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Simulation And Analysis of The Influence of Material, Plate Thickness, Bending Radius on Radius Prediction Error Due to Reverse Rebel When Bending Plates Using 3-Roller Machine

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Abstract:
The study focuses on predicting the final bending radius caused by the springback phenomenon and simulating the sheet metal bending process using a three-roll bending machine to analyze the influence of technical parameters on forming quality and efficiency.A model is developed in Abaqus software to simulate the bending process, taking into account variations in key factors such as sheet thickness, material properties, and more.The simulation results indicate that these parameters significantly affect the final curvature, stress distribution, and the degree of elastic recovery.This research contributes to the adjustment of the three-roll bending process toward optimizing performance and product accuracy.

Keywords: *Simulation, CAE, Abaqus, Three-roll bending machine,*

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I. Introduction

In the field of sheet metal fabrication, the bending process plays a crucial role in shaping products with curved geometries such as pipes, enclosures, steel structures, and furniture. Among the various methods, the 3-roll bending machine is widely used due to its simple structure, ease of operation, and ability to produce uniformly rounded profiles. However, to ensure precision and post-bending quality, it is essential to select and adjust appropriate technical parameters. Since physical experiments are often costly and time-consuming, numerical simulation has become a powerful tool for research and process optimization.

In recent years, numerous studies have focused on the analysis and simulation of the sheet bending process. To address the associated challenges, several numerical, analytical, and experimental investigations have been conducted. For example, KyuWon Kim (2019) proposed a predictive model to estimate the final radius, taking into account large deflections during bending [1]. Ahmed Ktari et al. examined the impact of roller diameter and the distance between the two lower rollers on final accuracy and shape [2]. Ming Yang et al. accurately calculated and simulated roller displacement, demonstrating its influence on bending moment and springback angle [3]. Multiple-pass methods tend to be costly due to material waste and production time, hence single-pass forming is preferred for high precision and productivity. A. H. Gandhi et al. conducted contact analysis between the sheet and both upper and lower rollers [4]. M. Philipp et al. highlighted mismatches in roller speeds leading to shape inaccuracies and slipping phenomena [5]. Salem J, Champliaud H, Feng ZK, Dao TM (2016) proposed an analytical model to predict roll bending force, residual stress, and power requirements [6]. Tan et al. presented a complex function method to evaluate the residual stress distribution [7]. Ozgu Senol et al. developed an ANN-based model incorporating bending parameters and springback behavior of stainless steel using a log-sigmoid prediction function [8].

In this paper, the study is based on the aforementioned literature and analyzes key factors influencing the final bending radius accuracy, such as material properties, sheet thickness, and bending radius. It also proposes a simplified method to predict post-bending radius, stress, and strain in an intuitive and user-friendly way.

The finite element analysis (FEA) was carried out using Abaqus FEA 6.14 (SIMULIA, Johnston, RI, USA). The model incorporates material nonlinearity, geometric nonlinearity, and contact nonlinearity to closely replicate real-world bending behavior.

II. Mathematical data and research methods

The plate is held by the 2 lower rollers and is moved down by the top roller, creating a bending force that causes the metal plate to deform. And when the top roller rotates, it creates a curvature radius for the plate in figure 1.

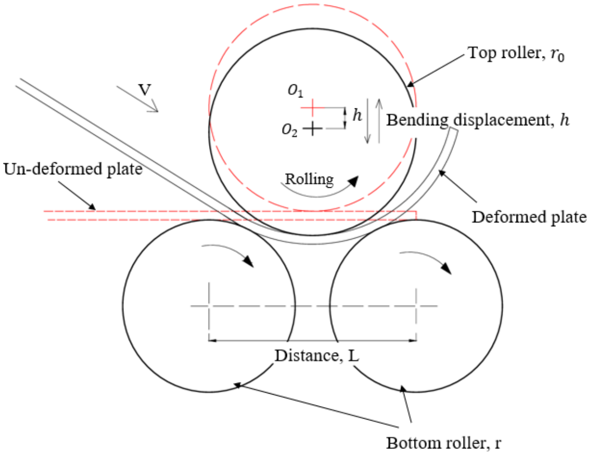


Fig1. Three-roller corner model

The bending radius R depends on the position of the neutral axis. For homogeneous plate materials the neutral layer position is in the middle of the plate.

KyuWonKim (2019) [1] developed a simple inverse elastic bending radius prediction model. When considering the ideal model when plastic yielding occurs, the stress does not increase and remains at the yield stress state, so the moment equation acting on the plate is expressed as follows:

$$M = 2w.\left(\int_0^{y_e} E\frac{y^2}{R}dy + \int_{y_e}^{\frac{t}{2}} \sigma_y y dy\right)$$

$$= \frac{w\sigma_y t^2}{4} - \frac{wR^2{\sigma_y}^3}{3.E^2} \qquad (1)$$

Where: w- Width of the plate
R- Bending radius
σ_y – Yield limit of material
E- Elastic modulus
t – Thickness of the plate

The change in curvature due to inverse elasticity can be explained by the moment-curvature diagram as shown in Figure 2.

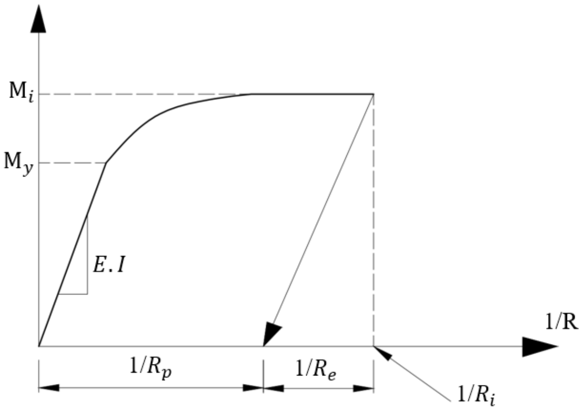


Figure 2. Moment-curvature diagram during plastic deformation

$$\frac{1}{R_i} = \frac{1}{R_p} + \frac{1}{R_e} \qquad (2)$$

Where:
R_e is the radius of curvature due to elastic deformation
R_p is the radius of curvature due to plastic deformation
R_i is the final radius of curvature, which is the radius R
According to Euler–Bernoulli bending theory: $\kappa = \frac{1}{R_e} = \frac{M_i}{EI}$ (3)
Substitute into formula (2)

$$R_p = \frac{REI}{EI-MR} \quad (4)$$

With I is the moment of inertia, for a plate-shaped part with a rectangular cross-section $I = \frac{bt^3}{12}$ (5)
Displacement of the top roller

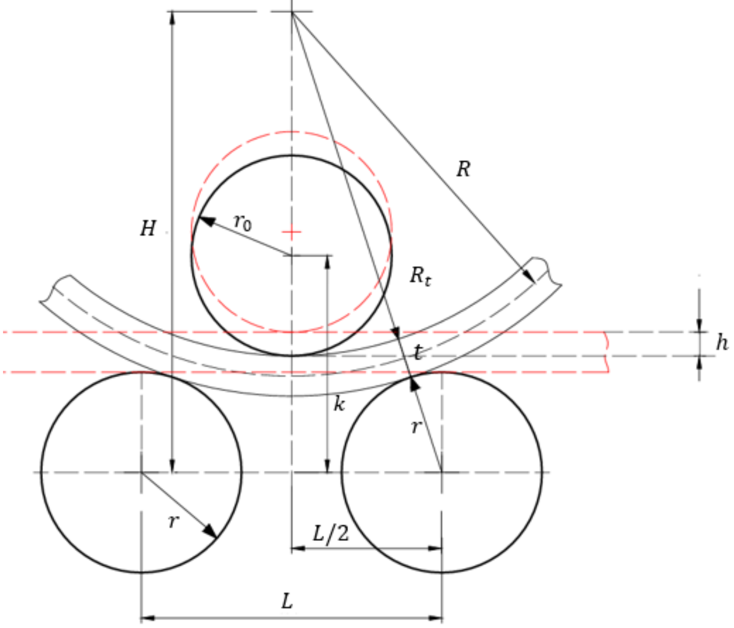


Fig 3. Vertical displacement diagram of the top roller

Distance between machine center to bottom roller center

$$H = \sqrt{(R_t + t + r)^2 - (L/2)^2} \qquad (6)$$

Distance between center of upper roller to center of lower roller

$$k = H - (R_t - r_0) \qquad (7)$$

Vertical pressing depth of upper roller:

$$h = (r_0 + r + t) - k$$

$$h = R_t + t + r - \sqrt{(R_t + t + r)^2 - (L/2)^2} \quad (8)$$

With $R_t = R - \frac{t}{2}$, Where R_t is the inner radius.

$$\Rightarrow h = R + \frac{t}{2} + r - \sqrt{\left(R + \frac{t}{2} + r\right)^2 - (L/2)^2} \quad (9)$$

III. Simulation of 3-roller plate bending model

Expected achievement: From the analyzed data, the error of bending radius prediction is obtained according to formula (4) for the model when bending a plate with moderate curvature. At the same time, the main influences such as thickness, material, bending radius on stress, force and rebound phenomenon are analyzed..

3.1. Input parameters

Problem: Bending a CT3 steel plate with width w = 300 mm and thickness t = 6 mm; bending radius R = 130 mm.

Table 1. Material specifications

Material	CT3	
Tensile strength (Mpa)	σ_k	370 ÷ 470
Elastic modulus (Gpa)	E	200
Yield limit (Mpa)	σ_y	235
Specific gravity (7850 kg/mm^3)	ρ	7.850
Poisson's ratio	v	0.3

Table 2. Model size parameter table

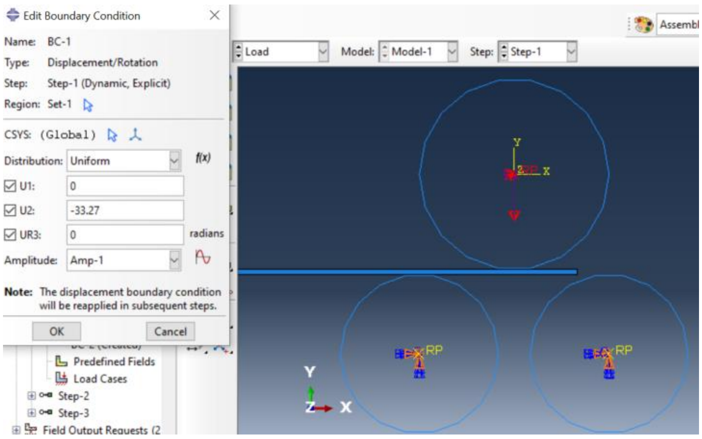
Top roller radius (mm)	r_o	120
Lower roller radius (mm)	r	100
Distance between 2 lower rollers (mm)	L	240

Table 3. Table of blank parameters and parameters involved in the bending process

Plate thickness (mm)	t	6
Plate width (mm)	w	300
Bending radius (mm)	R	130
Estimated rebound radius (mm)	R_p	140.7
Top roller displacement (mm)	h	33.27

3.2. Conduct simulation

- Proceed to bind the contact between the plate and the roller. The coefficient of friction between the rollers and the plate is assumed to be 0.2
- Step 1: The top roller moves down, creating a bending force, the top roller moves down 33.27 mm and fixes the 2 lower rollers to prevent rotation.


Edit Boundary Condition

Name: BC-1

Type: Displacement/Rotation

Step: Step-1 (Dynamic, Explicit)

Region: Set-1

CSYS: (Global)

Distribution: Uniform

☑ U1: 0

☑ U2: -33.27

☑ UR3: 0 radians

Amplitude: Amp-1

Note: The displacement boundary condition will be reapplied in subsequent steps.

Fig 4. Top roller displacement down 33.27 mm

- Step 2: The process of bending the plate to create curvature. The top roller rotates around the axis at an angular velocity of 0.5 rad/s and the 2 lower rollers rotate accordingly.
- Step 3: Unload by removing the link between the rollers.

3.3. Simulation results and discussion

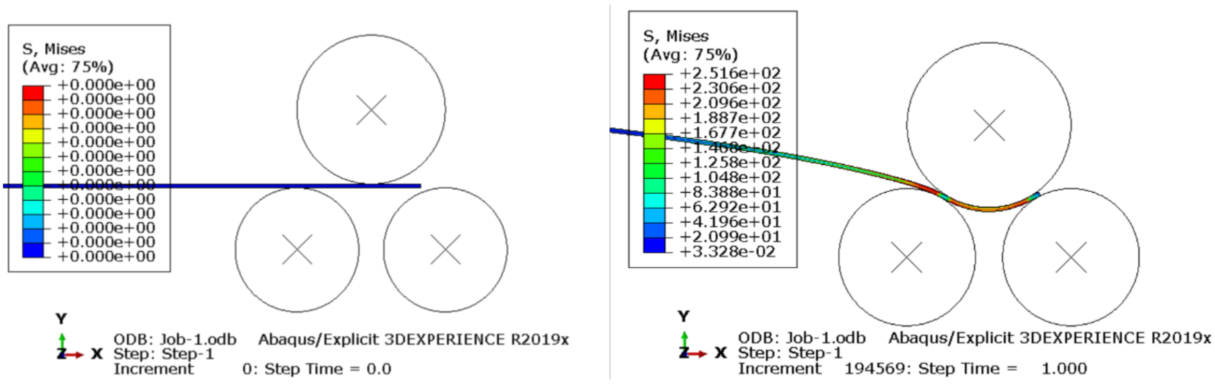


Fig 5. Initial stage of 2D plate bending process

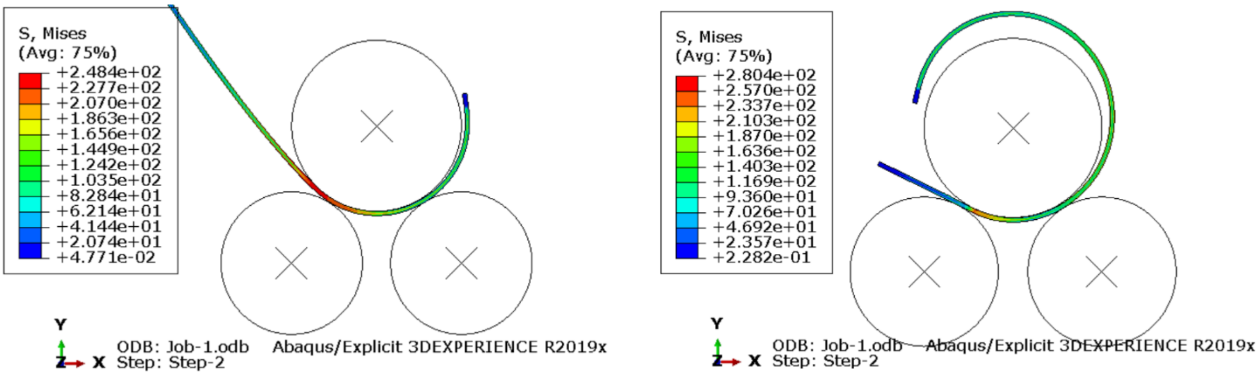


Fig 6. Intermediate stage of 2D plate bending process

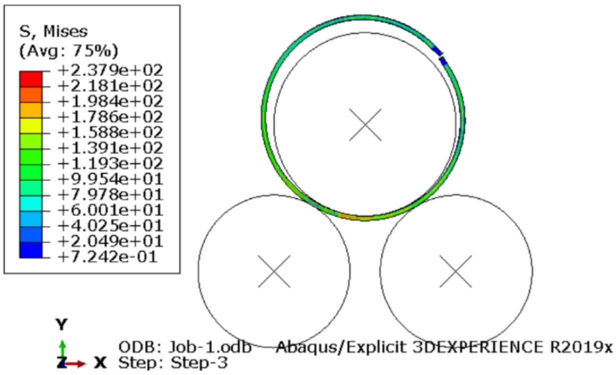


Fig 7. Final stage of 2D bending process

In the bending zone: The maximum stress during the bending process is 248÷280 Mpa, exceeding the yield limit (235Mpa), so the material moves to the permanent plastic zone and does not cause cracks on the surface of the plate. When subjected to plastic deformation, the closer to the middle of the plate (neutral layer), the less stress is shown in Figure 9. In addition, the beginning and end of the plate are subjected to very small stress, so they have not yet moved to the plastic zone but will spring back and not be deformed. When

The area after bending: when there is no more force applied, the reverse phenomenon begins even during the bending process. At this time, the stress in the neutral layer that has not yet moved to the plastic zone will spring back and stretch, causing the residual stress to increase in the middle of the plate due to internal force, so the closer to the neutral axis, the residual stress increases as shown in Figure 10. The inner and outer layers have been subjected to plastic deformation, so the residual stress is low and a part of the stress is transferred to the neutral layer.

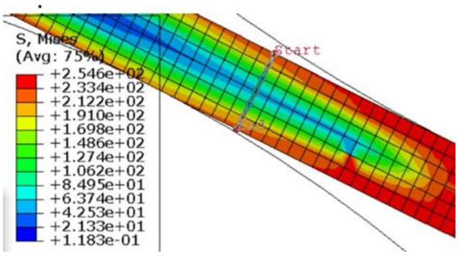


Fig 8. Plastic stress distribution

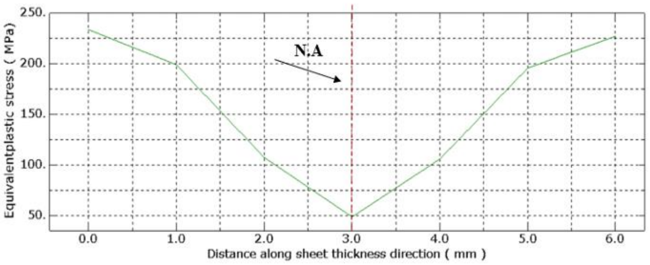


Fig 9. Plastic stress distribution along plate thickness t=6mm

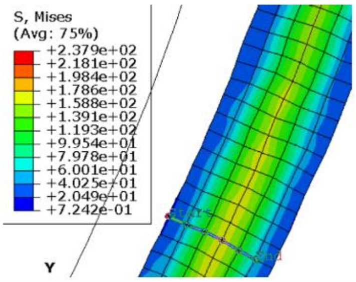


Fig 10. Residual stress distribution

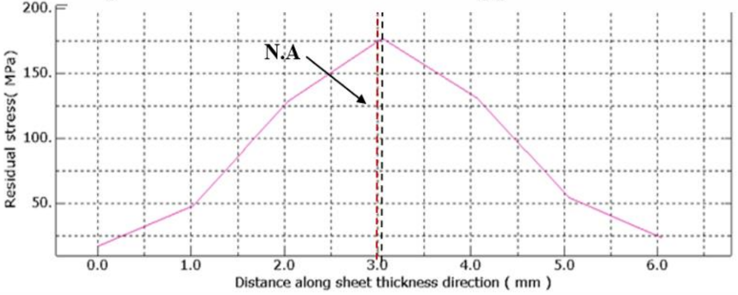


Figure 11. Residual stress distribution along plate thickness t=6mm

At the end of the bending process, the plate thickness remains constant, the residual stress is closer to the neutral axis in Figure 11. And the neutral axis has a very small displacement, which does not affect the final prediction much.

Measure the radius after simulation, in the case of the plate bent into a circular arc that does not match the roller and the curvature is not symmetrical, then we calculate the radius based on the coordinates of 3 points on the circular arc (beginning, middle, end of the plate). Measure this radius 3 times and choose the average value.

IV. Analyze factors affecting model price.

4.1. Thickness effect

The plate thickness is set at 6, 10, 16 mm. The material properties and boundary conditions are assumed to be the same.

Table 4 Bending parameters when plate thickness changes

Sample	Plate thickness (mm)	Top roller displacement (mm)	Radius after bending according to calculation (mm)	Radius after bending measured by simulation (mm)
1	6	33.27	140.7	138.2
2	10	32.94	136.2	134.6
3	16	32.46	133.8	132.7

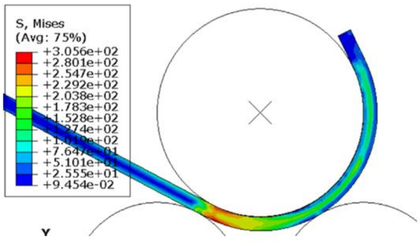


Fig 12. Mid-bending process t=16 mm

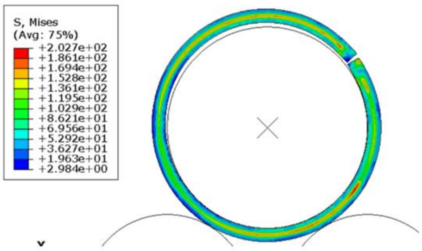


Fig 13. Finished bending process of t=16 mm plate

As the plate becomes thicker, the rebound phenomenon decreases. The error due to the formula predicting the bending radius is small. The bending shape is accurate, the bending process is stable. However, when the thickness increases, a larger stress is required for bending. It can be seen that the maximum stress when bending the plate t = 16mm is from 280 ÷ 305Mpa and the residual stress in the neutral layer is also large.

Therefore, we choose the appropriate plate thickness to ensure the shape, stability and stress to avoid cracking.

4.2. Material influence

To maintain the initial radius of the deformed steel plate at R130 mm. With a plate thickness of 6 mm, the top roller is placed at a position with a vertical displacement of 33.27 mm. The strength of the steel specimen is determined, Table 5 and Figure 14 and 15.

Table 5 Bending parameters when plate material changes

Sample	Yield limit (Mpa)	Tensile strength (Mpa)	Radius after bending according to calculation (mm)	Radius after bending measured by simulation (mm)
1	235	400	140.7	138.2
2	200	500	139.5	143.7
3	345	560	146.4	134.3

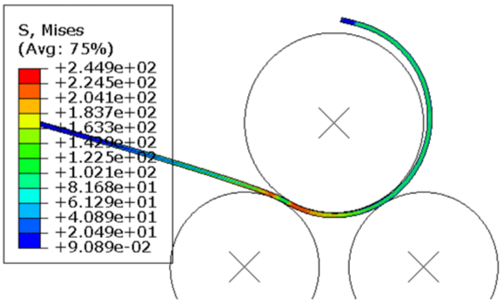


Fig 15. Stress when bending plate with sample material 2

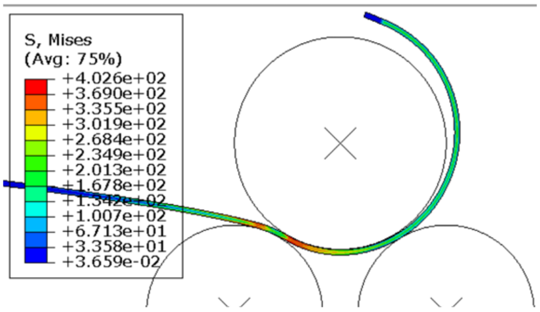


Fig 16. Stress when bending plate with sample material 3

With high yield strength material, the elasticity is less. However, high bending stress, with thin plate can cause scratches. The deviation between calculated and simulated bending radius is large.

It can be said that the formula for predicting the radius of this model also depends on the machine with a fixed bending force. When the bending force is fixed, the material with a small yield limit is easily deformed into the plastic region, while the material with high stiffness has insufficient bending force and many regions are easily elastic. As for the abaqus simulation, the bending force and contact change over time.

4.3. Effect of bending radius

Plate thickness, material properties and boundary conditions are kept unchanged, Table 6. When the bending radius increases, the reverse elasticity also increases due to the sliding phenomenon, poor contact leads to insufficient bending force, as well as with a thin plate thickness of 6mm, when bending with a large radius, the error in shape and size is large due to the stiffness of the plate.

Table 6 Bending parameters when bending radius changes

Sample	Bending Radius (mm)	Top roller displacement (mm)	Radius after bending according to calculation (mm)	Radius after bending measured by simulation (mm)
1	130	33.27	140.7	138.2
2	140	31.69	152.5	151.6
3	150	30.27	164.5	166.3

V. Conclusions

Plate thickness is a factor that strongly affects the curvature after bending. The thicker the plate, the less elastic recovery ability, the smaller the prediction error. The yield limit, the strength of the material greatly affects the calculated and simulated bending radius. When the bending force is constant and small, the material has a small plastic limit, the predicted radius deviation is smaller, the stress is smaller. When the bending force changes gradually, the plate with a low yield limit is prone to warping and cracking, and the shape deviation is large. The plate with a large yield limit is more stable. The larger the bending radius, the larger the shape deviation as well as the predicted radius error.

Thus, understanding and controlling the input parameters is an important basis for improving the geometric accuracy and forming efficiency in the three-roller bending process.

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