PREDICTION OF HEATING LINES FOR BENDING SHELL PLATING OF SHIP STRUCTURE: (PART I) UNIFORM CURVED SURFACES

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ABSTRACT

In plate bending by the line-heating method, decisions on the number of heating lines necessary to form the plate and their position are usually made by skillful workers. To automate the plate forming using the line-heating, prediction method to estimate the number of heating lines to bend unidirectional uniform curved surfaces is proposed in this paper as a first step. The phenomenon of bent plate around single heating line is discussed. Using 3-D finite element codes for the thermal-elastic-plastic and the heat conduction problems, numerical simulation is carried out to get an insight into the behavior of the bent plate around the heating line. Based on the computed results, idealization for the deflection shape of the bent plate by a heating line is made. Hence, a prediction method to estimate the number of heating lines, necessary to bend unidirectional uniform curved surfaces, has been proposed. Two case studies, cylindrical and twisted shapes, are discussed by applying the proposed method.

Keywords : Line- heating method, Plate forming, Number of heating lines , Unidirectional curved surfaces, Finite element method.

INTRODUCTION

Forming of three-dimensional surfaces of shell plating of ship structures is accomplished usually using the line-heating method. This method has the capability of forming complicated three-dimensional shapes which could not be achieved using other mechanical methods. In the line-heating method, the plate is bent under the influence of the bending and/or inplane plastic deformation created during the thermal heating and cooling processes. The resulting shape of the plate bent by the line-heating method is difficult to being predicted in advance due to the complex nature of the process. Thus, the skill and the experience of workers are indispensable elements to carry out the plate bending by the line-heating. However, advanced techniques which lead to the automation of the forming process can put the unrevealed skills and experiences of workers aside. Once the necessary information about the forming process by the line-heating method can be accumulated with the aid of computer simulation, mechanization of the process can be put into practical use in shipyards.

Towards the automation of plate forming process using the line-heating method, several experimental and theoretical studies were carried out. Nomoto *et al.* [1-2] presented a line heating simulator in which the plate forming by the heating process was explained using a simple mechanical model. This simulator can be used to train the craftsmen. Ueda *et al.* [3-6] proposed a computer-aided system for plate forming by line-heating to generate information on where, in which direction and how to heat. However, the general idea of generating process plan for heating instructions was proposed and details were not discussed. In addition, Lee [7] presented an algorithm to generate the marking data for plate forming by the line heating based on a simple mechanical model considering bending of beam only.

To automate the plate forming by the line-heating method, necessary information about the number of heating lines, their positions and the suitable heating conditions to get the desired deformation should be available in advance. To generate necessary information in plate forming, prediction method for the number of heating lines is proposed in this paper which is an extension of the previous work [8] presented by the author. The phenomenon of the bent plate around a single heating line is studied using 3-D finite element codes for the thermal-elastic-plastic and heat conduction problems. Numerical simulation is carried out to get an insight into the behavior of the bent plate around the heating line. Based on the computed results, an idealization for the deflection shape of bent plate by a single heating line is made. Thus, a prediction method to estimate the number of heating lines, necessary to bend unidirectional uniform curved surfaces, has been proposed. Two case studies, cylindrical and twisted shapes, are discussed by applying the proposed method.

PHENOMENON OF BENT PLATE BY LINE-HEATING

In forming a flat plate by the line-heating method, the plate is bent around the heating line as shown schematically in Figure 1. In the heated region, the compressive plastic strain that takes place has a certain distribution through the thickness of the plate. The plate is bent under the effect of this permanent deformation mainly in the perpendicular direction to the heating line making an angular distortion in the transverse direction which is considered the main source in forming the plate. Also, depending on the heating condition, there will be a certain angular distortion in the direction parallel to the heating line. In addition, 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 such as the heat input rate Q and the torch traveling speed v together with the thickness of the plate [8]. In the region bounding the plastic deformation, there is a very concentrated curvature in the perpendicular direction to the heating line. On the other hand, the remaining portion of the plate remains straight because there is no plastic deformation exists and only elastic response occurs. The previous explanation for the phenomena of bent plate around the heating line will be examined through the following numerical experiment.

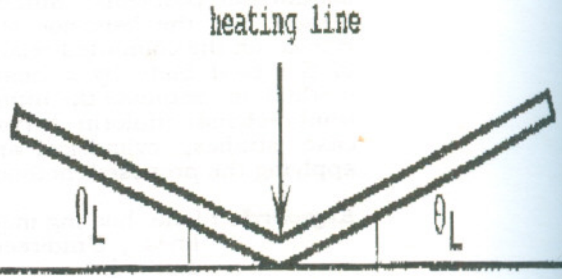

Figure 1 Bent plate by heating line

Method of Analysis

It is well known that the mechanism of plate bending using the line-heating method is highly complicated due to the material and geometrical non-linearities as well as the variation of temperature in the spatial and time domains. Thus, the developed 3-D thermal-elastic-perfect-plastic finite element code in Reference 8, in which large deformations are considered, is employed for the purpose of deformation analysis. In addition, to account for the temperature variation through the domain of the plate, the developed 3-D finite element code for the heat conduction problem in reference [8] is used. The validity of these developed FEM codes had been examined in Reference 8.

Model of Analysis

The considered numerical model is a steel plate of size 0.3×0.3×0.008 m. This plate is assumed to be heated along its longitudinal center line, x-axis, by a moving heat source from one end to the other as shown in Figure 2. The torch is moved with moving speed v and the heat input rate is Q. The variations of the mechanical properties of the material employed in the calculations with temperature are given in Figure 3. The thermal properties of the material, thermal conductivity λ, the specific heat c_p, the density ρ and the heat transfer coefficient γ, are assumed to be independent of the temperature and the following values were used in the computations [8]:

λ	= 67	J/m.s.K
c_p	= 4.1	kJ/kg.K
ρ	= 7.82	ton/m³
γ	= 1.13	J/m².s.K

The heat is applied in the form of heat flux q and its distribution is assumed to be a Gaussian distribution, shown in Figure 2, such that [8]

$$q(r) = q_{max} e^{-\xi r^2} \quad (1)$$

where r is the distance from the center of the heat source and q_{max} is the peak value of the heat flux which can be obtained using the heat input rate Q and the concentration coefficient ξ as follows [8]:

$$q_{max} = Q(\xi / \pi) \quad (2)$$

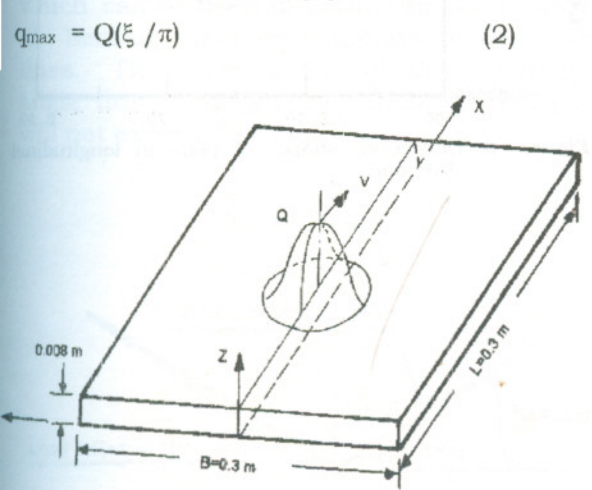

Figure 2 Model of analysis.

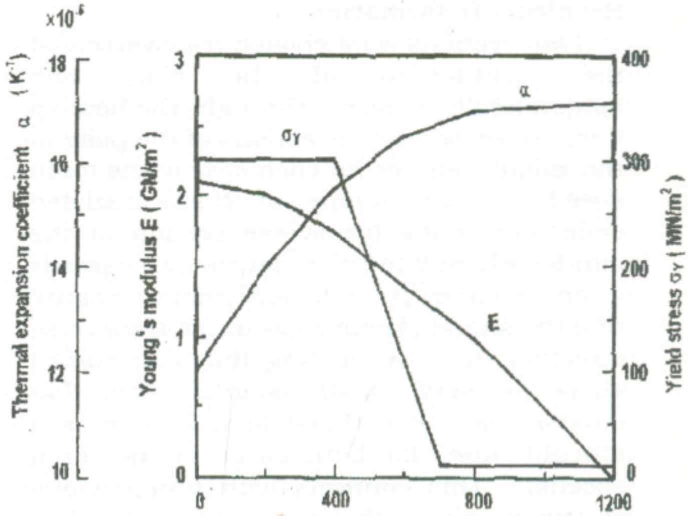

Figure 3 Temperature dependence of mechanical and physical propertis [5]

The value of ξ is assumed to be 3.1×10^3 m^{-2} in the analysis and two speeds for the moving torch were selected, V_1= 0.01 m/s, and V_2= 0.05 m/s. In addition, two values of the heat input rate, 4.6 and 10.4 kJ/s, respectively, were chosen corresponding to each traveling speed such that the maximum temperature of the heated surface becomes nearly the same, about 640 °C. From symmetry, one half of the plate is considered in the calculation and the employed mesh division is shown in Figure 4.

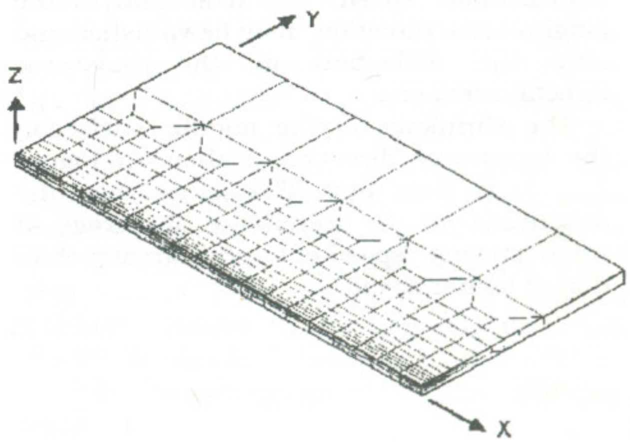

Figure 4 Mesh division used in calculations.

Resulting Deformation

Two sections were chosen transversely at the mid-length of the plate and longitudinally passing through the heating line, to show the deflections of the plate at the middle surface for each case of the torch speed. The shape of the calculated deflection along transverse section at the mid-length of the plate for the two cases is given in Figure 5. It is clear from this figure that the shape of deflection in the transverse direction to the heating line has curved shape of very small length. After that curved part, the shape of deflection is a straight line for both cases of the torch speeds. This confirms with the previous statement about the response of the plate which remains straight away from the location of heating line.

The longitudinal deflection of the plate is shown in Figure 6. It can be seen that the magnitude of deflection in the longitudinal direction is small compared with that in the transverse direction to the heating line. Besides, the deflection along the longitudinal center of the plate has two different directions for each case. At relatively low moving speed of the torch, 0.01 m/s, the shape of deflection in the longitudinal direction has a convex shape with respect to the heated surface. On the other hand, at higher moving speed, 0.05 m/s, it has a concave shape in the longitudinal direction. Thus, at a certain intermediate speed, the deflection in the longitudinal direction may be vanished and only the deflection in the transverse direction remains.

The shrinkage of the middle surface in the transverse direction is shown in Figure 7. It is clear from this figure that, the magnitude of the transverse shrinkage at small moving speed of torch is greater than that at higher speed.

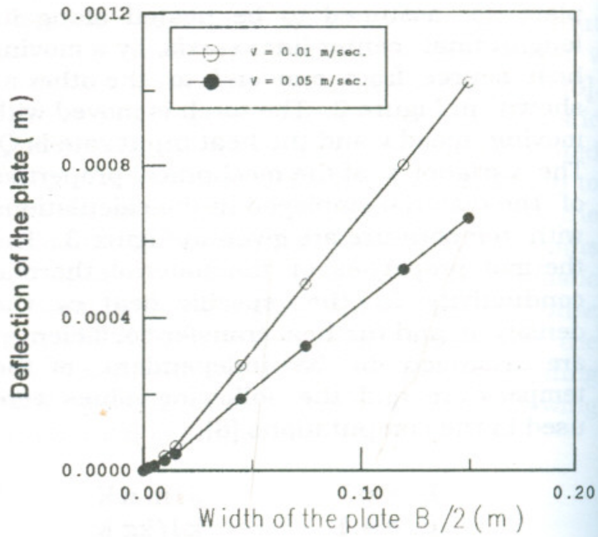

Figure 5 Deflection shape of plate in transverse

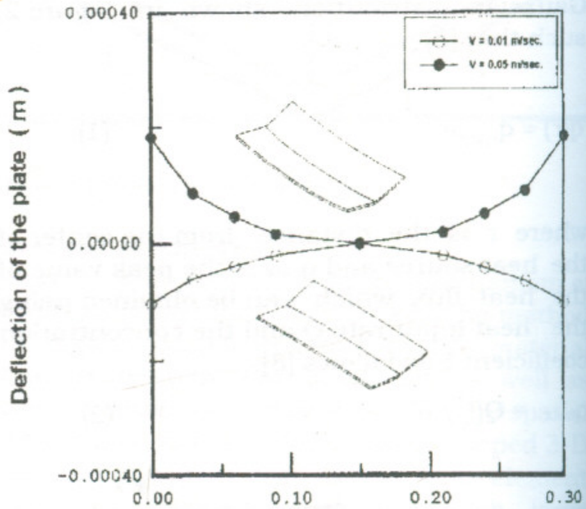

Figure 6 Deflection shape of plate in longitudinal direction.

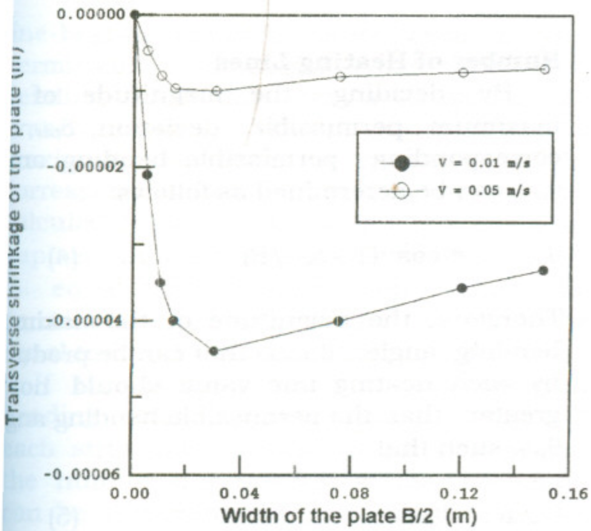

Figure 7 Inplane Shrinkage of plate in transverse direction

PROPOSED METHOD FOR ESTIMATING HEATING LINES

Basics of The Prediction Method

It is clear from figure 5 that the deflection shape of the bent plate around the heating line can be drawn by the dashed lines as shown in Figure 8. The length of the horizontal portion of the deflection shape depends on the size of the torch and almost it will be very small. For simplicity, the length of this flat portion is taken equal to zero and the considered idealized bending which can be used in predicting the number of heating lines corresponds to the solid lines. The error in the idealized bending angle due to neglecting this horizontal part will not exceed 5 %.

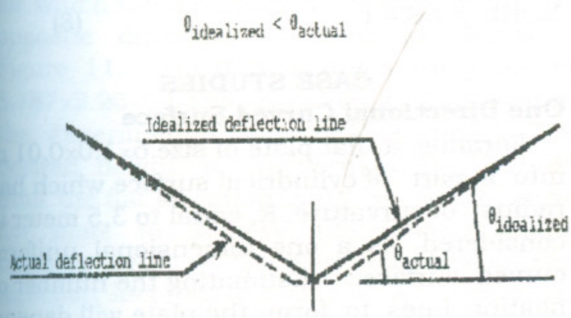

Figure 8 Idealized deflection shape

Based on the idealized deflection line, forming a flat plate into a unidirectional curved surface, such as a cylindrical shape, using the line-heating method can be thought as dividing the flat plate into several strips and bending every two adjacent strips around their line of conjunction a certain angle to approach the required curved shape. 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 and the angular distortion in the longitudinal direction can be ignored.
2. The inplane shrinkage effect will be neglected such that the desired surface is considered to be a developable surface.

Thus, the problem of approaching the required curved form can be treated by methods of geometry rather than continuum mechanics.

Deviation Between Approximate and Actual Shapes

If it is required to form a flat plate into a part of cylindrical surface, the problem is then reduced to make the flat width of the plate approaches the curved part of the cylinder. This can be approximated by dividing the width of the flat plate into a certain number of segments. Any two successive strips are interconnected by a heating line producing certain bending angle θ_L. The ends of each strip should lay on the desired curved part of the cylindrical surface as shown in Figure 9. The maximum deviation, δ, between the approximate and the actual curved shapes depends on the required curvature and the magnitude of the available bending angle that can be produced by the line-heating method. Based on the approximate shape shown in figure 9, the maximum deviation, δ, can be determined from the following equation:

$$\delta = R(1 - \cos\theta_L) \qquad (3)$$

Figure 10 shows the relationship between the maximum deviation of the strip, δ, and the radius of curvature R for different bending angles, θ_L. The selected range of radius of curvature, R, corresponds to that applicable in forming shell plating in shipyards [8]. In addition, the maximum bending angle, $\theta_{L(max.)}$, that can be obtained from the line-heating method will be nearly 1 degree (0.0174 rad). It is clear from figure 10 that the maximum deviation of the strip, δ, increases as the required radius of curvature, R, increases. Also, the maximum deviation, δ, increases as the bending angule, θ_L, increases.

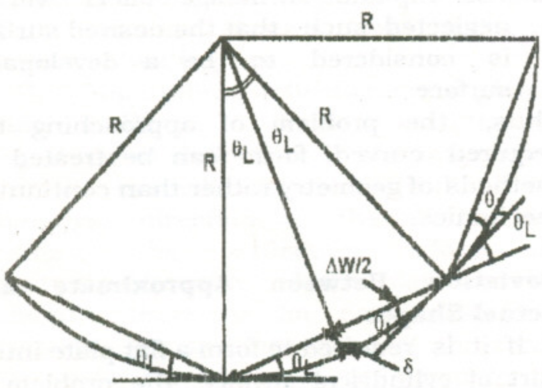

Figure 9 Deviation between approximate shape and actual curve.

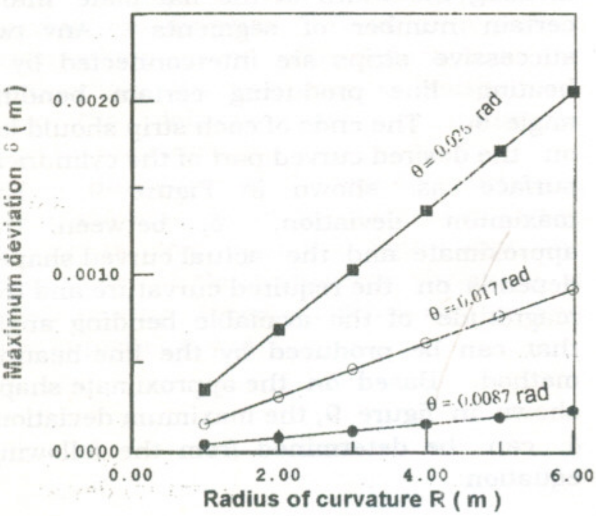

Figure 10 Relationship between maximum deviation and radius of curvature.

Number of Heating Lines

By deciding the magnitude of the maximum permissible deviation, δ_{per}, the corresponding permissible bending angle, θ_{per}, can be determined as follows:

$$\theta_{per} = \cos^{-1}(1 - \delta_{per}/R) \qquad (4)$$

Therefore, the magnitude of the maximum bending angle, $\theta_{L(max.)}$ that can be produced by each heating line value should not be greater than the permissible bending angle, θ_{per}, such that

$$\theta_{L(max.)} \leq \theta_{per} \qquad (5)$$

Hence, based on the bending angle, θ_L, that can be created by the heating line which satisfies the above constraint (5), the corresponding width of the strip , Δw, can be determined as follows

$$\Delta w = 2R\sin(\theta_L) \qquad (6)$$

The width of the plate, W, will be divided into a certain number of strips (NS) such that

$$NS = (W/\Delta w) \qquad (7)$$

where, W = width of the plate.
The width of the plate, W, should be divided into an integer number of strips, and any fraction should be approximated to one. Thus, the number of heating lines (NOHL) can be estimated based on the number of strips (NS) as follows:

$$NOHL = NS - 1 \qquad (8)$$

CASE STUDIES

One Directional Curved Surface

Forming a flat plate of size $6\times1.0\times0.01$ m into a part of cylindrical surface which has radius of curvature, R, equal to 3.5 meter is considered as a one dimensional uniform curved surface. Estimating the number of heating lines to form the plate will depend on the permissible deviation and maximum bending angle that can be obtained from the line-heating method. Since these values of permissible deviation and maximum bending angle are not available at the present stage, different magnitudes of maximum deviation are selected and the corresponding number of heating lines are calculated as given in Table I. For example, suppose that the permissible deviation, δ_{per}, is equal to 0.00025 meter, then the permissible bending angle, θ_{per}, will be equal to 0.0119 radian (0.68°).

If the heating line can produce such bending angle, subsequently the width of each strip, Δw, is equal to 0.084 meter and the number of strips (NS) will be 11.9 which can be approximated to 12 strip for a plate of width 1.0 meter. Then the expected number of heating lines (NOHL) equals to 11 heating line. It can noted from Table 1 that as the permissible deviation increases, the estimated number of heating lines will decrease and vice versa.

Table 1 Estimated number of heating lines to bend flat plate into a part of cylinder based on the permissible bending angle θ_{per}.

Permissible deviation δ_{per} (m)	Permissible bending angle θ_{per} (rad)	Width of strip (m)	Number of Heating lines NOHL
0.00010	0.0075	0.053	18
0.00025	0.0119	0.084	11
0.00050	0.0169	0.118	8
0.00100	0.0239	0.167	5

Two Directional Curved Surface

The selected case for the two directional uniform curved surface is the twisted plate for which the direction of one curvature is in opposite direction to other, as shown in Figure 11. The dimensions of the plate are 5.787×2.26×0.0155 m, taken as that used in the experimental model of Reference 4. The desired height at the corners of the plate from the flat situation is 0.1 m. Bending the flat plate to achieve the desired shape requires bending the plate from face side in direction inclined to x-axis by 45°. The other curvature is determined by bending the plate from the back side in perpendicular direction to the first one as shown in Figure 12. The deflection shape of this twisted shape can be given by the following equation:

$$w_o(x,y) = axy \qquad (9)$$

where, $a = (1/32.696)$

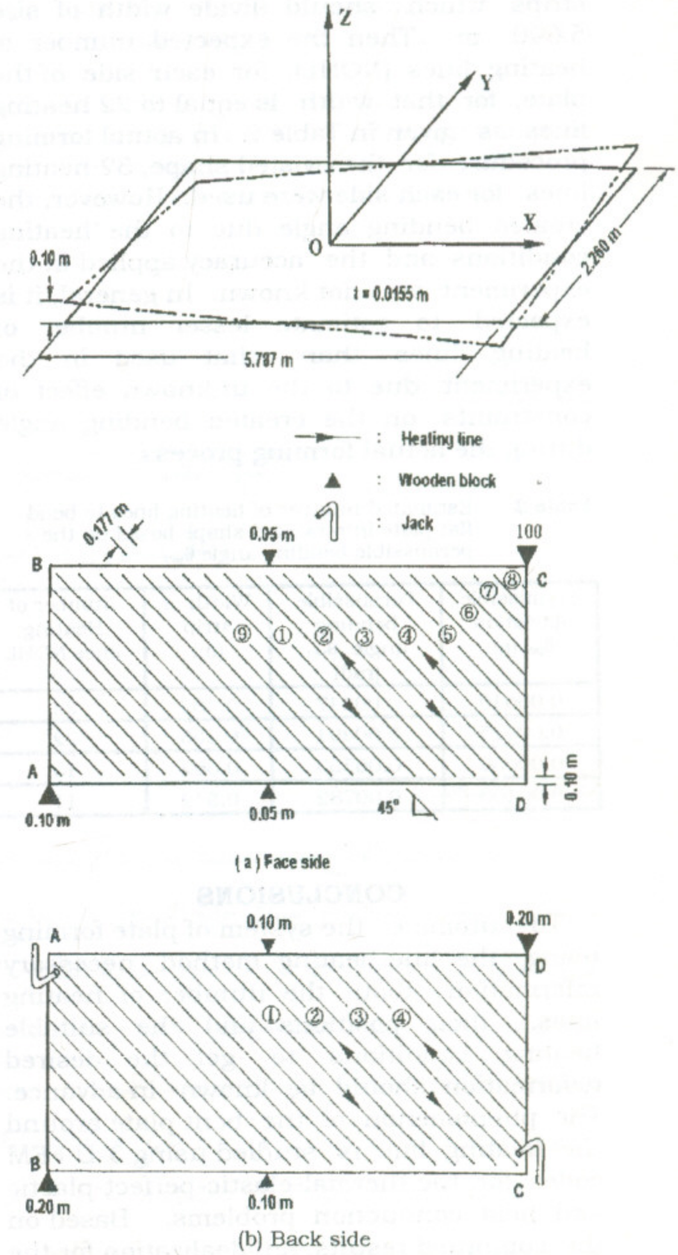

Figure 11 Twisted shape model used in experiment [4]

The radius of curvature for both directions is 32.696 m. Suppose the permissible deviation, δ_{per}, equals to

0.00025 m, then the permissible bending angle, θ_{per}, equals to 0.00391 radian (0.224°) as given in Table 2. If the heating line can produce such bending angle, therefore the width of each strip, Δw, is equal to 0.256 meter and the number of strips (NS) will be 22.22 which can be approximated to 23 strips which should divide width of size 5.690 m. Then the expected number of heating lines (NOHL), for each side of the plate, for that width is equal to 22 heating lines as given in Table 2. In actual forming procedure for the twisted shape, 32 heating lines for each side were used. However, the created bending angle due to the heating conditions and the accuracy applied in the experiment are not known. In general, it is expected to estimate lesser number of heating lines than that used in the experiment due to the unknown effect of constraints on the created bending angle during the actual forming process.

Table 2 Estimated number of heating lines to bend flat plate into twisted shape based on the permissible bending angle θ_{per} .

Permissible deviation δ_{per} (m)	Permissible bending angle θ_{per} (rad)	Width of strip (m)	Number of Heating lines NOHL
0.00010	0.00247	0.162	34
0.00025	0.00391	0.256	22
0.00050	0.00553	0.362	15
0.00100	0.00782	0.512	11

CONCLUSIONS

To automate the system of plate forming using the line-heating method, necessary information about the number of heating lines, their positions and the suitable heating conditions to get the desired deformation should be known in advance. The phenomenon of the bent plate around the heating line is studied using 3-D FEM codes for the thermal-elastic-perfect-plastic and heat conduction problems. Based on the computed results, an idealization for the deflection shape of bent plate by a single heating line is made. Thus, a method for predicting the number of heating lines, necessary to bend unidirectional uniform curved surfaces, has been proposed. Two case studies, cylindrical and twisted shapes, are discussed within the scope of the proposed method. From the present study, the following conclusions are drawn:

1. To bent a plate in the transverse direction to the heating line with a negligible longitudinal deflection in plate forming by line-heating, careful selection of traveling speed of the torch should be made.
2. The deflection shape of a bent plate by the line-heating method can be idealized as straight line rotates a certain angle about the heating line which is considered as a pivot.
3. Based on the previous idealization for the deflection shape of the bent plate, a method is proposed to predict the number of heating lines required to form unidirectional uniform curved surfaces.

REFERENCES

1. T. Nomoto,T.Ohmori, T. Ohmori, T. Sutoh, M.Enosawa, K. Aoyoma, and M. Soitoh. "Development of Simulator for Plate Bending by Line-Heating", Journal of The Society of Naval Architects of Japan, Vol. 168, pp. 527-535, (in Japanese), 1990.
2. T. Nomoto, S. Takechi, K. Shouli, K. Aoyoma, M. Enosawa, and M. Saitoh, "Development of Simulator for Plate Bending by Line-Heating Considering In Plane Shrinkage", Journal of The Society of Naval Architects of Japan, Vol. 170, pp. 599-607, (in Japanese), 1991.
3 Y. Ueda, H. Murakawa , A. M. Rashwan , Y. Okumoto and R. Kamichika, " Development of Computer Aided Process Planning System for Plate Bending by Line-Heating, (Report 1)- Relation between the Final Form of the Plate and the Inherent Strain", Journal of Ship Production, Vol. 10, No. 1 pp. 59-67, (1994).
4. Y. Ueda , H. Murakawa, A. M. Rashwan, Y. Okumoto and R. Kamichika, "Development of Computer Aided Process Planning System for Plate Bending by Line-Heating, (Report 2)- Practice for Plate Bending in Shipyard

Viewed from Aspect of Inherent Strain", Journal of Ship Production, Vol. 10, No. 4, pp. 239-247, (1994).

5. Y. Ueda, H. Murakawa, A. M. Rashwan, R. Kamichika, M. Ishiyama, and J. Ogawa, " Development of Computer Aided Process Planning System for Plate Bending by Line-Heating, (Report 3)- Relation between Heating Condition and Deformation", Journal of Ship Production, Vol. 10, No. 4, pp. 247-257, (1994).
6. Y. Ueda, H. Murakawa, A. M. Rashwan, R. Kamichika, M. Ishiyama, and J. Ogawa, "Development of Computer Aided Process Planning System for Plate Bending by Line-Heating, (Report IV)- Decision Making on Heating Conditions, Location and Direction " , Journal of The Society of Naval Architects of Japan, Vol. 174, pp. 683-695 (in Japanese), 1993, [Transactions of JWRI Vol. 22, No. 2 , pp. 305-313 (in English), (1993).
7. Lee J. ," Development of Automatic Marking Generation System for Plate Forming by Line-Heating", Journal of Ship Production, Vol. 12, No. 4, pp. 247-253, 1996.
8 Ahmed M. Rashwan ," Computer Aided Planning System for Plate Bending by Line-Heating", Ph.D. Dissertation, Osaka University, Japan, (1994).

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التنبؤ بخطوط التسخين لثنى ألواح القشرة لبدن السفينة (الجزء الأول) الأسطح ذات الانحناء المنتظم

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ملخص البحث

عند تشكيل ألواح بدن السفينة باستخدام طريقة التسخين الخطى، يستلزم تحديد عدد خطوط التسخين اللازمة للتشكيل مع تحديد أماكنها وكذلك حالة التسخين المناسبة لكل خط قبل تطبيق الطريقة. مثل تلك المعلومات يتم تحديدها عن طريق العمال ذوى الخبرة والمهرة. و لتطوير عملية تشكيل الألواح باستخدام طريقة التسخين الخطى لكي تصبح آلية ، تم اقتراح طريقة للتنبؤ بعدد خطوط التسخين لثنى الأسطح ذات الانحناء المنتظم في هذا البحث كخطوة أولى. وللوصول الى هذا الغرض، تم مناقشة الظواهر المصاحبة لثنى لوح بواسطة التسخين. وباستخدام كود ثلاثي الأبعاد لطريقة العناصر المحددة لكل من التحليل الحراري-المرن-اللدن و انتقال الحرارة تم عمل محاكاة عددية لمعرفة سلوك ثنى اللوح بواسطة خط التسخين. وبناء على النتائج التي تم حسابها ، تم عمل تمثيل لشكل الانحناء للوح المثنى بواسطة خط تسخين. وبناء على ذلك تم اقتراح طريقة للتنبؤ بعدد خطوط التسخين اللازمة لثنى الأسطح ذات الانحناء المنتظم. أيضا تم مناقشة تحديد خطوط التسخين لحالتي, سطح أسطواني و سطح ملتو الشكل ، باستخدام الطريقة المقترحة.