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Development of stress correction formulae for heat formed steel plates

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Abstract

The heating process such as line heating, triangular heating and so on is widely used in plate forming of shell plates found in bow and stern area of outer shell in a ship. Local shrinkage during heating process is main physical phenomenon used in plate forming process. As it is well appreciated, the heated plate undergoes the change in material and mechanical properties around heated area due to the harsh thermal process. It is, therefore, important to investigate the changes of physical and mechanical properties due to heating process in order to use them plate the design stage of shell plates. This study is concerned with the development of formula of plastic hardening constitutive equation for steel plate on which line heating is applied. In this study the stress correction formula for the heated plate has been developed based on the numerical simulation of tension test with varying plate thickness and heating speed through the regression analysis of multiple variable case. It has been seen the developed formula shows very good agreement with results of numerical simulation. This paper ends with usefulness of the present formula in examining the structural characteristic of ship's hull.

Keywords: Heat input; Heat transfer analysis; Line heating; Shell plate; Stress correction; Thermo-elasto-plastic analysis

1. Introduction

As it is well appreciated, plate forming is one of the key process in manufacturing ship structures. For the plate forming of curved surface found in bow and stern part heating forming method such as line heating and triangular heating is usually used, and very complicate physical and mechanical phenomena are involved in the process. Many researches have been carried out for the last several decades, and many researches are also in progress nowadays to enhance productivity. For example, Nomoto et al. (1991) developed simulator for plate forming and showed a couple of application examples on curved surface. Lee (1996, 1997) proposed an algorithm of generating heating line information by line heating based on mechanical model. Lee et al. (2002) suggested a simple prediction model for thermal deformation of steel plates by line heating and triangle heating through experiments.

Marine grade steel has higher strength than other materials and excellent characteristics in welding and fracture toughness. When steel plate is formed by heating method, there are significant changes in both mechanical and physical properties due to harsh thermal cycle during heating process. Especially the change of mechanical properties must affect the strength behavior when the part is subjected to impact load due to accident such as collision, grounding and so on. In spite of the importance of change of mechanical properties during heating, the research on the change of mechanical and physical properties of steel heated by some heating process is very rare. Jang et al. (2001) conducted studies on deformation characteristics due to heat forming and Ha (2001) and Jang et al. (2002) carried out experimental studies to predict deformation with considering phase transition due to weaved heating and water cooling effect. But there is rare study investigating the structural behavior of steel plate in plastic zone beyond elastic zone due to heating.

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This study is aimed at investigating the plastic material properties. Numerical simulation for the tension test has been carried out to investigate the hardening characteristics of steel plate heated by line heating method. From the present numerical simulation, it is found that numerical simulation of tension test agrees well with the result of tension test before diffusion necking occurs but there is much difference after diffusion necking. This may be due to that the results of tension test are uniaxial stress state although the real stress state is tri-axial after diffusion necking. Bridgman proposed the stress correction formula to compensate the multi-axial stress state after diffusion necking. However since panel type specimen is not axial symmetric, Bridgman's stress correction formula cannot be applied. Many researchers, for example Aronofsky (1951), Zhang and Li (1994) and Ling (1996), proposed stress correction formula to estimate the equivalent true stress from the average true stress of panel type specimens. Recently Choung (2007) proposed the stress correction formula beyond the diffusion necking which was derived based on the parametric numerical study for the panel type specimens of marine grade steel. However his formula cannot be applied to the steel plate formed by line heating. In this study transient thermal analysis has been conducted with varying heat input and plate thickness using the elasto-plastic properties of marine grade steel suggested by Lim (2012) based on the results of line heating and tension test. Then, a numerical analysis on tension test has been carried out for several models with varying heating conditions. Based on the present results, a stress correction formula which can be applied to the plate formed by line heating is suggested to correct tri-axial stress state of tensile specimen after necking. This is expected to be used as the fundamental information in studying structural behavior characteristics of marine grade steel formed by line heating.

2. Outline of thermo-elasto-plastic analysis

Thermo-elasto plastic analysis is, in theory, a coupled problem of heat transfer analysis and thermal deformation problems. Since deformation due to heating is small comparing with other dimensions such as width and length of plate, two problems can be solved independently. That is, two phenomena can be regarded as uncoupled problems (Shin, 1992; Lee, 2010; Kim and Lee, 2011). Firstly, the temperature distribution at any time is obtained through heat transfer analysis due to moving heat source, and inputted as the thermal load in the elasto- plastic analysis to obtain deformation due to moving heat source. Fig. 1 shows the overall flow of thermo-elasto plastic analysis. And considering effects of latent heat for the accuracy in realizing heat transfer, temperature dependent of physical mechanical properties shown in Fig. 2 are used in the present numerical analysis. As the heat flux model, the double Gaussian heat flux model suggested by Tsuji and Okumura (1988) is used to take into account both primary and secondary flames in the present numerical analysis. The heat flux distribution, q(r) of flame by combustion gas is shown in Fig. 3 and is given as follows

$$q(r) = \frac{6\eta Q}{R_1^2 + \beta R_2^2} e^{-\left(\frac{r}{R_1^2} + \beta \frac{r}{R_2^2}\right)} \quad (1)$$

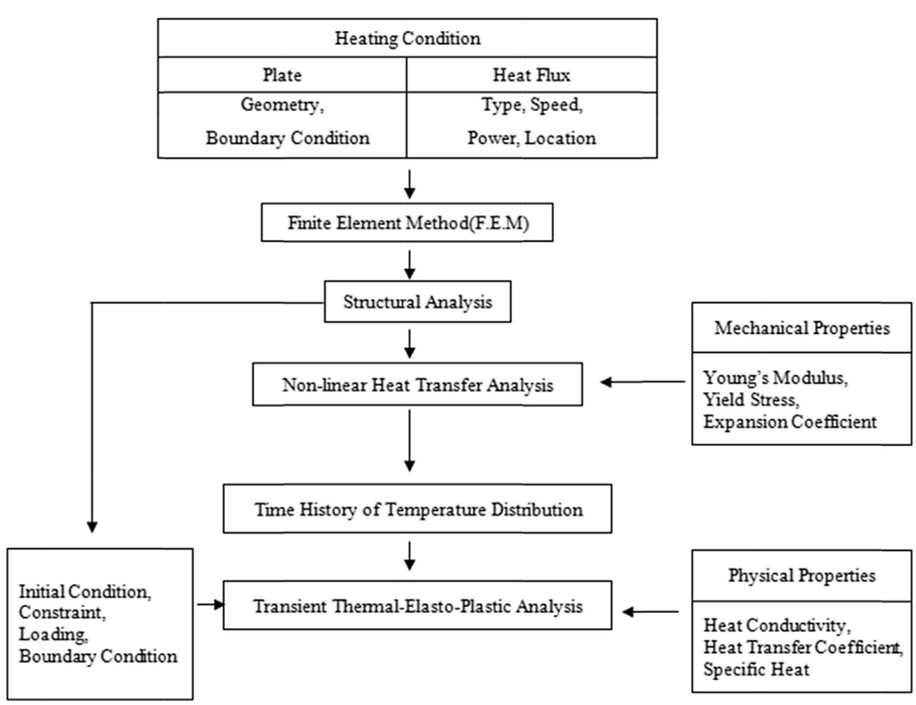

Fig. 1. Overall flow of thermo-elasto plastic analysis.

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