Prediction of heating lines for bending shell plating of ship structure: (part IV) inplane heating lines for saddle surface

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In this paper, a method is proposed to determine instructions for the position and the number of inplane heating lines necessary to form a single curved plate into a saddle surface. The procedure to determine the position and direction of heating lines is explained at first using FEM. Then, the number of inplane heating lines is determined using the proposed method based on the experimental data given in part (III) for the bending angle and the inplane shrinkage of sample plates due to a single heating line. To examine the validity of the instructions obtained from the proposed method to form a prescribed saddle shape, two experiments were carried out to form two plates with two different initial configurations using the line heating method, to the same saddle shape. The formed plates, based on the instructions obtained from the proposed method, were in good agreement with the prescribed saddle shape.

في هذا البحث تم اقتراح طريقة لاستنتاج أماكن و عدد خطوط التسخين الانكماشية اللازمة لتشكيل لوح ذو انحناء واحد إلى شكل البردعة. في البداية تم توضيح الخطوات اللازمة لإيجاد أماكن واتجاه خطوط التسخين باستخدام طريقة العناصر المحددة. بعد ذلك تم إيجاد عدد خطوط التسخين الانكماشية وأماكنهم باستخدام الطريقة المقترحة بالاعتماد علي نتائج التجارب الموجودة بالجزء الثالث عن زاوية الثني و الانكماش لعينات من ألواح الصلب نتيجة استخدام خط تسخين واحد. ولاختبار فاعلية التعليمات المستنتجة باستخدام الطريقة المقترحة, تم إجراء تجربتين لتشكيل لوحين مختلفين للحصول علي شكل البردعة بتطبيق طريقة التسخين الخطي. وكانت الأشكال الناتجة في حالة تطابق مرضية مع الشكل المطلوب تشكيله نتيجة تطبيق الأوامر باستخدام طريقة التسخين الخطي.

Keywords: Line heating method, Saddle shape, Bending angle, Shrinkage, Inplane heating lines

1. Introduction

Forming of a steel plate is carried out through creating permanent deformations into the plate. The line heating method is widely used to form complex shapes of curved plates in shipyards. Forming of the curved plates in shipyards is usually done by rollers or press machines in one direction and by the line heating in the other direction. Using the line heating method, the plate is bent under the influence of the compressive plastic deformation created by the thermal effects during the heating and cooling cycle. Forming of plates by the line heating method is carried-out by skilled and experienced craftsmen. The aging problem and the shortage in skilled workers have become a problem in many shipyards even in industrial countries [1-2]. To reveal the invisible skills, a system of computer-aided identifying instructions for plate forming by the line heating method should be developed. Several experimental and theoretical studies were carried out to put the line-heating method into practical use in shipyards [2-11].

In forming flat plates in two directions, bending deformation is generally required in one direction and inplane deformation is usually necessary for the other direction. The heating lines necessary to get the bending deformation are called the bending heating lines and those necessary to get the inplane deformation will be called the inplane heating lines. Rashwan [7-8] proposed an equation to estimate the number of bending heating lines necessary to bend a flat plate into a uniform single curved surface. An experimental verification was carried out to prove the validity of the instructions obtained based on the proposed equation. In addition, Salem et al. [9-10] developed an algorithm, generalizing the previous equation, to estimate the number of bending heating lines to form a flat plate to a single curved shape with variable curvature. Also, experimental verification was made and the validity of applying the instructions determined based on the developed algorithm was confirmed.

To form a flat plate to a saddle surface, which has two perpendicular curvatures in opposite directions, bending deformation is created for one curvature and inplane shrinkage is produced for the second curvature. Bending of plate in first direction can be done using mechanical and/or line heating [2]. The inplane heating lines are usually applied to produce inplane shrinkage for the second curvature. In this paper, a method is proposed to estimate the number and the position of inplane heating lines to obtain a saddle shape. The procedure to determine the position and direction of inplane heating lines is explained at first using FEM. Then, based on the data of measured bending angle and shrinkage given in part III, instructions are obtained for the number and final position of inplane heating lines necessary to form a curved plate into a saddle shape. To examine the validity of these instructions, two experiments were carried out to form two single curved plates, using the line heating method with two different heating conditions, into prescribed saddle shape. The resulting shapes obtained by applying these instructions using the line heating method were in good agreement with the prescribed one.

2. Position and direction of inplane heating lines

2.1 Position of heating lines

The position of inplane heating lines can be explained based on the inplane strain distribution of the desired shape. A saddle shape, shown in fig. 1, is chosen as an example with dimensions 1000×2000×16 mm for the flat plate. The maximum and minimum deflections are 29.69 and −39.58 mm, respectively. The considered saddle deflection shape is given by the following equation [2]:

$$W(x,y)=g(y)f(x)+h(y) \quad (1)$$

Where;

$g(y)= 1-(3/20)10^{-6}\times y$

$f(x)= (-4.897459443\times 10^{-8})(x-1000)(x+1925)x$

$h(y)= (8.162432405\times 10^{-9})(y-2000)(y+3850)y$

The bending and inplane strain distributions inherent to the desired shape can be obtained by forcing the flat plate to deform elastically to the required shape. A finite element program is used to force the flat plate to the desired shape and to compute the principal bending and inplane strain distributions. The distribution and magnitude of the principal bending and inplane strains for the considered saddle shape are shown in fig. 2. In this figure, the strain components are given as vectors representing their magnitudes and directions. The length of the arrow represents the scaled value of the strain in each element. The direction of the arrow's head for each vector, in-and-out directions, refers to the compressive and tensile components of the inherent strain, respectively.

One can note from fig. 2-a that the calculated principal bending strain distribution is dominant nearly in one direction, i.e. the width direction. On the other hand, the compressive inplane strain components, given in fig. 2-b, are observed to be dominant in the middle of the plate in longitudinal direction. Consequently, forming the saddle shape can be produced using mechanical or line heating method to get the bending deformation for the curvature in the x-direction. Then, the line heating method can be used to create shrinkage for the second curvature in the y-direction. The general rule in defining the position of inplane heating lines is that they should be applied at positions where the compressive inplane strains exist. The direction of inplane heating lines will be perpendicular to the direction of compressive inplane strain inherent to the desired shape. However, it can be noticed from fig. 2-b that the tensile components of the inplane strain are distributed along the edges of the plate. This tensile strain component cannot be created by the heating line method.

As a matter of fact, the plate forming process is a nonlinear process so that different procedures may be applied to achieve the same desired shape. Consequently, the tensile inplane strain components can be eliminated and only the compressive inplane strain components remain. The method of eliminating these tensile components for saddle shape is described in [2] and the result for the compatible compressive inplane strain is shown in fig. 3 [2]. Based on this result, one can see that only compatible compressive inplane strains exist that contribute greatly in forming the plate to the desired shape. In addition, these compressive inplane strains cover the whole domain of the plate. Hence the position of the inplane heating lines, for the saddle shape, can be the whole domain of the plate corresponding to the position of the compressive inplane strain. The suitable direction of the inplane heating lines will be discussed in the next section.

2.2. Direction of heating lines

It is assumed that straight heating lines are enough for forming the saddle shape as those carried out in real practice. Shrinkage of constant magnitude, which can be produced by line heating method, is applied in the domain of the plate. Also, certain direction of the applied shrinkage can be selected as initial direction and the inplane strain energy is being calculated. Afterwards, by changing the direction of the applied shrinkage and computing the corresponding strain energy, the direction of the applied shrinkage that produces minimum inplane strain energy will be the desired direction. Hence, the proper direction of inplane heating lines will be perpendicular to the direction of the applied shrinkage that produces minimum inplane strain energy in the plate.

An analysis is made on the selected saddle shape using the Finite Element Method to clarify the previous discussion. The initial shape, due to bending deformation, of the saddle surface is obtained at first by applying the calculated bending strain to the flat plate. Then small constant magnitude of shrinkage is applied in the form of prescribed displacements parallel to y-axis for the selected elements as shown in fig. 4. The corresponding direction of heating lines will be perpendicular to the selected direction for the applied shrinkage, that is parallel to x-axis, and this direction will be referred to as the direction of heating line with zero angle.

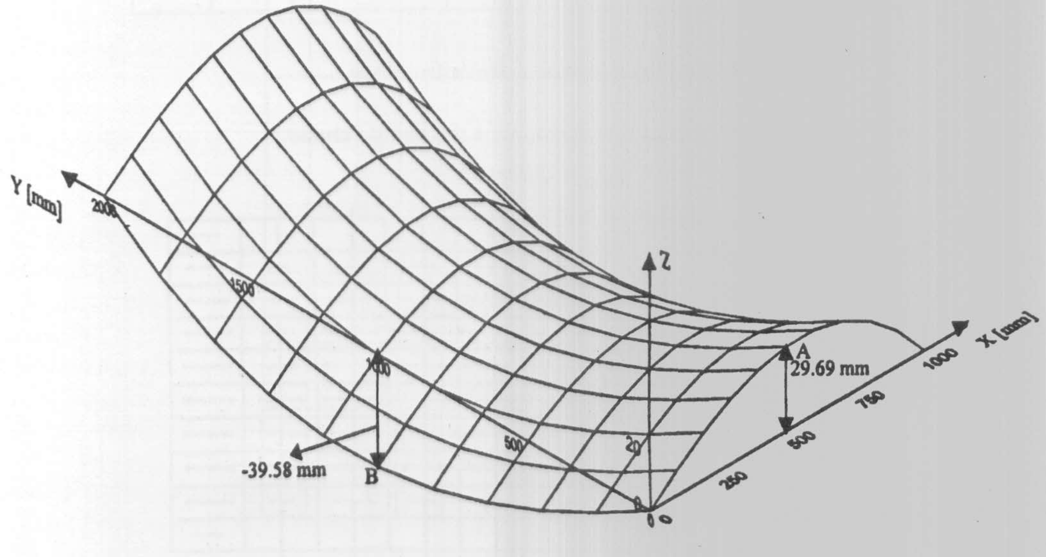
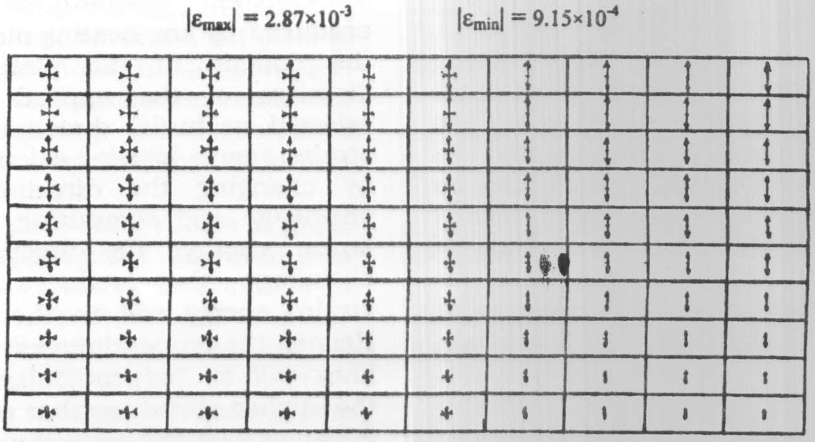
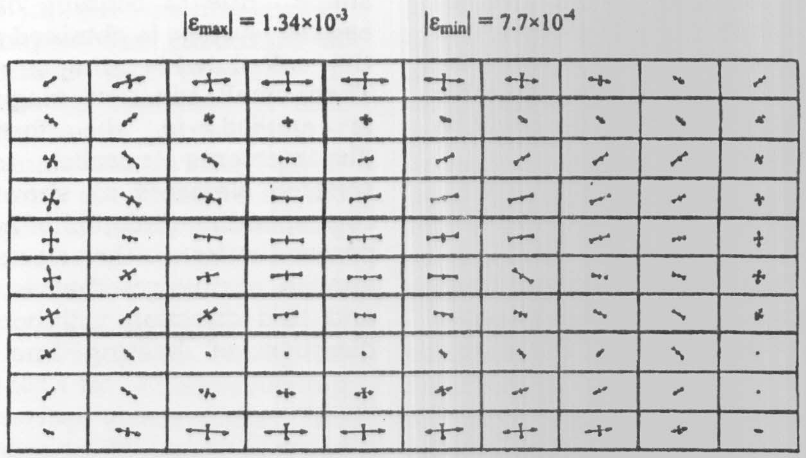


Fig. 1. Considered saddle shape.



a- Bending strain inherent to the desired shape



b- Inplane strain inherent to the desired shape

Fig. 2. Strain distribution for the saddle shape.

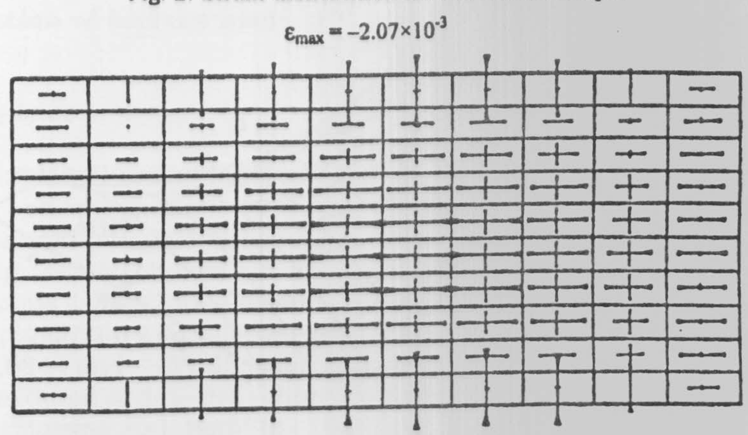


Fig. 3. Distribution of orthogonal compressive inplane strain.

Using FEM, small value of shrinkage is applied in incremental form, at the nodes of the chosen elements such that the plate is deformed to approach the desired shape with minimum error in the desired geometry. When the suitable magnitude of the accumulated shrinkage is determined for this direction, the inplane strain energy, U_m, can be computed as follows:

$$U_m = \int \sigma \varepsilon^T dv \qquad (2)$$

where σ and ε are the inplane stress and strain components, respectively. The integration is carried out over the entire volume of the plate. By changing the direction of the applied shrinkage, as shown in fig. 4, and computing its accumulated magnitude that is necessary to produce the desired shape with minimum error, the corresponding inplane strain energy can thus be determined. The direction corresponding to the minimum inplane strain energy will be the required direction. The magnitude of the accumulated shrinkage necessary to get the saddle shape with minimum error in geometry is then computed together with the inplane strain energy for different directions as given in table 1. It is clear from this table that the direction of zero angle, which produces minimum error in geometry, gives the minimum strain energy as expected for the saddle shape. In addition, the suitable magnitude of accumulated shrinkage increases as the angle with respect to zero angle direction increases and the corresponding strain energy increases as well. Thus, the proper direction of inplane heating lines can be decided as the direction of zero angle, parallel to x-axis, which gives minimum strain energy for the considered saddle shape.

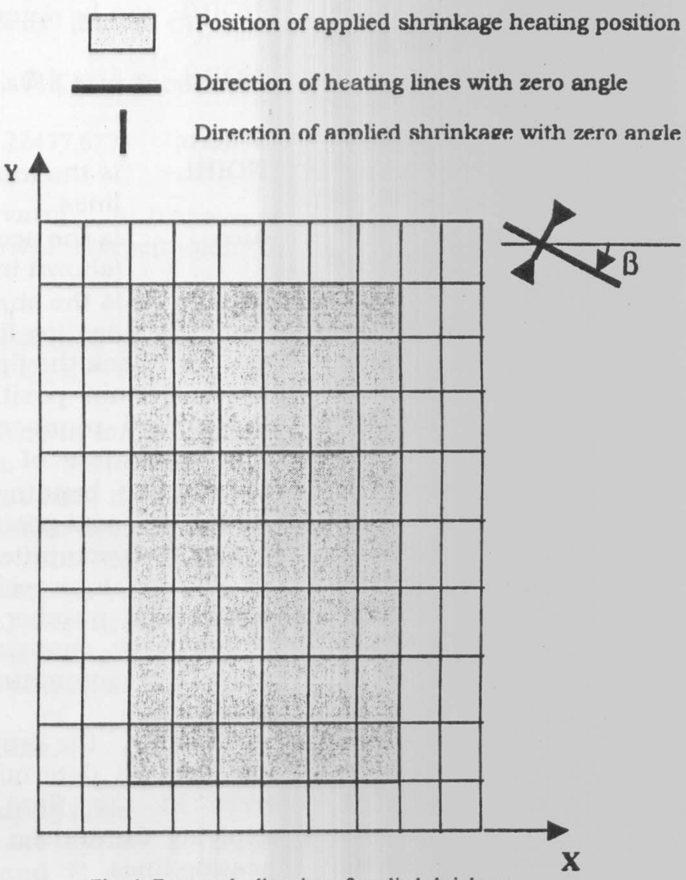


Fig. 4 Zero angle direction of applied shrinkage.

Table 1
Magnitude of accumulated shrinkage, error in geometry and strain energy for different directions

Direction of inplane heating lines [deg]	Accumulated shrinkage (δ_{acc})	Resulting deflection and error in geometry				
		Deflection at A [mm]	Error [mm]	Deflection at B [mm]	Error [mm]	Strain energy [N.m]
0	-1.2	25.6	-4.	-39.33	-0.25	1290.
30	-1.6	25.02	-4.6	-41.4	1.8	1334.6
45	-1.87	25.67	-4.	-38.47	-1.1	1525
60	-2.4	29.55	-0.136	-37.91	-1.7	1686.74

3. The proposed method

A method is proposed to estimate the number and position of inplane heating lines "NOIHL" based on the accumulated shrinkage using the finite element method. The procedure of the proposed method is as follows:

1. It is assumed that the bending deformation in the first direction can be obtained using any forming method.
2. The position of heating lines can be assigned for the whole domain of the plate for the saddle shape. The proper direction of heating lines is determined based on the minimum strain energy using finite element method.
3. Since the inplane heating line produces shrinkage δ, and bending angle θ, the ratio δ/θ can be evaluated from experiments as a parameter for different heating conditions and thickness of plate.
4. Small magnitude of shrinkage, $\Delta\delta$, and bending angle, $\Delta\theta$, is applied into the plate in incremental form such that the ratio between the applied shrinkage and bending angle, $\Delta\delta/\Delta\theta$, is the same as that determined from experiments. The shrinkage and bending angle are applied at the previous decided proper location and direction as prescribed displacements as shown in fig. 5. The accumulated magnitude of the shrinkage and bending angle that give the desired deflection with acceptable error are determined using the finite element method.
5. Based on the accumulated shrinkage in the plate, δ_{ACC}, and that produced by a single inplane heating line, δ_{HL}, according to certain heating conditions with the same ratio of $(\delta/\theta)_{HL}$, the number of inplane heating lines, NOIHL, can be determined as follows:

$$NOIHL = \delta_{ACC} / \delta_{HL} . \quad (3)$$

Where;

NOIHL is the number of inplane heating lines.

δ_{ACC} is the accumulated shrinkage (shown in fig. 5).

δ_{HL} is the shrinkage produced by single heating line (shown in fig. 6).

6. To check the final locations of the heating lines, certain positions are selected for the determined number of inplane heating lines. The magnitude of the shrinkage δ_{HL} with the appropriate bending angle θ_{HL} are applied at initial selected positions and the error in final geometry is computed using FEM.
7. The appropriate position of the determined number of inplane heating lines is obtained by changing their relative positions so as to get minimum error in the final desired geometry.
8. Finally, the proper length of each heating line can be determined based on minimum error in the final geometry obtained from applying δ_{HL} and θ_{HL} at the previous of inplane heating lines.

4. Experimental verification

4.1. Models of experiment

Two steel plates, A37, of dimensions 2000×1000×12 mm are used in the experiments. Two initial configurations of curved plates, i.e. parts of cylindrical and elliptical shapes, are used to get the desired saddle shape. The two models, cylindrical and elliptical shapes, are referred here to as model C and model E, respectively. Both models C and E are formed in the second, longitudinal, direction to achieve the same saddle shape using different heating conditions. The required deflection in the y-direction is determined from the term B in the following equation:

$$W = A + B. \quad (4)$$

Where,

$$A = \sqrt{r^2 - (y-500)^2} - 3968.627 \text{ (model C)}$$

$$A = a(\sqrt{1-(y-500)^2/b^2}) - 718.7362 \text{ (model E)}$$

$$B = -(\sqrt{R^2-(x-1000)^2} - 22477.627)$$

r is the radius of curvature in transverse direction for cylindrical shape(model C) = 4000 mm,

a, b are the short and long chords of, the elliptical shape (model E), a = 750 mm and b = 1750 mm

R is the radius of curvature in longitudinal direction = 22500 mm.

It should be noted that each model, C and E was formed using the line heating method from flat configuration into the parts of cylindrical and elliptical shapes. After forming the plates in x-direction, the first curvature direction, initial deflection for each model is created in y-direction as shown in fig. 7. The maximum magnitude of the initial imperfection is about 3.5 mm.

4.2. Number of inplane heating lines

Both the models C and E are forced to deform elastically from their initial positions to the desired shape. The initial configurations of models, part of cylindrical and elliptical shapes, are considered here without the initial imperfections, shown in fig.7, in y-direction. From the previous results concerning the direction of heating lines for the saddle shape, the necessary direction of the inplane heating lines to both models C and E is taken parallel to x-axis. From symmetry, only one quarter of the plate is analyzed and the accumulated shrinkage is computed using finite element method.

Two different heating conditions are applied for model C and model E, respectively, as given in table 2. This table shows the magnitude of measured shrinkage δ_{HL}, and bending angle θ_{HL}, given in ref. [11]. These results were obtained from applying single heating line on plate samples made of steel 37 and of dimensions 450×300×12mm. Due to the difference in applied heating conditions for the same plate thickness, the magnitudes of the measured shrinkage are 0.44mm and 0.21mm for model C and model E, respectively.

The accumulated shrinkage is determined as given in table 3 such that the error in approaching the required shape is as small as possible. Using the assigned values of δ_{HL} and the determined accumulated shrinkage δ_{ACC}, the number of inplane heating lines is computed using eq. (4). The computed accumulated shrinkage δ_{ACC}, the error in produced geometry and the number of inplane heating lines are given in table 3.

Based on the computed number of inplane heating lines and the assigned values of δ_{HL}, the final position and length of each heating line are determined using FEM. The determined position and the length for the heating lines are shown in figs. 8-a and 8-b for model C and model E, respectively. It should noted that if the number of heating lines is estimated based on the corresponding bending angle θ_{HL}, the necessary number of bending heating lines will be 1 and 2 for model C and model E, respectively. This number of bending heating lines is different from the number of inplane heating lines determined based on the accumulated shrinkage.

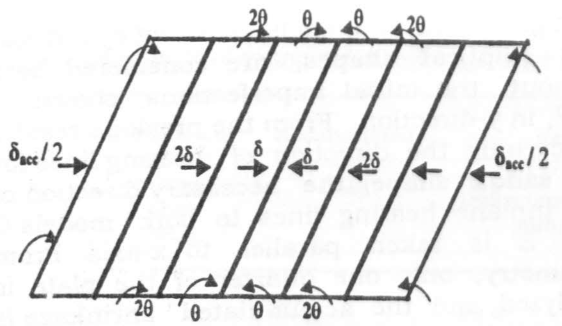


Fig. 5. Schematic representation of applied shrinkage and bending angle to the plate.

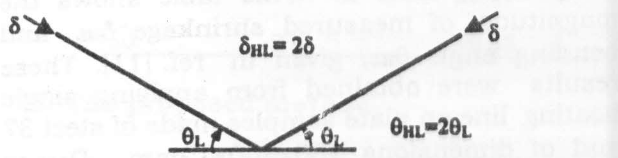


Fig. 6. Shrinkage and bending angle produced by single heating line.

4.3. Experimental verification for obtained instructions

Based on the determined positions for the inplane heating lines for both of the models C and E, the experimental procedure is carried out as follows:

(i) The position of inplane heating lines is marked as shown in fig. 8.

ii) The heating lines are applied on back surface of the plate, the concave surface of the model C and the model E at the predetermined positions. The heat source is moved along the marked lines at speed equals 1 mm/sec for each heating line according to the shown sequence in fig 8. The plate is left to cool down before starting a new heating line.

(iii) After finishing the heating and cooling down to the room temperature, the deflection is measured, using the measuring method shown in fig. 9, at 5 sections, A1, B1, C1, D1 and E1, along the length of the plate as shown in fig. 10. The measured results at the considered sections are converted to compare them directly with the target shape. The obtained shapes at these sections compared with the target shape are shown in fig. 11 for model C and in fig. 12 for Model E.

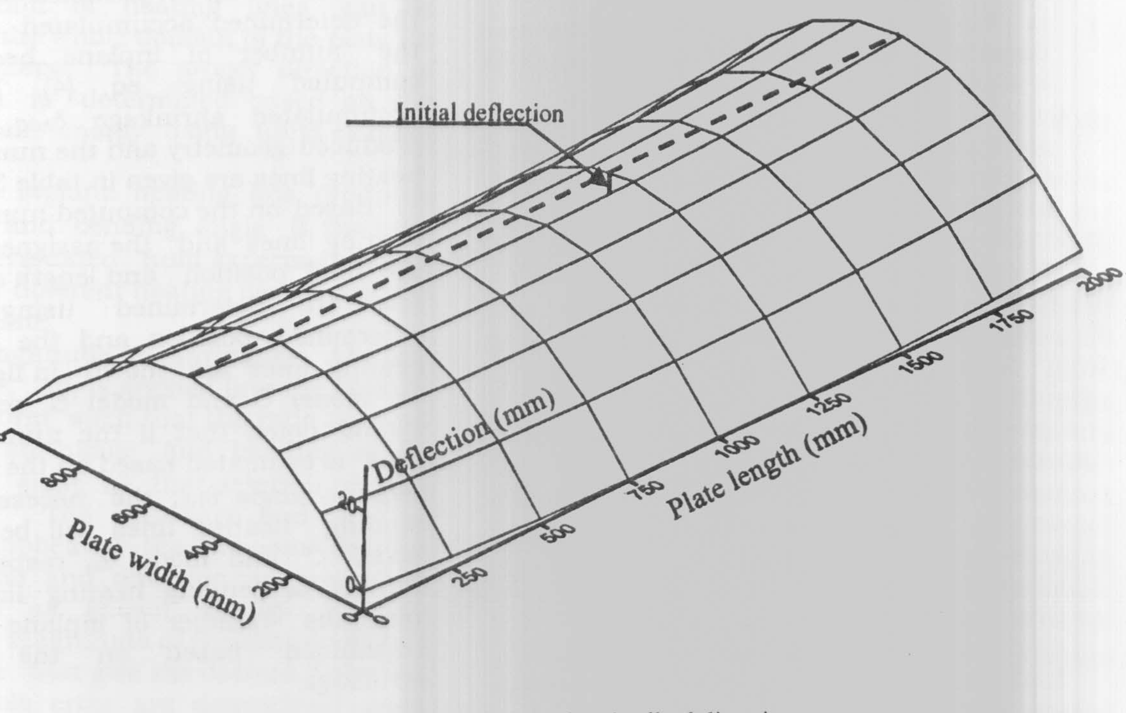


Fig. 7. Initial deflection of model C and E in longitudinal direction.

Table 2
Heating conditions and resulting shrinkage for both models C and E

Heating conditions	Model C	Model E
Burner type	ANM 5-12, BOC, 3/64	AHSO 10-20, 5 bar
Oxygen pressure	4 kg/cm²	5 kg/cm²
Acetylene pressure	1 kg/cm²	0.75 kg/cm²
Tip height	20 mm	20 mm
Torch speed	1 mm/sec	1 mm/sec
δ_{HL}	-0.44 mm	-0.23mm
θ_{HL}	0.0418 rad	0.024 rad
$(\delta / \theta)_{HL}$	10.53 mm/rad	9.6 mm/rad

Table 3
Accumulated shrinkage, resulted deflection, and error in geometry

	δ_{HL} [mm]	δ_{Acc} [mm]	NOIHL	Resulted deflection [mm]			
				Deflection at point A W_{max}	Error [mm]	Deflection at point B W_{min}	Error [mm]
Model C	-0.44	-1.6	4	28.166	3.2	-20.5497	1.682
Model E	-0.23	-1.65	8	26.6	4.6	-22.475	0.24

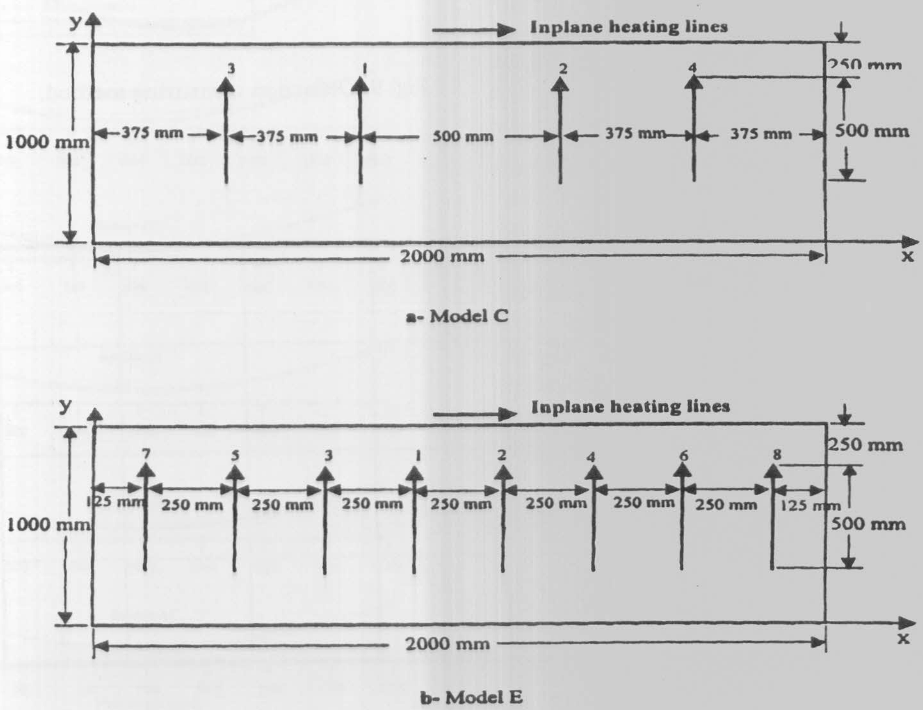


Fig. 8. Position and direction of in plane heating lines.

4.4. Discussion of results

One can see from figs. 11 and 12 that there is a good agreement between the obtained shape based on developed instructions and the required shape. The maximum error in deflection between the desired deflection and the formed shape is 3.26 mm for model C and 3.76 mm for model E. The magnitude of the initial imperfection for both models, is about 3.5 mm, should be included in the obtained value of error. Consequently, the magnitude of error should be reduced due to the initial imperfection leading to small amount of error. However, these values of error for both shapes are within the tolerance limits, ± 5 mm, given by Japan Shipbuilding Quality Standards [12]. Thus, the validity of applying the instructions determined based on the proposed method has been proven experimentally.

The determined position and the number of inplane heating lines, using the proposed method, for both models C and E, to achieve the same shape in the second direction for saddle shape are different. This is because the measured shrinkage δ_{HL} for a single heating line is different due to different heating conditions. Thus, the suitable heating conditions to produce the shrinkage δ_{HL} by each heating line are necessary to be identified in advance. In addition, if the bending angle θ_{HL} is used to estimate the number of heating lines to achieve the curved shape in the other direction, the number of heating lines should be 1 and 2 for model C and Model E, respectively.

This would not produce the desired shape since the actual number of inplane heating lines applied to get the desired shape is 4 and 8. Thus, to form saddle shapes in the second direction, the number of inplane heating lines should be estimated based on the shrinkage to from the plate in the second direction using the line heating method. It can be seen from figs. 11 and 12 that good agreement between the formed plate by inplane heating lines, based on the proposed method, and the target shape. Thus, the proposed method is valid to determine instructions about the number and positions of inplane heating lines necessary to form the saddle shapes.

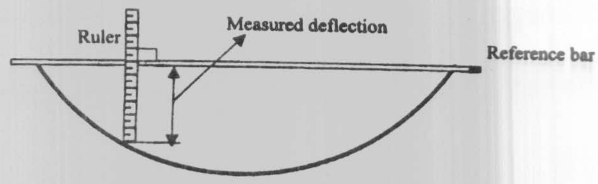


Fig. 9. Deflection measuring method.

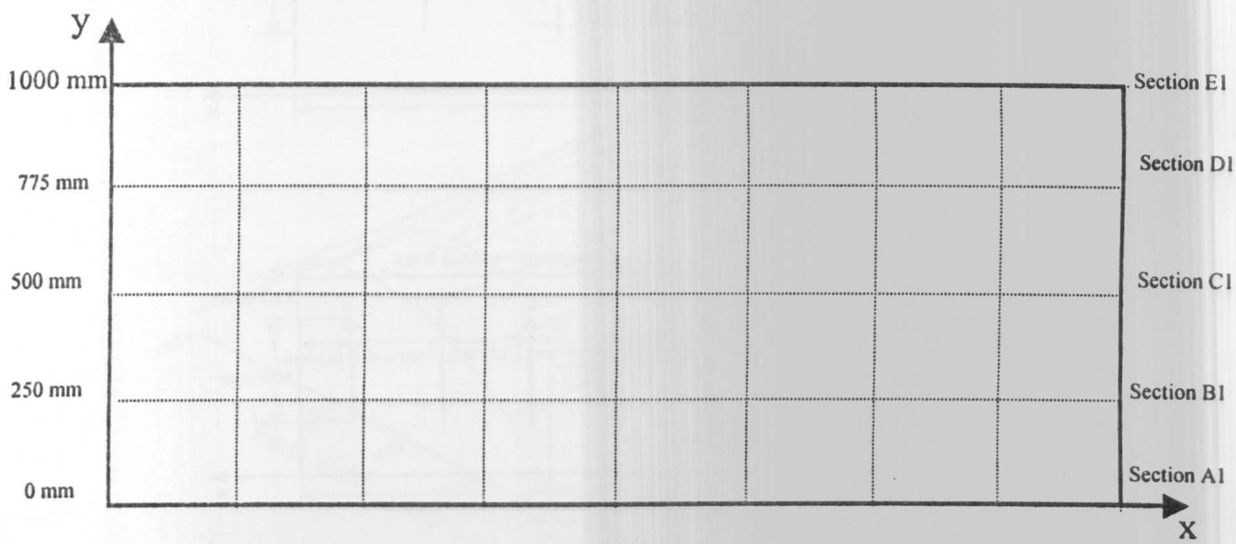


Fig. 10. Sections for deflection measurements in longitudinal direction.

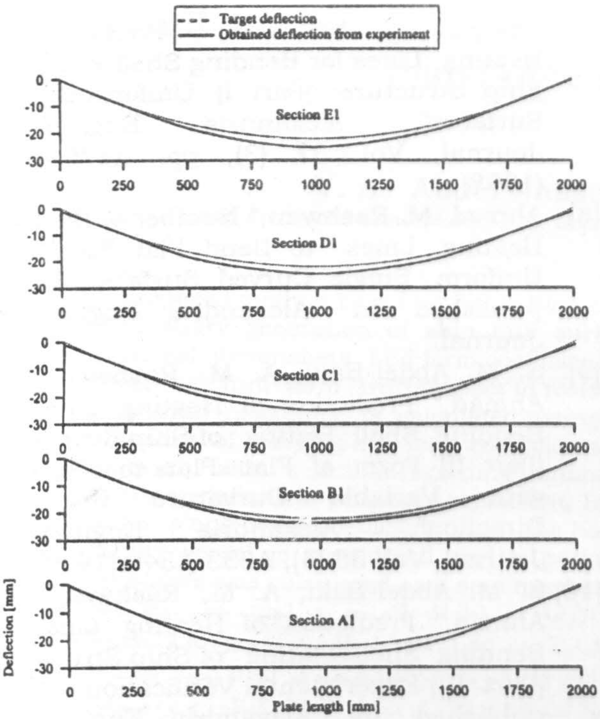


Fig. 11. Comparison between obtained deflection from experiment and target deflection at different sections (Model C).

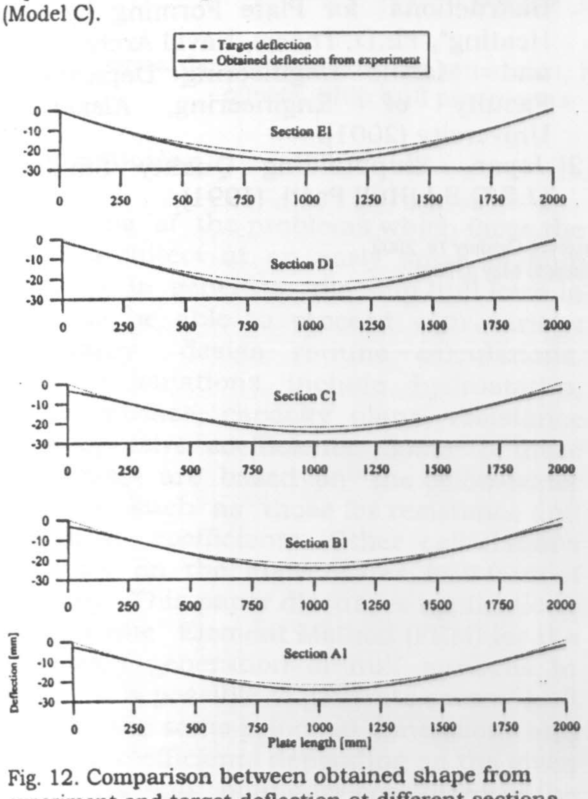


Fig. 12. Comparison between obtained shape from experiment and target deflection at different sections (Model E).

5. Conclusions

Through this study the following conclusions are drawn:

1. The proper position and direction of inplane heating lines can be decided based on the minimum inplane strain energy produced from applying constant magnitude of shrinkage at selected positions. The accumulated applied shrinkage can be determined using FEM.
2. Based on the computed accumulated shrinkage and the decided proper direction, a method is proposed to determine instructions regarding the number and position of inplane heating lines.
3. The validity of developed instructions, to form two different initial configurations to the same final saddle shape, using the proposed method is examined through experimental work. Good agreement between the formed plates by the line heating method and the desired shape is obtained proving the validity of developed instructions using the proposed method.
4. To estimate the number of heating lines necessary to form the saddle shape in the second direction, the number of heating lines must be determined based on the accumulated shrinkage and that produced by a single heating line. The number of heating lines based on the required curvature and the bending angle created by a single heating line will not produce the desired shape as proved by the experiments.
5. The procedure given by the proposed method can be applied in any shipyard and the only information needed is the bending angle and shrinkage produced by a single heating line on sample plates with different thickness and equipment used in that shipyard.

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