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# Development of Computer Aided Process Planning System for Plate Bending by Line Heating (Report I)

— Relation between the Final Form of Plate and the Inherent Strain —

Yukio UEDA<sup>\*</sup>, Hidekazu MURAKAWA<sup>\*\*</sup>, Ahmed Mohamed RASHWAN<sup>\*\*\*</sup>, Yasuhisa OKUMOTO<sup>\*\*\*\*</sup> and Ryoichi KAMICHIKA<sup>\*\*\*\*</sup>

## Abstract

*Plate bending by line heating can be considered as a process in which plates are bent to the three dimensional form by the plastic strain caused during the gas heating and the water cooling. Therefore, the plan making for this process can be separated into two parts. The first part is to decide what type and how much plastic strain should be given in which place of the plate. The second part is to find what are the proper heating and cooling conditions to get the desired plastic strain. The authors investigated the relation between the final form of the plate and the plastic strain or the inherent strain to be given for the plate bending. For this purpose, the Finite Element Method is employed. Based on the knowledge obtained through the analysis, a method to determine the part of the plate to be heated and the magnitude of the required inherent strain is proposed.*

**KEY WORDS :** (Line Heating) (Plate Forming) (Inherent Strain) (Computer Aided System) (Process Planing) (Finite Element Method)

## 1. Introduction

The flame bending process is widely used to form curved plates of ship structures. The line heating generally requires a skill or a workmanship. However, due to the high average age of skilled workers and the decrease of their number itself, the problem of how to maintain the production capability and these skills which have been inherited from worker to worker become serious issues in shipyards. There are many possible alternatives to solve these problems, such as an automatic process plan making system taking full advantage of computers and numerical simulation and automatic hardware system to carry out the plate forming. Some of the fundamental researches to realize such systems have been reported<sup>1)-7)</sup>.

In the plate bending process by the line heating, plastic deformations are created as a result of gas heating and water cooling and the plate is bent by these plastic deformations. Then the problem can be basically divided into two, such that,

- (1) where to apply the line heating and how much plastic deformation (inherent strain) is required to obtain the desired form?
- (2) what are the proper heating and cooling conditions to get the necessary inherent deformation?

The first problem is investigated as the primary stage of the research. The relationship between the final configuration of the curved plate and the inherent deformation to be given is clarified through serial computation using the Finite Element Method. Based on the knowledge obtained through the FEM analyses, a unique method that determines the position of the heating lines and the magnitude of the inherent deformation is proposed.

## 2. Fundamental Features of Proposed System

The plate bending process by line heating can be viewed as a process to form a plate into the desired shape using the shrinkage and the angular distortion produced through the plastic deformation during the line heating. Therefore, the shrinkage and the angular distortion which should be given by the line heating to form the plate is studied. **Figures 1** and **2** show a cylindrical plate and a shallow spherical shell, respectively, which are formed from flat plates as typical examples. The position of heating lines, the angular distortion (the magnitude of the shrinkage changes through thickness) and the inplane shrinkage (the magnitude of the shrinkage is uniform through thickness) to form the curved surfaces are shown in these figures. Figures 1-(a) and 2-(a) show the final

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\* Professor

\*\* Associate Professor

\*\*\* Graduate Student

\*\*\*\* Ishikawajima-Harima Heavy Industries Co., Ltd.

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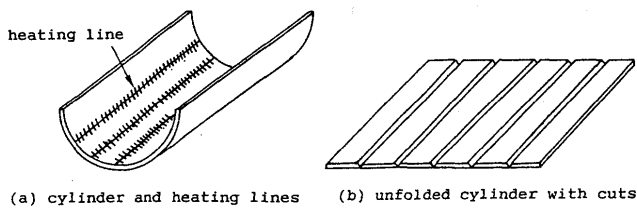


Fig. 1 Forming of cylinder.

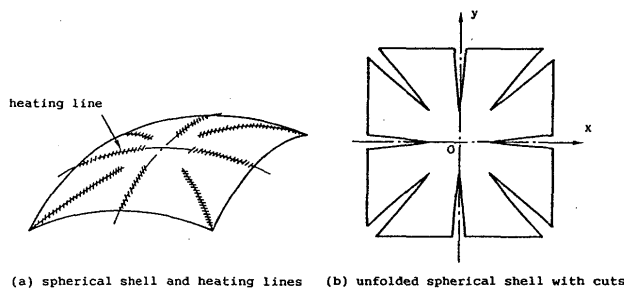


Fig. 2 Forming of shallow spherical shell.

form of the plate and the locations of heating lines. Figures 1-(b) and 2-(b) show the plates unfolded after cut along the heating lines. Intuitively, the magnitudes of the gap along the cutting line shown in Figs 1-(b) and 2-(b) correspond to the magnitudes of the shrinkage and the angular distortion required to produce the desired form. These simple examples suggest that the shrinkage is more important to form a spherical cap which has curvatures in two directions. On the contrary, only the angular distortion is necessary to create cylindrical shape which has unidirectional curvature as illustrated in the example. Therefore, to form plates with general three dimensional geometry which make ship structures, it may be necessary to combine both the inplane shrinkage and the angular deformation properly according to the situation. The magnitudes of the inplane shrinkage and the angular distortion which are necessary to form the plate into the given configuration can be computed based on geometry if the secondary effects, such as the spring back, are ignored. Based on such an idea, a method of process planning based on geometrical computation were proposed<sup>1)</sup>.

In this research, the final objective is to construct a computer aided process planning system for plate bending by line heating. This system is expected to be composed of the following three subsystems.

#### subsystem-1

The position and the direction of the line heating are determined for the given final configuration. Further, the kind of inherent deformation (inplane shrinkage

and/or angular distortion) and its magnitude are determined.

#### subsystem-2

Conditions of heating and cooling for producing the necessary inherent deformation, which is given by subsystem-1, are determined.

#### subsystem-3

Conditions to correct the geometrical error left after forming based on subsystems 1 and 2 are determined.

### 3. Inherent Strain in the Press Forming

#### 3.1 Example model

As it was mentioned previously, the inplane inherent deformation (shrinkage) and the bending inherent deformation (angular distortion) must be used properly in the forming process so as to get the desired form. If the inherent strain given to a plate does not satisfy the compatibility condition, secondary elastic deformation occurs. This elastic deformation corresponds to the spring back observed in press forming. The same phenomenon is observed in line heating and it is necessary to consider its effect. On the other hand, the spring back is expected to be closely related to the dimensions of the plate to be formed and the magnitude of deformation to get the final form. Therefore, the effect of these factors are examined through numerical analyses simulating the press forming process.

The plate considered is a flat plate of radius  $a$  and thickness  $t$  as shown in Fig. 3. This plate is assumed to be pressed by a spherical press die of radius  $R$ . The simulation was divided into the following two steps.

- (1) The forming process to make the spherical cap is analyzed till the complete press down by the Finite Element Method based on the large deflection elastic-plastic plate theory. The forming process is simulated by applying forced lateral deformation which is proportional to the height of the die at each nodes in incremental manner and the distribution of elastic and plastic strains are computed.
- (2) In the second stage, deformations of the plate when

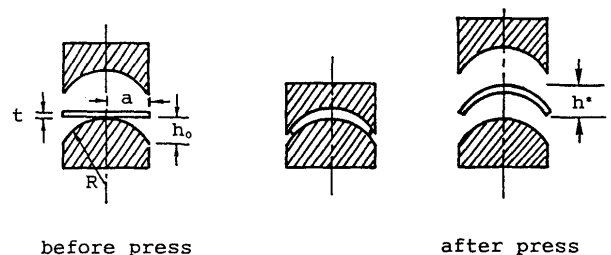


Fig. 3 Press forming of spherical shell.

various types of strains, which are determined based on the computed results obtained in the first stage, are given as the inherent strain are computed. The behavior of the plate is assumed to be elastic and the following five types of inherent strains  $\epsilon^*$  are considered.

a) all strain is given as the inherent strain

$$\epsilon^* = \epsilon^e + \epsilon^p$$

b) only plastic strain is given as the inherent strain

$$\epsilon^* = \epsilon^p$$

c) only elastic strain is given as the inherent strain

$$\epsilon^* = \epsilon^e$$

d) only inplane strain is given as the inherent strain

$$\epsilon^* = \epsilon^m$$

e) only bending strain is given as the inherent strain

$$\epsilon^* = \epsilon^b$$

where the inplane strain  $\epsilon^m$  and bending strain  $\epsilon^b$  are defined by the following equations.

$$\epsilon^m = \frac{1}{t} \int_{-t/2}^{t/2} (\epsilon^e + \epsilon^p) dz \quad (1)$$

$$\epsilon^b = (\epsilon^e + \epsilon^p) - \epsilon^m \quad (2)$$

The term "inherent strain" and "inherent deformation" in this report mean causes or sources of the residual stress and the deformation. In the actual computation, the inherent strain is applied incrementally as an initial strain to the flat circular plate.

The role of the strain components, such as elastic, plastic, inplane and bending strains, in forming the spherical cap is examined through numerical simulation described above. Especially, to study the effect of dimensions of the plate and the degree of the deformation due to the forming, a series of computations in which the plate thickness  $t$  and the height of the spherical cap  $h_0$  are changed as parameters are performed. In this serial computation, the radius of the plate is kept constant. The plate is assumed to be a perfectly elastic-plastic materials with yield stress  $\sigma_Y = 30 \text{ kgf/mm}^2$  (294 MPa). The plate thickness  $t$  and the height  $h_0$  are assumed to be,

$$t = 5, 10, 20, 30, 40 \text{ mm}$$

$$h_0 = 20, 50, 100, 150 \text{ mm.}$$

### 3.2 Compatible strain and spring back

If all strain ( $\epsilon^e + \epsilon^p$ ) is used as the inherent strain in the calculation of the second step, the configuration of the plate without external constraint coincides with the configuration of press die and internal stress in the plate becomes zero. This can be explained by the fact that residual stress is caused by incompatible strain field and compatible strain causes no stress. Also by the fact that strain as a whole, ( $\epsilon^e + \epsilon^p$ ), constitutes a compatible strain field. Further, it can be seen that no spring back occurs in this case because no residual stress is produced

in the plate. The fact that the computed results agree with the above theoretical prediction shows the validity of the FEM code developed for this research.

### 3.3 Effects of plastic strain and elastic strain

By comparing the deformed configurations obtained by giving only plastic strain and elastic strain, respectively, as the inherent strain, the contribution of each component of strain in plate forming can be evaluated. Due to the symmetry, one quarter of the plate was analyzed and the mesh division is shown in Fig. 4. Figures 5 and 6 show the deformation of the circular plate at the center  $h^p$  and  $h^e$ , when only plastic and elastic strains are given as the inherent strain, respectively. The relationship between the height at the center of the spherical cap  $h^p$  and  $h^e$  and the height of the press die  $h_0$  is given for cases with different plate thicknesses. The height of the plate after deformation is normalized with respect to the height  $h_0$ .

The influence of the plastic strain is examined first. The value  $h^p/h_0$  shown in Fig. 5 can be considered as the relative value of the permanent deformation which remains in the plate after releasing from the press die. Therefore,  $(1-h^p/h_0)$  represents the relative value of spring back. For example, when the height  $h_0$  is 20 mm and the thickness of the plate is 40 mm about 45 % of the deformation is released by spring back, while 55 % remains as permanent deformation. When the height  $h_0$  is large, the relative value of permanent derormation increases. Its value reaches about 95 % when  $h_0 = 120$  mm. From the comparison among cases with same height  $h_0 = 20$  mm, it is seen that the effect of spring back becomes greater as the plate thickness becomes small. When the plate thickness is very small as in the case of

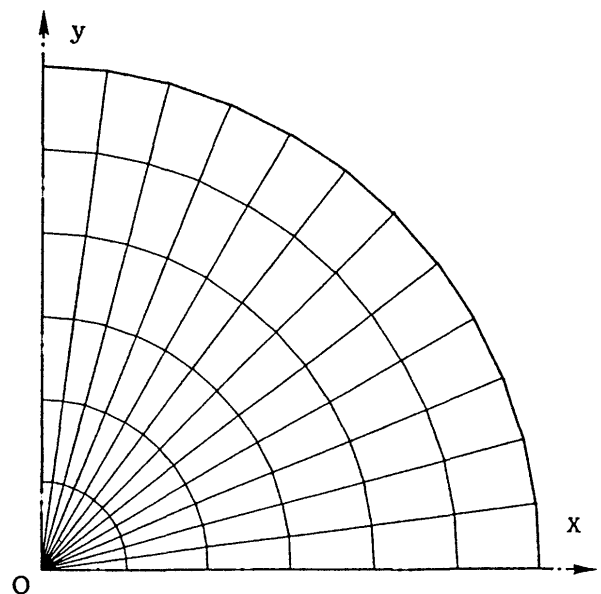


Fig. 4 Mesh division (one quarter of circular plate).

$t = 10$  mm and  $h_0 = 20$  mm, 100 % of the deformation is released by the spring back. This is due to the fact that deformation produced in the first step (pressing process) is small, and no plastic strain is created.

The influence of the elastic strain is examined in the same manner. Although applying the elastic strain as the inherent strain does not have apparent physical meaning as opposed to the case of plastic strain, the influence of the elastic strain upon the forming process is examined. The relative height of the plate  $h^e/h_0$  when only the elastic strain is given as the inherent strain is shown in Fig. 6. As the thickness  $t$  and the height  $h_0$  becomes small, the value of  $h^e/h_0$  becomes large. This result agrees with the characteristics of the spring back indicated by Fig. 5.

The ratio  $h^p/h^e$  is plotted against  $t/R$  in Fig. 7. The relative contribution of the plastic and elastic deformations on the forming process can be assessed from this figure. The abscissa of the figure  $t/R$  represents the degree of deformation in the plate. The value  $t/R$  corresponds to the maximum bending strain in the spherical cap. By introducing dimensionless parameter  $t/R$ , the results for different plate thicknesses are almost represented by single line. The small difference between the curves comes from the difference in another geometrical parameter  $a/R$ . Therefore, if  $a/R$  is same, all curves in Fig. 7. coincides with each other because of the similarity. As seen from the figure, the value of  $h^p/h^e$  increases as the parameter  $t/R$  increases. This implies that the spring back becomes relatively small when the thickness of the plate is large and the radius of the sphere  $R$  is small. Similar conclusion is reported in the reference<sup>4)</sup>.

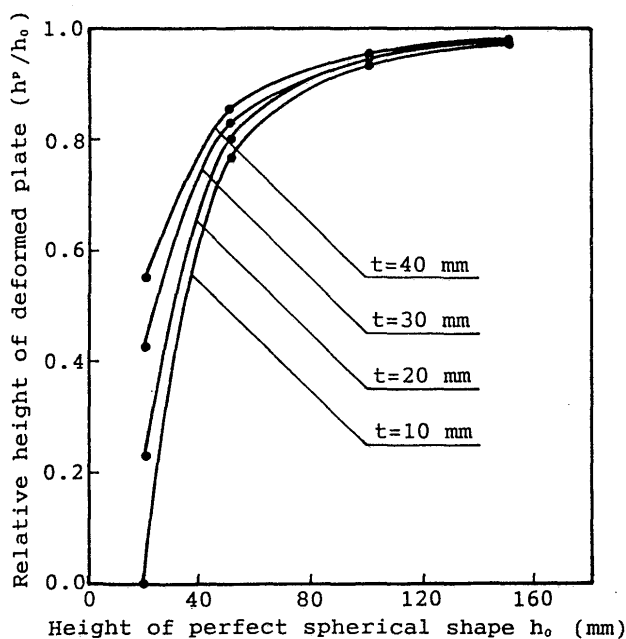


Fig. 5 Deformation of plate due to plastic strain.

### 3.4 Effect of inplane strain and bending strain

Figures 8 and 9 show the deformation of the circular plate at the center  $h^m$  and  $h^b$ , when only membrane and bending strains are given as the inherent strain, respectively. In general, membrane strain causes no deflection. However if the magnitude of the membrane inherent strain exceeds certain critical value, the plate buckles and deflection is developed. If the strain is less than the critical value, the plate remains flat. For example, the membrane inherent strain is small and

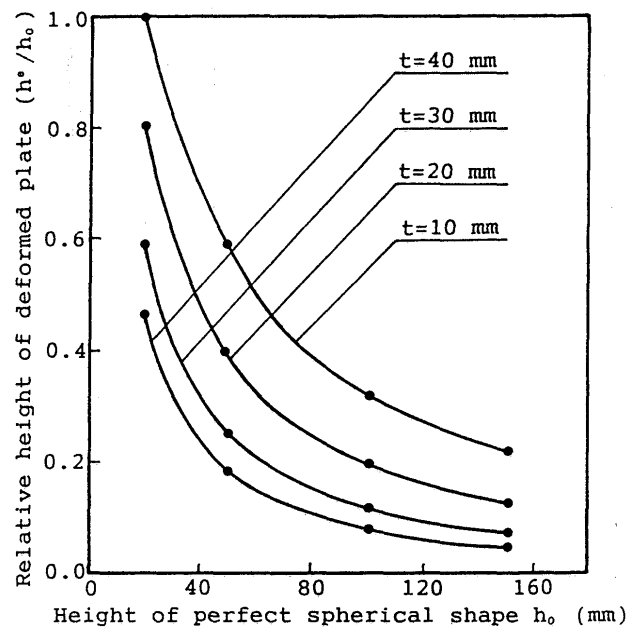


Fig. 6 Deformation of plate due to elastic strain.

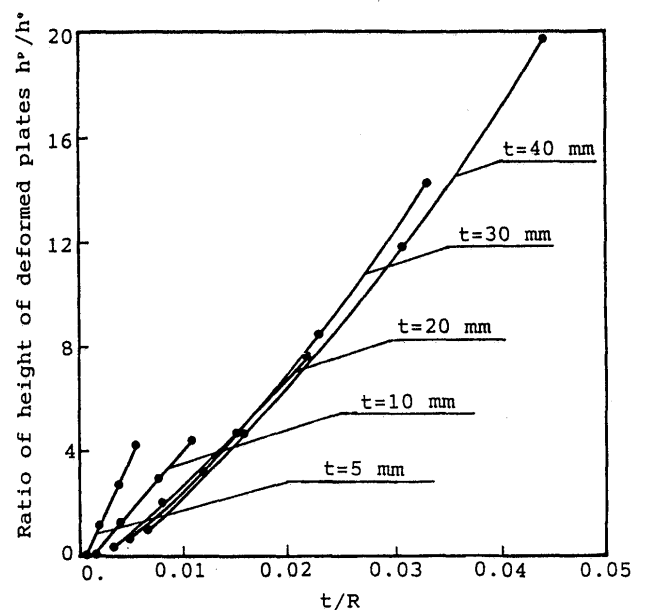


Fig. 7 Relative contributions of plastic and elastic strains for forming sphere.

bending deformation does not occur when  $t = 20$  mm and  $h_0 = 20$  mm in Fig. 8. Buckling is observed in other cases when  $t = 20$  mm.

It is observed that the contribution of the inplane strain becomes large as  $h_0$ , indicating the degree of forming, increases and the inplane strain is a dominant factor in such cases. For example, when the thickness of the plate  $t$  is 10 mm and  $h_0 > 60$  mm, 90 % or more of the deformation can be achieved by inplane strain alone. It is also observed that the contribution of the inplane

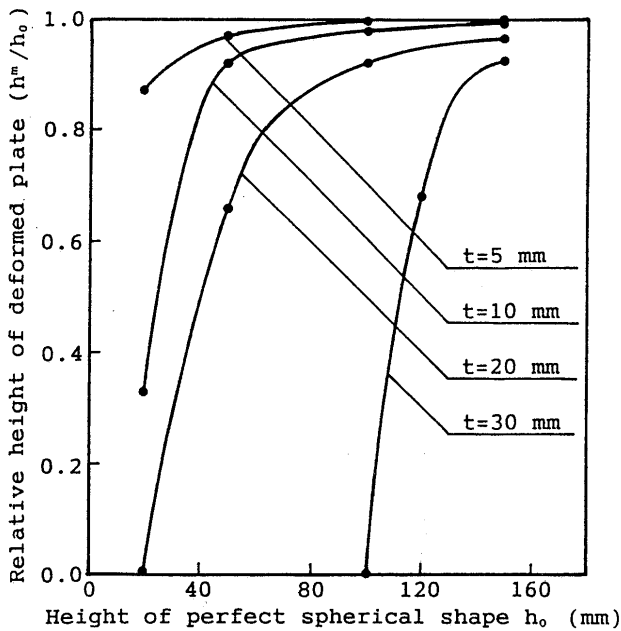


Fig. 8 Deformation of plate due to inplane strain.

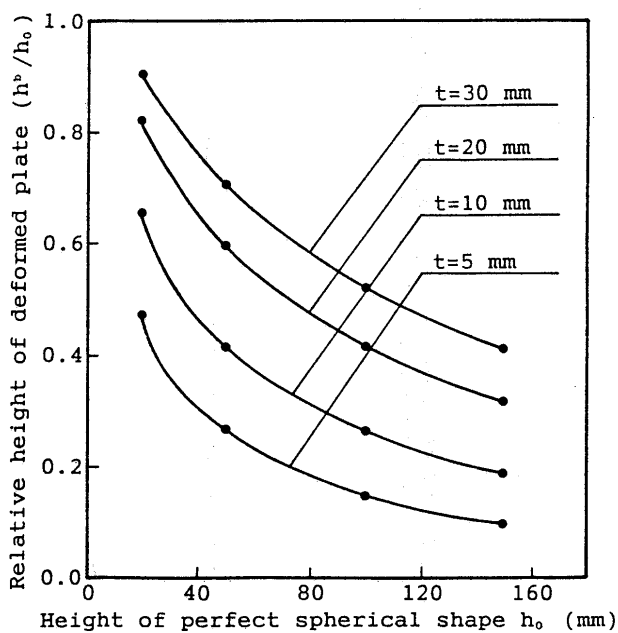


Fig. 9 Deformation of plate due to bending strain.

strain becomes predominant as the thickness becomes small.

Similarly, the result obtained by applying bending strain only is shown in Fig. 9. As opposed to the case of inplane strain, effect of bending strain becomes dominant when the thickness of the plate is large and  $h_0$  is small. Further, the relative contribution of the inplane and the bending strains is evaluated in Fig. 10. The ratio between the heights  $h^m/h^b$  is plotted against a dimensionless parameter  $a^2/Rt$  in this figure. The parameter  $a^2/Rt$  is related to the ratio between the circumferential inplane strain at the outer edge of the spherical cap  $\epsilon^m$  and the maximum bending strain  $\epsilon^b$ . It can be shown that these strains approximately satisfy the following relations.

$$\epsilon^m \propto (a/R)^2$$

$$\epsilon^b \propto t/R$$

Regardless of the thickness of the plate, all curves shown in Fig. 10 roughly coincide with each other. Thus, relatively general conclusion is drawn from the figure and valuable guidance is given. The value of  $h^m/h^b$  increases with that of the parameter  $a^2/Rt$ . This suggests that the bending inherent strain is more effective than the inplane inherent strain to form a spherical cap when the parameter  $a^2/Rt$  is small and vice versa when  $a^2/Rt$  is large.

#### 4. Forming of Spherical Cap

In the preceding chapter, the contributions of the inplane and bending inherent strains in plate forming and the characteristics of spring back are studied using the press forming as an example. Based on the fundamental knowledge obtained, a method to determine the position and the direction of the heating line in the case of line heating process is discussed in this chapter. Further, a

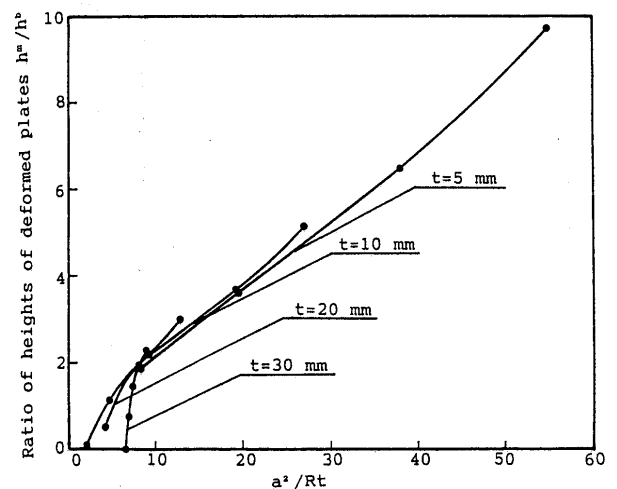


Fig. 10 Relative contributions of inplane and bending strains for forming sphere.

procedure to estimate the magnitude of the inherent strain to achieve the desired form of the plate is proposed.

#### 4.1 Position and direction of heating lines

The position of the line heating and the magnitude of the inherent deformation can be determined from the geometrical computation alone, when only the shrinkage is considered. However, it is necessary to use both the inplane and the bending inherent deformations for effective plate forming. Also, situation in which primary bending is applied by a press or a roll machine prior to the line heating may be expected. Considering these situations, the method based on the geometrical computation has a limitation in its applicability. As compared to this, the Finite Element Method is a superior tool to simulate the plate forming process exactly. In addition, it becomes a daily design tool as the development of powerful Engineering Work Stations (EWS). Therefore, the Finite Element Method is employed in this research and the possibility of determining the position of the line heating and the magnitude of the inherent deformation by large deflection elastic plate analysis is examined.

In the proposed method the heating position and the direction are determined according to the following procedure,

##### preparation

- (1) data input to give information about the initial and the final configurations of the plate to be formed. (The configuration after primary bending by press or roller can be chosen as the initial configuration.)
- (2) Finite Element mesh division for the initial configuration.

##### decision on heating position and direction

- (3) compute the strain caused by deformation from the initial configuration to the final one using elastic FEM analysis.
- (4) decompose the computed strain into inplane and bending components and display the distribution of their principal values on a graphic display.
- (5) from the distribution of inplane strain, the region where the magnitude of compressive principal strain is large is chosen as the heating zone and the heating direction is taken normal to the direction of the principal strain.
- (6) from the distribution of bending strain, the region where the absolute value of bending strain is large is selected as the additional heating zone and the heating direction is taken normal to the direction of the principal strain with the maximum absolute value.

#### 4.2 Type and magnitude of inherent strain

The inherent deformation necessary to form the plate corresponds to the gap appears along the cutting line as shown in Fig. 2. In the Finite Element analysis, the cutting lines are replaced by lines of elements with very small Young's modulus. One thousandth of the ordinary Young's modulus is used in the analysis. When such plate is deformed from the initial configuration to the final one, the strain is concentrated in the weak elements with small elastic constant. Such concentrated strain gives the magnitude of inherent strain or deformation necessary to form the plate.

#### 4.3 Numerical example

The problem of forming a spherical cap by the line heating is taken as an example. Assuming that the circular plate is an uniform elastic body and formed to the final configuration from the flat plate, the strain distribution due to the forming process is calculated. The inplane strain distribution obtained for the spherical cap ( $a = 500$  mm,  $t = 20$  mm and  $h_0 = 100$  mm) is shown in Fig. 11 as an example. The magnitudes and the directions of principal strains are shown by arrows. It is clear from this figure that the direction of the compressive inplane strain is circumferential direction. Thus, the direction of the line heating must be taken in radial direction which is normal to that of the principal strain. Also, since the distribution of the strain is uniform in the circumferential direction, the heating lines must be equally spaced. The maximum value of the inplane strain is  $1.6 \times 10^{-2}$ . On the other hand, the bending strain distribution is uniform and its value is given as  $t/2R = 7.7 \times 10^{-3}$ . Therefore, preferable location for heating can not be decided from the bending strain alone. By comparing the magnitude of the strain, it

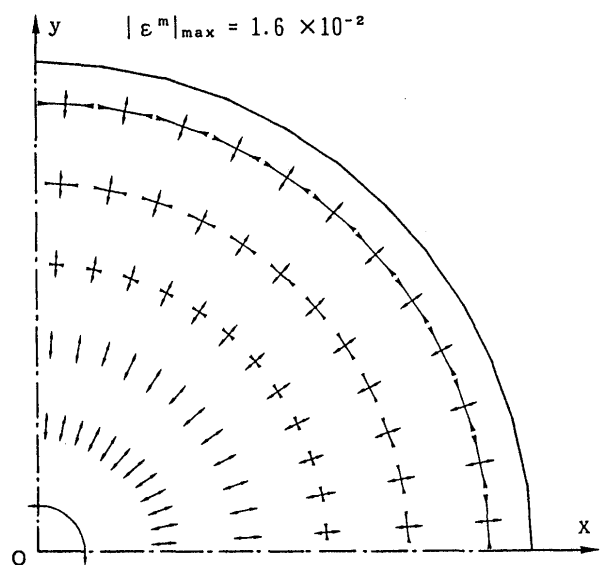


Fig. 11 Distribution of inplane strain ( $t = 20$  mm,  $h_0 = 100$  mm,  $R = 1300$  mm).

can be seen that the inplane strain is predominant in this case. Based on these observations, the heating zone represented by elements with small Young's modulus can be selected as shown by Fig. 12.

The deformation of the model shown in Fig. 12 is analyzed to estimate the inherent strains or deformations which are necessary to form the spherical cap. The distribution of inplane principal strain computed by this analysis is shown in Fig. 13. As it is seen from the figure, most of the compressive strain is concentrated in the

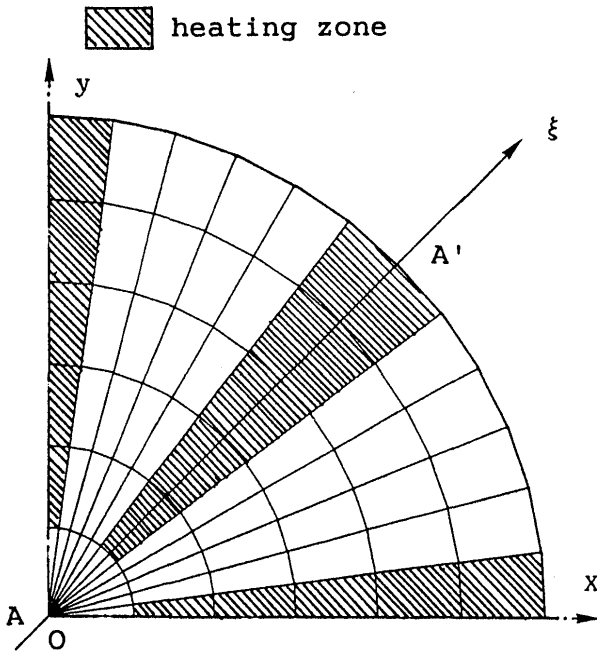


Fig. 12 Location of heating zone.

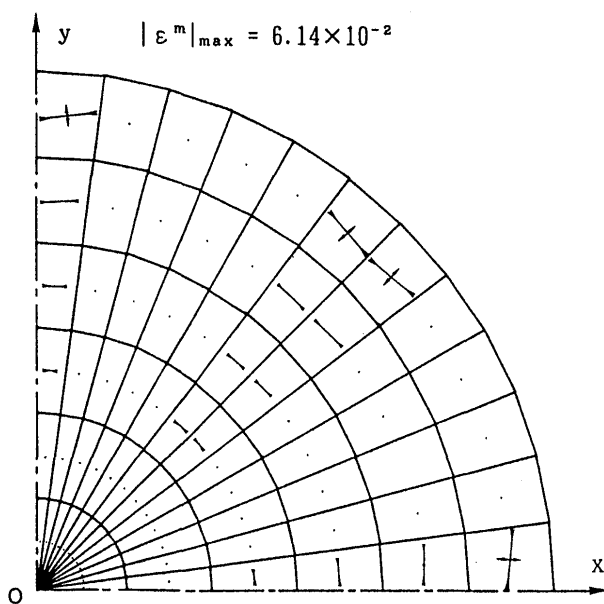


Fig. 13 Inplane strain distribution in plate with heating zone ( $t = 20$  mm,  $h_0 = 100$  mm,  $R = 1300$  mm).

elements locating in the heating area. The magnitude of inherent deformations in the forms of shrinkage and angular distortions can be obtained by integrating the strain of the element in the heating area. The distribution of the shrinkage  $\Delta s$  and the angular distortion  $\Delta \theta$  along A-A' are shown in Fig. 14.

To make sure that the desirable final configuration of the plate can be obtained by applying the inherent deformations which distribute only in the heating area, the deformation of a flat plate is computed. The concentrated inherent strains are applied as initial strains in the computation. The deformations are computed using three types of inherent strains, namely all strain components, only inplane components and only bending components.

Figure 15 shows the height  $h^*$  at the center of the spherical cap due to applying all strain components in the heating area as the inherent strain. The height  $h^*$  obtained by the deformation is smaller than  $h_0$  which is the desirable final height. This is due to the fact that the inherent strains outside the heating area are not taken into consideration. As the thickness of the plate increases and  $h_0$  is small, the height  $h^*$  retained by the deformation is small. The cases in which  $h^*/h_0$  is small can be categorized as the bending predominant type according to the conclusion obtained in the previous chapter.

Similarly, Figs. 16 and 17 show the results when only inplane and bending inherent strains are applied to a flat plate, respectively. When the thickness  $t$  is small and the height  $h_0$  is large, roughly 90 % of the desired configuration can be obtained by only inplane strain concentrated in the heating area. On the other hand, if the thickness is large and bending is predominant, it is necessary to consider the effect of the bending inherent deformation.

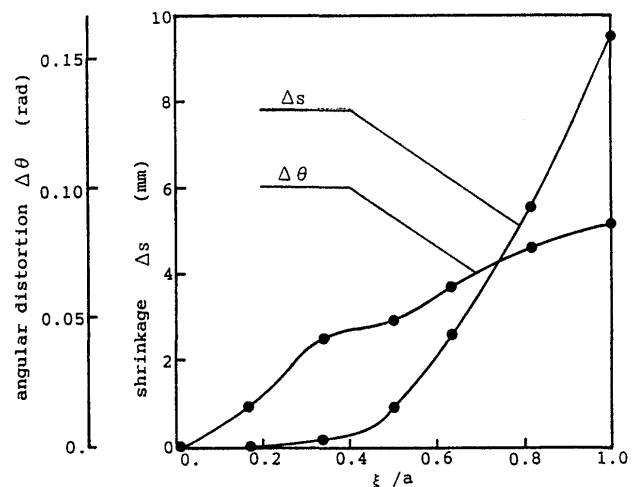


Fig. 14 Distribution of shrinkage  $\Delta s$  and angular distortion  $\Delta \theta$  along A-A'.



### 5. Forming of Doughnut Shape

A simple example of spherical shell was considered in the previous discussion and the outline of the proposed method is demonstrated. In this chapter, examples which are close to the real ship's hull will be examined. The actual form of curved plates resembles the portion of a curved surface of doughnut. This type of surface has curvatures in two directions as shown in Fig. 18. The values of the radii of curvature  $R$  and  $r$  were studied and

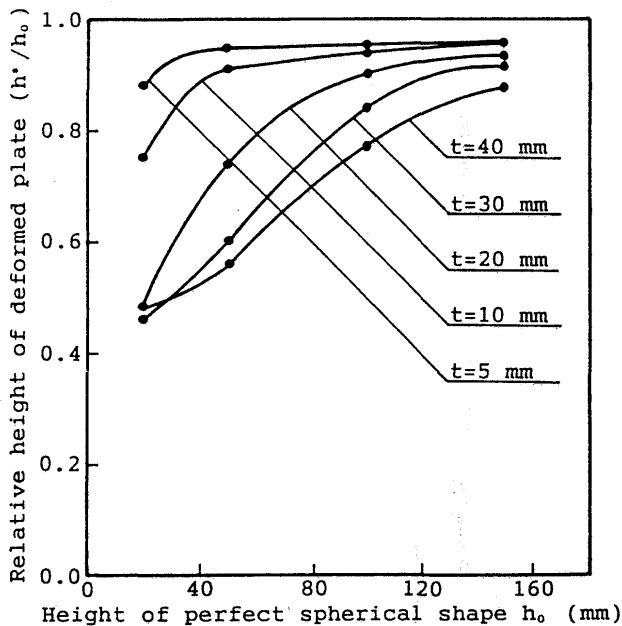


Fig. 15 Deformation of plate due to inherent strain concentrated in heating zone.

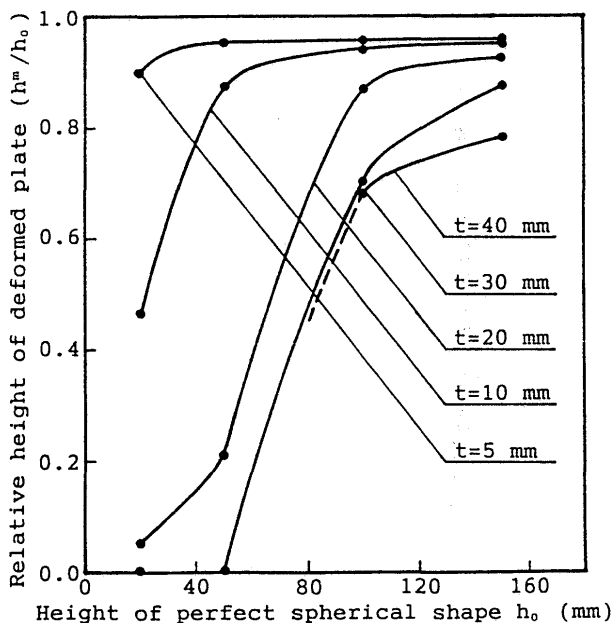


Fig. 16 Deformation of plate due to inplane inherent strain concentrated in heating zone.

reported in a paper<sup>4)</sup>. According to the report, the ranges of these value are,

$$-1.0 \times 10^{-4} < 1/r < 3.0 \times 10^{-4} \quad (1/\text{mm})$$

$$0.0 < 1/R < 3.0 \times 10^{-5} \quad (1/\text{mm})$$

Since it is more convenient when comparing with experimental data through similarity, the parameters  $1/r$  and  $1/R$  are transformed into dimensionless forms  $t/r$  and  $t/R$  using the plate thickness  $t$ . Assuming that the average thickness of plates used for curved members of a ship is about 20 mm, the range of the curvatures in dimensionless form become,

$$-2.0 \times 10^{-3} < t/r < 6.0 \times 10^{-3}$$

$$0.0 < t/R < 6.0 \times 10^{-4}$$

Then two cases, one is a pillow shape and the other is a

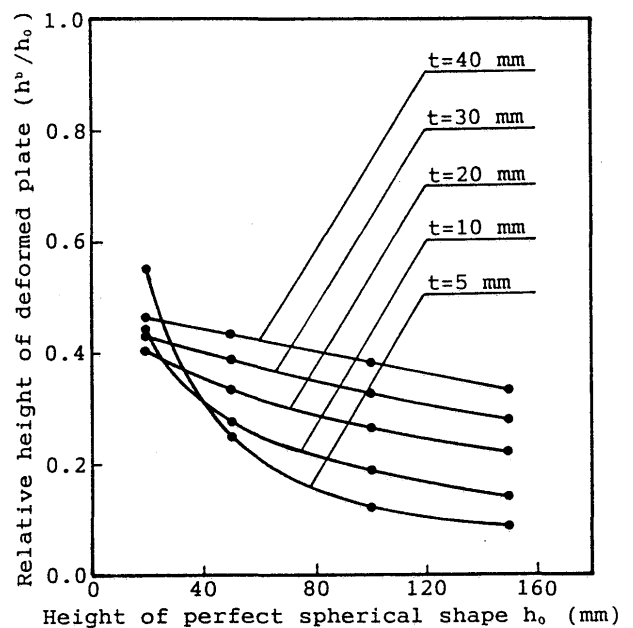


Fig. 17 Deformation of plate due to bending inherent strain concentrated in heating zone.

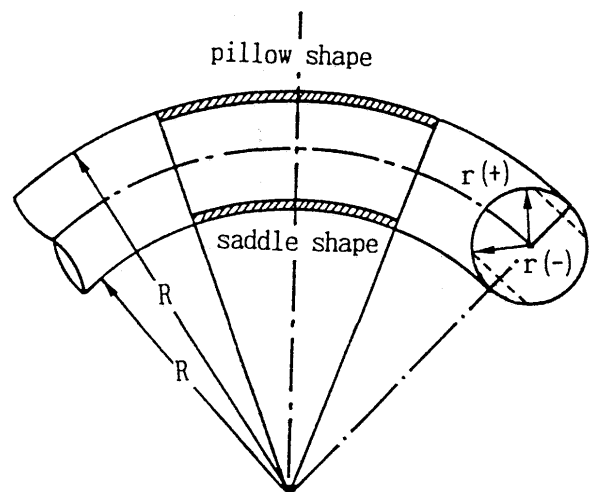


Fig. 18 Plates with doughnut shape.

saddle shape, which satisfy the above condition are considered as examples. The curvatures are assumed to be,

$$t/r = \pm 2.5 \times 10^{-3}$$

$$t/R = 5.0 \times 10^{-4}$$

Figure 19 shows the dimensions of the pillow and saddle models. The pillow type has the two curvatures in the same direction while the saddle type has the two curvatures in opposite directions.

As the first stage, the strain distribution is computed assuming that the flat plate is formed to a pillow shape and the plate is a homogeneous elastic body without cuts. Only one quarter of the model is analyzed due to the symmetry. The computed inplane strain is shown in the form of the distribution of the minimum or compressive principal strain in Fig. 20. The maximum absolute value is  $3.17 \times 10^{-3}$ . On the other hand, for the bending strain component, the bending strain along the short edge is dominant. The bending strain distributes almost uniformly and its value is approximately  $t/2r = 1.25 \times 10^{-3}$ . As the order of magnitude of inplane and bending strain is same in this case, it is difficult to form the plate only using inplane inherent strain. Therefore, it is practical and efficient to bend the plate in the width direction ( $y$  direction) by a press or a roll machine before the line heating as commonly done in shipyards. Thus, the plate in this example is assumed to be formed into cylindrical shape with radius  $r$  and formed into a pillow shape with its height  $h_0 = 100$  mm. The inplane principal strain

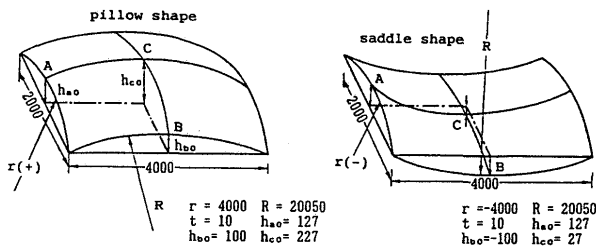


Fig. 19 Doubly curved plate models.

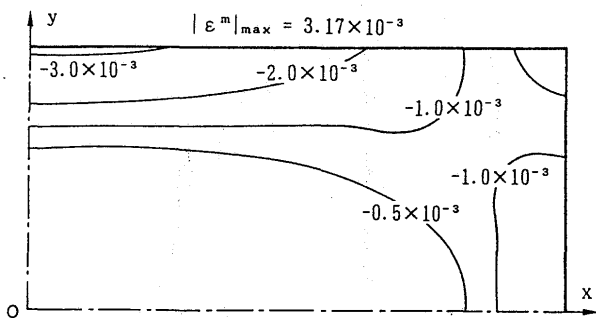


Fig. 20 Inplane strain distribution for plate formed from flat plate (pillow shape).

distribution is shown in Fig. 21. Also, the distribution of the maximum bending principal strain is shown in Fig. 22. It can be seen that the variation in the inplane strain is large. While, the bending strain distributes almost uniformly in the plate. The maximum values of the inplane and the bending strains are  $3.15 \times 10^{-3}$  and  $1.24 \times 10^{-4}$ , respectively. In comparison with the case of forming a pillow shape from a flat plate, the magnitude of the bending strain decreases, and it becomes one order smaller than the magnitude of the inplane strain. Since the inplane strain is dominant in this case, the heating position and the direction are determined from Fig. 21. Following the general rule that the line heatings are applied at the area where the compressive strain is large and heating direction is taken normal to the compressive strain, the heating area can be decided as shown in Fig. 23. The figure is suggesting that the edge part of the plate should be heated and it agrees with the real practice in shipyards. If Fig. 21 is closely examined, large tensile strain distributes in the center part of the plate. To include the effect from the tensile strain, part of the area with tensile strain is added as the heating zone. Then, the inherent strain which should be given along the heating line is computed by the elastic analysis using elements with small Young's modulus for heating area. The computed inplane strain distribution is shown in Fig. 24.

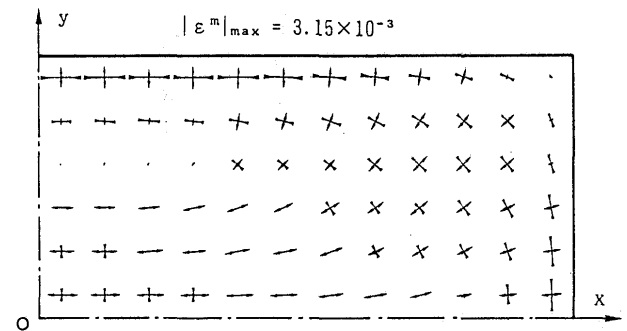


Fig. 21 Inplane strain distribution for plate formed from cylinder (pillow shape).

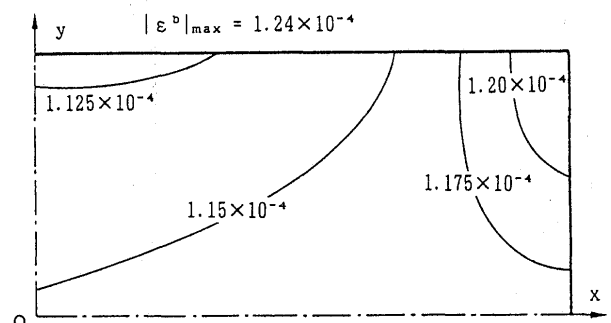


Fig. 22 Bending strain distribution for plate formed from cylinder (pillow shape).

As it is seen from the figure, most of the strain is concentrated in the heating area and the positive strains observed in Fig. 21 are disappeared. Further, the deformation of the cylindrical plate when the strain concentrated in the heating area is applied as initial strain is computed. The computed heights at points A, B and C are shown in Table 1.

Similarly, the forming of saddle shape plate is examined. The strain distribution when the cylindrical plate is formed into the saddle shape is computed. Since the bending strain is same as in the pillow shape except for the sign, only the inplane strain distribution is shown in Fig. 25. Based on this strain distribution, the heating area is determined as shown in Fig. 26 and the inherent strain concentrated along the heating line is computed. Further, the deformation of the plate due to applying the concentrated inherent strain is computed. The heights at the same points as the pillow shape are given in Table 1 together with those of the pillow shape. From Table 1, it is seen that the shape of the plate obtained by applying only the concentrated strain is within the error of 8 mm in the case of pillow shape. This value is considered to be small as compared with the height of the pillow  $h_0$ . While, the error in the case of the saddle shape is relatively large and it is 17 ~ 27 mm. Although the error in forming may

be large depending on the shape to be formed, the above examples show that the proposed method can be a promising method in planning the line heating process. However, it is necessary to provide a procedure for adjusting minor error since some error is always expected in the proposed method. Such correction procedure will be developed in the next stage of the research.

## 6. Conclusions

In the planning of plate forming process, it is necessary to determine the magnitude of the inherent deformation that should be given to the plate, as well as the position and direction of heating lines. Also, the heating and the cooling conditions to obtain the specified inherent deformation must be determined. A method for determining the position and the direction of a heating line and the magnitude of the inherent deformation

Table 1 Geometry obtained by applying inherent strain.

	pillow (mm)	saddle (mm)
$h_{0a}/h_a$	127.0/124.8	127.0/109.4
$h_{0b}/h_b$	100.0/100.2	-100.0/-79.7
$h_{0c}/h_c$	227.0/219.5	27.0/54.2

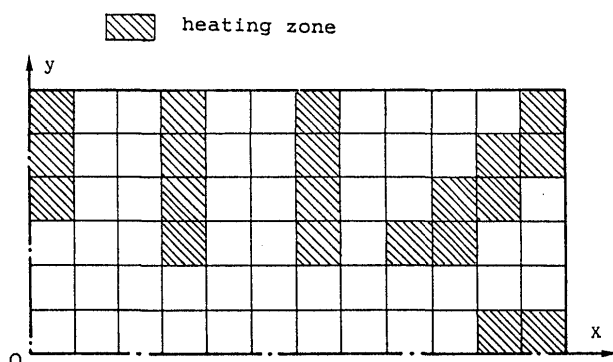


Fig. 23 Heating zone for forming pillow shape.

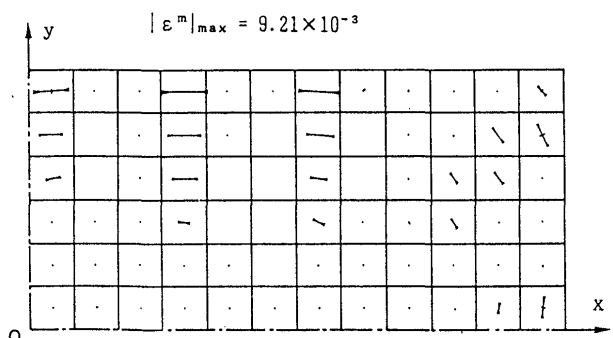


Fig. 24 Inplane strain distribution with heating zone (pillow shape).

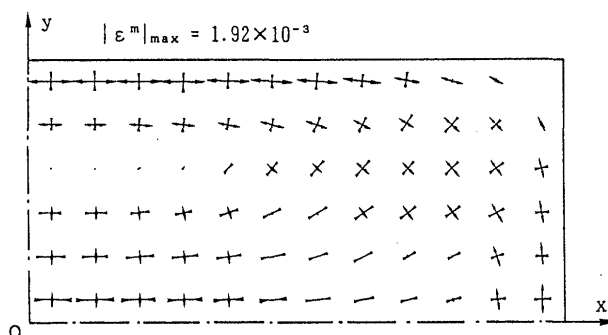


Fig. 25 Inplane strain distribution for plate formed from cylinder (saddle shape).

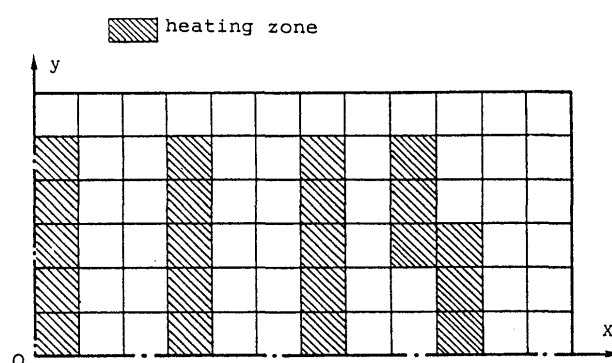


Fig. 26 Heating zone for forming saddle shape.

using the Finite Element Method is proposed in this paper and its validity was examined. The role of the inplane and the bending inherent strains as well as the characteristics of the spring back are studied using the press forming process of the spherical cap as an example. Further, the validity of the proposed method is examined through the forming of the spherical cap, the pillow and the saddle shapes by the line heating. Through the present study, the following conclusions are drawn.

- (1) For the successful and efficient plate forming by line heating, it is necessary to properly combine both the inplane and the bending inherent strains.
- (2) In the case of spherical cap, the inplane inherent deformation is predominant when the thickness is small and the curvature is large. In other words, when the parameter  $a^2/Rt$  is large, the inplane deformation becomes more important. Therefore, the line heating which gives more shrinkage than the bending is effective.
- (3) The validity of the proposed method to decide the position and the direction of the heating line was confirmed for the pillow and the saddle shapes. It is also shown that a precise information concerning the necessity of primary rolling process can be obtained.
- (4) The validity and the applicability of the proposed method for determining the magnitude of the inherent deformation that should be given along the heating lines are proved through numerical examples.

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