Prediction of heating lines for bending shell plating of ship structure: (part III) experimental verification

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In this paper, experimental measurements for the bending angle and the inplane shrinkage of sample plates due to single heating line are presented. These results can be used as database to obtain the necessary instructions to form a flat plate into a curved surface using the line heating method. In doing so, the algorithm given in part (II) of this research work is used to determine forming instructions by line heating method based on this database. The instructions resulting from this algorithm for a prescribed part of elliptical shape have been obtained. These instructions were applied experimentally to a flat plate and the formed shape was in good agreement with the desired shape.

في هذا البحث تم عرض نتائج القياسات العملية لزاوية الثني والانكماش لعينات من الألواح نتيجة استخدام خط تسخين واحد. هذه النتائج يمكن استخدامها كقاعدة بيانات لإيجاد الأوامر اللازمة لتشكيل لوح مستوي إلى سطح منحني باستخدام طريقة التسخين الخطي. هذا وقد تم استخدام الطريقة المقترحة في الجزء الثاني من هذا البحث، بمساعده هذه البيانات، لإيجاد الأوامر اللازمة لتشكيل لوح مستوي إلى سطح ناقصي الشكل. و بتنفيذ هذه الأوامر عمليا باستخدام طريقة التسخين الخطي لتشكيل لوح مستوي وجد أن الشكل الناتج من التشكيل في حالة تطابق جيد مع الشكل المطلوب الوصول إليه.

Keywords: Bending angle, Shrinkage, Line heating method, Number of bending heating lines, Single curved surface.

1. Introduction

Forn..ng of three-dimensional surfaces of shell plating of ship structure is usually accomplished with the line-heating method. This method can be used to form complicated shapes that could not be achieved using mechanical methods. The plate formed by the line heating method is bent under the influence of the bending and/or inplane plastic deformation created after the heating and cooling cycle. Due to the complex nature of the heating process, the resulted shape of the bent plate by this method is difficult to be predicted in advance. The skills and experience of workers are considered the indispensable elements to carry out the plate bending by the line-heating method. However, the shortage in skilled craftsmen has become a problem in many shipbuilding yards even in industr' .l countries [1-2]. To overcome this kind of shortage especially in developing countries, the unrevealed skill and experience of workers must be obtained using other methods. Once the necessary information about the forming process by the line-heating method can be determined with the aid of computer, the line heating method can be put into practical use in shipyards. Different studies were carried out using the computer technology in plate forming by the line-heating method [2-9].

Rashwan [7] proposed a method to estimate the number of bending heating lines that are necessary to form a flat plate to a uniform curved surface with a single curvature. Then, an algorithm is developed, extending this method, to estimate the number of bending heating lines to form a flat plate to a curved surface with variable curvature in one direction [8]. These two methods depend on the predetermined magnitude of the bending angle, θ_L, of plate bent by single heating line. Therefore, information about the bending angle and the transverse shrinkage of sample plates bent by a single heating line must be known as a first step. Also, to confirm the procedure that can be obtained from the developed algorithm, another experimental verification should be carried out.

In this paper, using oxy-acetylene as a heat source, two types of experiments were conducted. The first type of experiments, primary experiments, were carried out to measure the bending angle, θ_L, and the transverse shrinkage, δ_L, of a sample plate bent by a single heating line. The thickness of the plate and the torch speed are considered as variables in carrying out these experiments. On the other hand, the maximum surface temperature becomes fairly constant by controlling the oxygen and acetylene flow rates. Based on the measurements for the bending angle, θ_L, instructions are obtained usir.g the developed algorithm in reference [8] to form a flat plate into a prescribed part of elliptical surface. In the second type of experiments, the resulting instructions were applied, using the line heating method, on a flat plate and the geometry of the obtained surface was in good agreement with the prescribed one.

2. Primary experiments

The purpose of the primary experiments is to determine the magnitude of the bending angle, θ_L, and the shrinkage, δ_L, for sample plates of different thicknesses formed using a single heating line. The oxy-acetylene heat source is used in all experiments. To select the suitable size of plate samples, auxiliary experiments are carried out on different sample sizes.

2.1. Sample size

The auxiliary experiments are carried out on different sizes of plate, 8mm thickness, to obtain the suitable sample size. Two ratios of L/B, length/breadth, of 1.5 and 2 for the samples are considered. Six different sizes of the samples, three for each aspect ratio, are considered as given in table 1. The tests are carried out in Alexandria shipyard and the material of the plate is steel A37.

The heating process was carried out manually, using heating torch, on one surface along the mid-length of the sample. The heating direction is parallel to the width of the plate. The oxygen and acetylene flow rates are adjusted from the flame shape. In addition, the color of the heated surface is used to control the maximum surface temperature and the time of the heating process has been measured using a stopwatch. After completing the heating process, the plate is left to cool down to the ambient temperature and the deflection is measured at two points using dial gauges. Then the average bending angle and the average torch speed are computed based on the measured deflection and heating time, respectively. The results for the heating time, torch speed, and the bending angle are summarized in table 1. More details of these experiments can be found in reference [9].

Due to the difficulty in controlling the heating speed manually, only the dimensions of plates that have the same heating speed of 4mm/sec are considered in the selection process. The magnitudes of the bending angle are plotted against the heating length as shown in fig. 1. it can be seen from this figure that the change in the magnitude of bending angle due the change in plate dimensions is negligible. In other words, the bending angle is less sensitive to the changes in the dimension of the sample plate. Thus, a plate of dimensions 450×300mm is chosen in the primary experiments.

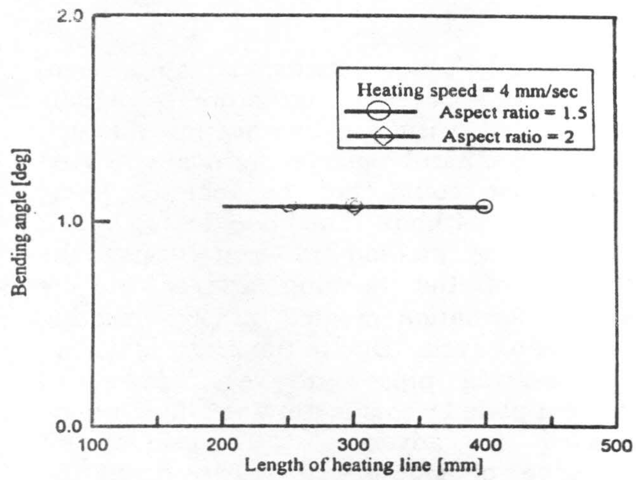

Fig. 1. Relationship between length of heating line and bending angle for different plate dimensions at constant heating speed.

2.2. Measurements of bending angle and shrinkage

The sample plate size of 450mm length and 300mm width was considered to carry out the primary experiments. These experiments were carried out in Alexandria shipyard. Four different plate thicknesses of 8, 12, 16 and 20 mm are chosen from steel A37. In addition, 4 samples for each plate thickness were considered to study the effect of heating speed on the produced bending angle and shrinkage.

To have a control on the torch speed, a semi-automatic cutting machine was used. The torch was fitted on a lever fixed with the carriage of the semi-automatic cutting machine as shown schematically in fig. 2. the carriage speed was limited to 10 mm/sec. Four dial gauges, with accuracy 0.01 mm, were used to measure the deflection and the shrinkage produced by a single heating line. To measure the deflection, the gauge was fitted on a horizontal lever that can be adjusted along vertical one mounted on the table.

Table 1
Measured bending angle for different plate dimension

Aspect ratio, L/B	Plate dimensions L×B×t [mm]	Heating time,T [sec]	Heating speed V=B/T [mm/sec]	Bending angle, θ_L[deg]
	400×200×8	50	4	1.06
	400×200×8	60	3.33	0.87
	400×200×8	50	4	1.08
	400×200×8	50	4	1.1
2				
	500×250×8	90	2.77	1.
	500×250×8	90	2.77	0.8637
	500×250×8	62	4.0	1.035
	500×250×8	62	4.0	1.1
	600×300×8	75	4.	1.05
	600×300×8	75	4.	1.09
	450×300×8	75	4	1.085
	450×300×8	75	4.	1.0675
	450×300×8	75	4.	1.0725
	450×300×8	95	3.15	1.3
1.5				
	600×400×8	110	3.636	1.08
	600×400×8	110	3.636	1.1914
	600×400×8	100	4	1.09
	600×400×8	100	4	1.056
	375×250×8	62	4.0	1.1
	375×250×8	50	5	0.8384
	375×250×8	62	4.	1.06
	375×250×8	62	4.	1.075

On the other hand, to measure the shrinkage, the gauges were fitted on light frame resting on the plate at the far edge from the heating line. This light frame rotates freely at its mid-length at the position of heating line as shown in fig. 2. this mechanism allows the gauges to measure the contraction induced in the plate during the edge rotation.

The applied heating conditions in the primary experiments are given in table 2. Since the heating speed and the thickness of plate are considered the varying parameters in these experiments, the flow rates of oxygen and acetylene are adjusted to get the right flame shape. In addition, the torch height is adjusted to give the desired surface color, black red-heat, corresponds to surface temperature of about 650°C. After completing the heating line and the plate was cooled down to the room temperature, the shrinkage and deflection are then measured. Based on the measured values of δ_a and v_b, taken as shown in fig. 3, the average shrinkage, δ_L, and the average bending angle, θ_L, are calculated.

Table 2
Heating conditions for experiments carried out in Alexandria shipyard

Oxygen pressure	4 (kg/cm^2)
Acetylene pressure	1 (kg/cm^2)
Tip height	20 (mm)
Type and size of burner tip	ANM, 5-12, BOC 3/64
Cooling method	Natural air cooling
Heating speed	1, 1.5, 2.5, 3.5, 4,5, 7, 10 (mm/sec)

The results of measurements for the bending angle, θ_L, and the shrinkage, δ_L, are plotted against the heating speed as shown in figs. 4 and 5, respectively. it is clear from fig. 4 that the bending angle decreases as the heating speed increases for the constant plate thickness. In addition, the bending angle decreases as the plate thickness increases for constant heating speed. On the contrary, for small torch speeds less than 2 mm/sec, for the given heating conditions, the bending angle decreases for small plate thickness less than 12 mm. The decrease of bending angle at small thickness and at low speeds is due to the small variation in temperature distribution through the thickness of plate causing dominant inplane shrinkage rather than out-of-plane deformation.

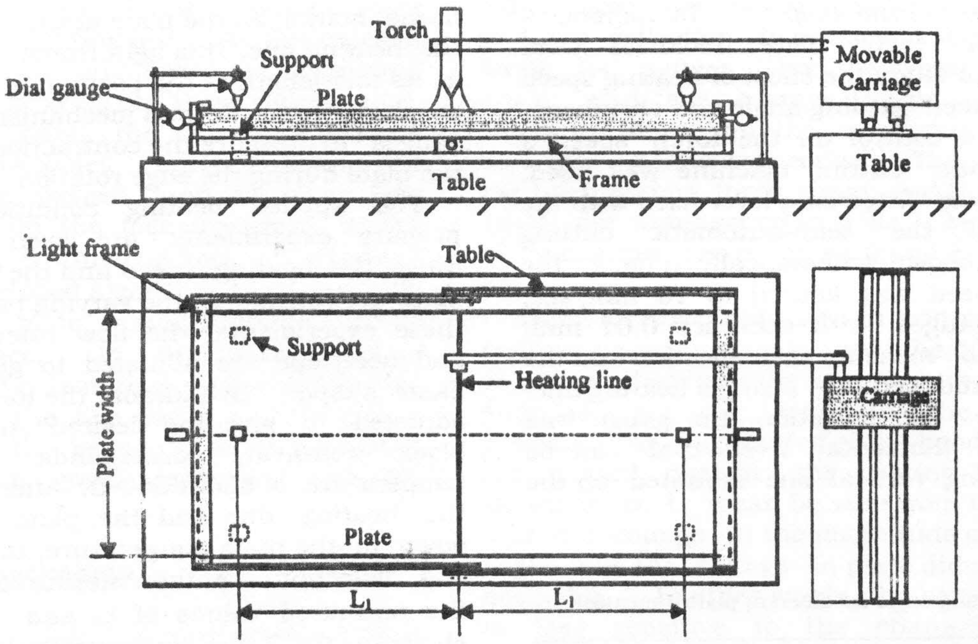

Fig. 2. Diagram of the experimental apparatus and measuring techniques.

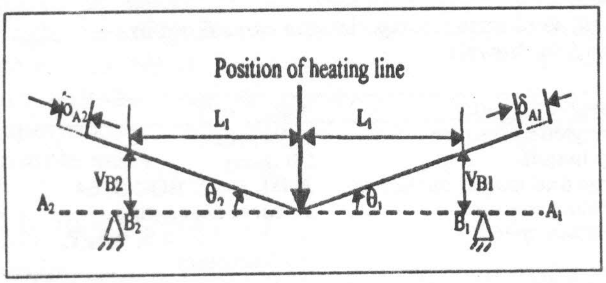

Fig. 3. Positions of measured deformation.

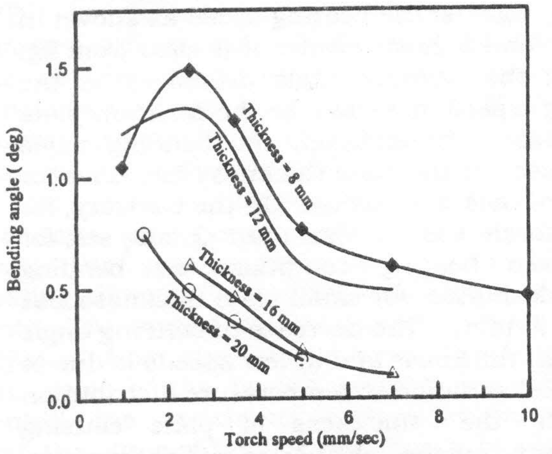

Fig. 4. Relationship between torch speed and bending angle, θ_{L1}, angle for different plate thickness (experiments performed in Alexandria shipyard).

For the shrinkage, δ_L, it is obvious from fig. 5 that the shrinkage decreases as the torch speed increases or as the plate thickness increases. The decrease in the magnitude of shrinkage is due to short penetration of heat through the plate thickness. It can be noted from fig. 5 that the shrinkage of plate thickness of 8mm does not exist due to the unsuitable contact between dial gauge and the plate.

Additional experiments were carried out in workshops of Behera Co., Alexandria branch. The applied heating conditions are given in table 3. a semi-automatic cutting machine was used in the heating process for a sample plate of thickness of 12mm. The material of the plate used in these experiments was also steel A37. The same procedure to measure the deflection and shrinkage was applied. The results of the measured bending angle and shrinkage are shown in fig. 6 for different torch speeds. The trend of both the bending angle and shrinkage for the considered plate thickness here is the same as that for the previous experiments.

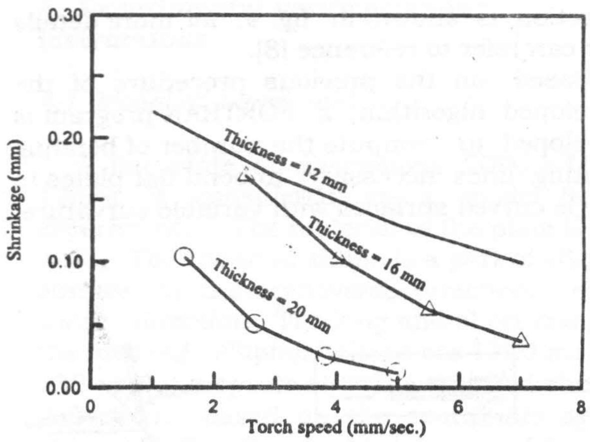

Fig. 5. Relationship between torch speed and shrinkage, δ_L, for different plate thickness (experiments performed in Alexandria shipyard).

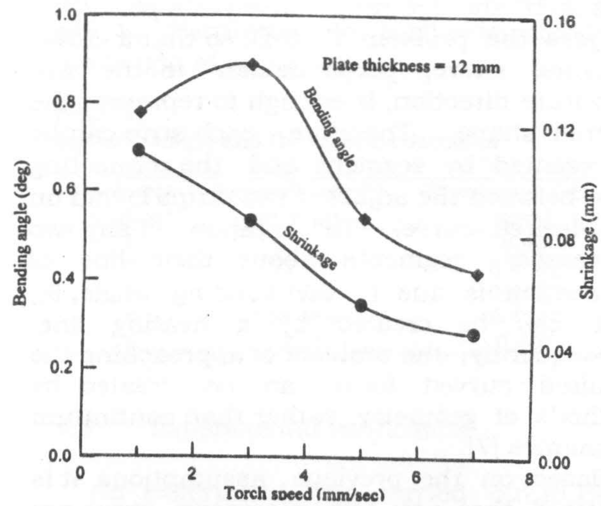

Fig. 6. Relation between bending angle, θ_L, shrinkage, δ_L, and torch speed (experiments performed in Behera Co.).

Table 3
Heating conditions for experiments carried our in Behera company

Oxygen pressure	5 (kg/cm²)
Acetylene pressure	0.75 (kg/cm²)
Tip height	20 (mm)
Type and size of burner tip:	AHSO, 10-20, 5 bar
Cooling method	natural air cooling
Heating speed	1, 3, 5, 7 (mm/sec)

The previous measurements for the bending angle, θ_L, and the shrinkage, δ_L, for sample plate bent by single heating line can be used as a database for the developed algorithm to obtain instructions for the numbeı of bending heating lines and their positions to form the plate.

3. Review of developed algorithm

When a heating line is being applied on a flat plate, the plate is bent around the heating line as shown in fig. 7. the created bending angle in the transverse direction can be considered the main source in bending of plates. 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. Generally, this shrinkage is necessary to form the double curved plates in the second direction of curvature.

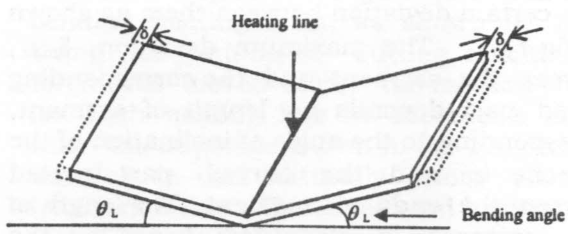

Fig. 7. Schematic representation of deformation due to single heating line.

To estimate the number of bending heating lines to bend a flat plate into a curved surface of single curvature, the following assumptions were given in [7]:

1) Each heating line can create a constant transverse bending angle θ_L along the heating length.
2) The effect of inplane shrinkage will be neglected and consequently the desired surface can be considered as a developable surface.
3) There is no interaction between each heating line and the preceding one.

Thus, forming a flat plate to a curved surface of single curvature can be achieved by dividing the flat plate into several strips and rotating every adjacent two strips around their line of conjunction a certain angle, θ, to approach the required curved shape. This reduces the problem to 2-D, so that a cross-sectional curve, perpendicular to the zero curvature direction, is enough to represent the desired shape. Therefore, each strip can be represented by segment and the connecting line between the adjacent two strips is laid on the desired curve. The rotation of any two successive segments about their line of connection is due to the bending angle, θ_L, that can be created by a heating line. Consequently, the problem of approaching the required curved form can be treated by methods of geometry rather than continuum mechanics [7].

Based on the previous assumptions, it is assumed that any two successive strips are interconnected by a heating line producing certain bending angle θ_L and the ends of the strip are laid on the desired curved part as shown in fig. 8. Therefore, two configurations will appear actual and approximate shapes, with certain deviation between them as shown in fig. 8. The maximum deviation, $\delta_{max.}$, between the segment and the corresponding curved part depends on length of segment, corresponding to the angle of inclination of the segment φ, and the curved part located between the ends of segment. The length of each segment is computed based on the maximum value of the segment inclination angle, $\varphi_{max.}$, that causes maximum deviation, $\delta_{max.}$, between each segment and the corresponding curved portion. This maximum deviation, $\delta_{max.}$, should be less than or equal to the permissible value, δ_{per}. However, the maximum deviation, $\delta_{max.}$, produced by the bending angle θ_L due to the line heating method and the practical curvature of plates in shipbuilding is usually small. Then, using incremental procedure and beginning with small value φ, the length of segment can be obtained with the knowledge of the function that represents the desired curve and the magnitude of the permissible deviation, δ_{per}, or the bending angle θ_L produced by a heating line. The flow chart of the developed algorithm to estimate the number of bending heating lines to bend flat plates into curved surfaces with variable curvatures in one direction is shown in fig. 9. for more details one can refer to reference [8].

Based on the previous procedure of the developed algorithm, a FORTRAN program is developed to compute the number of bending heating lines necessary to bend flat plates to single curved surfaces with variable curvature.

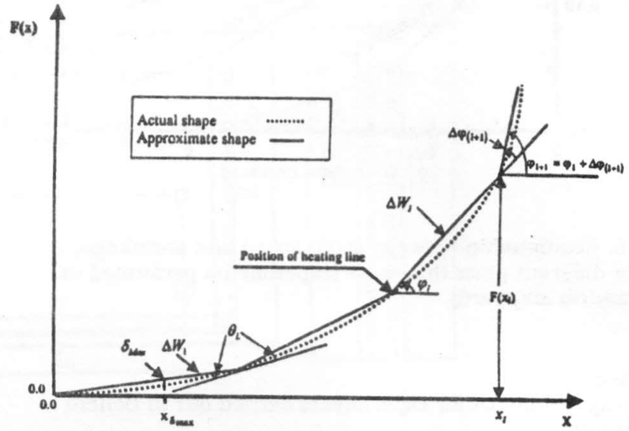

Fig. 8. Approximate and actual shapes of the curved plate.

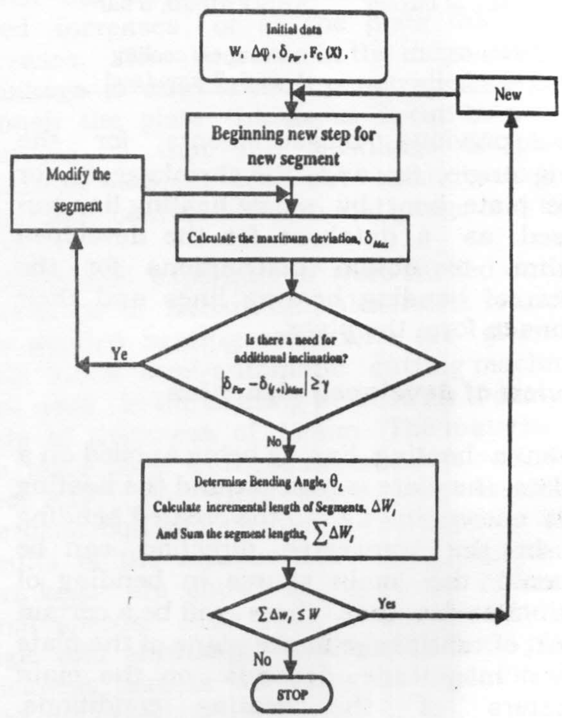

Fig. 9. Estimating number of bending heating lines algorithm.

4. Experimental verification for instructions

4.1. Model of experiment

A flat plate of dimensions 2000 × 1000 × 12mm is considered as a model for the experiment. The material of the plate is steel A37. The required shape is a part of elliptical surface in the transverse direction, i.e. the width direction. The long and short chords of the desired elliptical shape are 1750 mm and 750 mm, respectively. The required shape of deflection, based on the coordinate system shown in fig. 8, can be determined from the following equation:

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

4.2. Forming instructions

The developed algorithm in ref. [8] is used to obtain the necessary instruction that should be carried out by the line heating method to get the desired shape. The measured bending angle, given in table 3 for the sample plate of dimensions 450×300×12mm of the experiments carried out in Behera Co., is used to determine the instructions. The applied bending angle, equals 0.88 degree, at torch speed 3mm/sec has been used to determine the number of bending heating lines.

Based on eq. (1), the number of bending heating lines, for the chosen bending angle, can be estimated using the developed algorithm. From symmetry, only half of the curve is considered in computing the length of segments. The computed length of each segment and the resulted deviation are given in table 4 based on the selected bending angle. From table 4, the number of bending heating lines can be determined such that

$$NOBHL = \text{number of segments} - 1 = 10 - 1 = 9. \qquad (2)$$

The distance between each heating line corresponds to the length of each segment. Since the number of bending heating lines is an odd number, one heating line will be laid at the line of symmetry and half of the remaining will be distributed on each side according to the length of segments.

Table 4
Segment length and the resulted deviation

Segment number	Segment length Δw [mm]	Resulted deviation [mm]
1	122.32	0.46
2	121.47	0.4582
3	117.96	0.4423
4	114.589	0.4317
5	23.64	0.407

4.3. *Experimental verification*

An experiment was carried out in Behera Co. to examine the validity of the instructions obtained using the developed algorithm to form the flat plate into the desired elliptical shape. The positions of bending heating line are marked on the flat plate based on the estimated segment lengths and number of bending heating lines, as shown in fig. 10. Using an automatic cutting machine, the torch was moved along the marked position for each heating line in successive manner with the sequence shown in fig. 10. The plate was left to cool naturally before starting to heat a new line. The considered heating speed was 3 mm/sec and the distance between the torch tip and plate surface was 20 mm. After the heating process is finished and the temperature of the plate reached the room temperature, the deflection was measured at five sections, a, b, c, d and e shown fig. 11 using the measuring method shown in fig. 12. In fig. 13, the measured deflections at different sections are being compared with the desired shape. A comparison between the obtained three-dimensional shape by the line heating and the desired shape is shown in fig. 14.

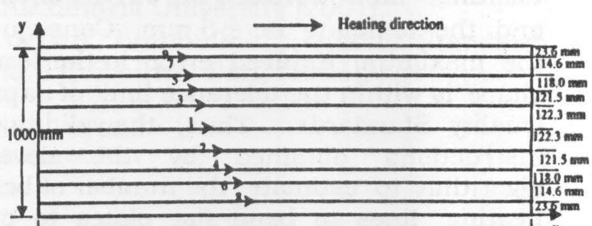

Fig. 10. Position and direction of ending heating lines.

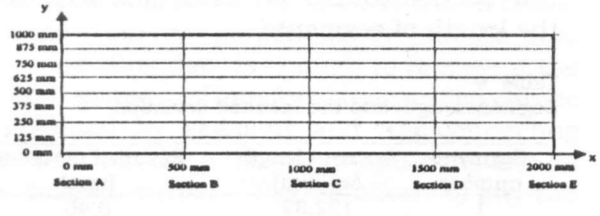

Fig. 11. Considered sections for deflection measurements.

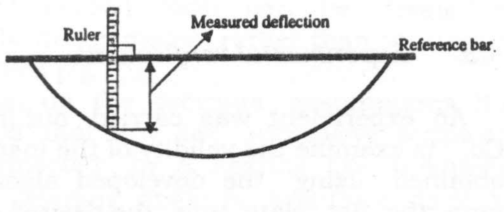

Fig. 12. Deflection measuring method.

4.4. Discussion of results

it can be seen from fig. 13 that the shape obtained from applying the determined instructions from the developed algorithm, using the line heating method, is in good agreement with the acquired one. It can be seen from fig. 13 that the obtained shape from experiment did not reach the desired shape as expected. This is mainly because the last two heating lines did not produce any bending angle due to the weak stiffness of these strips near the edges of the plate. In addition, the straightness of the flat plate surface before carrying out the heating process cannot be completely attained. However, the error between the obtained and the target shapes has a maximum value of 4.8mm, at the end sections **A** and **E**. According to the Japan Shipbuilding Quality Standards [10], the tolerance limit between the curved shell plate and the template is ±5 mm. Consequently, the maximum induced error in the resulting shape is within the tolerance limit of Japanese Quality Standards. Thus, the validity of the instructions obtained by the developed algorithm to estimate the number of bending heating lines to bend flat plates to curved surfaces with variable curvature has been attained.

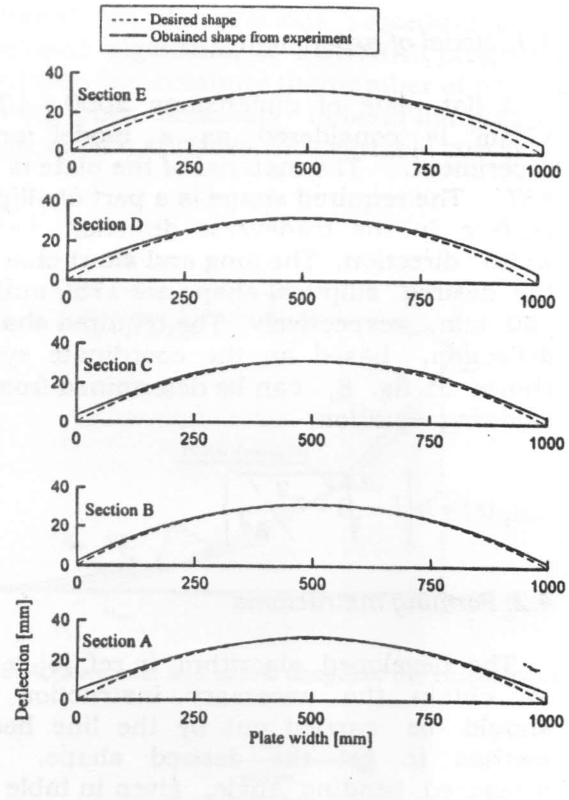

Fig. 13. Measured deflection at different sections compared with desired shape.

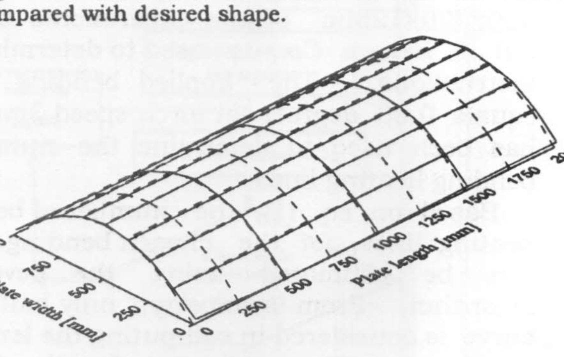

Fig. 14. Compression between 3-D shapes.

5. Conclusions

From the previous study the following conclusions can be drawn:

1. The primary experiments are necessary to be carried out to obtain the magnitude of the bending angle, θ_L, that is used by the developed algorithm to estimate the number of bending heating lines to bend a flat plate to a single curved surface with variable curvature.

2. The measured bending angle, θ_L, and shrinkage, δ_L, from the primary experiments can be employed as database that can be used for plate forming by line heating method.
3. Experimental verification is carried out to form flat plate into a part of elliptical shape based on instructions determined from the developed algorithm and the bending angle, θ_L, obtained from the primary experiments. The shape obtained from the experiment was in good agreement with the desired shape.
4. The developed algorithm can be used to determine the instructions that are necessary to bend flat plate to curved surface with variable curvature in one direction with acceptable accuracy using the line heating method.

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