model. The result can be concluded that the maximum web falling appears at the center of the web and it is related to the section dimension, the roll gap and the collar width. Through the simulation for multiple working conditions a regression formula has be obtain, which shows the relationship between the web falling and typical H-beam straightening parametric variables. Taking H200*100 H-beam for example, the influence of lateral gap S to the web falling is shown as Fig. 8, from the curves a coefficient A can be concluded as follows [13] :

$$A(S) = 0.44(S + 1.7)^2 + 4.46$$

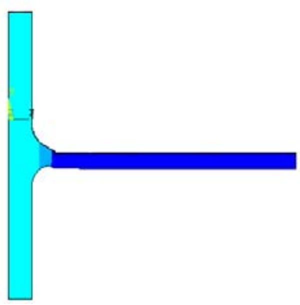


Fig. 7. Section deformation of H-beam in straightening.

The section deformation of tube is similar to that of H-beam (as shown in Fig. 9). The main section of a tube is flattening which consist of overall section flattening and local deformation.

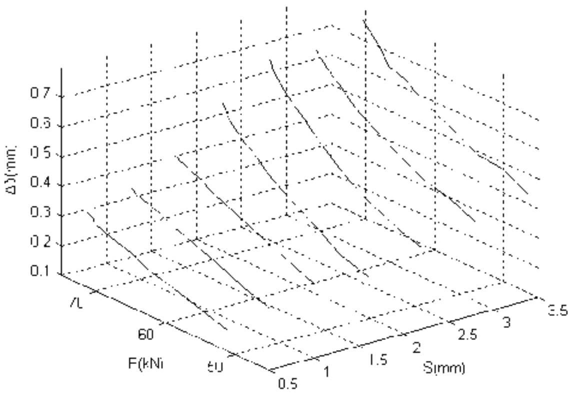


Fig. 8. The influence of lateral gap on the web falling.

Fig. 9. Section flattening of thin-walled tube in straightening process.

The simulation shows that the section flattening is related to the straightening force, geometric characteristics and longitudinal curvature. The section flattening becomes higher with the increase of the straightening force, and the trend is approximate to a part of quadric curve. So a regression formula which shows the relationship between the section flattening of tube and the straightening force can be described as follows:

$$\Delta\delta = A(R_m, t, p, a)F^2$$

Here the coefficient A is related to the specification of tube, roller spacing p and roller inclination a [14].

4. Optimization of Energetics Parameters and Loading Mode of Straightening

The lower lateral bearing capacity of the thin-walled section makes it more strict requirements to control the macroscopic energetics parameters of straightening, otherwise, the straightening force possibly cause uncontrollable section deformation and surface breakdown. Hence, the relations between bending moments, straightening force and bending deflections should be analyzed firstly in order to implement effective optimization of the macroscopic energetics parameters of straightening process.

Here is taken the straightening process of H-Beam with 9-roller variable spacing machine as example. Based on the elastic-plastic theory, the relations between the moment, straightening force and deflection of spacing-adjustable rollers was solved, and then a more reasonable distribution range of the straightening moment was acquired. The analytical mechanical model is shown in Fig. 10. This work provides a completely mathematical method to analyze energetics parameters of variable roller spacing straightening. Meanwhile, for convenient computing and a better understanding, simplified solution of the continuous straightening is given based on a model of straightening element. An universal deflection formulae is deduced as well which can be used in multi-roller straightening. The analytical models of a straightening uint is shown in Fig. 11 [15].

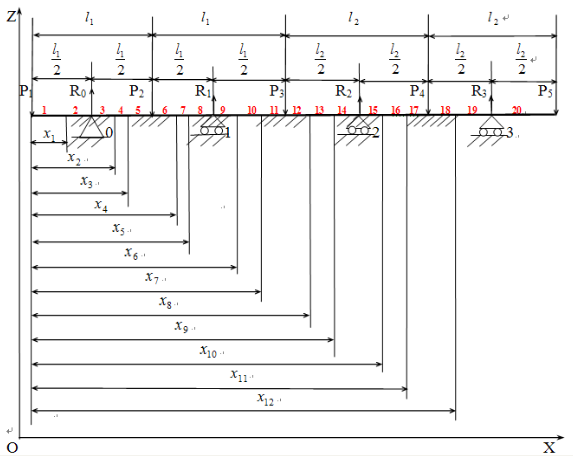


Fig. 10. Analytical model for continuous straightening.

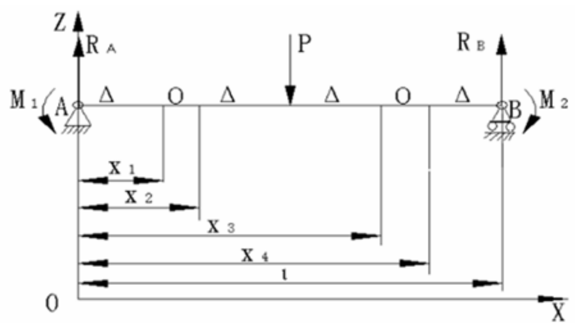


Fig. 11. Analytical model of a straightening unit.

Based on the analysis of the macroscopic energetics parameters, an optimizing model is built. Taking the minimum of maximum straightening force and total straightening force as target function and the roller spacing as the variable, the optimized roller layouts were obtained under three conditions: equal roller-spacing, semi-symmetric roller-spacing and random roller-spacing straightening. If taking the maximum straightening force as target, the optimization result shows that the theoretical maximum straightening force semi-symmetric roller-space straightening is reduced by 13 % than that of equal roller-spacing straightening, and the percentage rises to 22.1 % in the case of random roller-spacing straightening. If the total straightening force is set as target, the reduction percentages are 1.3 % and 2.1 % respectively.

Another possible way to control the surface quality and section deformation in the straightening process is to find new loading mode and change the transmission path of straightening force in transverse section of thin-walled member. Finally ideal multidimensional straightening is achieved. Some exploratory have been done in this hand, such as building a finite element simulation model and studying the feasibility of straightening by pressing the flange of H-beam (SPF) (Fig. 12). The result shows that the SPF method can avoid the web falling caused by the force pressed on web. Besides, the SPF method can effectively solve the problem of the shedding of oxide film caused by fillet stress concentration when straightening the web. However, the SPF method may cause stress concentration and plastic deformation at the end of flange. The overall height of the flange reduces obviously. It's not satisfying than the straightening by pressing the web when use the same reduction rules. However, this does not mean that SPF method is not feasible. Taking the plastic deformation of the top of flange into consideration and giving a certain compensation, it is still more likely to realize the goal of beam straightening with SPF method.

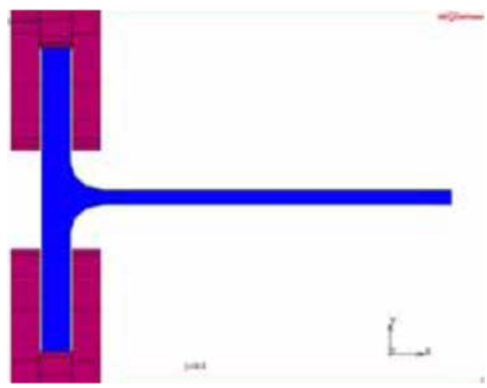


Fig. 12. FEM model of SPF method.

5. Conclusion

1. For thin-walled profiles with high section such as large scale H-beam, the heredity of longitudinal stress should be taken into consideration when theoretical model of straightening is built. The residual stress makes the section have very different bending characteristics.

2. Through finite element numerical calculation, the evolution of the stress and strain during straightening of the thin-walled members has been acquired, this work gives a comprehensive understanding to the deformation behavior of the members.

3. The section deformation has an ignorable effect on the setting of straightening parameter. A regression formula of section has been conclude based on a series of simulation on straightening process.

4. A complete analytical model has been built to calculate the macroscopic energetic parameters in straightening process. Based on this model, the straightening parameters of thin-walled member has been optimized and some probably reasonable loading modes for straightening H-beam have been discussed.

Acknowledgements

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