Acquisition of Line Heating Information for Automatic Plate Forming

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Currently, the promotion of productivity is a significant topic in shipbuilding. The line heating, used for forming curved plates, requires many man-hours and the empirical intuition of skilled shipwrights. Therefore, the automatic forming method is being widely studied for practical adoption in shipyards.

As an essential part of the automatic plate forming system, a new line heating simulator is suggested to acquire the heat information. In order to predict the heat-induced plate deformation, a thermal elasto-plastic analysis model is employed, which is based on the inherent strain method with the nonlinear finite element method. Heating paths are determined by geometric analysis of a target surface and an initial surface. Also, a surface mesh generation method is developed to link the finite element analysis and the determination of heat regions. The simulator includes modules of the above preliminary techniques and heat lines can be obtained. Some hull pieces similar to actual plates are tested. From the results, it is shown that our simulator can give heating information with good convergence from an initial surface to a target surface. With a line heating robot, it can contribute to the automation of the line heating process. Presentation

INTRODUCTION

The line heating method is a popular technique used in shipyards to form ship hull pieces. Even recently, skilled workers have performed the forming process by their empirical intuition and so no systematic way to effective formation has been found. The automation of it can reduce working time, rework costs, and inferior hull pieces; this is so attractive to shipbuilders who wish higher productivity of ships.

The forming process by heating has much complexity and uncertain factors that are obstacles to the automation. Of many difficulties, three main problems can be summarized as follows:

i) How can the heat-induced plate deformation be predicted under combinations of many heating conditions?
ii) On which regions of the plate should be heated and bent to minimize forming errors?
iii) How the techniques-i) and ii) can be integrated for practicality?

This study deals with the problems and proposes a solution to overcome them. We developed a simulator of the plate forming process by the line heating in which heat regions can be found under specified heat conditions; traveling speed, heat flux and so forth.

In order to predict the deformation of a plate, a thermal elasto-plastic analysis model proposed by Jang et al [1, 2] was adopted. The inherent strain produced in a heated zone can be substituted with the equivalent forces and moments in some assumptions: a circular disk-spring model, relevant inherent strain zones and so on. The complicated phenomena of the heated plate may be simplified and the deformation can be effectively estimated because the thermal elasto-plastic behavior of the plate is analyzed only by elastic finite element method. For large deformation analysis, Newton-Raphson method is used considering geometrical non-linearity of the deformed surface. Residual deformation is our main concern. No residual stresses were considered in the finite element analysis, therefore, the errors caused by neglecting them can be more realistically corrected in the next forming step [3].

In addition, we employed an algorithm to determine heating paths [4]. Candidate heat paths can be obtained by grouping extreme principal curvatures on a deflection difference surface that represent the difference between a target surface and a fabrication surface. By a convergence index that indicates the likelihood of the surfaces, one heat line is selected among the heat paths. The advantage of this method is believed to be the ability of adjacent heat lines to correct some uncertainty of a heating like the residual stress, which is based upon the step-by-step determination of the heat regions. The two techniques have proved to be fast and accurate. It is a desirable characteristic because the plate forming needs a number of the

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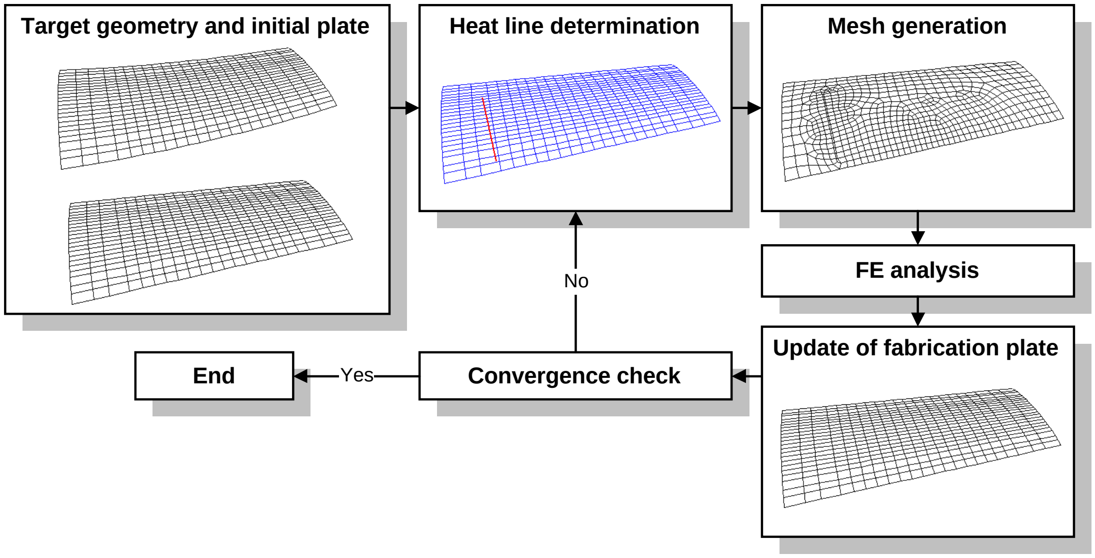


Figure 1 Overall procedure of the simulation of the line heating process

heating lines and the finite element analysis should be performed at each heating step.

In the analysis of shells such as ship hulls, quadrilateral elements have been known to show good performance in comparison with triangular elements. A general shell element called MITC4 [5] is used. For usage of it, the generated meshes should be only quadrilateral over a three dimensional surface domain. Since a heat line breadth is, in general, very small compared with hull piece's scale, the mesh must have good transitivity from large elements to small ones. Thus, the paving method suggested by Blacker et al [6, 7] is modified to satisfy the conditions and divide the fabrication surface and heat lines into well-shaping finite elements automatically, at each step. The surface mesh generation can play a role to link the two elemental methods mentioned above.

Moreover, all the surfaces are modeled with NURBS (Non-Uniform Rational B-spline Surface) to be compatible with CAD systems or ship product models. The surfaces are used in the differential geometry analysis and the mesh generation.

PROCEDURE OF THE SIMULATION

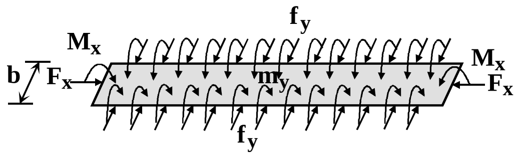
The objective of the simulation is to acquire the heating information necessary to form a given initial surface to a given target surface; heat regions, heating order, etc. By the algorithm of heat line determination, one heat line can be found and meshes are generated according to the line location and surface geometry. Then finite element analysis is performed with the equivalent nodal forces and moments calculated using given heat conditions. The fabrication surface is updated based on the surface deformation resulting from the finite element analysis. Next, convergence to the target surface is checked. The convergence index represents the resemblance of the target and deformed surfaces; if it is zero, the surfaces are perfectly identical. When the surface is converged enough to the target surface or no more heating lines are determined, the simulation is terminated. The overall procedure is illustrated in figure 1.

SIMULATION EXAMPLES

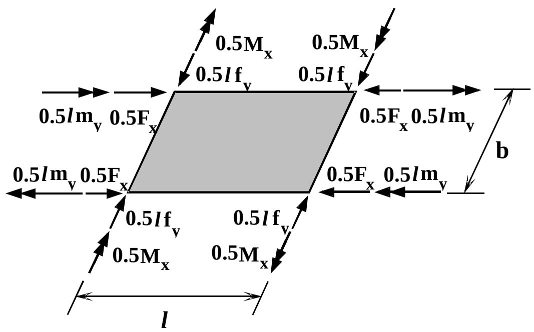
Several surface types were selected, similar to actual ship hull pieces; saddle type, concave type and skewed saddle type. Based on experimental data we assumed that heat conditions were fixed. Table 1 shows that the data and their equivalent loads calculated using the analysis model. A heat line is curvilinear and so the forces and moments

Table 1 Heat Conditions and equivalent forces

Traveling speed	0.3889 cm/sec
Heat input	2250 cal/sec
Inherent strain	0.00639
Heat line breadth	20 mm
Transverse bending moment (m_y)	220.8 kgf
Transverse shrinkage force (f_y)	31.9 kgf/mm
Longitudinal bending moment (M_x)	25534.1 kgf mm
Longitudinal shrinkage force (F_x)	3684.2 kgf



Equivalent forces and moments along a heat line



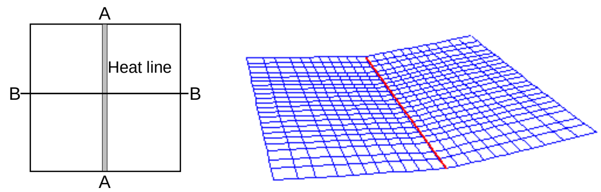
Load conditions at an element

Figure 2 Equivalent loads

should be loaded along the curve, that is, a geodesic connecting the heat line's start and end points. Figure 2 describes the distribution of the forces and the force boundary conditions of each element on the heat line.

Simple line heating

Using the conditions in table 1, we analyzed a simple heating example to know the behavior of the plate under a line heating. The heat line crosses a plate with the dimensions 1000×1000×20 (mm^3). The generated meshes of the deformed shape are shown in figure 3.



Heated plate Mesh for FEA (deformed shape)

Figure 3 Simple line heating example (magnified 30 times)

The maximum relative deflection of the plate along A-A section was 0.301mm and along B-B section was 1.693mm. From the result, the heat line would bend the flat plate in heating direction as well as the perpendicular direction, that is, to a concave configuration. This is due to the longitudinal and transverse moments acting together on the plate with the shrinkage forces.

In case of the saddle and concave surfaces, we imposed the different amount of curvature on the initial deformed surfaces to grasp the effect of the initial curvature. The plates' dimension is 1500×1000×20(mm^3). Tables 2, 3 and 4 show the geometry of the simulation examples and obtained heating lines. In each picture, solid and dotted lines represent front face heating and back side heating respectively. To recognize the fabrication errors, the target surface (gray color) and the deformed surfaces (black color) are also drawn. The deflection of all the surfaces is magnified five times for easy view. The heating lines' information is described in table 5 and the conver-

Table 2 Geometry of the saddle simulations and obtained results

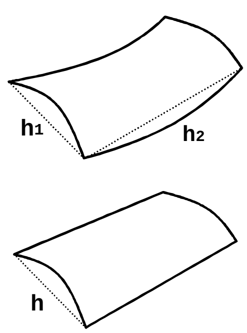
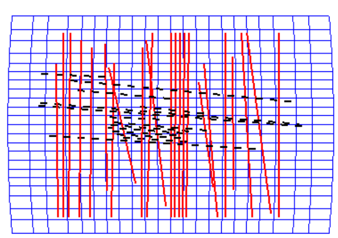
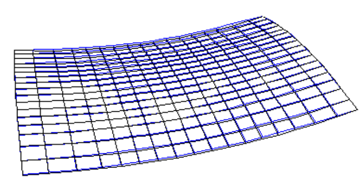
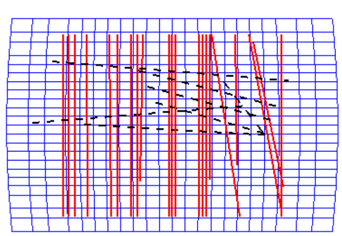
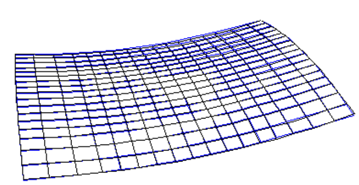
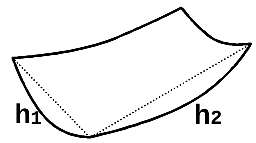
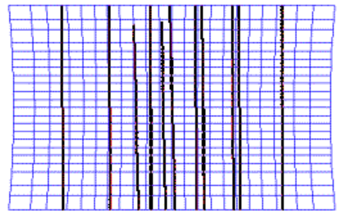
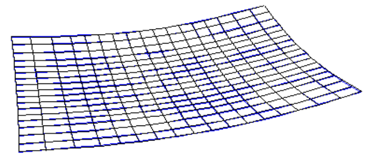
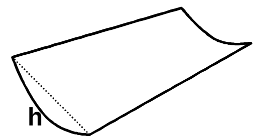
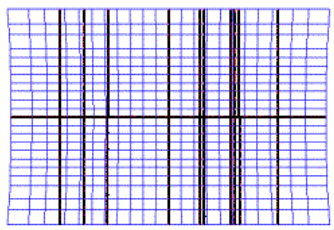
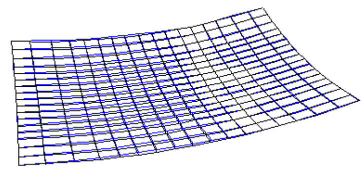
Surface type	Target surface and initial surface	Heating lines	Target and deformed surfaces
Saddle I h_1 = 12mm h_2 = 15mm h = 12mm			
Saddle II h_1 = 12mm h_2 = 15mm h = 14mm	1500×1000×20 mm^3		

Table 3 Geometry of the concave simulations and obtained results

Surface type	Target surface and initial surface	Heating lines	Target and deformed surfaces
Concave I h_1 =12mm h_2 =15mm h =12mm	 		
Concave II h_1 =12mm h_2 =15mm h =10mm	 1500×1000×20 mm^3		

gence index during the heating process in figure 4.

Saddle type

For the test of more realistic cases, we first adopted the saddle surface as the target surface of test simulation. The initial surfaces were modeled by cylindrical or single bent plate. To one initial surface, the curvature in the transverse direction was assumed to be identical to that of the target surface (we call it Saddle I for convenience), while to the other the initial curvature was larger than it (Saddle II). As can be seen in table 2, the trend of the acquired heating lines are in agreement with those we can guess intuitively. The front face was heated first until no more candidate heating lines on the face were found. If a plate didn't converge on the target, it was turned over and heated. The convergence index decreases gradually to 0.06, the convergence index objective value, with the exception that it increases slightly after the first turnover (figure 4a).

The number of the heat lines in Saddle II is smaller and the total heating length is shorter than those of the Saddle I. This is because line heating is likely to produce both transverse and longitudinal bending as mentioned in

Table 4 Geometry of the skewed saddle simulations and obtained results

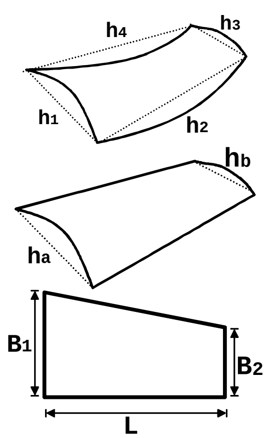
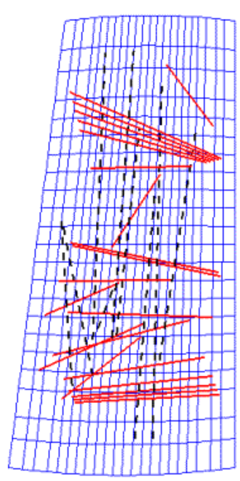
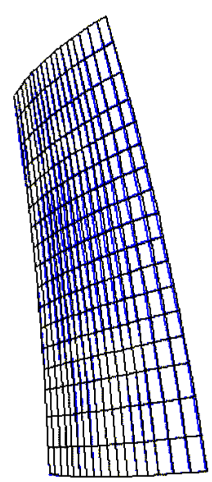
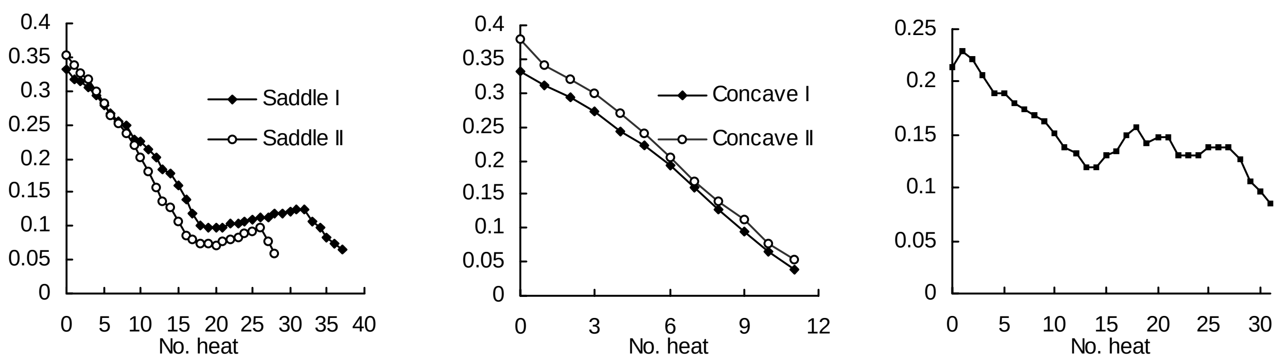
Surface type	Target surface and initial surface	Heating lines	Target and deformed surfaces
Skewed saddle type h_1 = 30mm h_2 = 20mm h_3 = 20mm h_4 = 15mm h_a = 30mm h_b = 20mm L = 4000mm B_1 = 2000mm B_2 = 1500mm	 		

Table 5 Numbers of the heat lines and heating lengths (mm)

	Saddle I	Saddle II	Concave I	Concave II	Skewed saddle
Total heat lines	37	28	11	11	31
Face lines	23	21	11	11	22
Back lines	14	7	0	0	9
Turnovers	2	2	0	0	2
Total heating length	25571.2	21982.7	10806.3	11472.2	41083.1
Face heating length	17657.4	17018.3	10806.3	11472.2	23785.3
Back heating length	7913.9	4964.4	0.	0.	17297.8



(a) Saddle types (b) Concave types (c) Skewed saddle type

Figure 4 Convergence indices

the simple heating example. So the curvature of the initial surface was reduced in reverse due to the opposite side heating. When fabricating the saddle type surface, therefore, it is effective to bend the initial surface some more than the intended longitudinal curvature. This seems to be consistent with the actual work experience in shipyards.

Due to the limits of the laboratory experiment, the heat flux used here was small compared with the intensity of the workers' gas torch. From this reason, the interval of the obtained heat lines tends to be narrow and irregular. We are developing an improved method to locate the heating lines evenly or regularly considering the practical heating process.

Concave type

The concave type has positive Gaussian curvature over the entire surface. As in the saddle type simulation, two initial surfaces were tested. The longitudinal curvature of one is equal to that of the target surface (Concave I) but a less curvature than it was given to the other (Concave II).

The heat lines are placed in the longitudinal direction to bend the plate transversely, as depicted in Table 3. In case of Concave II, the transverse heat line was first calculated and would deform the plate in the longitudinal direction owing to the discrepancy of the longitudinal deflection between the target and initial surfaces. Thus the total heating length of the concave II is longer, although the numbers of the lines are same and we could expect that Concave II had the better convergence, considering the plate deformation under a heating. Actually, to fabricate this type of surface, triangle heating is usually used. In other words, the transverse curve of the concave type can be generated by the shrinkage concentrated on the plate's edge in the longitudinal direction. Thus we can see that it is important to reflect the coupling effect of the curvature and inplane shrinkage in forming the concave surfaces.

Even in the simple cases simulated here, it can be revealed that the feature of the heat deformation and the target surface's geometry should be considered in determining the curvature of the initial cylindrical surface. Shipwrights have done it at the mechanical bending stage by roll pressing prior to the heating process.

The highest fabrication error in the finished plate, as well as in the saddle types, was within an acceptable range, 1.5mm.

Skewed saddle type

In this try, the geometry of the target surface was of saddle and skewed type and it originated from a real ship hull piece. The initial surface was singly curved. Heat lines and the information of heating are demonstrated in table 4. The maximum error between the target and fabricated plates was 2.2mm and two turnovers were required.

CONCLUSIONS

We present a simulator to acquire heat information to automate the ship hull bending process. The main information is heat regions, heating order, and turnovers with a given heat flux. It contains the modules of the heat line determination, prediction of plate deformation by heating, automatic mesh generation, and other methods for surface modeling. The heat line allocation patterns were similar to the yard work. We can know that the plate geometry and behavior of heated plate should be taken into account when flat plates are formed initially and mechanically to set up the heating process generating the compound curvature.

Though not considered here, a series of interface functions with the heating robot have been implemented for the actual ship hull manufacturing, and the plate behavior can be visualized for the worker to check the heating procedures. More research to enhance the simulator is in progress to generate even and regular heating patterns while minimizing the heat paths, and the clear relation of inplane with flexural deformations.

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