

# An Improved Inherent Strain Analysis for Plate Bending by Line Heating Considering Phase Transformation of Steel

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**The inherent strain method is known to be very efficient in predicting plate deformation due to line heating. However, in the actual line heating process in a shipyard, the rapid quenching changes the phase of steel. In this study, when calculating inherent strain, material properties of steel are applied differently in heating and in cooling, considering phase transformation. In this process, a new method which can reflect the thermal volume expansion of martensite is suggested. By this method, the plate deformations by line heating could be predicted more precisely.**

## INTRODUCTION

Plate deformation by line heating has been studied mainly through 2 approaches. One is thermal elastoplastic analysis, which uses the FEM code through direct heat input; the other is the equivalent loads method based on inherent strain. Of the two, the latter is widely used from the viewpoint of efficiency and accuracy (Jang, Ko and Seo, 1997). However, there is a limitation to this method, which is that there should be an appropriate assumption of the inherent strain region. Satoh, Matsui, and Terai (1969) presented the depth and breadth of the HAZ (heat affected zone) obtained from welding experiments, and they assumed the region to be elliptical. In many studies, the HAZ has played a role in the inherent strain region. In line heating, Jang, Ko and Seo (1997) suggested that the inherent strain region can be substituted with the mechanical melting region. This region is very similar that whose maximum temperature is over Ac1 (the temperature at which austenite begins to form during heating). They obtained the inherent strain by adding residual plastic strains in heating and in cooling by the spot heat source. By using this inherent strain, Nomoto, Ohmori, Satoh, Enosawa, Aoyama and Saitoh (1990) estimated equivalent forces.

The characteristics of shipyard line heating are very different from those of welding. First, a welding heat source is considered to be a straightforward progress. But shipyard line heating must have a progress of weaving motion by which the heat source is diversely input. Second, the external constraints of a welded structure affect the analysis of deformation; on the other hand, line heating has rather few external constraints. Third, plates must melt in welding for joining to take place, but the plate surfaces must not melt in line heating. Finally, the welded region is cooled by air, but line heating is cooled by water. In the water cooling process, the phase-transformed crystal structure of mild steel in heating cannot be returned to the original one in cooling.

Phase transformation induced by water cooling can change the crystal structure of steel to martensite. This study used different material properties of steel for heating and for cooling. In particular, martensite volume expansion was reflected by the coefficient of thermal expansion in cooling. Line heating experiments were also carried out to verify the proposed method. Calculated deformations by this method show fairly good agreement with the experimental ones. In the experiments, heating was done with weaving patterns, similarly to the heating pattern of actual workers. In the analysis, a weaving heat flux model (Jang, Ko, Moon and Seo, 2001) was also used.

## Inherent Strain

The inherent strain method is a form of simplified thermal elastoplastic analysis. Mild steel which experienced high temperature will produce residual strains by a relatively inexperienced adjacent region. These irrecoverable strains—which consist of plastic strain, thermal strain, phase transformation strain, and transformation-induced plastic strain—are called inherent strain (Eq. 1). It is assumed that inherent strain exists in a certain region. Equivalent forces can be obtained by integrating this strain about thickness (Jang, Ko and Seo, 1997):

$$\varepsilon^* = \varepsilon^{\text{th}} + \varepsilon^{\text{pl}} + \varepsilon^{\text{ph}} + \varepsilon^{\text{tr}} = \varepsilon^{\text{total}} - \varepsilon^{\text{el}} \quad (1)$$

where  $\varepsilon^{\text{th}}$  = thermal strain,  $\varepsilon^{\text{pl}}$  = plastic strain,  $\varepsilon^{\text{ph}}$  = phase transformation strain,  $\varepsilon^{\text{tr}}$  = transformation-induced plastic strain, and  $\varepsilon^{\text{el}}$  = elastic strain.

Eq. 1 shows the 2 ways in which to obtain inherent strains. But the plastic strains are hard to obtain, especially in thermal distortion. Thus, Jang, Lee and Ko (2002) suggested Eq. 2, obtained from the latter part of Eq. 1 by using the bar-spring model:

$$\varepsilon^* = \frac{\sigma_{Y\_bar}(Tc)}{E_{bar}(Tc)} \left( \frac{k_{bar}(Tc)}{k_{spring}(Ti)} + 1 \right) \quad (2)$$

where *bar* = region whose temperature changes by ( $Ti \rightarrow Tc$ ); *spring* = region whose temperature does not change (still  $Ti$ );  $k$  = stiffness;  $Tc$  = critical temperature (in general, Ac1); and  $Ti$  = room (initial) temperature.

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