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Effect of external load on angular distortion in fillet welding

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ABSTRACT

This paper studied the effects of the magnitude, the direction, and the release time of pre-tensioning stress on welding distortion and residual stress on thin steels for a ship in the pre-tensioning method above using the finite element method. It was found that pre-tensioning stress in the direction of weld path did not affect angular and longitudinal distortion but brought a decrease of 8% in the magnitude of welding residual stress which may affect the buckling strength. Meanwhile, pre-tensioning stress in the direction perpendicular to weld path resulted in a decrease of 40–60% in the magnitude of angular distortion. Also, when the pre-tensioning stress was released 60 min after the completion of welding, it had a decreasing effect of 10–20% more in the magnitude of angular distortion than when released immediately after welding.

1. Introduction

Angular, buckling, and longitudinal distortions [1–3] are easily induced in the welding process on thin steel structures because the stiffness of thin steel itself is less. These distortions change the shape and size of steel structures, which require additional correcting work in the process of assembling them, leading to a decrease in productivity and a falling-off in the quality of welded structures. To prevent these problems, a margin for welding shrinkage is allowed in the design stage, based on experience and measured data [4–7]. However, this method for determining the margin based on data has had difficulty taking into account variations in welding methods, welding materials, shapes of welded structures, etc. Therefore, elastic analysis using the inherent strain method [8–11] and equivalent load method [12,13] has been investigated to predict the welding distortion in large steel structures lately. Also, more aggressive methods to prevent the welding distortion have been studied, which include inverse elastic distortion, constraint method, cooling/heating method, and pre-tensioning method [14,15].

This paper studied pre-tensioning method of reducing welding distortion with the pre-tensioning stress [16,17] caused by external load at weld zone during fillet welding. The established studies have showed that the highest-reaching temperature and the magnitude of constraint are the main factors to bring out welding distortion [8]. The pre-tensioning method decreases welding distortion by controlling the constraint (stress) with pre-tensioning stress caused by external load. This method was first developed to control buckling distortion by welding on thin steels for railway vehicles, which is the way of welding with heating and pre-tensioning stress added onto a plate. Also, a series of researches similar to this method have been performed. One of them is the way of predicting the critical buckling strength [18,19] by thermal elastic plastic analysis. Another study [20] confirmed that to apply pre-tensioning stress to butt welding on thin steel structures has an effect of reducing longitudinal shrinkage and distortion in the direction of welding line and angular distortion in the direction perpendicular to welding line. The other method [21,22] using a thermo-elastic–plastic analysis verified that to model welding in the state of thermal tensioning minimizes buckling distortion due to welding by reducing the welding residual stress. However, to make the pre-tensioning method practicable, there is a need to investigate the effect of the release time, direction, and magnitude of pre-tensioning stress on residual stress and welding distortion more thoroughly, which are the most important factors linked directly to productivity and quality of welded structures.

Therefore, in this paper, when fillet welding is performed with pre-tensioning stress caused by external load on thin steel, the effects of the magnitude, the direction, and release time of pre-tensioning stress on welding distortion and residual stress are illuminated using the thermo-elastic–plastic analysis. And then, the effectiveness of reduction of distortion by pre-tensioning method gotten via the analysis is verified by experiment.

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2. Welding simulation

2.1. Analysis model and condition

Fig. 1 shows the analysis model, which consists of base plates (length × width × thickness; 800 × 400 × 5/8 mm) and a stiffener (length × height × thickness; 800 × 55 × 6 mm). The welding conditions are 240 A, 24 V, and 390 mm/min and the welding method is FCA welding process. The leg length is 3 mm and two fillet welds are deposited simultaneously on each side of the joint. Both base plates and a stiffener are made of mild steel (SM400).

Table 1 shows the analysis conditions. The analysis conditions including the magnitude, direction, and release time of pre-tensioning stress (0 min, 60 min) and thickness of the plate (5 mm, 8 mm) affect on the industrial applications and productivity as well as welding distortion and residual stress.

Fig. 2 shows all shapes of finite element mesh and welding zone mesh of 5-mm-thick base plates used in this study. The half model was employed to consider the symmetry of the fillet welding with two fillet welds deposited simultaneously on each side of the joint. The boundary conditions for the numerical analysis were taken considering the symmetric condition of the model and the prevention of rigid body motion. In this study, the residual stress distribution was simulated by an uncoupled thermo-mechanical finite element formulation using the MSC/Marc code as an analysis tool. Non-static thermal conduction analysis considers the dependence of physical constant of a material on temperature (Fig. 3a), thermo-elastic–plastic analysis considers the dependence of mechanical properties of a material on temperature (Fig. 3b).

Fig. 4a shows the model applying pre-tensioning stress in the longitudinal direction of weld path and Fig. 4b is the model applying pre-tensioning stress in the transversal direction of weld path. For stable analysis in mechanical analysis, the pre-tensioning stress was applied by forced displacement.

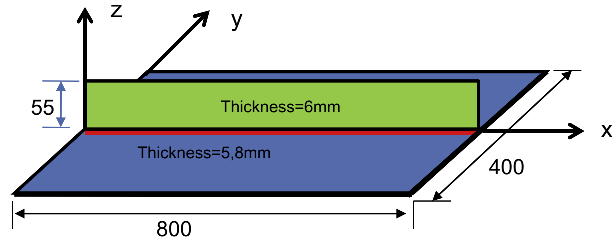

Fig. 1. Model of fillet weld.

Table 1
Analysis condition.

Direction of load	Mean tensile stress (MPa)	Base plate thickness (mm)	Time of load release from welding end (min)	
No load	–	5	–	–
	–	8	–	–
Welding direction	12	5	0	60
Width direction	6	5	0	60
	12	5	–	60
	6	8	0	60
	12	8	0	60

2.2. Modeling of welding heat source

MSC/Marc options including weld flux, weld filler, and weld path were used for modeling of welding heat source in thermal analysis. The ellipsoidal heat source model revealed that the temperature gradient in front of the heat source was not as steep as expected and the gentler gradient at the trailing edge of the molten pool was steeper than experimental measurements. Hence two ellipsoidal sources were combined as shown in Fig. 5. The front half of the source is the quadrant of one ellipsoidal source, and the rear half is the quadrant of another ellipsoid. The estimation of the heat input was made based on the Eqs. (1) and (2) [23]:

$$q_f(x,y,z) = \frac{6\sqrt{3}f_f Q}{abc_f\pi\sqrt{\pi}} \exp\left(\frac{-3x^2}{a^2}\right) \exp\left(\frac{-3y^2}{b^2}\right) \exp\left(\frac{-3z^2}{c^2}\right) \quad (1)$$

$$q_r(x,y,z) = \frac{6\sqrt{3}f_r Q}{abc_r\pi\sqrt{\pi}} \exp\left(\frac{-3x^2}{a^2}\right) \exp\left(\frac{-3y^2}{b^2}\right) \exp\left(\frac{-3z^2}{c^2}\right) \quad (2)$$

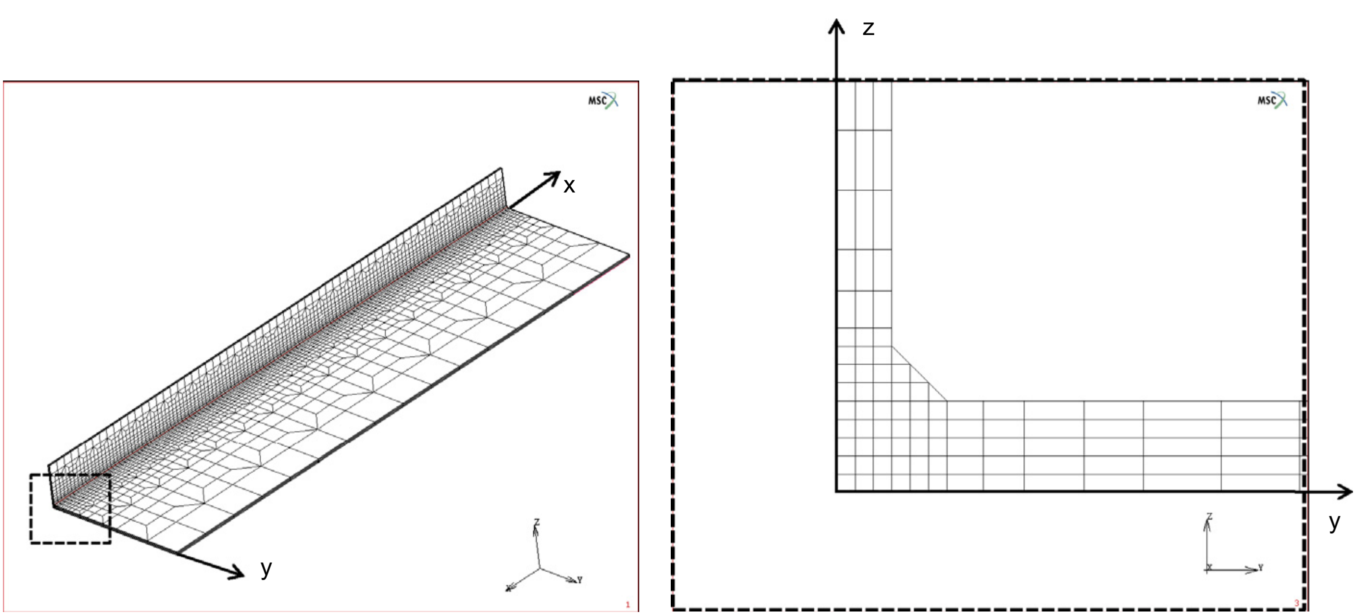

Fig. 2. Analysis model for fillet weld (t = 5 mm).