Numerical Analysis of the Structural Load of the Bending-Unit Roll Box in Tension Leveling with Different Strip Widths

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Abstract

To investigate the effect of strip width on the load-bearing capacity of tension-leveling equipment, a multi-span continuous beam model was used to theoretically derive the load distribution characteristics of the roll system structure in the bending unit under different strip widths. For "two-bending and two-leveling" equipment, the ultimate structural loads of the bending roll box under three strip widths were calculated by combining tension-leveling process analysis based on explicit dynamics with roll box structural load analysis based on implicit dynamics. The results show that changes in strip width cause variations in the maximum stress of the roll box structure and its location: when the strip width does not exceed the total supporting length of the backup rolls, the maximum stress of the roll box occurs at the force transmission position between the backup roll and the roll chock, at approximately 115 MPa; when the strip width is greater than the total supporting length of the backup rolls, the maximum stress of the roll box shifts to the contact position between the intermediate roll and the end backup roll, at approximately 205 MPa.

Full Text

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Zhang Huan[1,2], Zhu Yongwei[1,2], Yan Xuguo[1,2], Xia Xuhui[1,2], Wang Lei[1,2]

(1. Key Laboratory of Metallurgical Equipment and Its Control, Ministry of Education, Wuhan University of Science and Technology, Wuhan 430081;
2. Hubei Provincial Key Laboratory of Mechanical Transmission and Manufacturing Engineering, Wuhan University of Science and Technology, Wuhan 430081)

Abstract: In order to study the influence of strip width on the load bearing of tension-leveling equipment, a multi-span continuous beam model is used to theoretically derive the load distribution characteristics of the roller-system structure in the bending unit under different strip widths. For equipment with "two bending units and two straightening units," combining process analysis for tension leveling based on explicit dynamics and load analysis of the roll-box structure based on implicit dynamics, the ultimate structural loads of the bending roll box under three strip widths are calculated. The results show that changes in strip width cause changes in the maximum stress of the roll-box structure and its location: when the strip width does not exceed the total support length of the backup rolls, the maximum stress of the roll box appears at the force-transmission contact between the backup roll and the roll seat, at about 115 MPa; when the strip width is greater than the total support length of the backup rolls, the maximum stress of the roll box shifts to the contact between the intermediate roll and the end backup roll, at about 205 MPa.

Keywords: tension-leveling machine roll box; strip width; finite element analysis; multi-span continuous beam model

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Zhang Huan[1,2], Zhu Yongwei[1,2], Yan Xuguo[1,2], Xia Xuhui[1,2], Wang Lei[1,2]

(1. Key Laboratory of Metallurgical Equipment and Its Control, Ministry of Education, Wuhan University of Science and Technology, Wuhan 430081 Wuhan, China; 2. Hubei Provincial Key Laboratory of Mechanical Transmission and Manufacturing Engineering, Wuhan University of Science and Technology, Wuhan 430081 Wuhan, China)

Abstract: With the multi-span continuous beam model, the load distribution characteristics of the roller system structure in the bending unit are theoretically derived in order to investigate the impact of strip width on the load bearing of the tension-leveling equipment. For the tension-leveling equipment with two bending units and two straightening units, depending on the process analysis based on explicit dynamics and the structural load analysis based on implicit dynamics, the structural load of the bending roller box is calculated for three kinds of strip width. The result shows that with strip width not exceeding the support length, the maximum stress, located on the back-up roll in contact with the roller seat, is approximately

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Corresponding author: Wang Lei, Professor. E-mail: candywang@wust.edu.cn
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115 MPa, and with strip width exceeding the support length, the maximum stress, located on the intermediate roll in contact with the back-up roll, is approximately 205 MPa.

Key words: roller box of the tension-leveling equipment; strip width; finite element analysis; multi-span continuous beam model

The tension leveler is the core equipment in the finishing section of metal strip recoiling units. It effectively improves strip shape accuracy through repeated stretching and bending of the strip[1]. The bending roller box is a key load-bearing component of the tension leveler. Based on analysis of the curvature and bending moment at the contact between the work roll and the strip, Shinkin[2] proposed a simplified calculation method for roll reaction forces. By carrying out geometric structural analysis of the work-roll system of a leveler, Li Xintao[3] equivalently treated it as a three-hinge arch structure and performed force analysis. Cho et al.[4] studied the tension-leveling process using analytical methods and numerical simulation, respectively, and found that the work-roll reaction forces obtained by the two methods were basically consistent. For the "two-bending and two-leveling" process, Garcia et al.[5] obtained the work-roll reaction forces of the bending-roll unit under different working conditions in process simulation, further studied the load distribution of the roller-box structure, and provided theoretical guidance for the optimization of tension-leveling process parameters and equipment structure.

The structural load during roller-box service directly affects the stability and production sustainability of the tension-leveling process. Based on structural internal-force analysis, Zhao Chong et al.[6-7] treated the work-roll system as a multi-span beam model, and checked the strength of the roller box of a tension leveler from three aspects: journal torsional strength, roll-body bending strength, and roll-surface contact strength. For a medium-thick plate leveler, Qu Yan et al.[8] established both an overall mechanical model of the bending-roll device and a single-roll mechanical model to analyze structural loads, providing a theoretical basis for structural design. Combining material-mechanics calculation and finite element simulation, Lu Zhaocong et al.[9] analyzed the stress-strain of a roller box under extreme operating conditions, verifying the reliability of its structure. Combining structural-mechanics analysis and finite element simulation, Wang Yingrui et al.[10] characterized the load-bearing capacity of the roll system of a straightener using the inter-roll contact stress.

Operating conditions are important factors affecting roll load and may potentially influence the load distribution of the roller-box structure. Based on finite element simulation results, Xia Xuhui et al.[11] established the work-roll load response surface under changes in tension-leveling process parameters such as roll insertion amount and strip-steel tension. Belyaev et al.[12] studied the load of the roll system of a strip leveler and pointed out that strip width, inter-roll

Structure of lower bending roller box

Figure 1: Structure of lower bending roller box

clearance, and the number of supporting rolls have significant effects on its load distribution. Liu Dapeng[13] found that the surface stress of the work roll fluctuates with changes in strip specifications and strip-shape defects. However, current studies on the structural load of roller boxes mostly take structural reliability as the objective, and relatively seldom consider the influence of operating conditions on their distribution characteristics, making it difficult to reflect the working state of the roller box in the actual production process.

For the bending roller box of a tension leveler, this study is based on a multi-span continuous beam model. The internal forces of the roll-system structure under different strip widths are theoretically derived, and, in combination with explicit-dynamics and implicit-dynamics numerical calculation methods, the tension-leveling process and roller-box structural loads for three strip widths are comparatively analyzed, revealing the influence of strip width on the load distribution of the bending roller-box structure.

1 Theoretical Analysis of the Structural Load of the Bending-Unit Roller Box

1.1 Roller-box structure

The structure of the lower bending roller box of the tension leveler is shown in Fig. 1. It mainly includes three parts: the roll system, the roll seat, and the shaft-end fixing components. The roll system is the core component of the roller-box structure; it is in direct contact with the strip and provides the bending force. It is a three-layer, six-roll structure, including 1 work roll, 2 intermediate rolls, and 3 rows of discrete back-up rolls. The work roll has a length of 1 450 mm and a diameter of 30 mm; the intermediate roll has a length of 1 450 mm and a diameter of 35 mm; each row of back-up rolls consists of 7 back-up rolls, with a single back-up roll length of 132 mm and a diameter of 65 mm, and the total supporting length is 1 282 mm. The roll system is installed on the roll seat through the shaft head and shaft-end fixing components, and hydraulic transmission is used to achieve changes in the working position.

图 1　下弯曲辊盒结构图

Fig. 1　Structure of lower bending roller box

1.2 Analytical Modeling

In view of the characteristics of the discrete multi-segment supports of the roller system, a multi-span continuous-beam model is adopted for analytical modeling.

Fig. 2 Multi-span continuous beam model of bending roller system

Figure 2: Fig. 2 Multi-span continuous beam model of bending roller system

Fig. 3 Flow of numerical calculation of structural response of roll box

Figure 3: Fig. 3 Flow of numerical calculation of structural response of roll box

In the roller system, three support rollers are arranged in a fan-shaped pattern at the same axial position. Among them, the support forces of the rollers on both sides of the roller system cancel each other in the horizontal direction. Therefore, they can be uniformly simplified as in-plane vertical supports, as shown in Fig. 2. The total length of the continuous beam is 1 570 mm. The beam has 9 support points in total, numbered 0–8, with corresponding support forces $R_0 \sim R_8$. The uniformly distributed load q makes the working roller contact and bear force with the strip; its range is the strip width.

Fig. 2 Multi-span continuous beam model of bending roller system

The bending moments at each support of the continuous beam satisfy the following three-moment equation, namely

$$M_{n-1}L_n + 2M_n\left(L_n + L_{n+1}\right) + M_{n+1}L_{n+1} = -6\times\left(\frac{\omega_n x_n}{L_n} + \frac{\omega_{n+1}y_{n+1}}{L_{n+1}}\right) \quad (1)$$

where n is the support number, $n = 1 \sim 7$; M_{n-1}, M_n, and M_{n+1} are the bending moments at supports $n-1$, n, and $n+1$, respectively, in $\mathrm{N \cdot mm}$; L_n and L_{n+1} are the lengths of spans n and $n+1$, respectively, in mm; ω_n and ω_{n+1} are the areas of the bending-moment diagrams of spans n and $n+1$ under the action of external loads, respectively, in $\mathrm{N \cdot mm^2}$; x_n and y_{n+1} are the distances from the centroids of the areas ω_n and ω_{n+1} to supports $n-1$ and $n+1$, respectively, in mm.

2 Numerical Calculation of the Load on the Roll-Box Structure of the Bending Unit

The numerical calculation procedure for the load on the roll-box structure is shown in Fig. 3.

Fig. 3 Flow of numerical calculation of structural response of roll box

First, ANSYS/DYNA is used to perform an explicit dynamic solution for the straightening process under the limiting working condition involving elastic-plastic deformation of the strip, and the limiting load of the working roller is obtained. Next, the ANSYS/Static Structural module is used, taking the limiting load of the working roller as the input; the load range is the strip width. An implicit dynamic solution under steady loading is carried out for the roll-box

Fig. 4 Tension leveling line sketch

Figure 4: Fig. 4 Tension leveling line sketch

Fig. 5 Bending roll loads at different plate widths

Figure 5: Fig. 5 Bending roll loads at different plate widths

structural load, and the stress distribution of the roll-box structure is obtained. By changing the strip width in the process simulation and the input range of the limiting load of the working roller in the structural simulation, load analysis of the bending roll-box structure under different strip widths can be realized.

2.1 Explicit Dynamic Modeling of the Straightening Process

The structure of the key equipment of the straightening production line is shown in Fig. 4. The strip moves from left to right, passing in sequence through the entry tension roller group, the straightener, and the exit tension roller group. The exit and entry tension roller groups provide strip tension, while the straightener adjusts the strip curvature; it consists of two parts: the bending roller group and the straightening roller group.

Referring to the allowable range of the equipment, shell elements of 5 mm×5 mm are adopted for strip modeling, which can ensure calculation accuracy [11]. The thickness is 1.6 mm and the yield strength is 670 MPa. Each roller is modeled using rigid-body elements [14 − 16]. Deformation constraints are applied to the strip by controlling the Dirichlet boundary condition with a 2% elongation rate. Under a fixed elongation rate, the load on the bending roller is most affected by the insertion amount of the bending roller group; therefore, the insertion amount of the bending roller is set to the maximum value, 11 mm [11]. The strip width is designed with reference to the support length of the support rollers: when the strip width is smaller than the support width, it is taken as 1 090 mm; when the strip width is equal to the support width, it is taken as 1 282 mm; when the strip width is greater than the support width, the allowable maximum strip width of the equipment, 1 430 mm, is used. The variation trend of the working-roller load under different strip widths is shown in Fig. 5. The working-roller load gradually increases with time and tends toward a stable value after the process enters a steady state. When the strip widths are 1 430, 1 282, and 1 090 mm, respectively, the corresponding bending-roller loads are 277, 255, and 224 kN, respectively. The strip width and the stable operating load of the roller are approximately proportional.

Figure 4 Schematic diagram of the tension leveling production line

Fig. 4 Tension leveling line sketch

Figure 5 Bending roll loads at different plate widths

Fig. 5 Bending roll loads at different plate widths

Fig. 6 Finite element model of a curved roller box

Figure 6: Fig. 6 Finite element model of a curved roller box

2.2 Implicit dynamic modeling of roller-box structural loads

During the modeling of the bending roller box, fixed parts such as bolts and nuts were appropriately simplified. During mesh division: for regions with small dimensional variation and uniform loading, the element size was set to 8 mm; for regions with abrupt geometric dimensional changes and where stress concentration easily occurs, the element size was set to 2 mm. The final total number of meshes in the roller-box model was 434 017, as shown in Fig. 6. An influence analysis was carried out on the change in mesh size in regions prone to stress concentration. The variation of the maximum stress value of the roller box with the number of meshes is shown in Table 1. Under the same plate width, the relative error of the mean maximum stress values corresponding to different mesh quantities is within 10%. The bending-roll load was uniformly applied by means of nodal forces.

Table 1 The maximum stress value of the roller box simulation model varies with the number of meshes

Tab. 1 The maximum stress value of the roller box simulation model varies with the number of meshes

(Unit: MPa)

Number of meshes	Plate width / mm	Plate width / mm	Plate width / mm
	1 430	1 282	1 090
2×10^5	180.78	110.35	106.53
4×10^5	202.31	118.09	114.75
8×10^5	191.68	131.20	122.34

Figure 6 Finite element model of a bending roller box

Fig. 6 Finite element model of a curved roller box

3 Load analysis of roller-box structures with different strip widths

3.1 Roller-system load analysis

Based on the three-moment equations for internal-force analysis of a multi-span continuous beam structure, the structural internal forces of the roller system were calculated. The three-moment equations for three adjacent supports, 0–2, were established, and the bending moments at each support were solved. Thus,

$$\begin{cases} M_0L_1 + 2M_1(L_1+L_2) + M_2L_2 = -6\left(\dfrac{\omega_1x_1}{L_1} + \dfrac{\omega_2y_2}{L_2}\right) \\ M_1L_2 + 2M_2(L_2+L_3) + M_3L_3 = -6\left(\dfrac{\omega_2x_2}{L_2} + \dfrac{\omega_3y_3}{L_3}\right) \\ M_2L_3 + 2M_3(L_3+L_4) + M_4L_4 = -6\left(\dfrac{\omega_3x_3}{L_3} + \dfrac{\omega_4y_4}{L_4}\right) \end{cases} \tag{2}$$

where: $L_1 = 242$ mm; $L_2 = L_3 = L_4 = 181$ mm; $y_2 = y_3 = y_4 = 90.5$ mm; $\omega_2 = \omega_3 = \omega_4 = 4.9415 \times 10^5 q$; $M_0 = 0$; $M_3 = M_4$; and q is the uniformly distributed load on the roller system. The bending moments at supports 1–3 corresponding to different strip widths are shown in Table 2.

Considering the symmetry of the roller-system structure and loading, the bending moments under three strip widths were plotted, as shown in Fig. 7. When the strip width is 1 430 mm, the bending moments at supports No. 1 and No. 7 are the largest; when the strip width is 1 282 mm, the bending moments at supports No. 2 and No. 6 are the largest; when the strip ···

When the width is 1,090 mm, the bending moments at supports No. 3 and No. 5 are the largest. The position of stress concentration appears near the maximum bending moment in the roll-system structure.

Table 2 Bending moments at supports 1-3 under different strip widths

Tab. 2 1-3 pivot bending moments under different widths of the strip

Support bending moment and calculation parameter	Strip width/mm	Strip width/mm	Strip width/mm	Support bending moment and calculation parameter	Strip width/mm	Strip width/mm	Strip width/mm
	1 430	1 282	1 090		1 430	1 282	1 090
ω_1/(N·mm^2)	$5.177\,2\times10^5q$	$3.457\,5\times10^5q$	$283.215q$	M_2/(N·mm)	$-2\,581.78q$	$-2\,802.362q$	$-2\,643.8q$
x_1/mm	138.00	128.67	160.70				
M_1/(N·mm)	$-3\,293.76q$	$-2\,455.996q$	$-1\,076.93q$	M_3/(N·mm)	$-2\,759.78q$	$-2\,715.73q$	$-3\,165.27q$

Fig. 8 Equivalent force diagram of roller system under different widths of plate belt

Figure 7: Fig. 8 Equivalent force diagram of roller system under different widths of plate belt

(a) Strip width is 1,430 mm

(b) Strip width is 1,282 mm

(c) Strip width is 1,090 mm

Fig. 7 Bending moment distribution of the analytical model of structural mechanics of the roll system

The equivalent stresses of the roll system corresponding to the three strip widths obtained by numerical calculation are shown in Fig. 8. Support rolls No. 1–7 correspond to supports No. 1–7. When the strip width is 1,430 mm, the maximum stress of the roll system is located at its contact with support roll No. 7; when the strip width is 1,282 mm, the maximum stress is located at the contact between the roll system and support roll No. 6; when the strip width is 1,090 mm, the maximum stress is located at the contact between the roll system and support roll No. 3. The numerical results for the three strip widths all show that the maximum equivalent stress is near the position of the maximum bending moment in the structural-mechanics analysis, consistent with the position predicted by the analytical model.

The comparison between the maximum stress values of the analytical model and the simulation model is shown in Table 3. The simulation results and theoretical results have consistent trends with changes in strip width, and they are of the same order of magnitude. The assumptions and simplifications in the analytical model are relatively numerous, which is the main reason why the analytical results are larger than the simulation results.

Fig. 8 Equivalent force diagram of roller system under different widths of plate belt

Table 3 Comparison between the theory and simulation results of the maximum stress of the roll system

(Unit: MPa)

Maximum stress value results	Plate-belt width/mm	Plate-belt width/mm	Plate-belt width/mm
Maximum stress value results	1 430	1 282	1 090

Fig. 9 Equivalent force diagram of bending roller box under different widths of plate belt

Figure 8: Fig. 9 Equivalent force diagram of bending roller box under different widths of plate belt

Maximum stress value results	Plate-belt width/mm	Plate-belt width/mm	Plate-belt width/mm
Theoretical results	638.02	557.41	547.73
Simulation results	205.09	117.57	113.25

3.2 Load calculation of the roller-box structure

The equivalent stresses of the roller-box structure under three plate-belt widths are shown in Fig. 9; the maximum equivalent stresses are distributed at different force-transmission components. When the plate-belt width is 1 430 mm, the maximum equivalent stress of the roller box is 205.09 MPa, located at the edge position where the middle roller contacts the roller surface of No. 7 support roller; when the plate-belt width is 1 282 mm, the maximum equivalent stress is 118 MPa, located at the contact position between the roller end of No. 7 support roller and the roller seat; when the plate-belt width is 1 090 mm, the maximum equivalent stress is 113.25 MPa, located at the contact position between the roller end of No. 3 support roller and the roller seat.

The reasons for the variation in the maximum equivalent stress are analyzed as follows. When the plate-belt width is 1 430 mm, the support-roller bearing length is smaller than the loading length of the plate belt on the roller box, and the end of the roller system and the support roller form a cantilever-beam state, resulting in relatively large bending moments at the two ends of the beam and stress concentration. When the plate-belt widths are 1 282 and 1 090 mm, the support-roller bearing length is greater than the loading length of the plate belt on the roller box, and the bearing structure of the roller system and the support roller forms a simply supported beam; the support roller fully supports the roller system. Therefore, stress concentration occurs at the contact position between the support roller and the roller seat, and the specific position differs under the influence of the plate-belt width.

Fig. 9 Equivalent force diagram of bending roller box under different widths of plate belt

4 Conclusions

In this study, for the roller box of a stretcher, a method combining structural-mechanics analysis with finite-element numerical calculation was adopted to investigate the influence of different plate-belt widths on the load distribution of its structure, and the following conclusions were obtained.

1) The plate-belt width affects the distribution of the bending moment of the roll system. When the plate-belt widths are 1 430 mm (greater than the support-roller bearing length), 1 282 mm (equal to the support-roller bearing length), and 1 090 mm (less than the support-roller bearing length), the maximum bending moments of the roll system occur at the No. 1 and No. 7 support points, the No. 2 and No. 6 support points, and the No. 3 and No. 5 support points, respectively.

2) Under different plate-belt widths, the maximum stress and its position in the roller-box structure are different. When the plate-belt widths are 1 282 and 1 090 mm, the maximum equivalent stresses of the roller box are 118 and 113.25 MPa, respectively, located at the contact positions between the roller ends of the No. 7 and No. 3 support rollers and the roller seats; whereas when the plate-belt width is 1 430 mm, the maximum equivalent stress of the roller box is 205.09 MPa, located at the edge contact position between the middle roller and the roller surface of No. 7 support roller.

3) Under the allowable plate width of the stretcher, the maximum stress of the roller box is 205.09 MPa, far less than the yield strength of 45 steel, 355 MPa, verifying the reliability of the roller-box structure.

The study of the load distribution of the bending roller box of a stretcher under different plate-belt widths can not only guide the plate-width applicability design of stretching equipment, but also

This provides a theoretical reference for fault prediction of roller boxes. Subsequent research will consider optimizing the structural design of the roller box so as to improve stress concentration while achieving lightweighting.

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