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Numerical Analysis of the Straightening Process of Thin Plate Structures by Elastic FEM based on the Inherent Strain Method†

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Abstract

Welding distortion is practically an expected feature in shipbuilding, with a few exceptions; when thick plates are used, for example. Nowadays, the trend is to use thinner plates in order to reduce weight, aiming to reduce waste of fuel. However, thin plates are drastically affected by welding distortion, this finally represents a significant - unnecessary expenditure of money and time on straightening the structure. Here it is necessary to realize that even with the most effective welding process, welding distortion in thin plates appears, so it is unrealistic to think about free of distortion lightweight welded structures. Although there have been gradual movements to optimize the straightening process, still many question remain to be answered. In this paper, an Elastic Finite Element Model based on Inherent Strain Method is developed in order to study the process of straightening deformed plates. Some techniques, usually used in the practice, are numerically evaluated and their effectiveness compared. Finally, useful recommendations that aim to the optimization of the process are drawn.

KEY WORDS: (Straightening), (welding distortion), (line heating), (inherent strain), (FEM)

1. Introduction

Avoiding welding distortion has been a main purpose in the shipbuilding industry since welding is used to join materials. The main reason is because distortions are not approved and neither, help in acquiring high quality products. This is unfortunate since, in shipbuilding, the control of the distortion presents serious economic issues associated with the construction of large welded structures. For example, the difficulty of fixturing and jigging presented by welding one welded assembly to another. On the other hand, welding distortions are difficult to eradicate since the thermal cycle, generated during the welding process, will appear, except in, a joining process that does not increase the material temperature, is used [1, 2].

Since it is difficult to avoid welding distortion, it must be corrected in order to achieve the requirement. In order to do that, a straightening process, using gas torch, induction or laser heating, is used. Here is pertinent to mention that straightening a deformed plate is not an easy task and not something people can learn in a couple of hours [3, 4].

In the last decades, many researches, about straightening warped plates have been presented. Some aim to understand the mechanism of straightening a distorted plate. Another group tried to develop methods for reducing distortion and a third group aims for the automation of the process [1, 2, 3, 4, 5, 6 and 7]. The results can be reduced to simple words: the mechanism of straightening by means of heat is not well understood neither is an automated system able to accurately straighten a distorted plate.

The author aims to develop an automatic system for straightening deformed plates without significant human help. In order to achieve this, prediction of the plate distortion due to heating is needed. Here it is important to mention that the finite element method has become the most appropriate tool for performing such task.

Although, the thermo-elastic–plastic FEM can be used to simulate the straightening process, a very long computational time is needed even when faster computers are used. The thermo-elastic–plastic FEM, elastic FEM based on the inherent strain theory [8, 9, 10, 11 and 12], can be utilized to predict heat-induced deformation. Comparing with the thermo-elastic–plastic FEM, only a very short computational time is needed to complete the simulation even for complex heating patterns. Moreover,

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only the elastic modulus and the Poisson's ratio at room temperature are used in the elastic FEM, and the temperature dependent material properties are not needed [13].

2. Concepts of inherent strain and inherent deformation

An in-house 3-D thermal-elastic-plastic solid finite element code [13] is employed to investigate the relationship between the inherent strain and the final configuration of the plate to be achieved. The procedure of simulation consists of two steps:

First, the components of inherent strain obtained through 3D thermo elasto-plastic analysis [14], are transformed into strain components as follows:

$$\varepsilon^*_x = \delta^i_x / b \tag{1}$$

$$\varepsilon^*_y = \delta^i_y / b \tag{2}$$

$$\theta^*_x = \theta^i_x / b \tag{3}$$

$$\theta^*_y = \theta^i_y / b \tag{4}$$

Where b is the breadth of the elements in which the inherent strains are introduced. For simplicity, it is assumed that all the four inherent strain components are introduced into the same area (the heating area). **Figure 1** shows an example of the FEM model and the area in which the inherent strains are introduced. Second, these inherent strain components are introduced into the elastic FEM as primary strains, and the heat-induced deformation is estimated through elastic FE analysis.

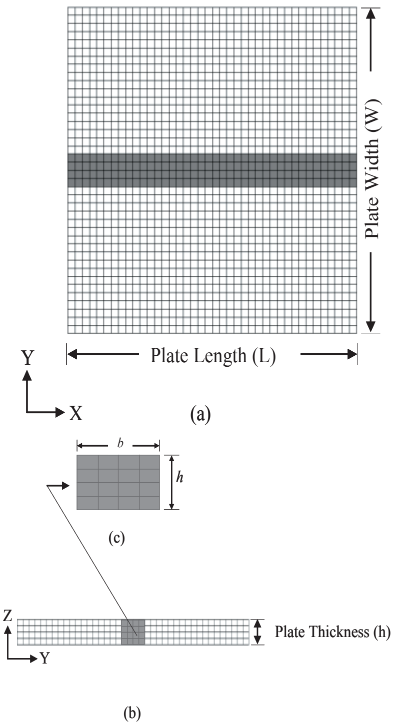


Fig. 1 Schematic of elastic FEM model (a) Top surface, (b) Distribution through the plate thickness, and (c) Area in which the inherent strains are introduced

To simplify the analysis, uniform distribution of inherent strains is assumed at the central region of the plate while at both edges; average values of inherent strains are used. The deflections computed by the thermal-elastic-plastic FEM and the elastic FEM are compared in **Fig. 2.** The deflection along the transverse section at the center and that along the heating line are shown in these figures.

As it may be observed, the heat-induced deformation computed by the thermal-elastic-plastic analysis is accurately reproduced by the elastic analysis. This suggests that the elastic FEM can be employed to predict the heat-induced deformation due to line heating if the inherent strain is known in advance. However, in straightening deformed plates combinations of heating lines are needed. Thus, it is necessary to consider complex heating patterns in order to develop an automated system. In the next section, the case of complex heating scheme is discussed.

3. Prediction of heat-induced deformation of complex heat pattern using elastic FEM

In straightening warped plates, combination of heating lines, in different directions, are applied until the plastic strain required to flatten the plate is finally attained.

On the other hand, when two heating lines are applied close to each other, inherent strain is not a single addition of that produced by each heating line [14]

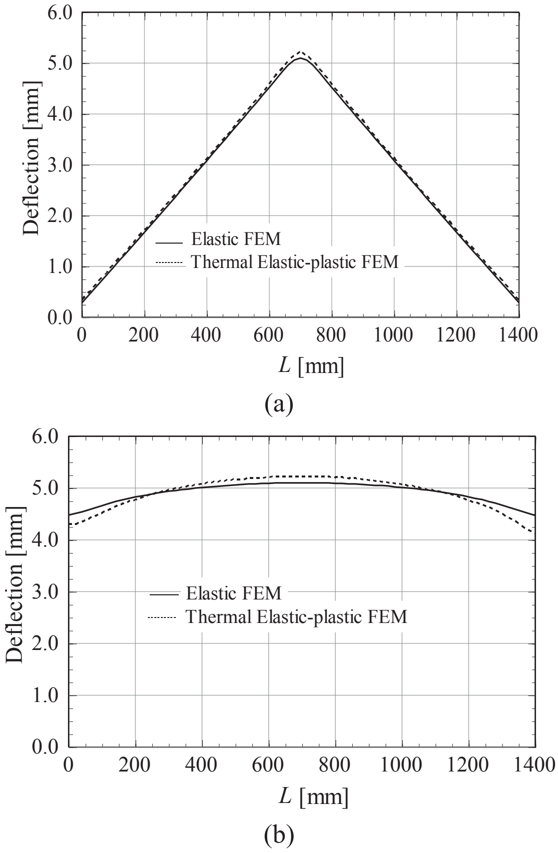


Fig. 2 Deflection distributions, in the middle section, produced by a single heating line (a) Transverse to the heating line and (b) Along the heating line

With the purpose of explaining this difference, the effect of prior heating lines on inherent strain produced by a current heating line is first examined. This influence is mainly because the inherent strain and the residual stress influence each other.

Figure 3 shows a square plate where a combination of six heating lines is applied. In this case, 3D thermal elastic plastic analysis is used to simulate deformation. The first three lines are applied in the X-direction. The remaining three lines are normal to the first three (Y - direction). **Figure 4** shows the distribution of inherent strain (plastic strain) along each heating line as obtained by FEM. Despite the fact that all the heating lines are applied under the same heating and cooling condition, it is clearly observed that the distribution of inherent strain shows a complex distribution. This proves that simple addition of inherent strain produced by individual heating lines does not produce enough accuracy in the deformation predicted by FEM. Thus, it is necessary to analyze the influence of multiples heating lines on the deformation.

To gain a better comprehension of this, effect of a previous heating line on the inherent strain of an overlapped, that is the case of parallel and crossed heating lines are examined in detail [14].

3.1 Basic definitions

In order to clarify the inherent strain produced by various heating lines, the following is considered:

1- In case of individual heating, the deformation in the transverse direction of the heating line, regardless of the coordinate system, is called inherent transverse shrinkage/bending while that in the longitudinal direction of the heating line is called inherent longitudinal shrinkage/bending as shown in Figure 5(a).

2- In case of multiple heating lines, the total inherent strain is achieved by integrating the inherent strain normal to the coordinate axis (x) along the plate length. When the orientation of a heating line is not the same as that of the coordinate axis x and y, coordinate transformation is carried out.

3.2 Proposed method to predict heat-induced deformation of complex heat pattern

As demonstrated above, heat-induced deformation due to line heating can be accurately predicted by elastic FEM if the inherent strains are known. However, in real forming by line heating, where complex heating patterns are used, the inherent strain is influenced by many factors [14]. In order to evaluate these influences in the analysis of plate straightening, the following approach is proposed:

Step 1: Predict the four components of inherent strain at the central region of the plate.

Step 2: Predict the four components of inherent strain at plate edges. Figs. 6 and 7 show an example of such a relationship. More detail can be found in [14].

Step 3: Make corrections to the values obtained in Step-1 and 2 for location of heating and plate size.

Step 4: Based on the sequence of heating, determine if overlapping, parallel and/or cross effect need to be considered. Then, obtain the correction values from databases. Figs. 8 to 13 show examples of such relationship. More detail can be found in [14].

Step 5: Introduce the correction values obtained in Step-4 into the values of inherent strains predicted in Step-1 to Step-3.

Step 6: Introduce the inherent strain obtained in Step-6 into the elastic FEM model.

Step 7: Repeat Step-1 to 7 for each additional heating line.

Step 8: Perform elastic FE analysis.

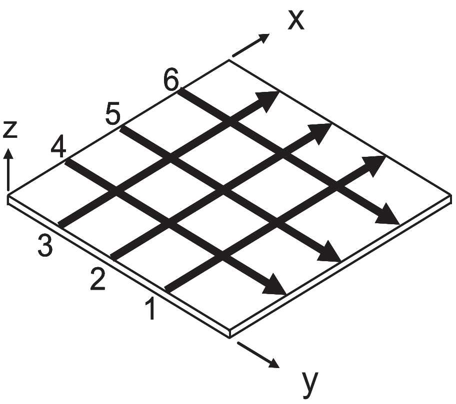
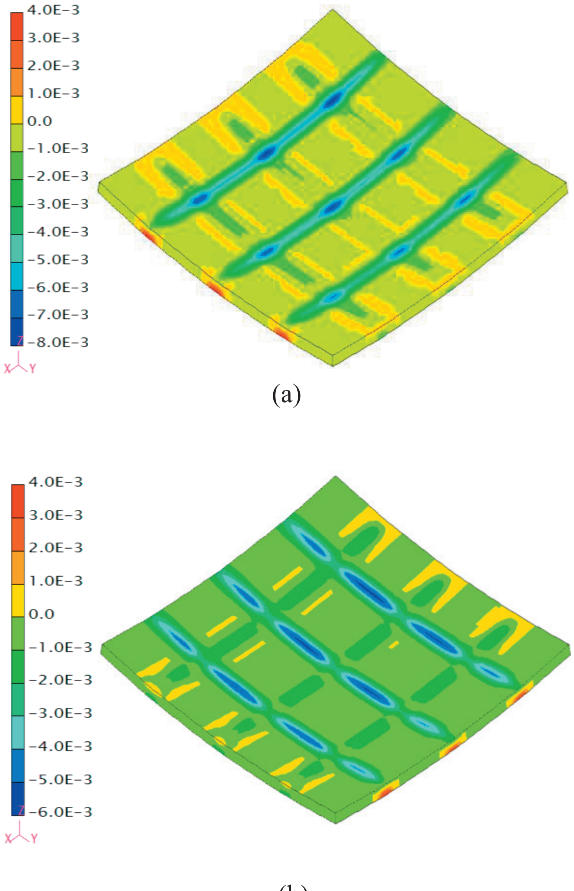


Fig. 3 Schematic of multiple heating lines



(a)

(b)

Fig. 4 Distribution of plastic strains caused by several heating lines (a) ε_x and (b) ε_y

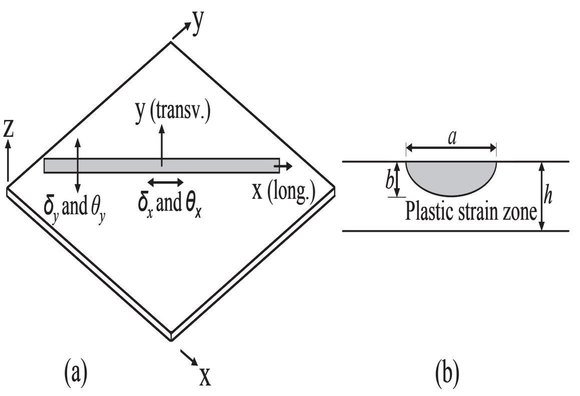


Fig. 5 Definition of inherent strain, (a) For arbitrary direction, (b) Integration area

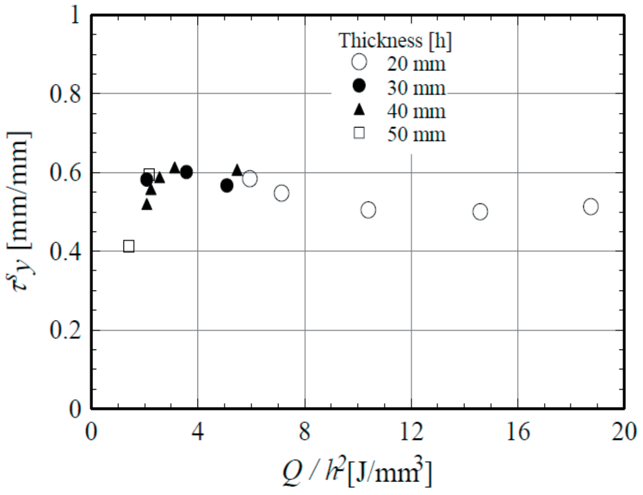


Fig. 6 Relation between edge effect on transverse shrinkage and heat input parameter Q/h^2 at the entrance plate edge

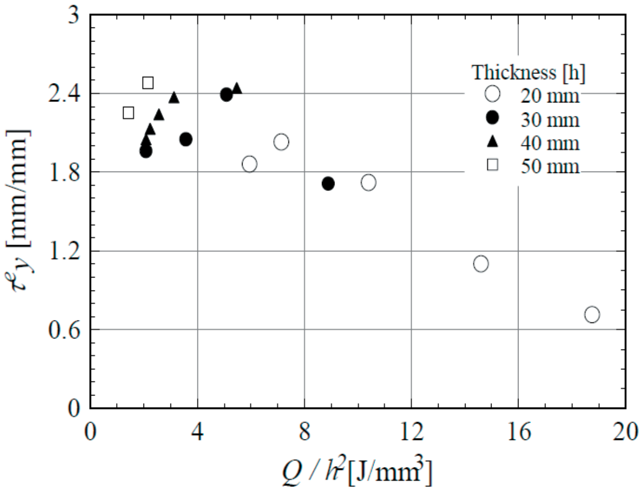


Fig. 7 Relation between edge effect on transverse shrinkage and heat input parameter Q/h^2 at the exit plate edge

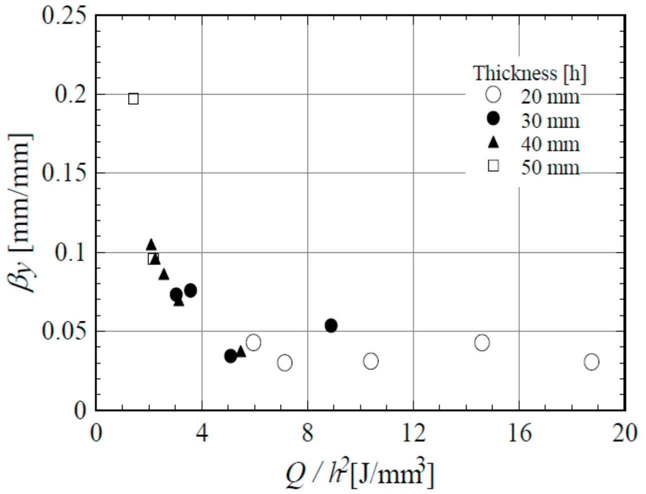


Fig. 8 Relation between overlapping effect on transverse shrinkage and heat input parameter Q/h^2

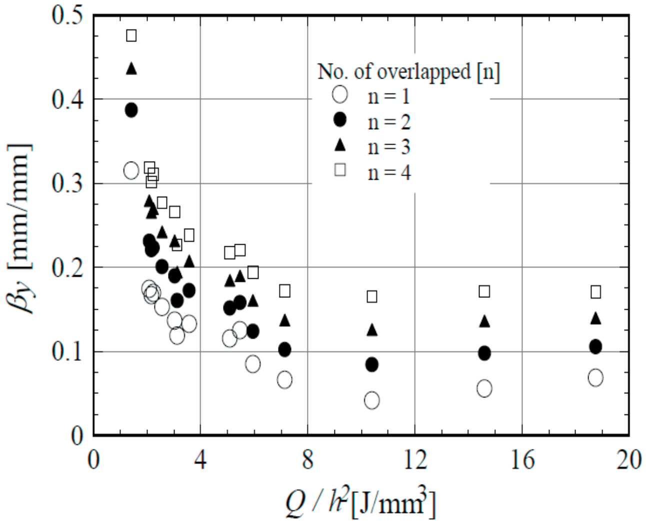


Fig. 9 Relation between overlapping effect on transverse shrinkage and heat input parameter Q/h^2 for multiple overlapped heating lines

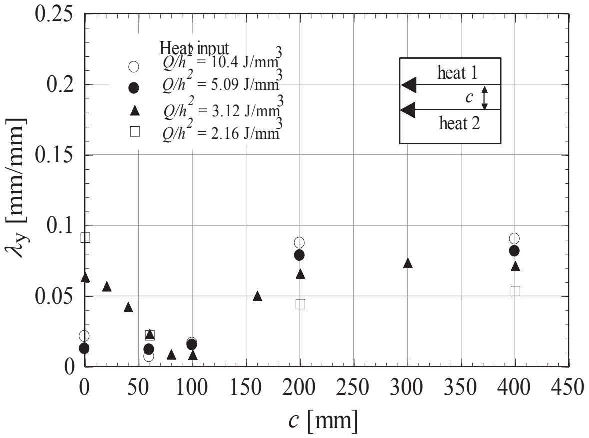


Fig. 10 Relation between parallel effect on transverse shrinkage and separation between parallel heating lines for different values of heat input parameter Q/h^2

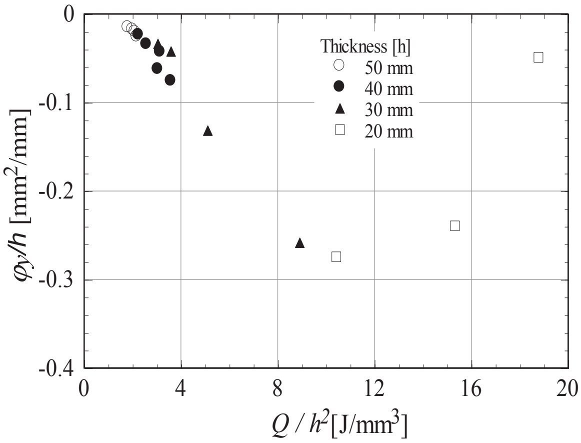


Fig. 11 Relation between cross effect on transverse shrinkage and heat input parameter Q/h^2

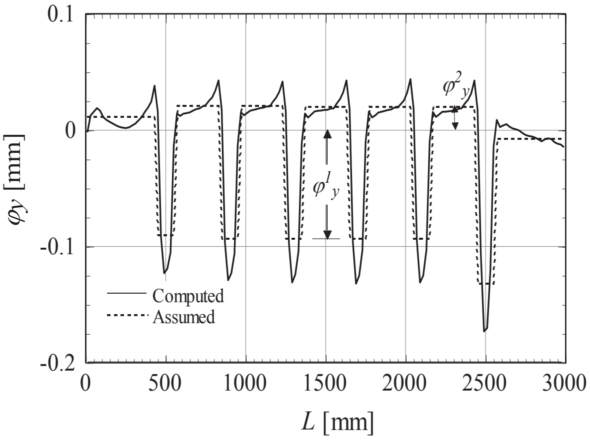


Fig. 12 Comparison between assumed and computed cross effect on transverse shrinkage for multiples heating lines

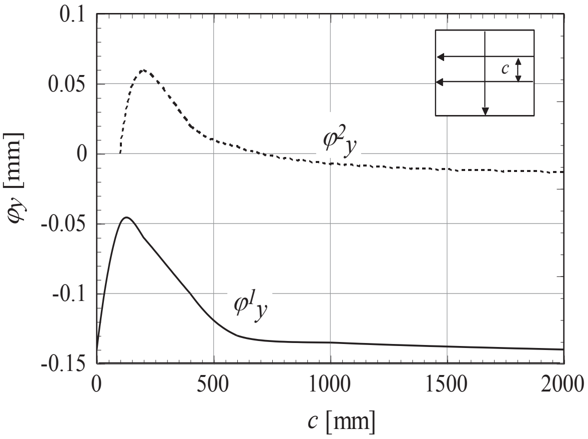


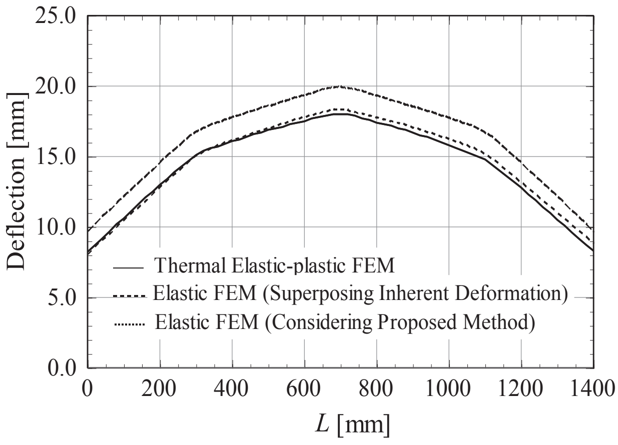
Fig. 13 Relation between cross effect on transverse shrinkage and separation between parallel heating lines Stage

3.3 Application of proposed method to predict heat-induced deformation under complex heat patterns

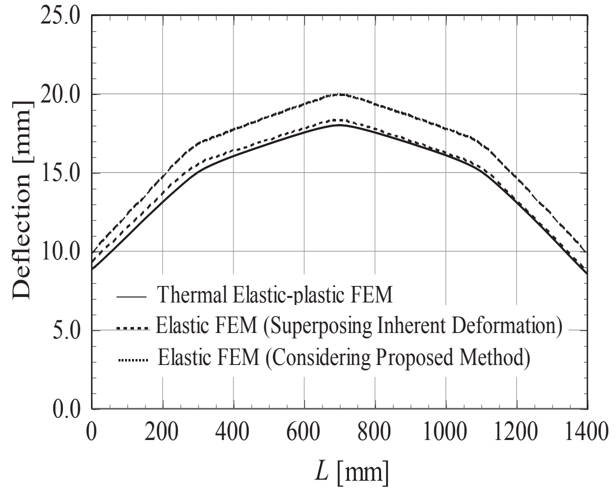
In order to evaluate the effectiveness of the proposed method, the heating pattern shown in Figure 3 is simulated by using both, 3D thermal elasto-plastic and elastic analysis. For simplicity, the heating sequence is as shown in the figure. At first, the heat-induced deformation is estimated by using the 3D thermal elasto-plastic FEM. Then, two types of elastic FEM are performed: First, superposing inherent strain for individual heating lines without considering any influential factors other than heat input and plate thickness, second, applying the proposed method considering the influential factors (Figs. 6 to 13, for example).

The deflections computed by the three methods are compared in Fig. 14. By simple inspection, it can be concluded that the distribution of deflection predicted by the proposed method matches that computed by the thermo-elastic–plastic FEM exceptionally well, while that predicted by superposing inherent strain does not.

As may be observed, the difference between the deflections produced by the two elastic analyses is only about 2 mm approximately. However, it increases with the number of heating lines due to the influence of residual stresses.



(a)



(b)

Fig. 14 Comparison of deflection distributions for multiples heating lines predicted by thermal elasto-plastic FEM and elastic FEM (a) Along plate length (W/2) and (b) Along plate width (L/2)

This influence plays a key role on the prediction of heat-induced deformation by elastic FEM. Therefore, elastic FEM in which the inherent strains are simply superposed may not be used to predict heat-induced deformation.

In addition, the computational time is much shorter than that used in the thermo-elastic–plastic FEM. In the present study, the total computational time is almost 36 hours for the thermo-elastic–plastic FE model, whereas the computational time of the elastic FE model is shorter than one hour (including pre-processing). In case of a more complex heating pattern, the computation time required for thermal elasto-plastic FEM proportionally increases with the number of heating lines while that required in elastic FEM is roughly the same for all cases.

4. Optimization of the straightening process

As it is explained in previous sections, the straightening process is quite complicated. In performing such a procedure, time and energy play a key role. Thus, both of them need to be carefully controlled in order not to spend more than previously estimated. In addition, a wrong straightening procedure may result in unnecessary re-work that produces additional cost.

Aiming to optimize the straightening process; influential factors affecting the process, are studied. From that, the indices α_1 and α_2 are drawn. Where α_1 is the relationship between the time needed to complete the straightening process of a specific plate and the amount of plate deformation to be straightened, α_2 represents the relationship between required heat and the amount of deformation to be deformed as given by equation 5 and 6, respectively:

$$\alpha_1 = \text{deformation/total time ((mm or radians) /sec)} \qquad (5)$$

$$\alpha_2 = \text{deformation/total energy ((mm or rad)/ (J/mm))} \qquad (6)$$

In order to evaluate these two parameters, three different combinations of heating lines (see Table 1) were simulated up to straighten a warped plate. The plate model is shown in **Fig. 15**. Plate size is 300x300x6 mm. The maximum deflection is given in Z direction and is about 4 cm, from the center of the plate to a straight line in the plane XY. The initial deflection is the same in both, the X and Y direction.

Figure 16 shows an example of the Z direction displacement after one line heating applied at the center of the plate. Table 1 summarizes the results of the analysis. As it is shown in the table, combination number 3 provides the best result. This is because in the first and the second case, re-work, in order to repair edge defects, was needed. Despite the fact that results prove that the straightening process can be optimized, this computation was only carried out for three straightening techniques. In straightening deformed plates, however, different techniques are used. Thus, it is necessary to incorporate all of them into the analysis in order to propose final optimization parameters. This will be presented in forthcoming papers.

8. Conclusions

An elastic analysis based on the inherent strain method is performed to examine the straightening process. From the analysis, a method to predict heat-induced deformation produced by complex heating scheme has been proposed.

In this method, the inherent strain of an individual heating line is predicted based on the given heating condition and plate thickness. Then, using the effect of influential factors, corrections necessary to the inherent strain are made. The same procedure is followed for each heating line according to the heating sequence. Through numerical analysis, it has been demonstrated that this method can easily and accurately predict heat-induced deformation during the straightening process.

Finally, the optimization of the straightening process is evaluated from the point of view of two parameters, time and consumed energy. Both of them related to the amount of deformation straightened. It is shown that using these parameters it is possible to obtain the most effective technique to be used in straightening warped plates.

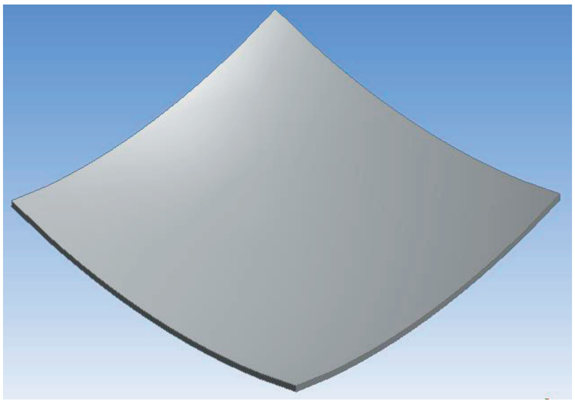


Fig. 15 Plate model used in optimization of the straightening process

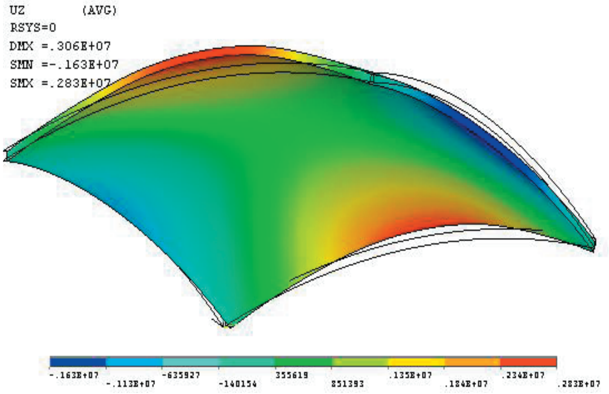


Fig. 16 Example of deformation in Z direction after a single heating line

Case	Description	α_1	α_1
1	Five parallel lines in X direction followed by five parallel lines in Y direction. In both cases, heating lines are applied over the total length of the plate.	0.13	0.0036
2	Five parallel lines in X direction followed by five parallel lines in Y direction. In both cases, the line heating is applied over the total length of the plate. However, in this case, the sequence was changed, first in X direction, second in Y direction and so on.	0.13	0.0044
3	Five parallel lines in X direction followed by five parallel lines in Y direction. In both cases, the starting and the ending point of each line heating were at 25 mm from the plate edges (considering edge effect)	0.16	0.0047

Table 1 Straightening conditions and optimization parameters

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