Research Report

Highly Accurate Numerical Prediction of Springback Shape of Stamped Thick Metal Sheet

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厚板成形形状の高精度予測技術

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Abstract

In sheet metal forming simulations, the widely used shell elements are assumed to be in the plane stress state, as defined by the Mindlin-Reissner theory. Unfortunately, numerical prediction with conventional shell elements is not accurate for bending radiuses that are small relative to the sheet thickness. This is mainly because the stress and strain formulation for a conventional shell element does not actually reflect reality. So, to accurately predict the springback of a sheet with a severe bend, we have proposed a method for measuring the through-thickness strain. The stress and strain are formulated based on measured and calculated values for a solid element, as well as a proposed shell element that is based on a formulation that has been newly incorporated into the FEM code. We have confirmed the accuracy with which this method can predict the springback shape of two bending processes. As a result, we found that we can accurately predict the springback shape even after severe bending. From the viewpoint of computation cost, the proposed shell element is much more effective than a solid element.

Keywords: Sheet metal forming, Finite element method, Numerical analysis, Bending, Springback, Shell element

要　旨

板成形シミュレーションで利用されているシェル要素はM-Rの仮定に基づき，平面応力状態として定式化されている。この従来型のシェル要素を用いたスプリングバックの予測結果は，自動車のフレームやサスペンション部品の型設計に利用するには十分な精度ではない。これはそれらの部品のように，板厚に比べて曲げ半径が小さい場合には従来型のシェル要素のひずみ，応力の定式化が実際の現象に即していないためである。そこで，新たに考案した測定法でせん断ひずみの板厚方向分布を測定した。これらの実験とソリッド要素の計算結果により新たにひずみ，応力を定式化したシェル要素を考案した。その新しいシェル要素をFEM解析に導入する。さらに，U曲げ，ハット曲げの2種類の成形事例について，従来のシェル要素，実験，およびソリッド要素の結果と比較することで，提案シェル要素を用いたスプリングバックの予測精度について検証した。提案したシェル要素を用いることにより厳しい曲げ成形に対しても高精度で，短い計算時間でスプリングバック予測ができることを示した。

キーワード　板成形，有限要素法，数値解析，曲げ，スプリングバック，シェル要素

1. Introduction

Numerical simulations of sheet metal forming have exhibited huge advances over the past ten years or so.[1-3] They have been applied to the production of auto body parts and even side panels, which are the largest parts for which sheet metal is used. Breakage and wrinkling can be practically evaluated by sheet metal forming simulations, but the forming accuracy such as the springback shape is only partially calculated. In the future, there will be a strong demand for commercially viable high-level simulations capable of shortening vehicle development times and enabling coordination with overseas production facilities.

For sheet metal forming simulations, the widely used shell elements are assumed to be in the plane stress state, as defined by the Mindlin-Reissner theory.[4] Unfortunately, numerical prediction using conventional shell elements is not accurate when the bending radius is small relative to the sheet thickness. Rather, parts such as those with design break lines and hemming, as well as underbody parts, are more likely to be thought of as being stamped under conditions that exceed the application limits of shell elements. We considered the accuracy of the springback prediction with conventional shell elements that are incapable of fully representing the above-mentioned parts. The main reason for this is because the stress and strain formulation of conventional shell elements does not actually reflect reality.

This paper proposes a new measuring method to confirm the through-thickness shear strain distribution. A new shell element is proposed based on the results obtained from both experiments and solid FEM simulation. The newly formulated shell element is introduced into FEM analysis. In addition, the results of calculations using the new proposed shell element are compared with both the results of experiments and calculations using the solid element on models of U- and hat-shaped bending.

2. Formulation of strain

The through-thickness strain distribution in a bend was measured to formulate the strain. A strain gauge, mark-off line and indentation were used for the measurements. The surfaces and edges were used for the measurement. For the formulation, it is necessary to measure the strain distribution at the center where there is no influence from the stress state at the edge. Then, a solid element FEM is used to consider the measurement method for the through-thickness strain distribution. Therefore, we proposed a new method in which a pin is buried under a prepared hole, after which the strain is measured from the deformation (**Fig. 1**).

2. 1 Measurement method

The pin has a prismatic shape and parallel rectangular grooves leading up to the surface of the specimen, which are used for locating after the deformation (**Fig. 2**(a)). The grooves were aligned parallel with the width edge and buried by copper plating. The pin was lightly press-fitted into the square hole of the specimen, after which the position of the pinhead was aligned with the surface of the test piece. The length of the pin was assumed to be the initial distance between a neutral plane and the surface, and was determined by FEM analysis. The specimen was cut out in a plane parallel to a width central section, which included the grooves buried by plating of the pin, as shown in Fig. 2(b). The coordinates of the angular points in the grooves were measured, and then the change in the through-thickness direction was determined. Next, an across-the-width central section including the center part of the pin but without the grooves was cut out, and the through-thickness angle distribution between the side of the pin and the normal to the neutral

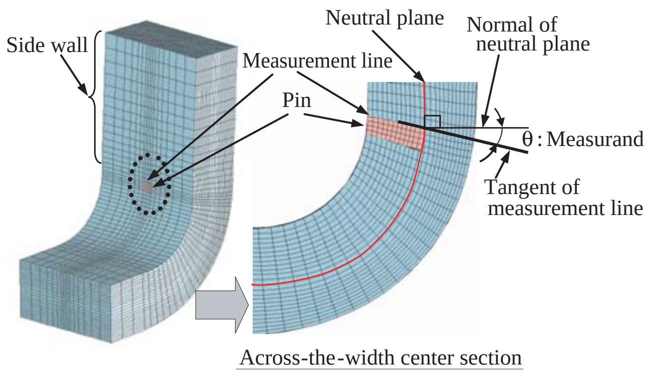


Fig. 1 Measurement method. (Measurement line is a location where θ is the most inhomogeneous)

plane was calculated based on the above-mentioned change in the through-thickness direction (Fig. 2(c)). **Figure 3** shows the measurement results. If the bend radius R is 7 or less, then the angle is large at the center and contradicts the assumption for a conventional shell element, where the shear strain is constant in the through-thickness direction.

2. 2 Formulation

We compared the solid FEM with the results shown in Fig. 3, and confirmed that the actual through-thickness strain distribution could be estimated using the FEM. **Figure 4** shows the through-thickness shear strain distribution of the FEM analysis. The results were approximated by a quadratic function, and the curves were also plotted. Based on these results, we can assume the following. The shear strain actually grows near the center of thickness, and plastic deformation is caused at the center even though it does not occur with a conventional shell element. In addition, the unbending force increases because of plastic deformation near the center of the thickness. Therefore, we assumed that the formulation whereby the shear strain rises near the center of thickness was adequate, and that it is appropriate to assume the equation quadratic polynomial, which does not need additional parameters. We decided to consider the nonlinearity of the through-thickness shear strain by applying the following expression.

$$\gamma_{yz} = \left(\frac{\partial w}{\partial y} - \theta_x\right)\left(1 - \frac{4}{h^2} z^2\right) \quad \cdots\cdots\cdots\cdots\cdots (1)$$

$$\gamma_{zx} = \left(\frac{\partial w}{\partial x} + \theta_y\right)\left(1 - \frac{4}{h^2} z^2\right) \quad \cdots\cdots\cdots\cdots\cdots (2)$$

3. Formulation of through-thickness stress

The through-thickness stress is thought to originate in the contact pressure because the work bends as a result of continuous contact with the dies in a common bending process. On the other hand, the equilibrium of stress in the work can be

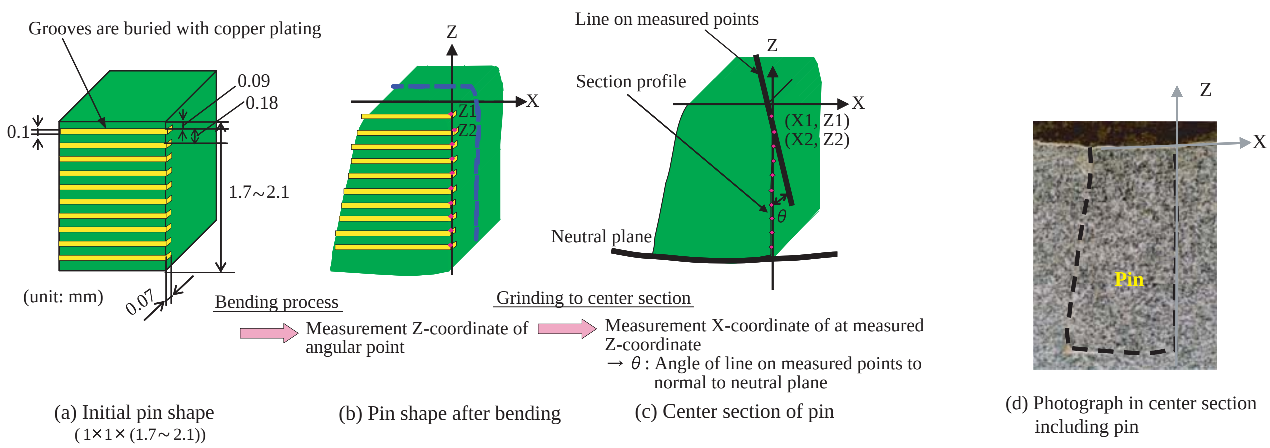


Fig. 2 Measurement method for through-thickness shear strain.

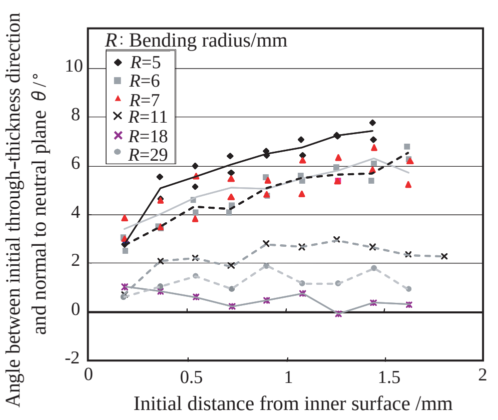


Fig. 3 Measurement values of θ.

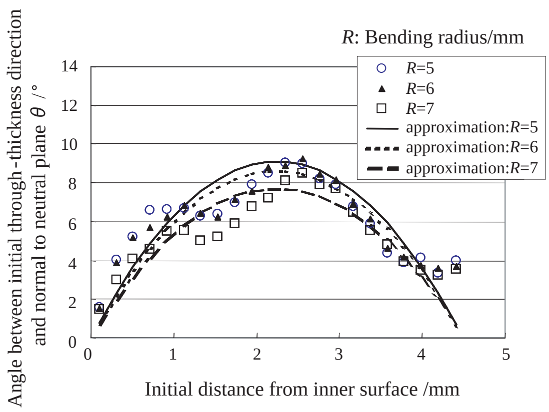


Fig. 4 Approximation of numerical results of θ.

illustrated by the following expression.

$$\frac{\partial \sigma_{rr}}{\partial r} + \frac{1}{r}\left(\sigma_{rr} - \sigma_{\theta\theta}\right) + \frac{1}{r}\frac{\partial \tau_{r\theta}}{\partial \theta} + \frac{\partial \tau_{zr}}{\partial z} + F_r = 0 \quad \cdots (3)$$

The through-thickness stress relates to the bending stress when the shear stress is disregarded in the above-mentioned expression. The through-thickness stress is believed to be considerable when the bending stress is large and the bending radius is small. These indicate that the through-thickness stress originates chiefly from the bending deformation and the contact pressure with the dies. Hence, the stress can be formulated using the following expressions.

3. 1 Through-thickness stress from bending deformation

The next expression has equality based on the equilibrium of stress in the case of bending deformation. Here, σ_{zb} is the through-thickness stress and σ_x is the hoop stress.

$$\frac{\partial \sigma_{zb}}{\partial z} = \frac{1}{r}\left(\sigma_x - \sigma_z\right) \quad \cdots\cdots\cdots\cdots\cdots\cdots (4)$$

We assumed that the distribution of σ_{zb} was shown by using this expression and the least square.

3. 2 Through-thickness stress from contact

We assumed that the distribution of the through-thickness stress caused by the contact (σ_{zc}), according to Reissner's theory, when the sheet is subject to contact pressure (σ_p) from the tool can be illustrated by the following expression (h: thickness).

$$\sigma_{zc} = -\frac{3}{4}\sigma_p \left\{ \frac{2}{3} - \frac{2z}{h} + \frac{1}{3}\left(\frac{2z}{h}\right)^3 \right\} \quad \cdots\cdots\cdots (5)$$

Here, the contact pressure (σ_p) is assumed to be the value at which the contact force is divided in the effective contact area.

4. Implementation of proposed formulation in FEM

The main area where the proposed shell element is introduced to FEM is the flow for calculating the reaction force from the displacement increment of the main FEM program. **Figure 5** shows the flow. It differs from the calculation flow for a conventional shell element in the following points.

(1) Calculate the contact pressure at the contact location and then compute the through-thickness stress from contact (σ_{zc}) using Eq. (5).
(2) Calculate the through-thickness stress from the bending deformation (σ_{zb}) based on the curvature radius and the stresses using Eq. (4).
(3) Calculate stresses that satisfy the yield criteria when σ_z is given.

The method for introducing the proposed shell element changes the loop for updating the stress from displacement, while the rigidity matrix remains unchanged. Therefore, it is easy to introduce the proposed shell element into all the FEM codes.

5. Results and discussion

The proposed shell element was verified for U- and hat-shaped bending processes, both of which are basic bending processes.

5. 1 U-shaped bending process

In this processing, the influence on the springback angle of the punch shoulder radius was compared. The specimen was 590 MPa class hot-rolled steel with a thickness of 4.5 mm. The work was stamped by applying back pressure with a pad. The springback calculation used a method that considers the plastic strain dependency of the pseudo-elastic modulus and Bauschinger effect during the unloading

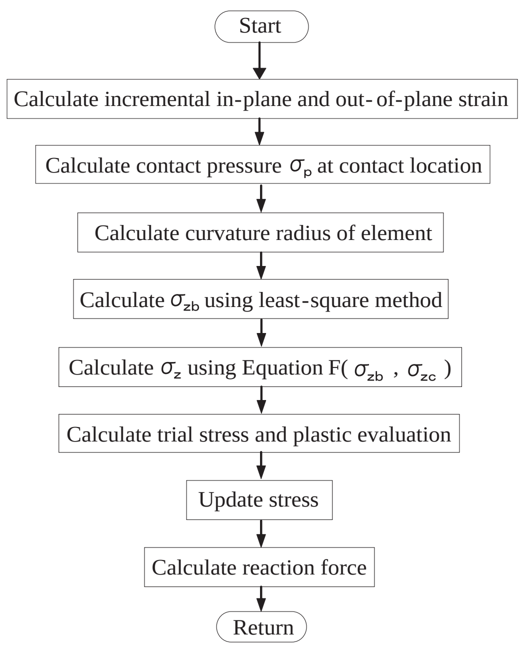


Fig. 5 Flowchart of numerical algorithm for implicit integration using proposed shell element.

process, as proposed by several authors. The results obtained by calculation were compared with those of the experiments and are shown in **Fig. 6**. The results were calculated using the proposed shell element, solid element, and conventional shell element. It was found that the accuracy of the proposed shell element is equal to the solid results without depending on the punch shoulder radius. There are large differences between the results obtained with the conventional shell element and those with the solid element when the ratio of the bend radius and thickness is less than 5. We confirmed that the proposed shell element was effective for severe bending where the ratio of the bend radius and thickness is less than 5.

5. 2 Hat-shaped bending process

The shoulder radius of the punch and die are some of the factors that determine the springback shape in hat-shaped bending. The radius of the die shoulder is discussed here. The specimen was 440 MPa class hot-rolled steel with a thickness of 2.3 mm. **Figure 7** shows the springback shape when the radius of the die shoulder is 3 mm as an example of our calculation results. The result of our experiments and the results obtained using the solid element had little tendency to springback, while the result obtained with the conventional shell element showed a spring-go phenomenon different from the others. On the other hand, the result obtained using the proposed shell element closely corresponds to the results obtained with the solid element. The values used for the springback evaluation were the opening distance and the curvature, and are shown in **Fig. 8**. The values are compared for three radii of the die shoulder. **Figure 9** shows the results. It was found that the two values obtained using the conventional shell element differ greatly from the others when r/t = 1.3. With the conventional shell element, the opening distance and curvature are negative and large, and indicate the spring-go phenomenon. On

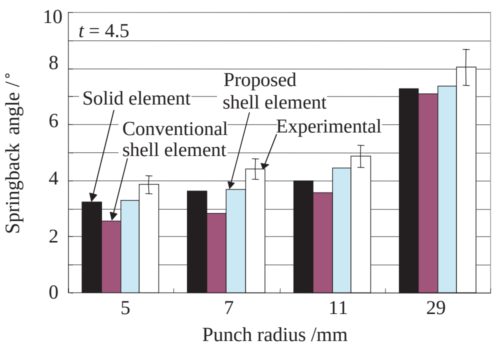


Fig. 6 Springback angle in U-shaped bending.

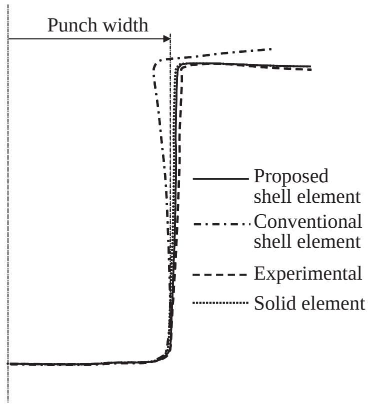


Fig. 7 Springback shape in hat-shaped bending.

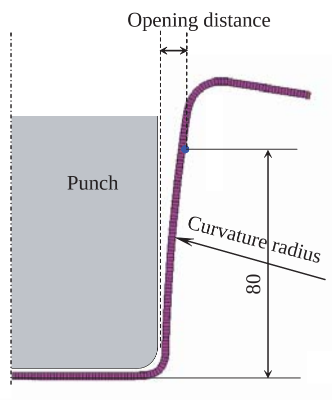
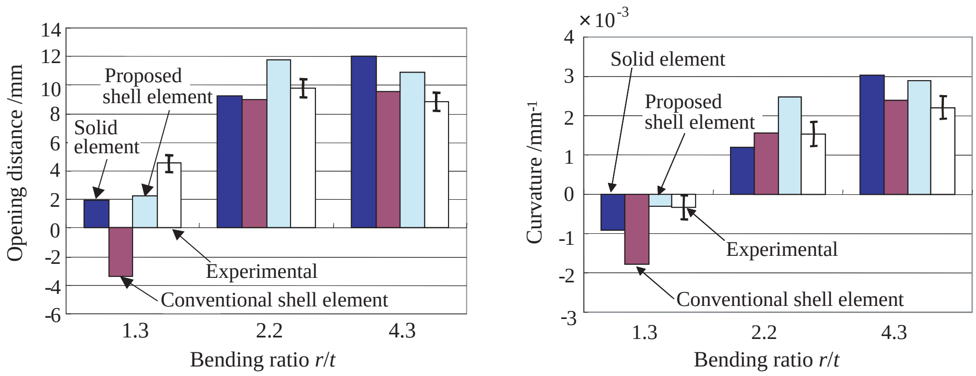


Fig. 8 Opening distance and curvature radius.



(a) Opening distance

(b) Curvature

Fig. 9 Relationship between bending ratio r/t and springback evaluation values.

the other hand, the results obtained with the proposed shell element correspond both to those obtained with the solid element and those obtained by experimental. Moreover, the calculation time for the proposed shell element was about twice that for a conventional shell element. On the other hand, when this object is modeled using a solid element for high prediction accuracy, the calculation time is ten times longer than with a conventional shell element, and it is expected to become several hundred times longer in the case of actual auto body parts. The above-mentioned results suggest that the accuracy of the springback prediction can be improved and the increase in calculation time suppressed when the proposed shell element is applied to FEM.

6. Conclusion

To accurately predict the springback of a bent sheet with a severe bend, a method of measuring the through-thickness strain has been proposed. The stress and strain were formulated based on the results obtained by measurement and calculation using a solid element, as well as the proposed shell element that was based on a formulation that is newly introduced to the FEM code. The accuracy of this method's prediction of the springback shape of two bent processes has been confirmed. As a result, we found that the springback shape can be predicted with high accuracy even under severe bending. Moreover, the calculation time with the proposed shell element is about twice that for a conventional shell element, and has been shortened to about 1/20 that of a solid element. In addition, further shortening to 1/100 or less compared to the time needed for a solid element is considered possible for actual auto body parts. Therefore, the springback prediction method using the proposed shell element is useful in die design from the standpoints of efficiency and accuracy.

References

1) Tsutamori, H., Iwata, N. and Suzuki, N. : "Prediction of the Geometrical Defects of Sheet Metals in 3 Dimensional Shape", J. Jpn. Soc. Tech. Plast., **44**-513(2003), 1024-1028
2) Takamura, M., Ohura, K., Sunaga, H., Kuwabara, T., Makinouchi, A. and Teodosiu, C. : "Sheet Forming Simulation Using Static Explicit FEM Program Coupled with Elastic Deformation of Tools", J. Jpn. Soc. Tech. Plast., **47**-540(2006), 64-68
3) Tsutamori, H. and Yoshida, F. : "Analysis of Springback in Sheet Metal Stamping Considering Elastic Deformation of Dies", J. Jpn. Soc. Tech. Plast., **46**-532(2005), 407-411
4) Reissner, E. : " The Effect of Transverse Shear Deformation on the Bending of Elastic Plates", J. Appl. Mech., **67**(1945), A69-A77

(Report received on Jun. 21, 2006)

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