PREDICTION OF HEATING LINES FOR BENDING SHELL PLATING OF SHIP STRUCTURE: (PART II) FORMING OF A FLAT PLATE TO A SURFACE WITH VARIABLE CURVATURE IN ONE DIRECTION

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ABSTRACT

To automate the plate forming process using the line-heating method, decisions made by experienced craftsmen should be determined from a certain computational model. A prediction method to estimate the number of heating lines to bend a flat plate to an open circular cylindrical surface was proposed in part I by the second author. In this paper, an algorithm is presented to estimate the number of heating lines to form such flat plate to surface with variable curvature in one direction. Based on the idealization of the deflection shape of the plate bent by the heating line method as given in part I, a general procedure is presented here to estimate the number of heating lines necessary to bend a flat plate to an open cylindrical surface with variable curvature in one direction. A computer program is developed based on this algorithm and the number of heating lines for a bilge plate is computed. A comparison is made between the results obtained from this program and the previous results given in part I to examine the validity of the proposed algorithm. In addition, another two curved shapes of variable curvatures are considered to illustrate the usefulness of the proposed algorithm in predicting the number of heating lines and their position.

***Keywords*::** Line-heating-method, Plate forming, Heating lines, Cylindrical surface, Deflection

INTRODUCTION

The line-heating method is considered a versatile tool in forming complex curved shapes of plates in shipbuilding and ship repair industry. The practice of forming plates by this method depends highly on the experience and skill of workmen. However, experienced workers are decreasing in number and many shipyards are looking forward to automate this technique of plate forming. To achieve this goal, a certain computational model ience of craftsmen. Several experimental and theoretical studies were carried out to automate the plate forming using the line-heating method [1-7]. Nomoto *et al.* [1-2] presented a line heating simulator in which the plate forming using the heating process was explained through a simple mechanical model. This simulator can be used to train the craftsmen. Ueda *et al.* [3-6] proposed a computer-aided process planning system for plate forming by the line-heating method. This system was used to generate general information on where, in which direction and how to apply the heat. However, the general idea of generating process plan or heating instructions was proposed but details were not discussed. Also, Lee [7] presented an algorithm to generate the marking data for plate forming by line heating based on a simple mechanical model considering beam theory.

To plate forming by the line-heating method, the number of heating lines, their positions and the suitable heating conditions to get the desired deformation are considered the necessary information. Rashwan [8] proposed a method to estimate the number of heating lines necessary to bend a plate to an open circular cylindrical surface. An idealization for the deflection shape of a plate bent by a single heating line was made. Based on this approximation, a prediction method to estimate the number of heating lines was proposed.

In this paper, an algorithm is presented to estimate the number of heating lines (NOHL) to bend a flat plate to an open cylindrical shell with variable curvatures. To examine the validity of the proposed procedure, the number of heating lines necessary to form a bilge plate is estimated based on NOHL algorithm. A comparison is made between the computed results based on NOHL algorithm and those obtained in Reference 8. Also, two different shapes of unilateral variable curvatures are considered to demonstrate the usefulness of the proposed NOHL algorithm.

DEFLECTION SHAPE OF BEND PLATE BY HEATING LINE

When the line-heating method is applied to form a flat plate, the plate is bent around the heating line as shown schematically in Figure 1. The compressive plastic strain in the heated plate mainly in a perpendicular direction to the heating line as discussed in Reference 8. The created angular distortion in the transverse direction is considered the main source in forming the plate and it is called the bending angle. Besides that there will be a certain amount of shrinkage in the plane of the plate and its magnitude depends on the main parameters of the heating conditions. It was shown in Reference 8 that the deflection shape of the middle surface of the plate in the transverse direction to the heating line has a curved shape of very small length. The remaining parts of deflection are straight lines. It was concluded in Reference 8 that the deflection shape of the middle surface of the plate athwart the heating line can be approximated by the two solid lines as shown in Figure 2.

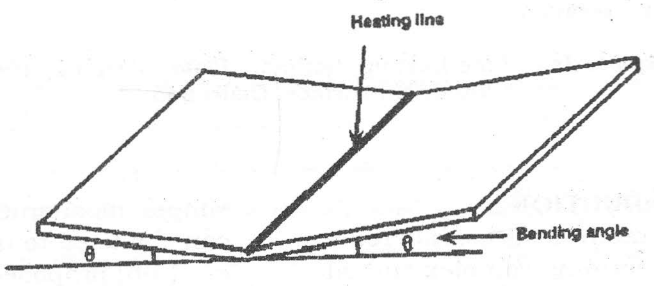

Figure 1 Bending of plate around the heating line

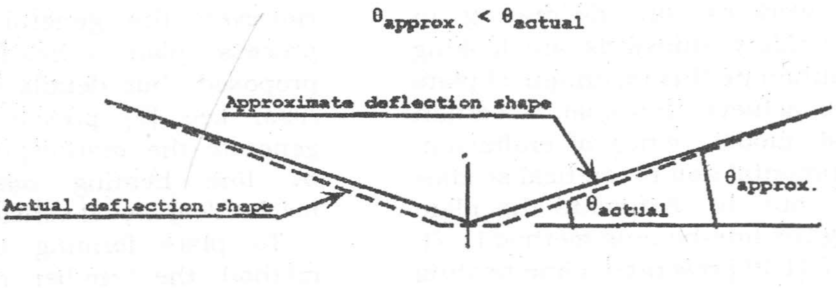

Figure 2 Idealized deflection shape of bent plate

Based on the previous idealized shape of deflection, forming of may be achieved by dividing the flat plate into several strips and rotating every two adjacent strips around their line of conjunction at a certain angle to approach the required curved shape. In addition, the line of conjunction is considered to be laid on the desired curve. Hence, the required number of heating lines can be estimated based on the following assumptions:

1) Each heating line can create a constant transverse bending angle θ_L along its length.
2) The inplane shrinkage effect will be neglected so that the desired surface may be considered a developable surface.

Subsequently, the problem of approaching the required curved form can be treated by methods of geometry rather than continuum mechanics [8]. These assumptions will be applied to estimate the number of heating lines necessary to bend a plate to an open cylindrical shell.

PREDICTION OF HEATING LINES

Basics of Procedures

Based on the previous assumption, the desired curved shape can be achieved through dividing the curved length into a number of segments. Thus, the problem is reduced to find the optimum number of segments, with permissible deviation from the desired shape, to approach the desired curved shape.

Suppose that it is required to form a flat plate into a unilateral curved surface with variable curvature. If the length of the desired curve is to coincide with the width of the plate, then the flat plate can approach the curved shape by dividing its width into a certain number of segments. Any two successive strips are considered to be interconnected by a heating line producing certain bending angle θ_L. The ends of each strip are considered to be laid on the desired curved part as shown in Figure 3. The maximum deviation between the segment and the actual curve depends on the angle of inclination of the segment, φ, and the curved part located between the ends of segment. Then, a trial and error procedure is applied to compute the maximum angle of inclination, $\varphi_{max.}$, of the segment that causes maximum deviation, $\delta_{max.}$, between the curve and the segment. This maximum deviation, $\delta_{max.}$, should be less than or equal to the permissible value, δ_{per}.

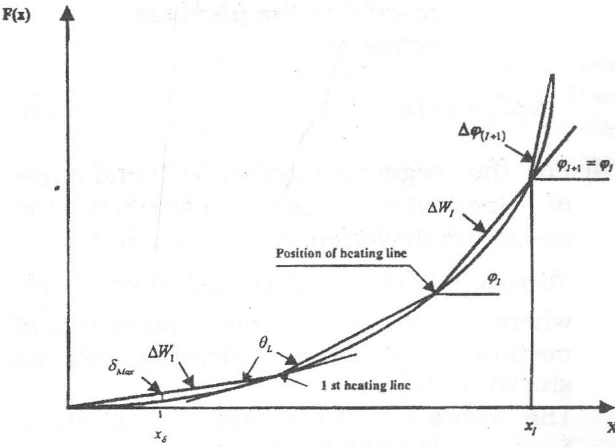

Figure 3 Approximate and actual shapes of the curved part of the plate

NOHL Algorithm

The procedure of prediction of number of heating lines (NOHL) algorithm to bend plates of variable curvatures in one direction, shown in Figure 4, is given as follows:

1) Define the curve equation representing the desired curved surface $f_c(x)$ based on a certain coordinate system. Also, define a certain value for the permissible deviation, δ_{per}, and the incremental inclination angle of segment $\Delta\varphi$.
2) Begin with new segment with iteration, J=1, for calculating the maximum deviation, δ_{max}.
3) The equation of the segment number (I+1), $f_{(i+1)s}(x)$, will be given as follows:

$$f_{(i+1)s}(x) = x \tan \varphi_{(i+1)} + A \quad (1)$$

where,

$A = f_c(x_{ini}) - x_{ini} \tan \varphi_{(i+1)}$

x_{ini} = horizontal coordinate at the beginning of segment

$\varphi_{(i+1)}$= the total angle of inclination of the segment number (I+1) with respect to the horizontal axis as shown in Figure 3.

$= \varphi_{(i)} + \Delta\varphi_{(i+1)}$ (2)

and

$\Delta\varphi_{(i+1)}$ = the angle of inclination of the segment number (I+1) with respect to the previous segment.

$$\Delta\varphi_{(i+1)} = j \times \Delta\varphi \quad (3)$$

4) For the segment number (I+1) and angle of inclination, $\varphi_{(i+1)}$, calculate the maximum deviation, $\delta_{(i+1)max.}$, such that

$$\delta_{(i+1)max.} = \{f_s(x_{(i+1)\delta}) - f_c(x_{(i+1)\delta})\} \cos\varphi_{(i+1)} \quad (4)$$

where, $x_{(i+1)\delta}$ = the position of maximum deviation along x-axis as shown in Figure 3.

The value of the maximum deviation, $\delta_{(i+1)max.}$, should be nearly equal to the permissible deviation, $\delta_{per.}$, such as

$$|\delta_{per} - \delta_{(i+1)max.}| \leq \Upsilon \quad (5)$$

where Υ = is a certain small number.

5) If the above condition given by Equation 5 is not satisfied go to step (3) to begin another iteration and increasing or decreasing the inclination angle of the segment $\Delta\varphi_{(i+1)}$ by amount $\Delta\varphi$.

6) Once the above condition given by Equation 5 is satisfied, the length of segment, ΔW, is computed based on the intersection of the segment, the straight line, and the curve. In addition, the required bending angle, $\theta_{(i+1)L}$, corresponding to the maximum deviation, $\delta_{(i+1)max.}$, can be determined from the angle of inclination of the segment, $\Delta\varphi_{(i+1)}$, as follows:

$$\theta_{(i+1)L} = 0.5\,(\varphi_{(i+1)} - \varphi_{(i)}) = 0.5\Delta\varphi_{(i+1)} \quad (6)$$

7) Repeat the steps from step (2) till the intersection of last segment with the curve coincide with the end of the curve or there is no intersection with the remainder part of the curve.

8) The number of heating lines (NOHL) will be equal to:

NOHL = (number of segments -1) (7)

It should be noted that the position of the first heating line should be defined in a slightly different way. The end of the first segment is determined as doing steps from (3) to (6). The second segment is determined based on the tangent at its beginning as shown in Figure 3.

CASE STUDIES

Number of Heating Lines for a Bilge Plate

A FORTRAN program is developed to examine the validity of the procedure of NOHL algorithm. Since the radius of curvature, R, and the width of the plate, W, are the main parameters in forming bilge plates, a bilge plate of radius 3.5 meter and width 1.0 meter is considered. The number of heating lines necessary to approach this shape can be estimated based on the proposed equation given in Reference 8, such that:

$$NOHL = (W/\Delta w) - 1 \quad (8)$$

where,

Δw = length of segment

$$= 2R\sin\{\cos^{-1}(1-\delta_{per}/R)\} \quad (9)$$

The estimated length of segment and the number of heating lines based on the above equations and the developed program are shown in Table 1 for different values of permissible deviation, δ_{per}. It is clear from Table 1 that the accuracy of the calculated segment length is very satisfactory and the error in estimating this length does not exceed 1%.

Curved Shapes of Variable Curvatures

Two different shapes of plate with variable curvatures are investigated to examine the usefulness of the proposed NOHL algorithm. Elliptical and sinusoidal shapes along transverse direction of the curved plates are considered. The length of each plate in the direction of curvature is assumed to be 1.0 meter. The equations representing each curve, corresponding to the coordinate system shown in Figure 3, are given as follow:

Elliptical shape:

$$f_{ellip}(x) = b\left\{1 - \sqrt{1 - x^2/a^2}\right\} \quad (10)$$

where,
where,
c= 0.40 meter, and w = 1.10 meter

Four values for the permissible deviation, δ_{per}, 1, 3, 5 and 10 mm are considered. The

approximate shapes of the elliptical and sinusoidal curves for the above values of permissible deviations are shown in Figures 5 and 6, respectively, as compared with the actual curves. It is clear from these figures

a and b= the long and short chords of the elliptic shape.

a = 1.4 meter and, b = 0.5 meter.

Sinusoidal shape:

$$f_{sin}(x) = c\{1 - \cos()\} \quad (11)$$

that as the permissible deviation decreases, the number of heating lines increases. Also, the length of segment decreases along the curve of small radii of curvature and vice versa.

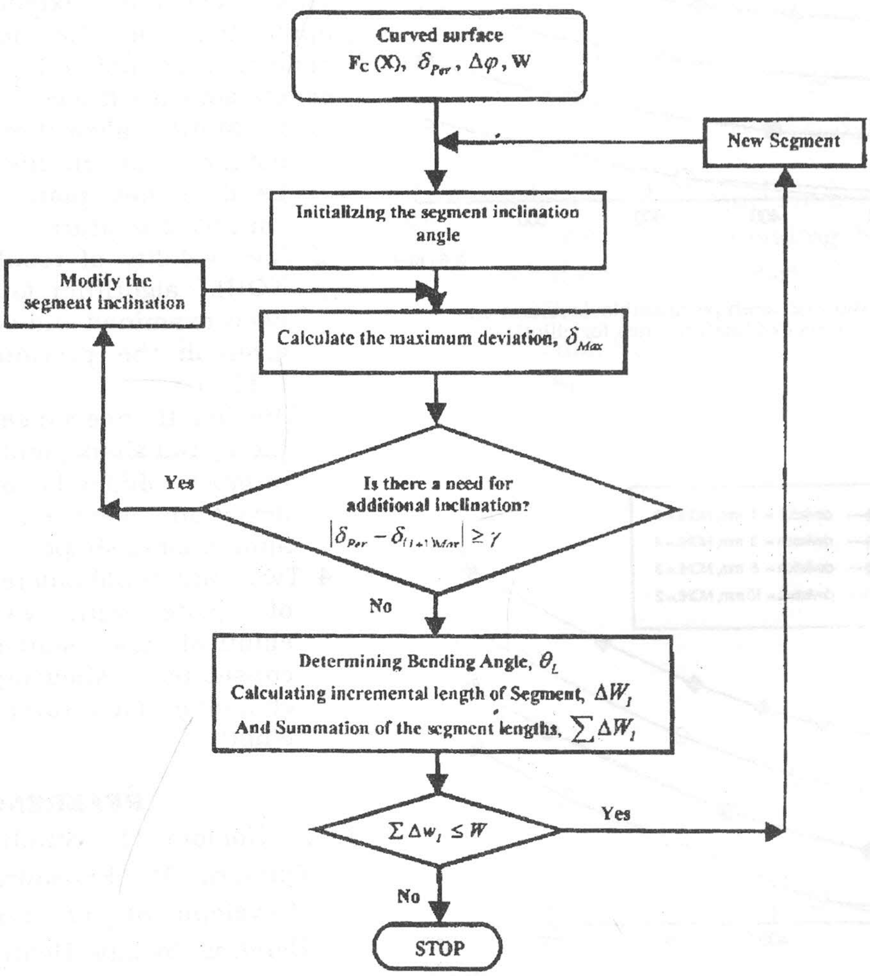

Figure 4 Prediction of number of heating lines (NOHL) algorithm

Table 1 Comparison between segment length based on NOHL Algorithm and Equation 9

Permissible deviation, δ_{per}, (mm)	Segment length ΔW based on NOHL algorithm (mm)	Segment length ΔW based on Equation 9 (mm)	Number of heating lines
1	167.0	167.3	5
3	289.7	289.8	3
5	374.7	373.0	2
10	528.5	528.7	1

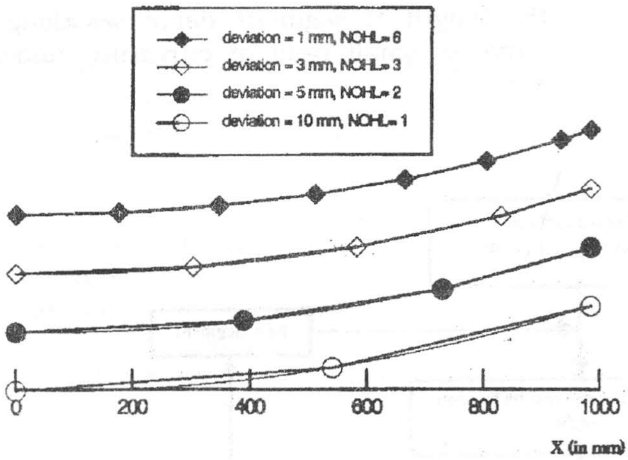

Figure 5 Relation between permissible deviation and the number of heating lines for elliptical shape

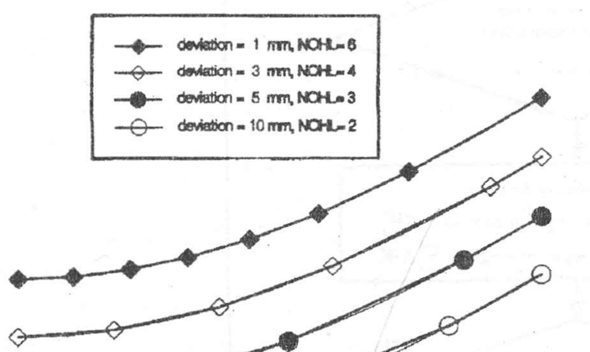

Figure 6 Relationship between permissible deviation and the number of heating lines for sine shape

CONCLUSIONS

Information about the number of heating lines, their position, and the suitable heating conditions are necessary for the automation of the plate forming process in shipyards using the line-heating method. This research extends the previous application of the idealized shape of deflection in Reference 8, and the following conclusions are drawn:

1. A NOHL algorithm is proposed to estimate the number of heating lines to bend a flat plate to a surface with variable curvature.
2. The validity of results obtained using NOHL algorithm for a bilge plate has been examined and compared with those given in the previous report as given in Table 1.
3. The length of each segment to approach the actual shape, and subsequently their number, depends on the permissible deviation between the actual and approximate shapes.
4. Two additional different curved surfaces of plate with variable curvatures, elliptical and sinusoidal shapes, are considered showing the effect of changing curvatures along the curved length.

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التنبؤ بخطوط التسخين لثني ألواح القشرة لبدن السفينة: (الجزء الثاني) تشكيل اللوح المسطح إلى سطح ذو تقوس متغير في اتجاه واحد

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ملخص البحث

لكي تصبح عملية تشكيل الألواح الحديدية لبدن السفينة آلية باستخدام طريقة التسخين الخطي, يجب تحديد عدد خطوط التسخين اللازمة للتشكيل مع تحديد أماكنها وكذلك حالة التسخين المناسبة لكل خط ، والتي تتم بواسطة العمال ذوي الخبرة ، باستخدام نموذج حسابي. في الجزء الأول من هذا البحث تم اقتراح طريقة لحساب عدد خطوط التسخين اللازمة لتشكيل الألواح إلى أسطح دورانية مفتوحة ذات تقوس ثابت. و في هذا الجزء الثاني للبحث ، تم اقتراح طريقة لحساب عدد خطوط التسخين اللازمة لتشكيل الألواح المستوية إلى أسطح ذات تقوس متغيّر في اتجاه واحد. ولذلك تم عمل برنامج لهذه الطريقة وتم اختبارها بحساب عدد خطوط التسخين اللازمة لتشكيل لوح أسطواني الشكل ومقارنة هذه النتائج بمثلها في الجزء الأول. أيضا لبيان شمولية الطريقة المقترحة، تم حساب عدد خطوط التسخين اللازمة لتشكيل ألواح مستوية إلى أسطح دورانية ذات انحناء متغيّر في اتجاه واحد.