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A Two-Dimensional Simulator for Plate Forming by Line Heating

by

Jong Gye Shin*

선상가열(Line Heating)에 의한 평판가공 Simulator 연구

신종계*

Abstract

In order to simulate the line heating process which is a three-dimensional transient thermo elastic plastic state, a simple modified strip model is suggested. First attempt is made to verify the validity of the model using a finite element program, and the result gives good agreement with the plate theory where conventional two-dimensional model fails totally.

요 약

선체 등의 곡면 가공에 사용되고 있는 Line Heating(선열가공)법의 역학적 이해를 통하여 3차원 열탄소성 변형을 simulation하는 model을 유도하고 유한요소 프로그램을 이용하여 model의 효용성을 검증하였다. 이미 제안된 다른 model이 결과를 주지못하는 온도분포를 채택하여 본 model이 좋은 결과를 주는 것을 확인하였다.

1. Introduction

Line heating is the process of forming curved shapes from flat plates by a moving heat source along straight lines on the top of a plate as shown in Fig. 1. The line heating method has been found useful for applications in the manufacturing of ships structures, primarily for parts involving double curvature. Shipyards have been using this method to bend plates to the desired shapes with and without press machines.

Press bending is used for simple or single curva-

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*정회원, 해사기술연구소

ture shapes, while the line heating is imperative for highly curved or double curvature shells. Many advantages of the line heating method over the conventional mechanical forming method have been recognized by the National Shipbuilding Research Program in U.S.A.[12].

Another important application of the line heating method is the post-welding removal of welding distortions. This straightening process also uses the spot heating. The line heating is useful to remove angular distortions, while the spot heating is good for removing buckling type distortions. An automation algorithm or the removal of undesired distortions using robots was suggested by Masubuchi and his colleagues at M.I.T.[9].

Among the factors that determine the final permanent shape of the flat plates are :

distance between torch-tip and plate
torch travel speed
pressure and quantity of applied gases (usually, oxygen and acetylene)
plate thickness
cooling methods
material of plate
etc.

Implicitly, the skill of a workman is also a key factor. At present, bending paltes and reducing welding distortions by a torch is primarily done manually and is based on experience rather than scientific understanding.

Oxyacetylene has been a common heat source for current line heating processes. A major disadvantage of the oxyacetylene line heating is the material degradation. A better control of the temperature may be essential for approval of the method for higher tensile steel applications. In general, the procedure is approved by the American Bureau of Shipping to the maximum heating temperature of 650°C. Scully surveyed the possibility to use the laser heating[14]. However, whatever the heat source is, the basic mechanics of the process are the same.

The effects of the cooling methods are studied by Araki *etal.*[2]. Their experiments showed that the back side water cooling method gave greater angular distortion than the air cooling or the water cooling on the heat side did.

The line heating process is a three-dimensional transient thermo elastic plastic state. In a view point of the moving flame, the process is known to the quasi-steady state. Two motivations are arisen to develop a simple model which can simulate the complex behavior of the line heating;for possibel automation of the line heating process and for correction to the previously developed simulation models.

In order to simulate the three-dimensional transient thermo elastic plastic behavior of the mechanics of the line heating process, two-dimensional models have been widely considered. Iwamura and Rybicki used a two-dimensional beam model which was taken normal to the heatime line and was analyzed using a finite element to have discrete tempe-

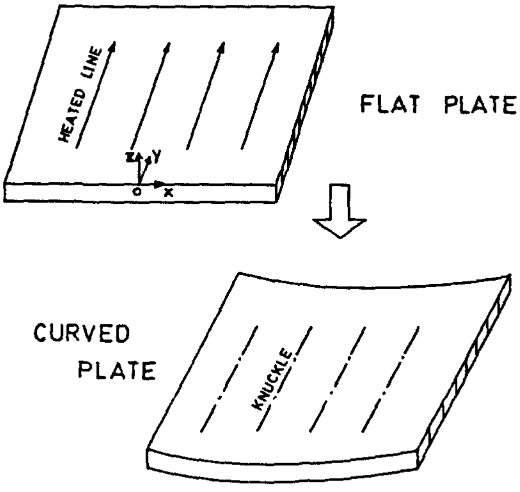

Fig. 1 Plate forming by line heating

rature distributions during the line heating process was suggested by Iwasaki *et al.*[6]. Nomoto *et al.* developed a simplified nonlinear elastic plate bending model instead of thermal elasto-plastic and large deformation analvsis [13]. An 8-node isoparametric shell element is used for FEM analysis of the developed simulator. A special attention can be paid that they used the high-frequency induction heating to bend the plate during their experiments. All of the beam models lack a detailed description of the physics behind the process, and fail to predict some experimental results [7] [8].

The main focus of this paper is the development of a simple model to simulate the line heating process. A two-dimensional beam model with springs is suggested, and numerical analysis using ADINA is performed to verify the validity of the model. The results show that the proposed model agrees with the plate theory where the conventional models fail totally.

2. Line Heating Process

The entire schematic procedure for manufacturing curved shells by the line heating method is illustrated in Fig. 2. For analyzing the plate bending, the dimensions and boundary conditions of the plate should be known. For plate forming, usually all the boundaries are free since the plate is resting on the floor or on a specially designed table. But for the removal of residual distortions, the boundary conditions may vary in diferent cases.

The type of heat source and the thermal properties such as heat conductivity of the plate should also be known. Then, the amount of heat input and its distribution, the torch speed, cooling method and the heating location will be chosen initially as system parameters. These parameters are to be changed if they turn out not to produce the desired shapes. From the given data and initial system parameters, the external heat conditions are determined and the heat equation can be solved[10]. The obtained temperature field becomes the thermal loadings for the stress-strain analysis. The transient thermal elastic plastic analysis is performed to find the desired shape and residual stresses in the plate with temperature-dependent material properties, such as Young's modulus and the yield stress. If the shape obtained is not the one required, the initial parameters are changed accordingly and the procedure described above is repeated until the desired shape is obtained.

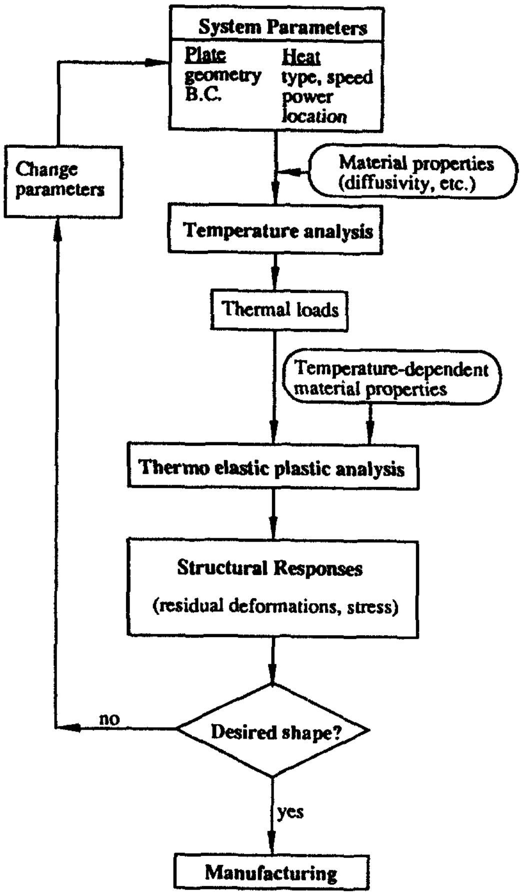

Fig. 2 An overview of line heating process

3. Temperature Field

A flame, welding are or a laser beam moving on top of a solid produces a transient temperature field. All of the above heat sources can be modeled as moving distributed heat sources. A general solution of a distributed heat source travelling on the surface of a semiinfinite plate 33has been obtained by Eagar and Tsai [4]. They assumed a Gaussian distribution for the heat flux.

The line heating process is considered to behave according to the uncoupled theory of thermo mechanics [3]. Therefore, the heat conduction problem is solved independently. The temperature field serves as pseudo forces for the stress analsis.

A typical exmple of a temperature field for a plate with dimension 2m×1m×20mm and a heat source with flame effective power of 1920 cal/second and speed of 7.5mm/second is shown in Fig. 3 from [10]. The heat source is moving in the x-direction and it is noted that when the torch is far enough from the plate edges, the temperature distribution relative to an observer moving in the same direction and with the same speed as the heat source is unchanging. This phenomenon is referred to as quasi-steady state and, as will be seen later, it is possible to reduce the computational effort due to this characteristic. The eage effect is not included in this paper.

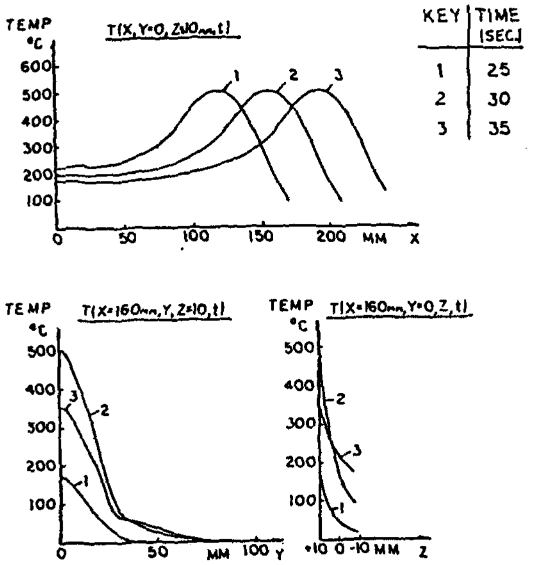

Fig. 3 Temperature field due to a moving torch [10]

Note that the gradient of the temperature in front of the torch is larger than that behind the torch. It is also clear form Fig. 3 that the temperature distribution is three-dimensional when viewed from a moving coordinate system and it is also transient when viewed from a fixed point. The temperature is maximum just below the torch and decreases dramatically to zero in both the y-and z-directions (room temperature taken as zero).

4. A Simulation Model for Coupled Plates

4.1 Basic idea

The purpose of developing a new simulation model is to achieve better understanding of the three-dimensional effects on residual deflections and stresses during the process of plated forming by the line heating method. The idea of a modified strip for the elastic case proposed by Shin [15] is extended for studying the transient thermo elastic plastic plate bending. This modified strip was proved to be more effective for the analysis of nonuniformly loaded plates than the conventional strip intoduced by Timoshenko and Woinowsky-Krieger [16].

It is noted that the residual bending, which occurs in the moving torch case, cannot be achieved using the linear distribution of the temperature if a conventional strip model is applied.

A new strip model is shown in Fig. 4. The vertical springs in this model represent the effect of the bending rigidity of the adjacent plates, while the horizontal springs represent the effect of the stretching rigidity of the adjacent plates. By the use of the linear total strain assumption a beam theory for the modified thermo plastic strip is derived. As a result, the significance of the coupling between the in-plane out-of-plane problems is revealed.

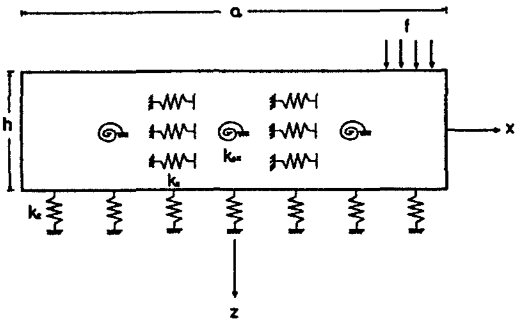

Fig. 4 A Modified strip model

4.2 Governing Equations

The line heating process of forming involves several heating and cooling cycles, and due to the plastic strains which are induced during the process the desired shape is obtained. Thus, in order to derive the algebraic equations elastic plastic thermal stress strain relationships must be used.

There are three basic assumptions which are made in this derivation. First, linear strain across the thickness, secondly small deflections are assume, and thirdly, shear strains are neglected.

These three assumptions lead to the following expression for the displacement u in the x-direction.

$$u = u_O - z\frac{dw}{dx} \tag{1}$$

where u_O is the displacement of the midplane in the x-direction and w is the lateral displacement. both w and u are functions of x which are the unknowns of the problem. From the above expression for the displacement, we obtain the corresponding total strain as

$$\varepsilon_x = \varepsilon_{xo} - z\frac{d^2w}{dx^2} \tag{2}$$

Equilibrium equations are obtained by considering an element from the beam. The equilibrium in the horizontal direction gives

$$\frac{dN}{dx} = c_1 u_0 - c_2\frac{dw}{dx} \tag{3}$$

where c_1 and c_2 are defined by

$$C_1 = \int_{-h/2}^{h/2} k_x \, dz$$

$$C_2 = \int_{-h/2}^{h/2} k_X z \, dz$$

The equilibrium in the vertical direction forces and moment can be combined to generate the following equation.

$$\frac{d^2M}{dx^2} = -f + k_Z w - (k_{0X} + c_3)\frac{d^2w}{dx^2} + c_2\frac{du_0}{dx} \tag{4}$$

where

$$C_3 = \int_{-h/2}^{h/2} k_X z^2 \, dz$$

Here, f is externally applied force, k_Z is the stiffness of the vertical spring, M is the moment resultant in the strip, and k_{0X} is the stiffness of the torsional spring. Eq. (3) and (4) are two equilibrium equations to be solved simultaneously. Since the problem includes plastic deforamtions, and incremental formulation of the two governing equations is more suitable.

The total strain increment consists of three independent strain components, which are the elastic, plastic, and thermal strain increments. Using the flow fule for plasticity and temperature-dependent material properties, the incremental forms of the two equilibrium equations can be derived as follows.

$$D_1\frac{d^2\Delta u_O}{dx^2}-D_2\frac{d^3\Delta w}{dx^3}-c_1\Delta u_O-c_2\frac{d\Delta w}{dx}$$

$$=\frac{d}{dx}\left(\Delta N^{th}+N^{*}\right) \tag{5}$$

$$D_2\frac{d^3\Delta u_O}{dx^3}-D_3\frac{d^4\Delta w}{dx^4}-c_2\frac{d\,\Delta u_O}{dx}+\left(k_{0X}+c_3\right)$$

$$\frac{d^2\Delta w}{dx^2}-k_Z\Delta W=-\Delta f+\frac{d}{dx}\left(\Delta M^{th}+M^{*}\right) \tag{6}$$

Here, Δ is a symbol of the increment with respect to time or temperature. The exact form of used quantities are shown in Appendix. The above governing equations, Eq.(5) and (6), show that with added springs the in-plane and out-of-plane displacements are coupled. The coupled equations can be solved numerically with the use of approximate boundary conditions and as appropriate choice of k_X, k_Z and $k_{\Delta X}$. Choosing the springs may well depend on further evaluation of the mechanics of the line heating method. In this paper, the foundations for the use of a modified thermo plastic stripmodel in terms of the above coupled equations are set. First attempt to verify the validity of this model is made for the uncoupled case using a finite element program in next section.

5. Numerical Example

A moving heat source is used to demonstrate the need for a modified thermo plastic strip model. In this case, a moving torch is heating the plate and a linearly varying temperature is used. The effect of the moving position of the torch is simulated by the time-phasing of the temperatures of the different domain elements as shown in Fig. 5, where the element numbers correspond to those of Fig. 6. The results will show that in this case the process is definitely thermo elastic plastic, whereas the use of the conventional strip theory would have resulted in an elastic process. That is, internal constraints due to the temperature variations along the heating line cause differences between the total and the thermal strains throughout the plate, in spite of the constant temperature gradient through the plate thickness. In other words, elastic strains are produced, and as the yielding stress is reached, plastic strains are developed.

To analyze the residual bending of this transient elastic plastic plate, a modified strip is taken from the center of the plate when the torch is passing on it. The center strip with the temperature field is shown in Fig. 6.

The temperature varies linearly through the thickness direction(z-direction) and is a step function in the length direction (x-direction). A finite element computer code, ADINA [1], is used to verify

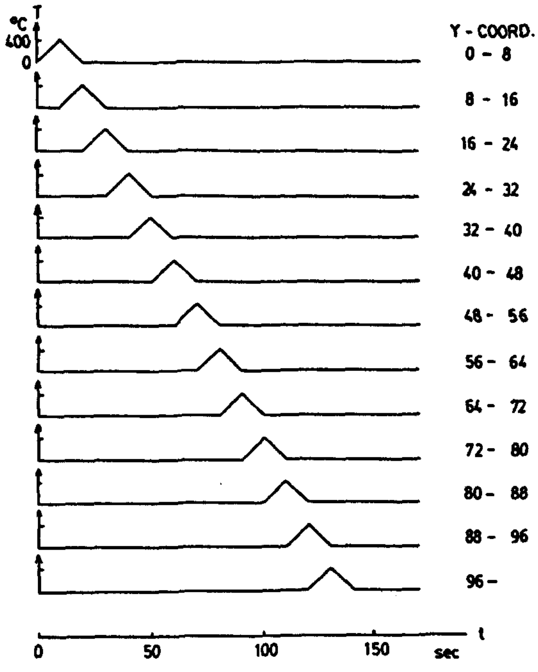

Fig. 5 Time-phasing of temperature distribution

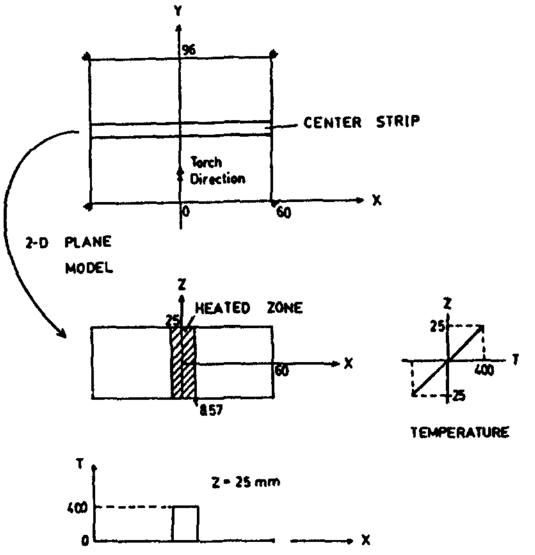

Fig. 6 Center strip and temperature field

the feasibility of a modified thermo plastic strip theory. A plane stress analysis of the modified strip has been chosen to analyze the transient thermo elastic plastic plate bending.

Fig. 7 shows the finite element modeling of the center strip. Using symmetry, on the strip is modeled. The intersection with the midplane is taken to be clamped and the horizontal degrees of freedom along the symmetry line are restrained. Some obervations are made through a preliminary elastic finite element analysis. When the temperature distribution is linear along the thickness, it is expected that axial stress will not be generated in the beam whatever the temperature level is. The initial results obtained from a preliminary elastic analysis using two-dimensional plane stress elements indicated that axial stresses are generated throughout the beam. The contradiction is explained in the following. The difference comes from the fact that the temperature distribution is not a smooth function, but a step function along the x-direction which creates numerical errors. To get more accurate results, finer mesh is required expecially at the discontinuity. Increasing the number of elements results in increasing computer time and cost, which is very unfavorable to our purpose. Realizing that the unheated zone experience a rigid body motion, the initial finite element model was modified such that only the heated zone is included. With this modification the elastic analysis of the heated zone by plane stress elements gives zero axial stresses, and the unheated zone has no axial stresses and moove rigidly. The numerical results of this model agreed well with the theoretical prediction.

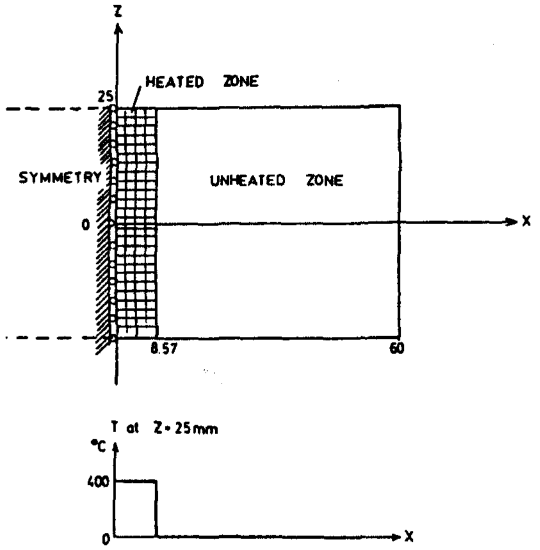

Fig. 7 Two-dimensional finite element modelling

Here, it is noted that the residual bending, which occurs in the moving torch case, cannot be achieved using the linear distribution of the temperature if a conventional strip method is applied. Therefore, a modified strip method is inevitable to capture the residual bending. Distributed springs can be added vertically and horizontally. No torsional springs are added because they involve rotations which are not used as degrees of freedom in two-dimensional plane elements. Physically the vertical springs affect the vertical stresses, which is unfavorable, as it may channge the nature of the plasticity. The simulation of a beam requires that only axial stresses be included. Therefore, only horizontal springs are finally added to the strip. These springs have an effect similar to that of the other springs as they add restraint to the bending.

Different distributions of the spring are tested to explore their significance. This includes constant and linear distribution. The results using constant stiffness of the spring distribution are shown in Fig. 8, 9 and 10, compared with those from Moshaiov and Vorus [11]. In Fig. 8, the residual stress near the top and the bottom of the plate agrees very well, especially for the value of k of 40000 kg/mm. As the stiffness k is increased, the residual stresses are also increased across the section. Inside the plate, the trend of the distribution of the residual stress is similar, but quantitatively the stress from the modified strip theory is less than and the of the plate theory. It is noticed that the axial resultant and the moment resultant along the

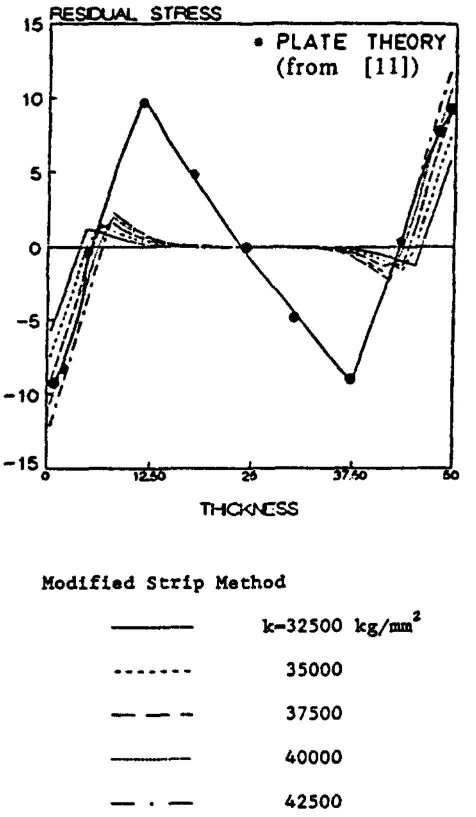

Fig. 8 Residual stress along plate thickness

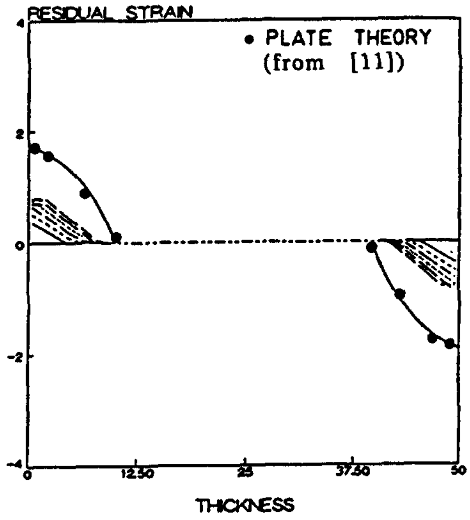

Fig. 9 Residual strain along plate thickness

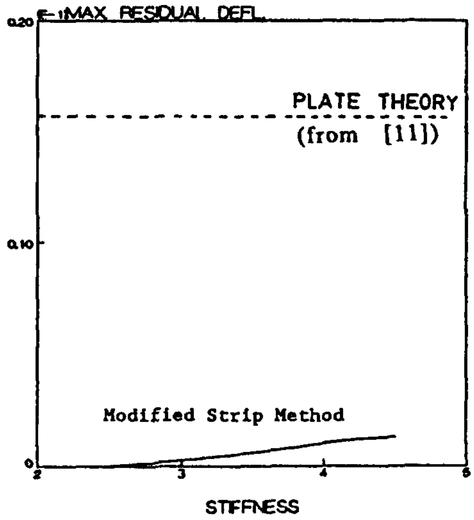

Fig. 10 Residual deflection at the tip of plate

symmetry line are zeroes as expected. In Fig. 9, the residual strains along the thickness direction at the symmetry line are shown for various stiffnesses k. The trend of the result of the modified strip agrees with that of the plate theory. However, the magnitude given by the modified strip theory is about one-fourth of the magnitude given by the plate theory for K=40000kg/mm. Fig. 10 shows the the residual deflections at the tip of the strip (x=60mm) for different stiffnesses k. The deflection at the tip of the strip is calculated by extrapolating the displacement at the tip of the finite element model (that is, x=8.57mm) The displacement at the tip of the strip for k=40000kg/mm is also one-tenth of the displacement of the plate theory.

6. Conclusions

The line heating process is a transient thermo elastic plastic state. A new strip model is suggested to simulate the line heating process. The governings of the strip are obtained as a coupled form between the in-plane and out-of-plane displacements. This idea comes from the present understanding of the mechanics of line heating. A finite element program is used for a simple uncoupled case. Also, a specil temperature distribution is selected to verify the validity of the proposed model. The result shows that the new model is effective over the conventional models. Further development is required for the new model to give better agreement quantitatively with exact plate theory.

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Appendix

The followings are the quantities which lare used in Eq. (5) and (6).

$$D_1 = \int_{-h/2}^{h/2} E^{ep}\, dz$$

where

$$E^{ep} = E\,(1 - \frac{\lambda E}{\lambda E + H})$$

Here, H is the hardening coefficient, and λ is the parameter which determines elastic and plastic path.

$$D_2 = \int_{-h/2}^{h/2} E^{ep} z\, dz$$

$$D_3 = \int_{-h/2}^{h/2} E^{ep} z^2\, dz$$

$$\Delta N^{th} = \int_{-h/2}^{h/2} E^{ep}\, \Delta \varepsilon_x^{th}\, dz$$

$$\Delta M^{th} = \int_{-h/2}^{h/2} E^{ep}\, \Delta \varepsilon_x^{th} z\, dz$$

where

$$\Delta \varepsilon_x^{th} = \Delta \alpha\,(T - T_o) + \alpha \Delta T$$

where α is the coefficient of thermal expansion, T is the current temperature and T_o is the reference temperature, $\Delta \alpha$ and ΔT are the increment of α and T.

$$N^* = \int_{-h/2}^{h/2} \frac{\Delta E}{E^2} E^{ep} \sigma_x\, dz$$

$$M^* = \int_{-h/2}^{h/2} \frac{\Delta E}{E^2} E^{ep} \sigma_x z\, dz$$