# A NEW APPROACH TO DETERMINE SUITABLE HEATING PARAMETERS FOR HULL PLATES FORMED BY TORCH LINE HEATING

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**Abstract:**

*In shipbuilding, the process of forming a flat metal plate into a curved hull plate with a compound shape is very important and greatly affects many economic and technical factors such as strength, quality, and aesthetics of the hull, construction cost, and time, etc. Currently, the forming method of curved hull plates by line heating is used effectively and commonly in many shipyards, however, its main problem is very difficult to determine where and how much to heat on the flat metal plate to obtain the plate of a certain shape. In this paper, a finite element model is established and adjusted based on the actual data to numerical simulate the process of forming hull plates by using flame torch line heating. Based on this model, the suitable position and temperature for the torch line heating process are determined to form a metal plate into a hull plate of a given desired shape. This research was applied to form by torch line heating two plates, symbols K1 and K10, located at the bulbous bow of a 20,000 DWT cargo ship built at Camranh Shipyard in Vietnam. The test results are as expected with displacement deviations between the actual plate surface and the desired curved surface in the range of ± 3%.*

*Keywords:* finite element model, forming method, hull plate, shipbuilding, torch line heating.

## 1. Introduction

A ship's hull is made up of curved plates welded together, therefore, the process of forming flat metal plates into curved hull plates, especially compound doubly curved plates in areas where the hull form has a great change in curvature such as bow, stern, bulb bow, etc. is very important and has a great influence on many economic and technical factors such as strength, quality, and aesthetics of the hull structures, construction cost and time, etc. In shipbuilding, two main methods widely used to form hull plates are mechanical forming and heating forming. Mechanical forming is implemented based on a deformation mechanism of material to form the curved plates by mechanical forces which are created using the manual method or specialized machines e.g. plate rolling machine. This method is usually suitable for forming the hull plates of a simple curved shape, mainly for mass production. Heating forming, also known as line heating, is a method of moving a heat source along defined lines, called heating lines, to locally heat the metal plate at a specified temperature to form the desired curvature of this plate. Three types of heat sources commonly used in line heating are flame torch (oxy-acetylene or oxy-gas torch), induction heating, and laser in which line heating by a torch or a set of torches is commonly used in many shipyards due to their advantages such as simple and inexpensive equipment, the ability to form doubly curved plates with the minimal value of residual stress, making the hull plates with locally thicker, suitable for the automation, etc. However, its main disadvantage is very difficult to determine suitable heating parameters such as the heat source speed, heat input, position of heating lines, etc. to form a flat metal plate into a plate with an exact desired shape. Until now, many studies related to line heating have been performed to find ways to better control this process. These studies cover many different research directions, however, they can be grouped into three main topics, including: (i) theoretical and experimental studies on line heating, (ii) numerical models to simulate the line heating process, and (iii) plan of heating lines.

Our review of the studies related to the above three research topics on the forming by line heating gives the following observations and conclusions.

(i) Theoretical and experimental studies have been performed by many researchers to study the mechanism of line heating, predict the final plate shape based on set either the thermal model, mechanical model, or both. A thermal model with heat loss and distributed heat source was first given by Rosenthal et al. (1946) to determine an analytic solution of temperature field with a moving heat source by the heat conduction equation. Base on this model, some modified models have been proposed to develop and applied for the other problems, e.g. Eagar and Tsai (1983) developed a transient model of the temperature field in a semi-infinitive body. More recently, Nguyen et al. (1999) conducted research and proposed the analytical solution for a transient temperature of a semi-infinite body subjected to the 3D moving heat sources instead of a heat flux surface. The mechanical models are often developed based on beam or plate theory, and known mechanical principles. A simplified mechanical model was first proposed by Jang and et al. (1997) aids to predict inherent strain zone size and deformations on a heated plate by line heating based on a simple thermal elastoplastic analysis. Moshaiov and Vorus (1987) studied the mechanics of the flame bending process, then used a strip model for analyzing line heating, but this model was not suitable for the experimental data (Moshaiov and Shin, 1991). The combined thermal and mechanical model was developed by Anderson (1999), in which the thermal model is used to determine the critical isotherm which defines the strain zone size in the mechanical model. It can be seen that, for simplicity, most of the existing analytical models have to be based on very limited assumptions so they often predict the deformation of the heated plate either inaccurately, inefficiently, or both. The experiments were performed by Masubushi and Luebke (1988), Masubushi and Jones (1999), Kyrsanidi (1999), etc. studying the relations between bending angles and heat power, heat source speed, the position of heating lines. However, most of these studies are performed for laser forming whose heat source is easier to control power and distribution compared to the other heat sources.

(ii) Numerical models have been developed recently by researchers such as Hsiao et al. (1997), Ji and Wu (1998), Yu (2000), Clausen (2000), etc., and have achieved some success in predicting the final heated plate shape. However, since the plate forming process by line heating is a couple of nonlinear thermo-mechanical processes which makes the complete numerical simulate very difficult, especially when applying on the actual hull plate. In addition, most numerical models are usually finite element model which is established based on theoretical or experimental formulas for a laser heat source to simulate and compute line heating process.

(iii) Most studies on determining the suitable location plan for the heating lines are based on differential geometry analysis of the forming surface, along with the expansion methods of the curved hull plates (Mitamura, 1961). These can be either lines connecting points of extreme curvature on a different surface, which is the difference between the initial flat surface and the forming surface (target surface) (Jang and Moon, 1998), or are lines passing through points of similar curvature on the forming surface (Shin et al., 1996), or their direction is normal to the direction of principal curvature or principal strain with the extreme value of strain of forming surface (Ueda et al., 1994, Yu et al., 2000). In our experience, Ueda's method is probably suitable because the direction of the extreme compressive strain is also normal to heating lines.

Many studies have provided some encouraging results, but most of them are rarely applied in practice because most of the finite element models in the existing studies are established only for the plate, and the heating process is simulated using theoretical thermal equations which are usually established based on the laser heat source and some unrealistic assumptions. In addition, not many studies on the heating line by using the flame torch have been applied to form the hull plates because it is difficult to control the deformation of the curved plate and the heating parameters so this process must be still carried out manually based on the experiences of the skillful shipbuilders. The purpose of this article is to present a new approach for determining the heating parameters suitable for the method of line heating using a flame torch to form the flat metal plate in the complex curved plate of the hull. This will aid the shipbuilders to determine the most suitable heating parameter, including the position of the heating lines on the plate and the input temperature for each line, as well as predict the final shape of the hull plates after forming using line heating with a flame torch.

## 2. Material and Research Method

In this study, a finite element model was established to simulate and compute the line heating process by the flame torch in the forming of the actual hull plates of a built ship. The heating parameters including the position of the heating lines and the temperature for each line are adjusted based on the actual data to ensure the accuracy of this numerical model. The studied results have been applied to form the actual hull plates for validating the effectiveness of this new approach. In addition, field research was also carried out in several Vietnamese

shipyards to collect the practical data on the line heating by a flame torch and the typical shape of the actual hull plate which serves the research purposes of this study as follows.

## 2.1 The heating conditions

- The speed of heat source speed depends on heat flux, amount of heat, plate thickness, desired curvature, etc. With line heating by flame torch, the heat source speed depends on the type of torch and is usually in the range V = (4÷7) mm/s, where V = (6÷7) mm/s for plate thickness (8÷6) mm, V = (4÷5) mm/s for plate thickness greater than 16 mm.

- The width of the heating lines depends on many factors such as distance between the torch position and plate heating surface, the radius of the heat-affected area, the size and desired curvature of the hull plates. The actual statistics show that the heating line width in flame torch line heating is in the range (10 - 20) mm.

- Amount of heat or temperature for each line heating depends mainly on the material of the hull plate. The shipbuilding steel plate is mild steel or low carbon steel, so it should only be heated in the temperature range (550÷800)°C, so as not to change the mechanical properties of the material. However, some shipbuilding steel plates are high strength or high carbon steel, the heating temperature can be increased to about 900°C because its melting point is higher.

In addition to the above conditions, the heat source speed and the heating line width depend very much on the skill and experience of the shipbuilders to keep a constant distance between the flame core and plate surface throughout the heating process. Fig.1 describes the proper position of the flame torch relative to the heating plate in practice.
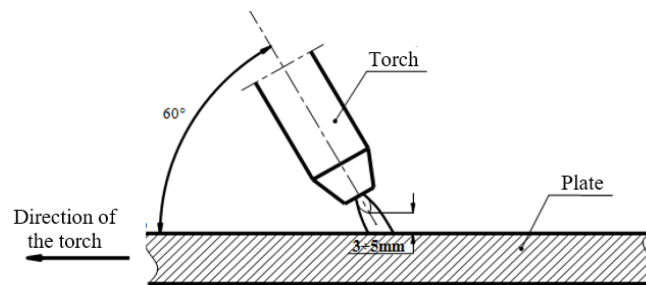


Fig. 1: Proper position of the flame torch relative to the heating plate

## 2.2 Curved shapes of actual hull plates

The metal plates used in practical production are often divided into singly curved plates and doubly curved plates. The singly curved plate has a zero Gaussian curvature at all points on the surface, e.g. a parabole shape, so it can be formed by mechanical forming such as pressing, cold-rolling, etc., while the doubly curved plate has non-zero Gaussian curvature, e.g. an ellipse or hyperbolic shape, so it is often applied to surfaces with high demands on hydrodynamics, esthetics, etc. The actual survey results showed that the hull plates also consist of singly and doubly curved plates with actual diverse shapes, and can be classified into curved shapes as shown in Fig. 2.
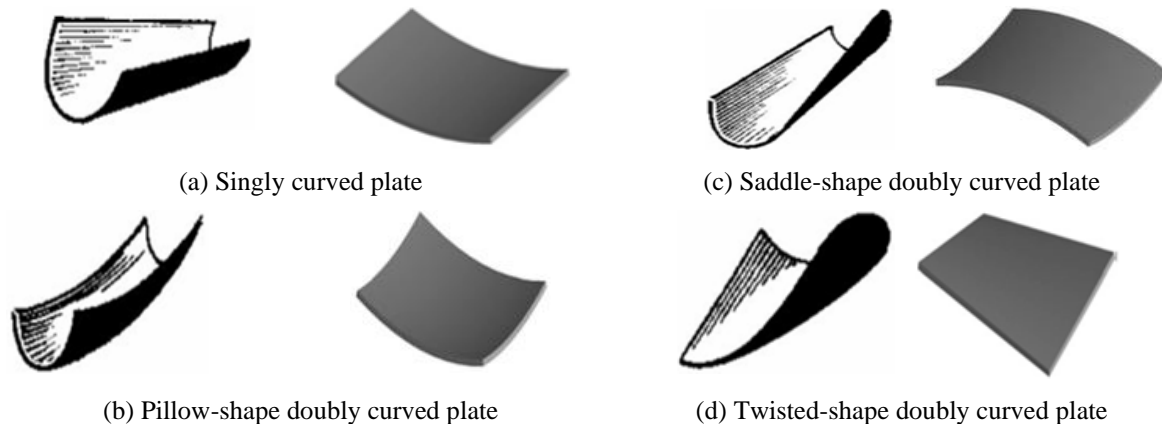


(a) Singly curved plate

(c) Saddle-shape doubly curved plate

(b) Pillow-shape doubly curved plate

(d) Twisted-shape doubly curved plate

Fig. 2: Typical curved shapes of actual hull plates

## 2.3 Selection of curved plates to study

In the scope of this study, two typical actual hull plates consisting of a singly curved plate and a doubly curved plate which are located on the bulbous bow of a 20,000 DWT cargo ship built at Camranh Shipyard in Vietnam in 2017, are selected to study the process of forming using flame torch line heating. Their general type, as shown in Fig. 2a and Fig. 2d, is common on the conventional hulls. The actual shapes and locations of these hull plates, which are denoted UHU-K#1 (abbreviated as K1) for a doubly curved plate, and UHU-K#10 (abbreviated as K10) for a singly curved plate on the hull expansion drawing of this cargo ship's bulbous bow, are shown in Fig. 3. They are developable plates with their planar expansion plate having the same thickness of 10 mm, along with a length of 2105.5 mm and minimum width of 1078.4 mm for the K1 plate (see Fig. 4), and length of 1770.1 mm and minimum width of 1197.0 mm for K10 (see Fig. 5). Since the typical thickness to width ratio of both plates is less than 0.1 the thin plate theory can be applied to them. It also means that the basic assumptions of a thin plate can be allowed for these plates as for most other hull plates.
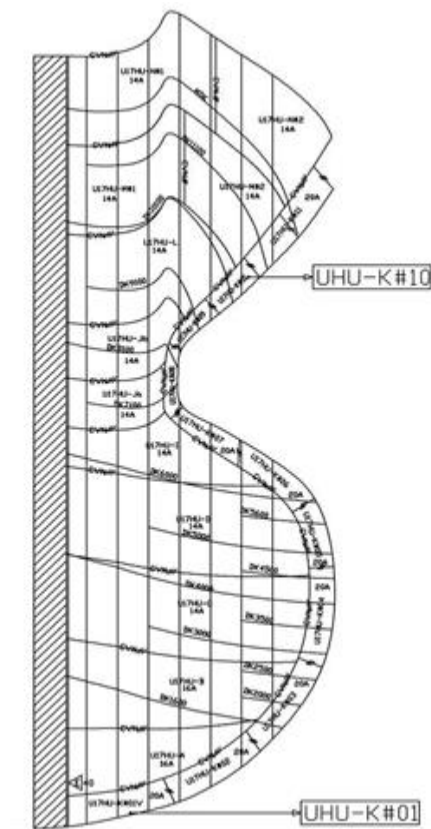


Fig. 3: Hull plate expansion drawing of bulb bow

In this approach, the line heating process to form a plate with a given curvature is performed as follows:

 (i) Develop the computation curved plate and preliminary plan some heating lines on its planar expansion plate.

 (ii) Establish a finite element model of a structure consisting of a planar expansion plate in step (i) linked with heating lines to simulate the line heating process for the computation curved plate.

(iii) Determine the heating parameters suitable for the desired curved plate by determining the displacement of the actual curved plate at some specific positions, then adjust the input heating parameters including position and temperature of each heating line on the structural model established in step (ii) until the displacement values computed by finite element model match actual data at the corresponding positions.

(iv) Fabrication of a planar expansion plate defined in step (i) and conduct line heating for this plate with the heating parameters defined in step (iv), then determine the displacement value of formed curved plate at the positions given in step (iii).

 (v) Compare the displacement values of the computation curved plate computed by a finite element model in step (iv) and the actual fabrication data in step (v) at the given positions to validate the research results.

## 3. Results and Discussions

### 3.1 Develop and preliminary plan of heating lines on the planar expansion plate

Methodically, the curved hull plate can be expanded using known theoretical methods or specialized software. In this study, we use Ship Constructor, specialized software for ship structure analysis and is commonly applied in many Vietnamese shipyards today, to implement the planar expansion of the K1 and K10 curved hull plates, and obtained two planar expansion drawings of these two hull plates as shown in Fig. 4 and Fig. 5, respectively. Also, the planar expanded plates exported from Ship Constructor are usually preliminarily marked with the heating line plan as shown in these same figures. It is worth mentioning that despite great efforts to form the plates K1 and K10 according to these suggested heating lines and temperatures, the desired plate shapes were not obtained.
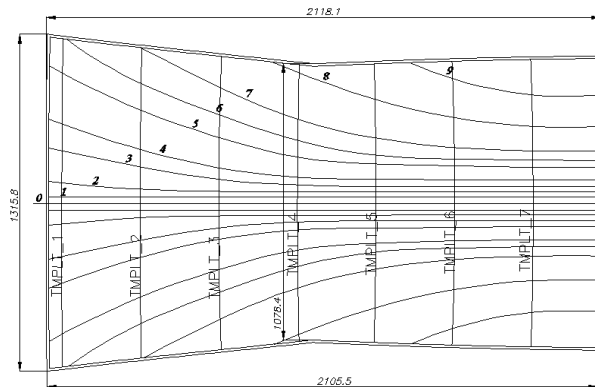


Fig. 4: Planar expansion drawing of K1 plate          Fig. 5: Planar expansion drawing of K10 plate
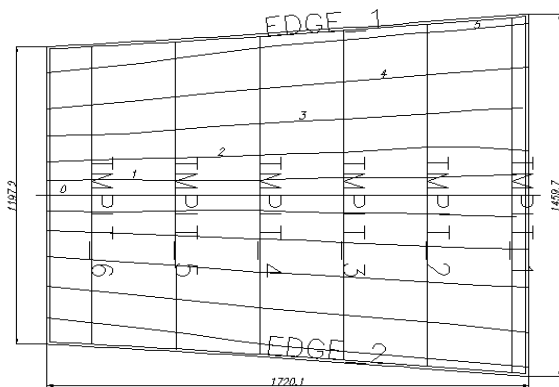
In the absence of pre-marked heating lines, they can be preliminarily determined as follows:
- The heating lines are normal to the direction of principal curvature or principal strain of curved plate surface, where the principal strain is strain along the principal curvature of the curved surface and can be determined based on a known surface theory (Carmo, 1976), Azariadis and Aspragathos, 1997).
- The heating lines are located towards the principal strain zone and along the centerline of the desired plate surface, so symmetry conditions should be utilized in the finite element model to reduce the number of degrees of freedom, i.e. reduce computation time.

### 3.2. Establish a finite element model to simulate the line heating process

As stated above, it is not easy to accurately numerical simulate the process of line heating using the flame torch. Different from the existing studies where the finite element model is established only for the computational plate, while the heating process is described by some theoretical thermal equations which are usually established based on the laser heat source and some unrealistic assumptions. This has made it difficult and inflexible to adjust the input heat parameters when forming the hull plate using flame torch line heating. In this study, a finite element model of computation plates, K1 and K10, linked with heating lines will be established directly in Ansys, a popular software for structural analysis by finite element method, to numerical simulation and computation of the forming process by line heating with a flame torch. As a result, it is very easy to adjust the position and temperature of the heating lines to achieve a given desired curved plate.

#### 3.2.1. Create a 3D model of computation plate

Create a 3D model of a planar expanded plate in Ansys is not difficult, but a new ideal and feature in this study is the technique of creating a 3D model including a plate linked with heating lines to simulate directly in Ansys the line heating process, as follows.

- Select the problem and solution as follows: *Start Ansys Multiphysics → Enter /Prep 7 on Command Prompt → Select structural and thermal problems in the Ansys menu.*

- Select the computational element type as follows: *Preprocessor → Element Type → Add/Edit/Delete → Add... → Library of Element Types → Structural Mass Solid → 10node 187 → Apply → OK.*

   Here, we used the SOLID 187 element because it is well suited to the features of the problem given in this study. It is a 3D tetrahedral with 10 nodes, each node has three degrees of freedom with three x, y, z displacements, and is well suited to modeling irregular meshes, and has plasticity hyperelasticity, creep, stress stiffening, large deflection, and large strain capabilities. More details about this element can be found in the Ansys literature.

• Set up material properties for the computational element

The material of the hull plates is a mild steel plate with mechanical properties at different temperatures are determined by comparison of three data sources of Patel (1985), Richter (1973), and Birk-Sorensen (1999). Table 1 shows the values of the mechanical properties of the mild steel plate at an initial temperature of 25°C required to simulate study plates.

Table 1: Material properties of mild steel plate at 25°C

| Thermal Conductivity (W/m$^0$C) | Yield stress (MPa) | Young's modulus (GPa) | Thermal Expansion ($10^{-6}$1/°C) | Poisson's Ratio | Density (kg/m$^3$) |
|---|---|---|---|---|---|
| 35 | 207 | 200 | 14 | 0.3 | 7850 |

The process of setting material properties to the selected element in Ansys is performed by the following steps:

- *Preprocessor → Material Props → Material Models... → Define Material Model Behavior → Structural → Linear → Elastic → Isotropic → Enter values for Young's modulus (EX) and Poisson's ratio (PRXY).*

- *Define Material Model Behavior → Structural → Nonlinear → Inelastic → Rate Independent → Isotropic Hardening Plasticity → Mises Plasticity → Bilinear → Enter a value for Yield Stress.*

- *Define Material Model Behavior → Thermal Expansion or Thermal Conductivity → Isotropic → Enter the values for Thermal Expansion (ALPX) and Thermal Conductivity (KXX).*

• Create a 3D model of the planar expanded plates with heating lines.

Create a 3D model of the planar expanded plates with the given dimensions in Ansys is generally not difficult, but the special item here is to model a 3D plate with heating lines to simulate the process of line heating forming. The process of creating the 3D geometry model with the heating lines of the K1 plate in Ansys is performed by the following steps:

- Save the file of the K1 plate's planar expansion drawing exported from ShipConstructor as two separate files, including a file of 3D geometry model and a file of heating lines of the K1 plate under the .iges file format, e.g. K1_plate.iges and Heating_ line_K1.iges in any graphic software such as Autocad software, to generate them into 3D solid objects as shown in Fig. 6 and Fig. 7, respectively.
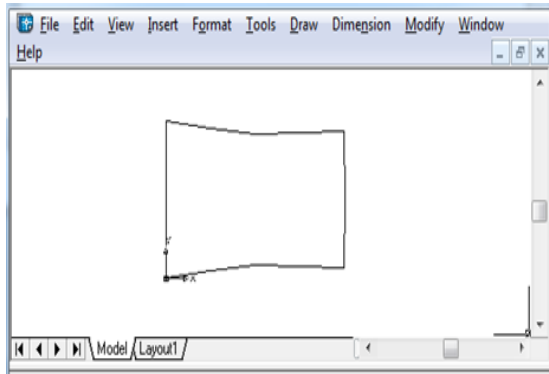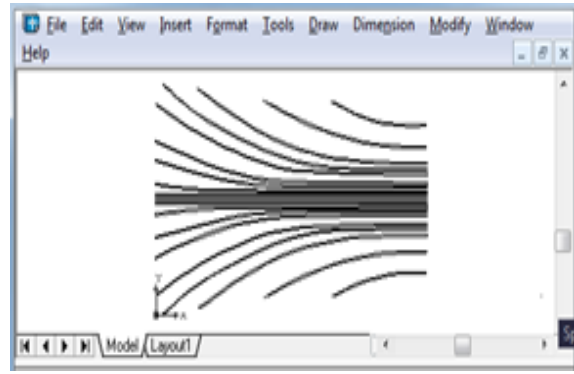


Fig. 6: Solid geometry model of K1 plate in AutoCad

Fig. 7: Solid heating lines model of K1 plate in AutoCad

- Import the K1 plate model into Ansys software as follows: *File → Import → IGES → Select K1_plate.iges → Select → Everything → Oblique View → OK.* This will display the K1 plate on the screen.

- Import all heating lines into Ansys as follows: *File → Import → IGES... → Heating_line_K1.iges → OK → Plot → MultiPlots → Delete all lines and surfaces, leaving only lines in the XY plane:*



✓ *Preprocessor → Modeling → Delete → Areas Only → Delete Areas Only → Pick all* (Fig. 8).

✓ *Preprocessor → Modeling → Delete → Lines Only → Right View → Box → select the lines outside the XY plane → OK → Front View → Plot → Mutil-Plots.*
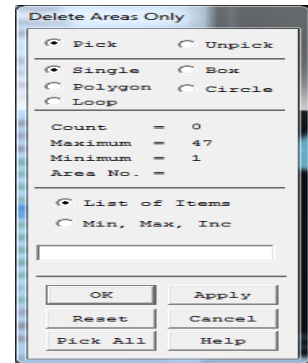
Fig 8: Delete areas only dialog box

- Create heating lines on the K1 plate as follows:

✓ *Select → Entities → Selec Entities → click Area, By location, Z Coordinates → Enter 0 for Min, Max → Plot → Area → OK*. This will display the K1 plate in the XY plane on the screen as shown in Fig. 9.

✓ *Main Menu → Preprocessor → Modeling → Operate → Booleans → Divide → Area by line → Click_Area → OK → Plot → Lines → Divide Area by line → Loop → Select all heating lines → OK*. This will display all heating lines on the plate as shown in Fig. 10.
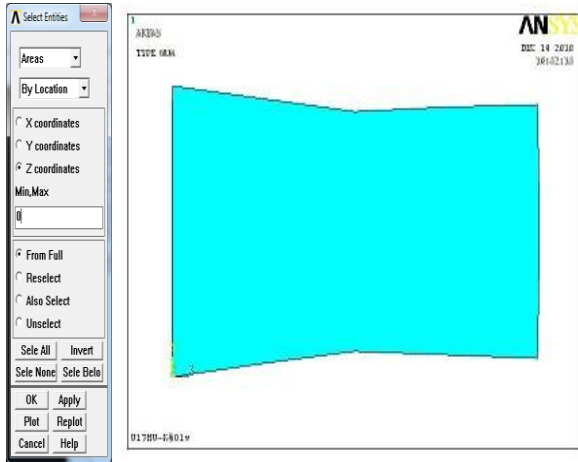


Fig. 9: Display K1 plate in the XY plane    Fig. 10: Display heating lines on the K1 plate
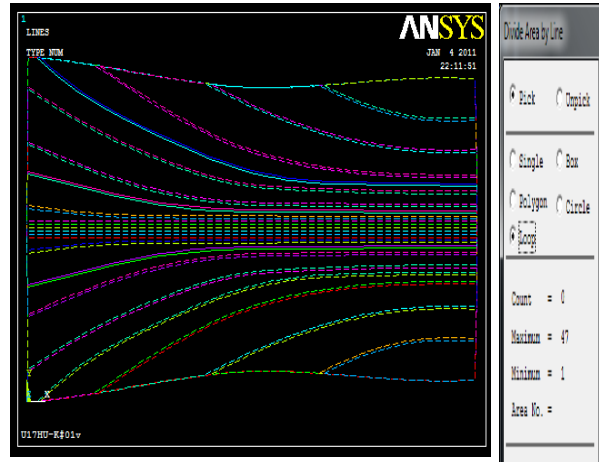
3.2.2. Generate the mesh for the plate model

In the forming of the metal plate by line heating, large heat transfer and plastic deformation of the material occurs in the area around the heat zone, while the remaining areas on the plate have not large change in temperature and deformation so just create a coarser mesh with fewer nodes and elements to reduce and to save computation time. This can be done by using the manual mesh tool in Ansys to generate the different mesh for each area on the plate, specifically in this case with the K1 plate as follows: *Main Menu → Preprocessor → Meshing → MeshTool → Click Set button under Global Size Controls → Enter an element length of 20mm → OK → Select Volume with Test and Free → Mesh → Pick All →* display the uniform mesh over the entire K1 plate as shown in Fig. 11a. By doing the same but choosing a smaller element length, a more suitable mesh model is obtained for the K1 plate as shown in Fig. 11b, where the mesh is thicker in the areas around the heating lines.
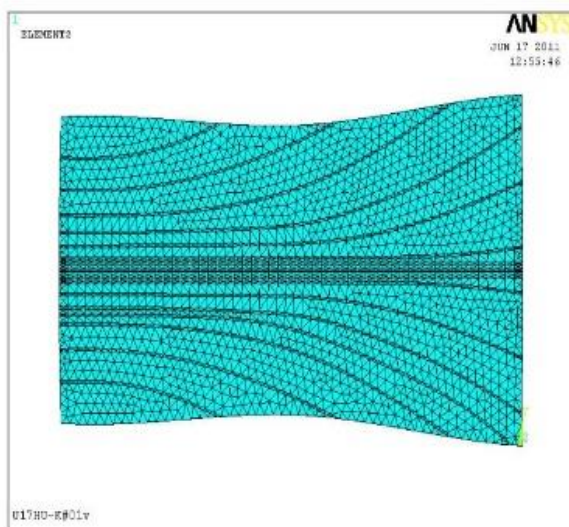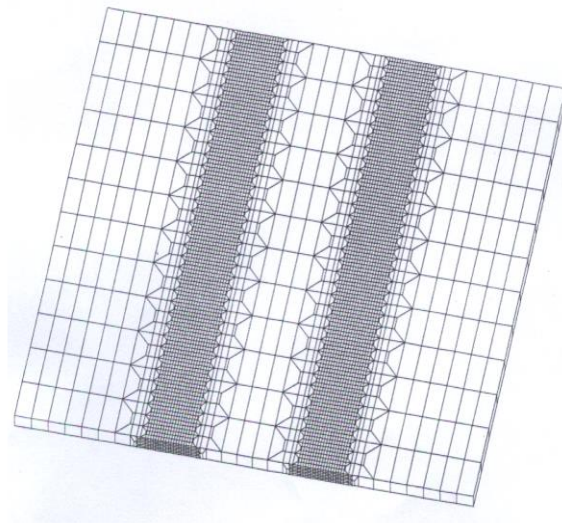


(a) Initial mesh    (b) Mesh after re-meshing

Fig. 11: Mesh of the K1 plate

3.2.3. Establish the mechanical boundary conditions for the plate model

In this problem, the mechanical boundary conditions of the plate model are set based on the principal strain direction of the desired curved surface as follows:

- The surface of the K1 plate is curved in both the X and Y directions, so its model should be placed on four fixed supports to block the horizontal displacements at four corners of the K1 plate (Z = 0) (Fig. 12).

- The surface of the K10 plate is curved in Y directions, so it must be placed on six fixed supports which are evenly spaced along the two edges, and symmetrically across the centerline of the plate as shown in Fig. 13.
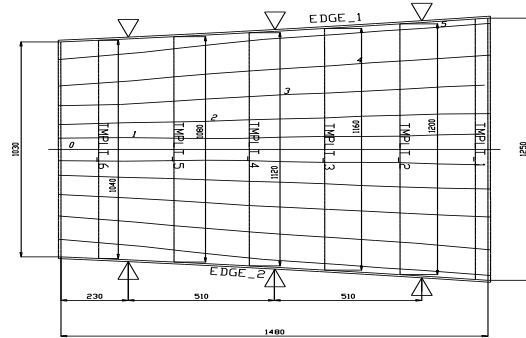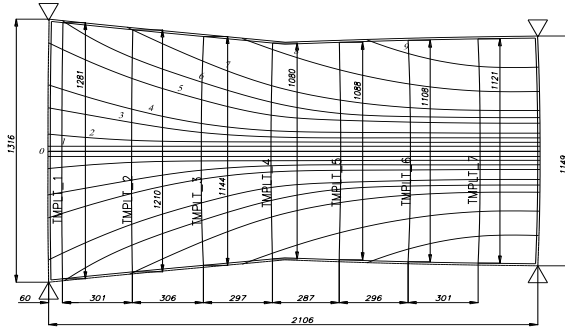
Fig. 12: Mechanical boundary conditions of the K1 plate

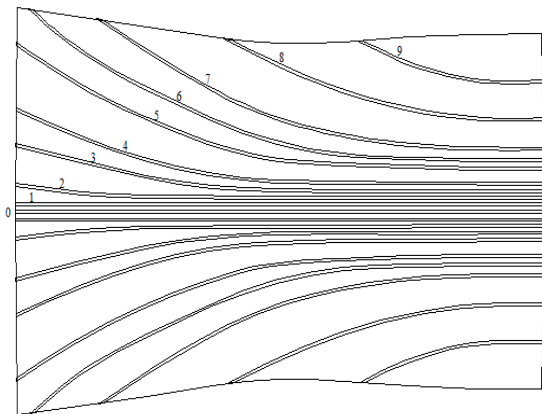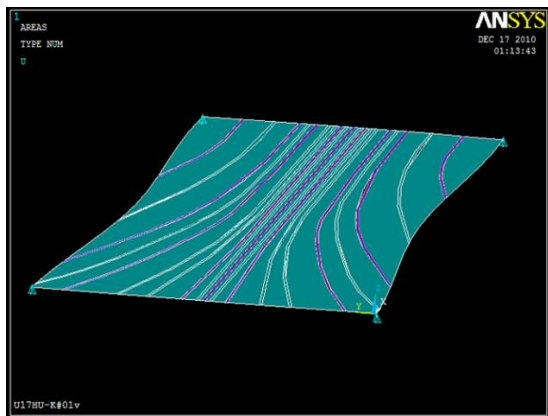Fig. 13: Mechanical boundary conditions of the K10 plate

For the K1 plate, these boundary conditions are set in Ansys as follows:

- ✓ Set plate thickness as follows: *Select → Entities… → Click Area, By location, Z Coordinates → Enter 10 for Min, Max → Plot → OK → display K1 plate with thickness t = 10 mm.*

- ✓ Set the mechanical boundary conditions for K1 plate as follows: *Preprocessor → Loads → Define Loads → Apply → Structural → Displacement → On Keypoints → Apply U, ROT on KPs → Click 4 points at 4 corners of the plate → OK → UZ = 0 → OK.*

3.2.4. Determine load models acting on the plate

The load applied in the forming process by line heating is the heating source along the heating lines on the plate. Based on actual collected data as presented above, set heating parameters for the metal plate forming by torch line heating, including the heating source speed on all heating lines is 6 mm/s; the width of all heating lines is 10 mm, and the temperature for each line is in the range of (550 - 800)°C corresponds to torch heating (see section 2.1). The heat load is set on the plate model in Ansys as follows:

- Display heating lines on the K1 plate model as follows: *Select → Entities → Click Area, By location, and Z Coordinates → Enter 0 for Min, Max → Plot → OK → Front View → OK.* This will display the K1 plate model with the mechanical boundary conditions (Fig. 14a) and numbered heating lines (Fig. 14b).

(a) K1 plate model with the mechanical boundaries    (b) K1 plate model with the numbered heating lines

Fig. 14: K1 plate model with the mechanical boundary conditions and heating lines plan

- Set the heat load as follows: *Main Menu → Preprocessor → Loads → Define Loads → Apply → Structural → Temperature → On Areas→ click any heating line, e.g. zero heating line (Fig. 15) → OK → Display dialog box for applying the temperature → Apply the corresponding temperature for 0 heating line.*
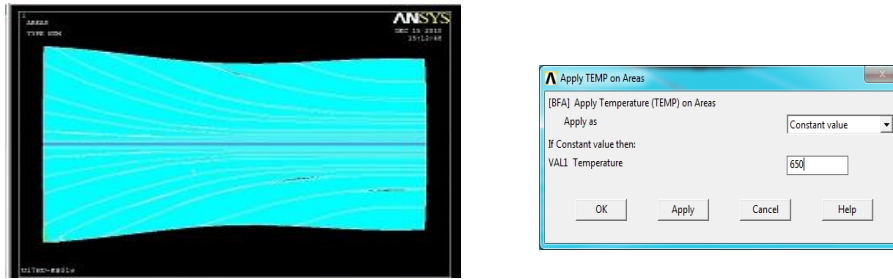


Fig. 15: Select zero heating line to apply temperature

By doing the same, all remaining heating lines are also applied to the corresponding temperature, respectively. At this point, our purpose is just to establish a finite element model for simulating the process of the line heating, so the position and temperature of each heating line can be preliminarily determined as described in section 3.1. In this study, the suggested heating lines exported from Ship Constructor software will be used. As can be seen in Fig 4 and Fig. 5, the heating lines exported from Ship Constructor for K1 and K10 plates are evenly spaced on either side of the zero heating line which coincides with the plate's symmetry axis. For example with the K1 plate, there are 9 heating lines located on either side of the zero heating line linked with its planar expansion plate in Ansys and apply the heating parameters according to the data given in Table 2. It means that only heating lines 0, 2, 4, 6, 8, and 9 with corresponding temperatures are applied in the same way as for the zero heating line above.

Table 2: Position and temperature of heating lines

| Heating line | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| Temperature (°C) | 700 | 0 | 680 | 0 | 680 | 0 | 680 | 0 | 650 | 650 |

3.2.5. Solve and output computation results

Run the solution of the problem as follows: *Main Menu→ Solution → Solve → Current LS → Solving → OK.* After solving, output the computation results as follows:

- *Main Menu → General Postproc → Plot Results → Plot Deformed Shape → Def + undef edge → OK.* This will display a graph of plate displacement (Fig. 16a).

- *Main Menu → General Postproc → Contour Plot → Nodal Solu/Element Solu → von Mises stress → OK.* This will display a graph of equivalent stresses at the nodes (Fig. 16b) and at the elements (Fig. 16c).
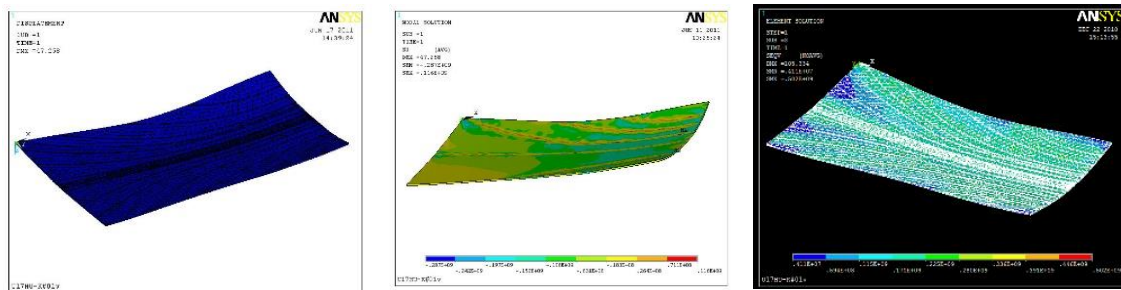


(a) Displacement graph     (b) Equivalent stress at the nodes   (c) Equivalent stress at the elements

Fig. 16: Graph of displacement and equivalent stress of K1 plate

To determine the values of strain, displacement, and stress of the plate at any position, e.g. at the position of the plate templates (TPL), output the above values at the element nodes as follows:

- *Main Menu → General Postproc → Query Results → Subgrid Solu → Click Stress, X-direction SX → OK → click any point on the plate surface→ OK.*

- *Main Menu → General Postproc → List Results → Nodal Solution/Element Solution→ click Z-Component of displacement → print the Z-Component of displacement.*

### 3.3. Determine the suitable heating parameters for desired curved plate

After establishing the finite element model of plate linked with heating lines in Ansys, proceed to determine the heating parameters of the model suitable for the desired curved plate can be determined as follows:

(i) Determine the vertical displacements at the midpoint of some cross-sections of the given curved plate. For example, the vertical displacements at midpoints of 7 cross-sections (denoted TMPLT) of the K1 plate are determined in Autocad or Ship Constructor software as shown in Fig. 17. The dimension of these cross-sections will also be used to make the templates for fabrication and test the actual curved plate (see Fig. 26).

(ii) Use the trial and error method to change the heating parameters (position and temperature of the heating lines) of the finite element model in the manner described in section 3.2 until the deviations of the vertical displacements which are computed by Ansys and determined in step (i) at the corresponding positions of the computation plate are within the allowable limit, about ±3%, as for common engineering problems in shipbuilding.
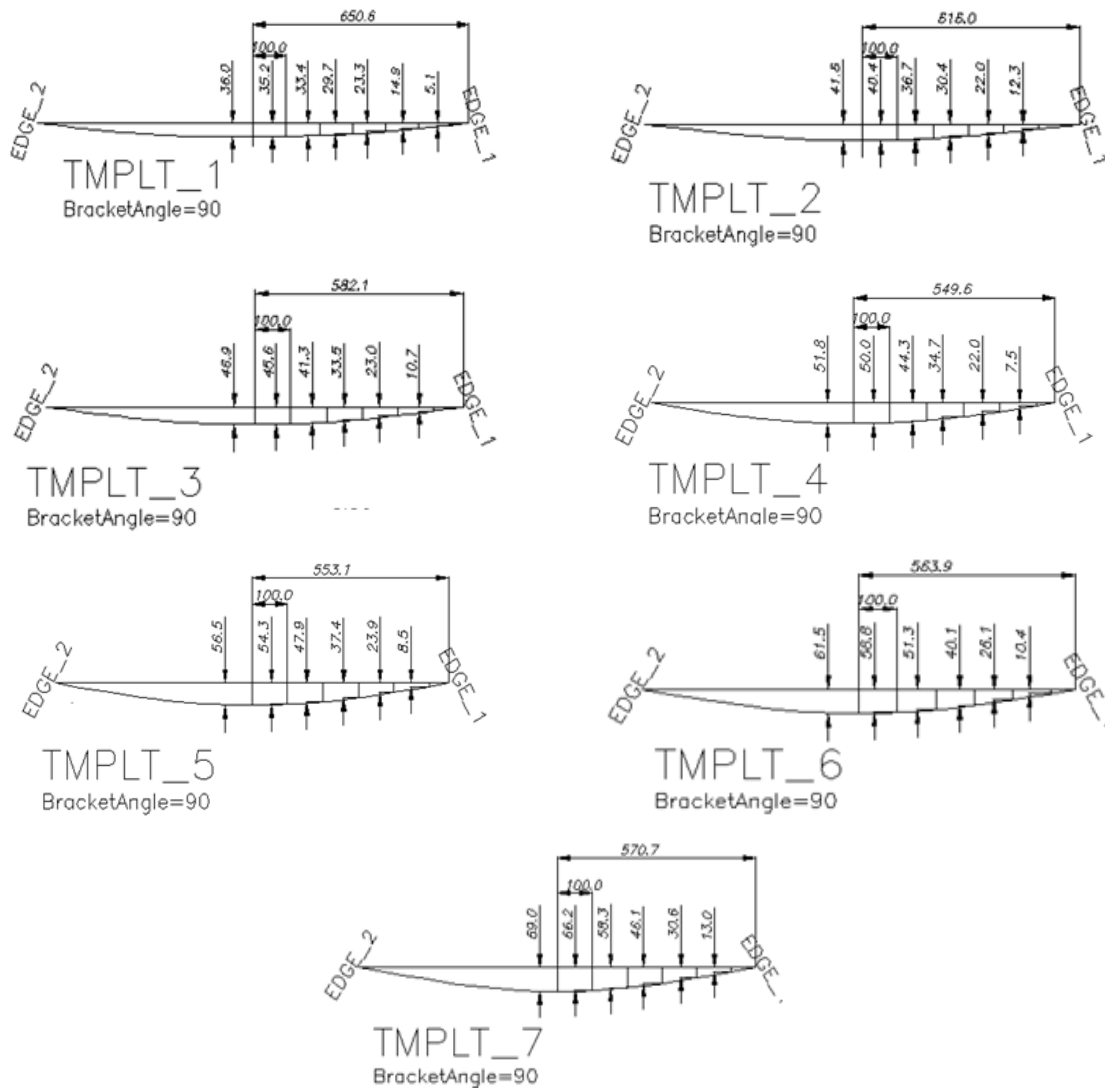


Fig. 17: Displacement at midpoints of the templates of the K1 plate surface

The number of computation cases more or less depends on the complexity of the computation plate and the researcher's experience in identifying the tendency of displacement of the computation plate according to the change of heating parameters. In this study, there are 14 such cases for the K1 plate, and 6 cases for the K10 plate. Some specific computation cases for K1 and K10 which are performed as the general case in section 3.3.1 will be presented in the following section, where each case will include a table of heating parameters similar to Table 2, a comparison table of displacement values, and graphs of the equivalent stresses and displacements of plates.
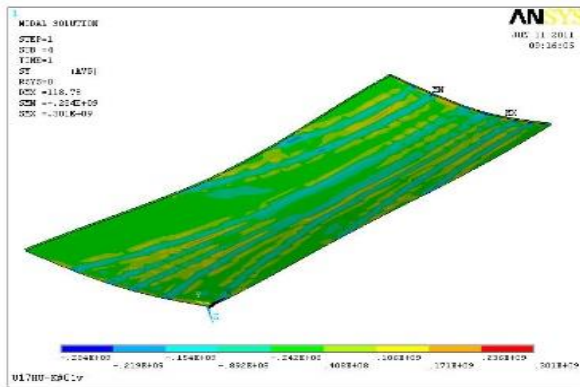
3.3.1. For K1 plate

• Case 1

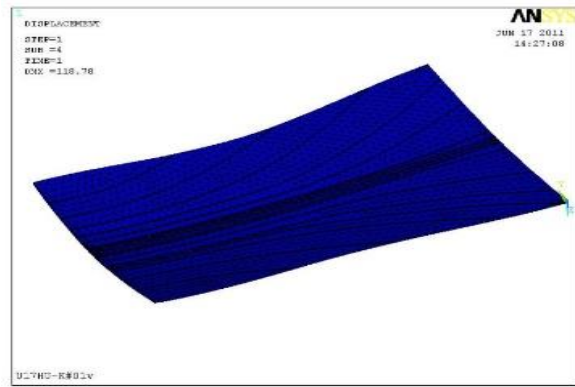Table 3: Position and temperature of the heating lines in case 1 for K1 plate

| Heating line | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| Temperature (ºC) | 0 | 0 | 750 | 0 | 700 | 0 | 700 | 0 | 650 | 650 |

Table 4: Compare vertical displacement values at the template positions of the K1 plate in case 1

| Plate template positions | TPL1 | TPL2 | TPL3 | TPL4 | TPL5 | TPL6 | TPL7 |
|---|---|---|---|---|---|---|---|
| Vertical displacements of actual plate surface (mm) | 36.0 | 41.6 | 46.9 | 51.8 | 56.5 | 61.5 | 69.0 |
| Vertical displacement computed by Ansys (mm) | 46.8 | 57.3 | 59.6 | 61.6 | 67.7 | 73.8 | 81.8 |
| Deviation (%) | -30.0 | -37.7 | -27.1 | -18.9 | -19.8 | -20.0 | -18.6 |



(a) Equivalent stress                    (b) Displacement

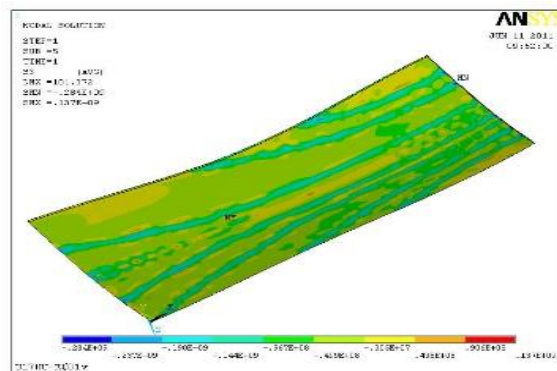Fig. 18: Graph of equivalent stress and displacement for case 1 of K1 plate

• Case 2

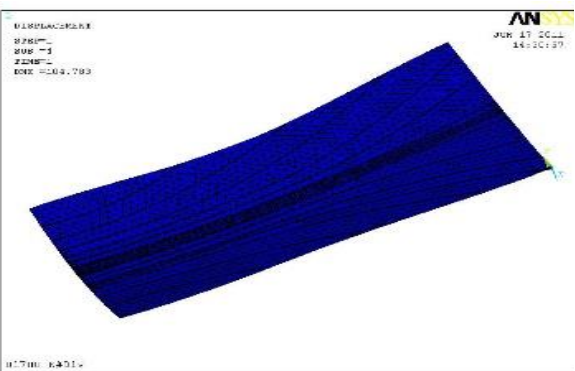Table 5: Position and temperature of the heating lines in case 2 for K1 plate

| Heating line | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| Temperature (ºC) | 750 | 0 | 0 | 0 | 700 | 0 | 600 | 0 | 600 | 600 |

Table 6: Compare vertical displacement values at the template positions of the K1 plate in case 2

| Plate template positions | TPL1 | TPL2 | TPL3 | TPL4 | TPL5 | TPL6 | TPL7 |
|---|---|---|---|---|---|---|---|
| Vertical displacements of actual plate surface (mm) | 36.0 | 41.6 | 46.9 | 51.8 | 56.5 | 61.5 | 69.0 |
| Vertical displacement computed by Ansys (mm) | 36.8 | 44.9 | 46.2 | 47.7 | 53.1 | 58.4 | 65.6 |
| Deviation (%) | -2.2 | -7.9 | 1.5 | 7.9 | 6.0 | 5.0 | 4.9 |



(a) Equivalent stress                    (b) Displacement

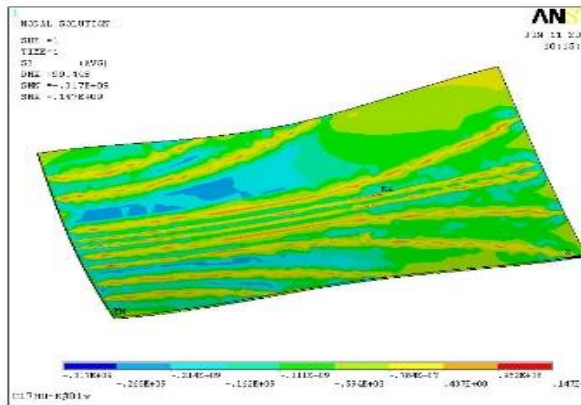Fig. 19: Graph of equivalent stress and displacement for case 2 of K1 plate

• Case 3

Table 7: Position and temperature of the heating lines in case 3 for K1 plate
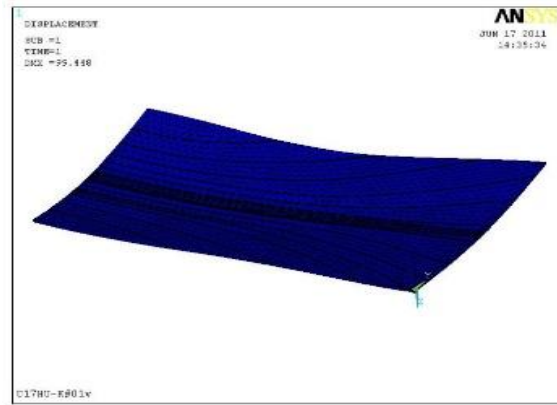
| Heating line | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| Temperature (ºC) | 0 | 750 | 0 | 0 | 650 | 0 | 600 | 0 | 600 | 600 |

Table 8: Compare vertical displacement values at the template positions of the K1 plate in case 3

| Plate template positions | TPL1 | TPL2 | TPL3 | TPL4 | TPL5 | TPL6 | TPL7 |
|---|---|---|---|---|---|---|---|
| Vertical displacements of actual plate surface (mm) | 36.0 | 41.6 | 46.9 | 51.8 | 56.5 | 61.5 | 69.0 |
| Vertical displacement computed by Ansys (mm) | 38.8 | 45.7 | 47.5 | 49.4 | 54.8 | 60.4 | 67.4 |
| Deviation (%) | -7.8 | -9.9 | -1.3 | 4.6 | 3.0 | 1.8 | 2.3 |



(a) Equivalent stress                    (b) Displacement

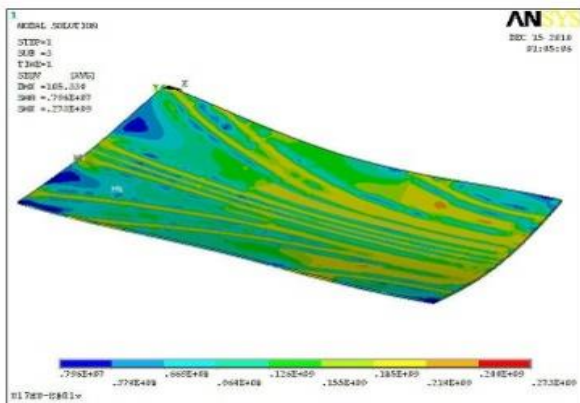Fig. 20: Graph of equivalent stress and displacement for case 3 of K1 plate

• Case 4

Table 9: Position and temperature of the heating lines in case 4 for K1 plate

| Heating line | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| Temperature (ºC) | 650 | 0 | 600 | 0 | 0 | 600 | 0 | 600 | 0 | 600 |

Table 10: Compare vertical displacement values at the template positions of the K1 plate in case 4

| Plate template positions | TPL1 | TPL2 | TPL3 | TPL4 | TPL5 | TPL6 | TPL7 |
|---|---|---|---|---|---|---|---|
| Vertical displacements of actual plate surface (mm) | 36.0 | 41.6 | 46.9 | 51.8 | 56.5 | 61.5 | 69.0 |
| Vertical displacement computed by Ansys (mm) | 36.7 | 42.5 | 47.5 | 52.1 | 56.8 | 60.8 | 69.2 |
| Deviation (%) | -1.9 | -2.2 | -1.3 | -0.6 | -0.5 | 1.1 | -0.3 |
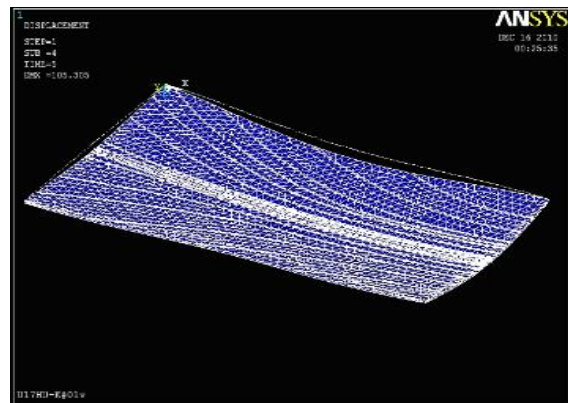


(a) Equivalent stress                    (b) Displacement

Fig. 21: Graph of equivalent stress and displacement for case 4 of K1 plate

3.3.2. For K10 plate

Simulation of the line heating process for the K10 plate in Ansys is done similarly to the K1 plate presented above. The difference is in the geometrical boundary conditions and the positions of heating lines as shown in Fig. 13. In addition, the displacements at the midpoint of the six template positions of the planar expansion plate are used to achieve the suitable heating parameter for forming the K10 curved plate as shown in Fig. 22.
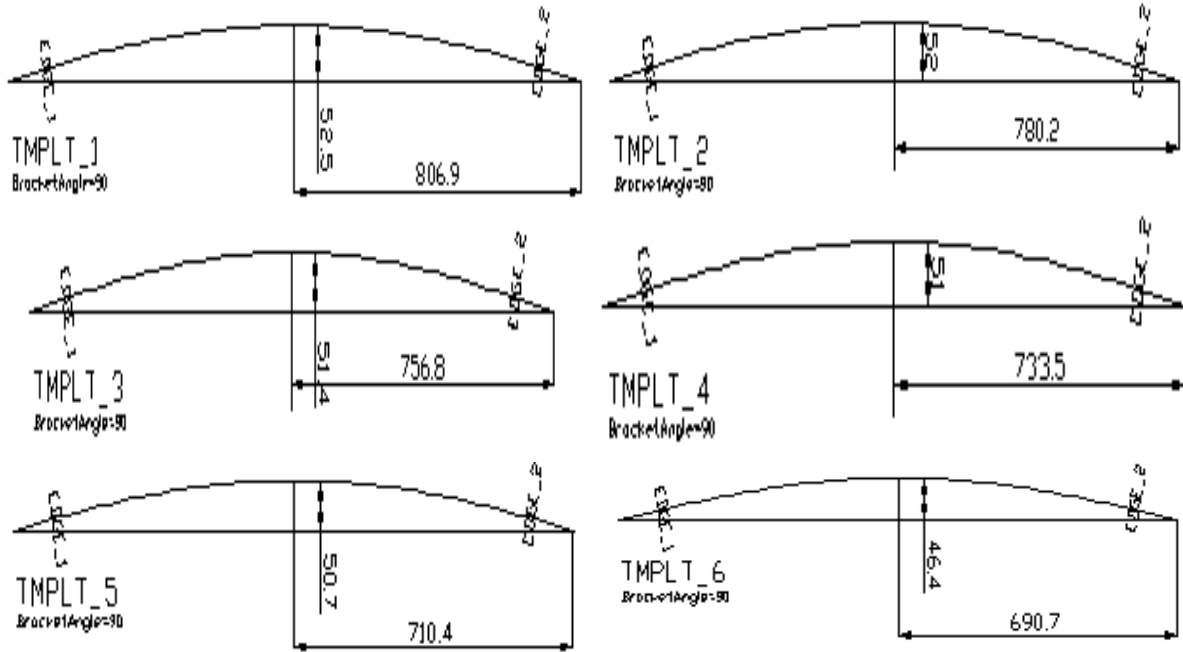


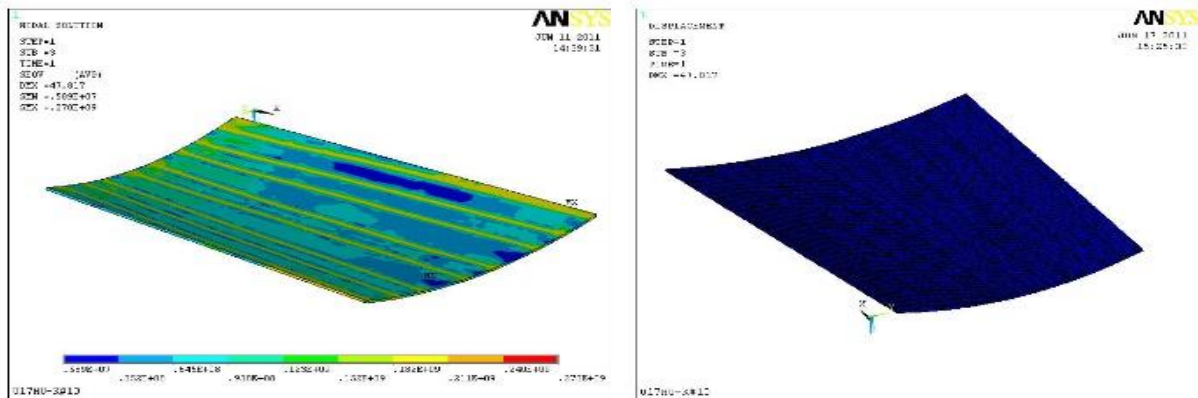Fig. 22: Displacement at midpoints of the templates of the K10 plate surface

• Case 1

Table 11: Position and temperature of the heating lines in case 1 for K10 plate

| Heating line | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Temperature (ºC) | 0 | 600 | 0 | 550 | 550 |

Table 12: Compare vertical displacement values at the template positions of the K10 plate in case 1

| Plate template positions | TPL 1 | TPL 2 | TPL 3 | TPL 4 | TPL 5 | TPL 6 |
|---|---|---|---|---|---|---|
| Vertical displacements of actual plate surface (mm) | 52.5 | 52.0 | 51.4 | 51.0 | 50.7 | 46.4 |
| Vertical displacement computed by Ansys (mm) | 44.4 | 46.7 | 47.6 | 47.8 | 47.3 | 45.1 |
| Deviation (%) | -15.4 | -10.2 | -7.4 | -6.3 | -6.7 | -2.8 |



(a) Equivalent stress          (b) Displacement

Fig. 23: Graph of equivalent stress and displacement for case 1 of K10 plate
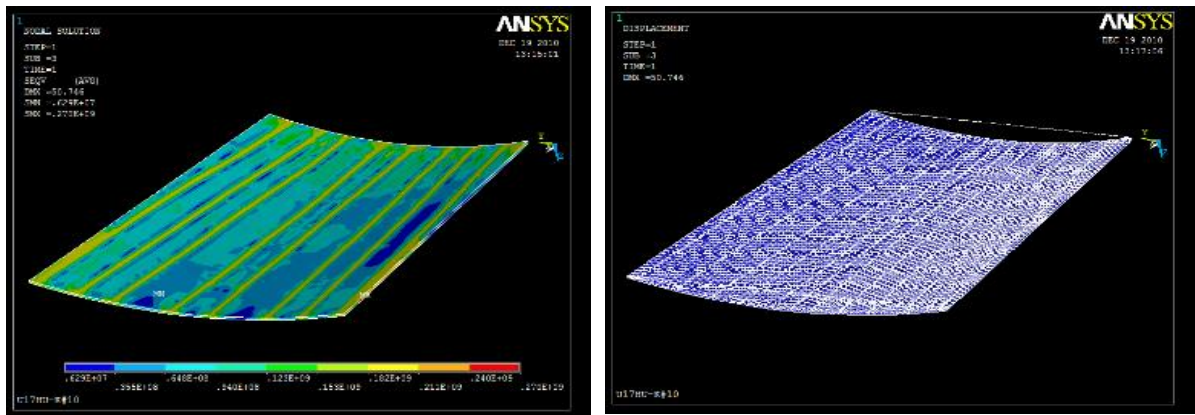
- Case 2

Table 13: Position and temperature of the heating lines in case 2 for K10 plate

| Heating line | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Temperature (°C) | 0 | 650 | 0 | 600 | 600 |

Table 14: Compare vertical displacement values at the template positions of the K10 plate in case 1

| Plate template positions | TPL 1 | TPL 2 | TPL 3 | TPL 4 | TPL 5 | TPL 6 |
|---|---|---|---|---|---|---|
| Vertical displacements of actual plate surface (mm) | 52.5 | 52.0 | 51.4 | 51.0 | 50.7 | 46.4 |
| Vertical displacement computed by Ansys (mm) | 53.5 | 51.7 | 50.9 | 50.7 | 50.1 | 46.8 |
| Deviation (%) | 1.9 | -0.6 | -0.9 | -0.6 | -1.2 | 0.9 |



(a) Equivalent stress          (b) Displacement

Fig. 24: Graph of equivalent stress and displacement for case 2 of K10 plate

## 3.4. Testing fabrication of the K1 plate

Based on some typical computation cases for the K1 plate above, it can be found that the heating parameters of the forming process by line heating corresponding to case 4 for the K1 plate and case 2 for the K10 plate are the closest reality. To evaluate the accuracy of the results computed from the simulation model, we formed the K1 curved plate by line heating with a flame torch according to heating parameters in case 4 at Camranh Shipyard in Vietnam. Fabrication of the K1 plate is carried out as follows.

- Locate the position of the heating lines in case 4 on the planar expansion plate of the K1 curved plate in preparation for forming this plate by the torch line heating (Fig. 25).
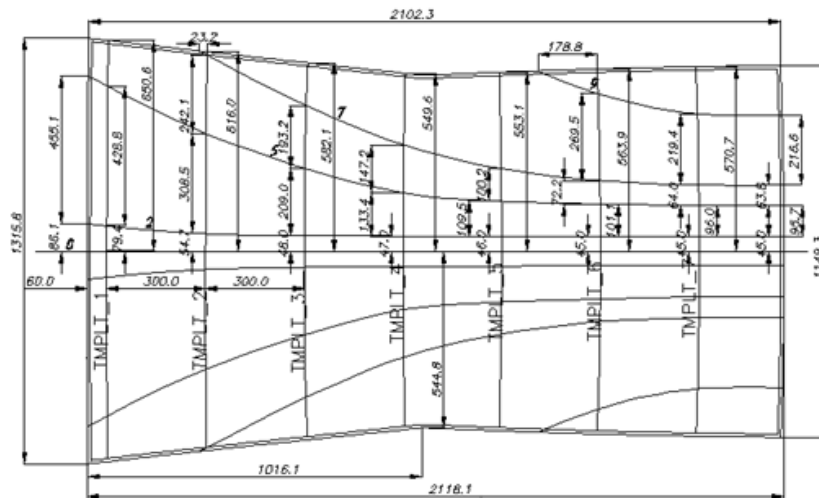


Fig. 25: Determine the position of the heating lines on the planar expansion plate of the K1 curved plate in case 4

- Mark the position of the heating lines on the planar expansion steel plate of the K1 curved plate according to

the dimensions defined in Fig. 25 as shown in Fig. 26a.

- Use a torch to heat along the marked heating lines in the planar expansion plate with the heating parameters as determined in Table 9. The result is a curved plate as shown in Fig. 26b.
- Fabricate the plate templates at each of their position according to the dimensions specified in Fig. 17 as shown in Fig. 26c.
- Use fabricated templates to verify the shape of the curved surface after forming by the line heating method using a flame torch.



(a) Mark the heating line on the initial planar plate     (b) Shape of the curved K1 plate after forming



(c) Fabricate the templates at the test positions according to their dimensions on the drawing



(d) Verify the transverse curvature of the K1 plate     (e) Verify the longitudinal curvature of the K1 plate

Fig. 26: Testing fabrication of the K1 plate

After forming, measure the actual displacement of the formed plate surface at points on the plate templates, with 20 points are chosen per template, i.e a total of (7x20) points are used to create the actual surface of the K1 plate. The measured results show the displacement deviations between the actual surface and the desired plate surface, at the template positions are within ±3% as shown in Table 15.

Table 15: A comparison of displacement at plate template positions

| Plate template positions | TPL1 | TPL2 | TPL3 | TPL4 | TPL5 | TPL6 | TPL7 |
|---|---|---|---|---|---|---|---|
| Vertical displacement of the desired plate surface (mm) | 36.0 | 41.6 | 46.9 | 51.8 | 56.5 | 61.5 | 69.0 |
| Vertical displacement of the actual formed plate surface (mm) | 35.8 | 42.8 | 47 | 51.5 | 56 | 59.7 | 67.5 |
| Vertical displacement deviation between desired and actual plate surface (%) | 0.6 | -2.9 | -0.2 | 0.6 | 0.9 | 2.9 | 2.2 |

This can also be seen when these two surfaces are superimposed as shown in Fig.27, where the red surface is the formed plate surface, the blue surface is the desired surface.
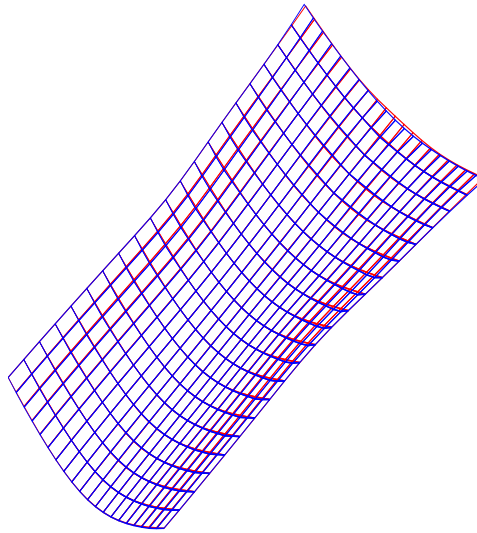


Fig. 27: Compare the surface of the formed plate and the desired plate

## 4. Conclusions

Our study has provided a new approach to effectively solve the complex problem of line heating in shipbuilding. The difficulties in determining the heating parameters for the torch forming of hull plates, which have not been studied fully in other studies, have been overcome based on a combination of ShipConstructor and Ansys software. ShipConstructor aids the expansion of a curved hull plate into a planar plate with a pre-marked heating line plan, while Ansys aid to determine the positions and temperature suitable for heating lines by the finite element model. In this study, the finite element model is established for the computational structure consisting of the computational plate linked with heating lines located on the plate. As a result, it is very easy to apply the flame torch forming and adjust the input heating parameters to achieve a desired curved plate. Based on such a computation model, the hull plate forming process is solved by the inverse method, that is, the actual curved hull plate with the displacement of the desired curved surface has been predetermined, and the heating parameters are adjusted to achieve the displacements at some corresponding positions on the plate. Our study has shown that doing so makes it easier to find a solution, ensure accuracy, and be applicable in practice. This approach has been applied to form other hull plates in some Vietnamese shipyards in the same way because the plates on the bulbous bow like the K1 plate are often the most complex curvature of the conventional hulls. By processing the actual and computational data obtained in forming various hull plates using our new approach, a solution to the suitable heating parameters for the flame torch forming is achieved faster and more accurately. These have brought about great economic and technical efficiency by significantly reducing construction cost and time, and improving the quality and aesthetics of the hull structure.

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