Computer-Aided Design for Cold Roll Forming of Light-Gauge Steel Members*

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In order to estimate the number of roll passes necessary to form light-gauge steels for general structures, the relationship between the shape factor and the number of roll passes for various sections is investigated by arranging the data collected from several companies. Furthermore, allotment of roll bend angle at any stage is carried out under the hypothesis that the locus of the edge of the section on the horizontal plane is modified by the cubic curve. An interactive computer graphic system, which introduces a floating index in an equation, is developed, and this new CAD system enables a roll designer to engage in dialogue with the computer. The roll flower for the sash section, track sections, keystone plate and deck plate sections and pipes sections designed by this new CAD system agreed well with actual roll drawings.

Key Words: Computer Aided Design, Cold Roll Forming, Estimation of Passes, Allotment of Roll Bent Angle, Roll Flower

1. Introduction

The most important and also the most difficult part of the design of cold rolls to form light-gauge steels for general structures is the planning of the progressive shapes of the material and thus the determination of the number of roll passes necessary to form a given shape. Research on the computer-aided design of cold rolls, in which a computer makes these determinations, was recently carried out. Research on CAD of the cold roll is divided broadly into two groups. One is data-based method by which the roll design techniques used in roll production companies are arranged10, and the other is the analytical method that mathematically shows deformation of sheet metals in the roll forming process10. These methods have their own respective features, but the authors are conducting research on CAD on the basis of a data base which enables the roll design of complex sections such that the deformation of sheet metals can not be mathematically shown.

This paper deals with the procedure of how to arrange judgment, knowledge and know-how for the roll design which is extracted from several roll drawings and data, and also the method of constructing an interactive computer graphic system which enables dialogue between the roll designer and the computer. In addition, it shows how to apply this interactive computer graphic system and examines a few samples which were designed by this system.

2. Classification of Light-Gauge Steels for General Structures

Research on construction of data bases for cold rolling begins with the classification of shapes formed into four groups: symmetrical sections, asymmetrical sections, wide-profile sections and pipe sections. Our experiment1314 that several shapes formed by a cold
roll forming machines have shape defects of their own make to classify several shape sections into four such groups. The research on this CAD system is carried out by using standard sections selected from catalogue No. 265 of HITACHI Metals, Ltd.

3. Determination of the Number of Passes

3.1 Symmetrical section

Figure 1 shows the relationship between the shape factor $\Phi_i$ and the number of roll passes $N$ used to form those sections. The shape factor expresses the degree of roll forming severity and is defined by the value of $Fnt$, where $F$ and $t$ are the total length and the thickness of the flange, respectively, and $n$ is the total number of bent corners of the section. By writing a hypothesis curve in Fig. 1, which varies widely, the following interesting conclusions can be reached. (1) Cross sections in Fig. 1 can be classified into two groups depending on whether they are sections of the so-called hat types (sections shown in the left region such that the flange part of the edge of the section turns to the outside) or of the C-channel types (sections shown in the right region such that the same part turns to the inside). (2) Products of the C-channel type need larger passes than those of the hat type. As a consequence, the shape factors of symmetrical sections are calculated after classifying the products into either of the section types, and therefore, the estimation of the number of passes that are needed to form a given shape can be carried out by using this figure.

3.2 Asymmetrical section

Figure 2 shows the relation between the shape factor $\Phi_2$ of asymmetrical sections and number of roll passes $N$ used to form those sections. In the determination of the shape factor, attention must be paid to the fact that there are two methods of roll design used to form a sheet metal into an asymmetrical shape as shown in Fig. 2. Design method (A) is to set the principal axis of the section in parallel with the spindle of the forming machine and (B) is to set it without inclining the principal axis of the section. The shape factor was defined by the following method after asking HITACHI Metals, Ltd. about the production method of asymmetrical sections shown in their catalogue. The calculation of the shape factors of design method (B) is carried out in a manner similar to that for a symmetrical section. Namely, the sum of the product of $F_i$, $n_i$, and $t$ on the left flange portion and that of $F_i$, $n_i$, and $t$ on the right flange portion, i.e., $F_i n_i t + F_i n_i t$, is defined as the shape factor, where $F_i$ and $n_i$ are the flange length and number of bent corners on the left flange, respectively, $F_i$ and $n_i$ are the corresponding values on the right flange, and $t$ is the thickness. Shape factors of the (A) design method in Fig. 2 are treated in a manner similar to that in the (B) design method, except for the consideration of the number of bent corners. As an example for (A), the number of bent corner of P portion is divided into halves, and each half is added to the number of bent corners of the left and right flanges, respectively. The numbers in the figure are the same as those of the illustrations.

3.3 Wide-profile section

Figure 3 shows the relationship between the shape factors of wide profile sections $\Phi_3$ and number of roll passes $N$.
passes used to form those sections. Shape factors are given by $\phi = n W_b / W_s$, where $W_s, W_b, n$ and $n$ denote the half-width of sheet plate, half-width of final section, height of cross section and number of bent corners, respectively. The broken-line area shown in Fig. 3 is the result of data taken from the catalogue of HITACHU Metal Ltd., published in 1977, and the solid-line area shows the recent data of the same company and of authors. This is very interesting because Fig. 3 shows the great progress made in the roll design during the past ten years. This paper shows the CAD samples designed on the basis of recent data.

3.4 Pipe section

Using roll drawings and data collected from several companies, the relationship between the shape factor for pipe sections and number of roll passes has been investigated. We obtain the result that the number of roll passes is almost constant regardless of the diameter and thickness of the pipe. Therefore, we designed a pipe by using 10~12 passes, which are the traditional number of production passes, having break/down forming 7~8 and fin pass forming 3~4, respectively.

4. Method for Determination of Forming Angle

4.1 Symmetrical and asymmetrical sections

On the basis of the actual roll design method, the following equation is considered. Namely, assuming that the bend angle on each roll pass gives the optimum distribution when the locus of the flange is assumed to be a cubic curve as shown in Fig. 4, the equation for the forming angle is obtained as follows: Here Eqs. (1) and (2) represent the cubic curve and the boundary conditions, respectively.

$$y = Ax^3 + Bx^2 + Cx + D$$  \hspace{1cm} (1)

$$y = 0 \quad \text{at} \quad x = 0$$  \hspace{1cm} (2)

$$y = H(1 - \cos \theta_i) \quad \text{at} \quad x = N$$  \hspace{1cm} (3)

The roll bend angle $\theta_i$ at any stage $i$ is given by Eq. (4)

$$\cos \theta_i = 1 + (1 - \cos \theta) \left\{ 2 \left( \frac{i}{N} \right)^3 - 3 \left( \frac{i}{N} \right)^2 \right\}$$  \hspace{1cm} (4)

Introduction of a floating index $k$ in Eq. (4) as shown in Eq. (5) enables a roll designer to dialogue with the computer.

$$\cos \theta_i = 1 + (1 - \cos \theta) \left\{ 2 \left( \frac{i}{N} \right)^{2(k+1)} - 3 \left( \frac{i}{N} \right)^{2(k+2)} \right\}$$  \hspace{1cm} (5)

Though this equation is obtained from a simple channel section, we applied it to the design of a section with multiple-bent corners of complicated shapes.

4.2 Wide-profile section

The locus of the edge of the wide-profile section on the horizontal plane is assumed to be a cubic curve, as shown in Fig. 5. The cubic curve and the boundary conditions are given by Eqs. (1) (2) and (6):

$$y = AX^3 + BX^2 + CX + D$$  \hspace{1cm} (6)

Fig. 4 Formula for determining the successive bend angles of the passes

Fig. 5 Horizontal locus of a plate edge hypothesized for designing a wide-profile section

at \( x=0, \ y=W_1 \) \\
\( x=N, \ y=W_2 \) \hspace{1cm} (6)

The half-width of the section \( y_i \) at any stage \( i \) is obtained as Eq. (7):
\[
y_i=(W_i-W_2)\left\{\frac{1}{N} \frac{1}{N} - 3 \frac{1}{N} \right\} \hspace{1cm} (7)
\]
where \( N \) is the total number of passes. The next step of roll design is to determine the bend angle \( \theta_i \) at any stage \( i \). Let us assume that the ribs in Fig. 5 are formed from the central portion in order. \( Y_s, Y_s, \) and \( Y_f \) are the half-width of the section when the middle rib, the second and the third ribs have just been finished, respectively. Then, the relation between bend angle \( \theta_i \) and half-width \( y_i \) at any stage \( i \) is obtained as follows:

\[
\begin{align*}
\text{at } y_i \leq y_i < W_i, \quad & y_i = W_i - a(1 - \cos \theta_i) \quad \text{(a)} \\
\text{at } y_i \leq y_i < y_s, \quad & y_i = W_i - a(1 - \cos \theta_i) - 2a(1 - \cos \theta_i) \quad \text{(b)} \\
\text{at } y_s \leq y_i < y_s, \quad & y_i = W_i - 3a(1 - \cos \theta_i) - 2a(1 - \cos \theta_i) \quad \text{(c)} \\
\text{at } W_i \leq y_i < y_f, \quad & y_i = W_i - 5a(1 - \cos \theta_i) - 2a(1 - \cos \theta_i) \quad \text{(d)}
\end{align*}
\]

where \( \theta_1 > \theta_2 > 0 \) and "\( a \)" is the width of the oblique side. It is possible to construct the interactive computer graphic system by introducing the floating index \( k \) in Eq. (7) as shown by Eq. (9):
\[
y_i=(W_i-W_2)\left\{\frac{1}{N} \frac{1}{N}^{k+i} - 3 \frac{1}{N}^{k+i} \right\} \hspace{1cm} (9)
\]
We can obtain the bend angle \( \theta_i \) by giving each value of \( W_i, W_2, N, a, k, \) \( y_s, y_s, \) and \( Y_f \) in Eqs. (8) and (9) by the dialogic style.

4.3 Pipe section

Pipes are usually formed by three methods: circular forming, edge forming and double radii forming. Designs for each method are as follows.

(a) Circular forming

The forming is carried out under the hypothesis that the product of the radius \( R \) and the bend angle \( \theta_i \) is always constant, as shown in Fig. 6, when the cubic curve and the boundary condition are given by Eqs. (1), (2) and (10).
\[
\begin{align*}
\text{at } x=0, \ y=L/2 \\
\text{at } x=N, \ y=0
\end{align*}
\]

The projected distance of the pipe edge \( y_i \) on the horizontal plane is obtained as Eq. (11),
\[
y_i=\frac{L}{2}\left[\frac{1}{N} \frac{1}{N} - 3 \frac{1}{N} + 1 \right] \hspace{1cm} (11)
\]
where \( N \) and \( L \) are the total number of passes and the width of a sheet plate. The forming condition for circular forming gives Eq. (12), and Eq. (13) is geometrically obtained from Fig. 6.
\[
\begin{align*}
\rho_i \cdot \theta_i &= \text{constant} \hspace{1cm} (12) \\
\rho_i \cdot \sin \theta_i &= y_i \hspace{1cm} (13)
\end{align*}
\]
Equation (14) is given a floating index \( k \) in Eq. (11) to obtain the bend angle \( \theta_i \) and the bend radii \( \rho_i \) with dialogic style.
\[
y_i=\frac{L}{2}\left[\frac{1}{N} \frac{1}{N}^{k+i} - 3 \frac{1}{N}^{k+i} + 1 \right] \hspace{1cm} (14)
\]
Consequently, \( \rho_i \) and \( \theta_i \) at any stage \( i \) are obtained from Eqs. (12), (13) and (14) by giving the number of total stages \( N \), the width of a plate \( L \) and the floating index \( k \).

(b) Edge forming

This design method takes the hypothesis that the bend radius at any stage always keeps the radius of the finished pipe \( R \), and that the arc length of a pipe gradually increases as shown in Fig. 7 (a). The CAD for this case is carried out by using Eqs. (1), (2), (10) and Eq. (15), which shows the hypothesis of this design method,
\[
R=\text{constant} \hspace{1cm} (15)
\]
\[
y_i=\frac{L}{2} - R(\theta_i - \sin \theta_i) \hspace{1cm} (16)
\]

\[\text{Fig. 6} \quad \text{Horizontal locus of a plate edge hypothesized for designing pipe (circular forming)}\]

\[\text{Fig. 7} \quad \text{Roll design methods}\]

JSME International Journal

as well as Eq. (16), which can be geometrically obtained from Fig. 7(a). Consequently, bend angle \( \theta_i \) at any stage \( i \) is obtained from Eqs. (14), (15) and (16) by giving the total number of stages \( N \), the width of a sheet plate \( L \) and the pipe radius \( R \).

(c) Double radii forming

This method, shown in Fig. 7(b), consists of the mixed circular method and edge method. Equations (1), (2), (10) and (11) are also used for this method, and the following condition is given as follows.

(1) The forming of the first stage is carried out by the edge forming method.

(2) In forming the one-half of the sheet width from the second stage to the last stage, the part from the edge to \( \pi D/4 \) (\( D \): final pipe diameter) is bent by edge forming, and that from \( \pi D/4 \) to \( \pi D/2 \) is bent by circular forming.

(3) The allotment of the bending angle of (2) above is equal. From these forming conditions and Fig. 7(b), the following relations are obtained.

\[
\rho_{ci} \theta_{ci} = (L/2 - R \theta_{ci})
\]

\[
\theta_{ci} = \theta_{ci} + \frac{i-1}{N-1} \left( \frac{\pi}{2} - \theta_{ci} \right)
\]

where, \( \rho_{ci}, \theta_{ci} \): bend radius and bend angle at any stage \( i \) formed by the circular forming, \( \theta_{ci} \): bend angle at any stage \( i \) formed by the edge forming. The projected width of the part from the pipe edge to the center on the horizontal plane is given by Eq. (19).

\[
y_i = (\rho_{ci} - R) \sin \theta_{ci} + R \cos(\theta_{ci} + \theta_{ei} - \pi/2)
\]

Substituting Eq. (7) into Eq. (19), We obtain Eq. (20) as

\[
y_i = \left( \frac{L/2 - R \theta_{ci}}{\rho_{ci}} - R \right) \sin \theta_{ci} + R \cos(\theta_{ci} + \theta_{ei} - \pi/2)
\]

Bend angles \( \theta_{ci}, \theta_{ei} \) and bend radius \( \rho_{ci} \) from the second stage \( i=2 \) to the last stage \( i=N \) can be obtained from Eqs. (14), (17), (18) and (20) by giving the total number of stages \( N \), final pipe radius \( R \) and bend angle \( \theta_{ei} \) at the first stage.

5. Examination of Computer-Aided Design Method for Roll

5.1 Symmetrical and asymmetrical sections

This paper omits explanation of the application method of this system because it has already been presented in the previous paper\(^{11} \). This paper shows a few samples (Figs. 8, 9 and 10) of CAD which are subsequently applied for more complicated sections.

5.2 Wide-profile section

A keystone plate shown in Fig. 11 is adopted as an example of the application method of this CAD system.

(a) Determination of forming process

The forming of one rib in the middle of the sheet plate is followed by the forming of two ribs on both sides of the middle rib. In this way, we adopt the forming process in which the number of ribs increases gradually starting at the middle of the sheet plate (see Fig. 5).

(b) Estimation of passes

The shape factor \( \phi \) for this section is \( \phi = n W_1 h / W_2 = 1.009 \) mm, where the symbols have the folllowing meanings:

\[
\text{Fig. 8 Example of CAD of track section (14 passes used)}
\]

\[
\text{Fig. 9 Example of CAD of track section (14 passes used)}
\]

\[
\text{Fig. 10 Example of CAD of track section (12 passes used)}
\]

\[
\text{Fig. 11 Keystone plate section adopted for examination of CAD}
\]
Fig. 12 Result of CAD for a keystone plate (k is floating index, and bend angles for each bending procedure are shown on the right side)

Fig. 13 Example of CAD of deck plate (14 passes used)

Table 1 Half-widths of the keystone plate at each stage

<table>
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<tr>
<th>i</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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</table>

Fig. 14 Examples of CAD by circular forming (a), edge forming (b) and double radii forming (c)

Eq. (8), where (a), (b), (c) and (d) of Eq. (8) are used in the cases of i=1~4, 5~7, 8~10 and i=11~16, the bend angle θ is calculated. The allotment of stages and bend angles are shown in Fig. 12 (a).

(d) Examination of roll flower

When the values of the floating index are given as k=0, 0.2 and 0.4, the shapes of each stage are obtained as shown in Figs. 12 (a), (b) and (c). White circles shown to compare with the result of the actual draw-
Fig. 15 Comparison between hypothesized locus in CAD and projected points of pipe edges quoted from actual roll drawing

5.3 Pipe section

Figures 14 (a), (b) and (c) show the roll flowers obtained by this CAD system. Figure 15, showing the comparison between the result obtained by this CAD system and the actual roll drawing, is for ascertaining whether the author's proposal is the design method with propriety. Loci of the pipe edges designed by substituting $k=0$ and $k=0.1$ into Eq. (14) are shown by the solid and chain lines in Fig. 15. When $k=0 \sim 0.1$ is given in Eq. (14), it is found that the calculated projection of pipe edges is in accord with that of the actual roll drawing.

6. Conclusions

(1) The equation for the forming angle is obtained under the hypothesis that the bend angle on each roll pass gives the optimum distribution when the locus of the flange is assumed to be a cubic curve, and figures proposed to estimate the number of roll passes for each section are combined with this equation to obtain the computer aided design system.

(2) An interactive computer graphic system is established. Namely, the modified equation that introduces a floating index $k$ to the equation mentioned above enables a roll designer to dialogue with the computer.

(3) Several results obtained by this CAD system are in good agreement with drawings of the actual roll design.

Acknowledgments

The authors express their sincere thanks to Mr. I. Matsune, Mr. M. Iwama and Mr. T. Inoue of HITACHI Metal, Ltd., and Mr. K. Mochida of Ohta Seisaku-sho for useful discussions in connection with this work.

References


