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Prediction of the welding distortion of large steel structure with mechanical restraint using equivalent load methods

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Abstract

The design dimension may not be satisfactory at the final stage due to the welding during the assembly stage, leading to cutting or adding the components in large structure constructions. The productivity is depend on accuracy of the welding quality especially at assembly stage. Therefore, it is of utmost importance to decide the component dimension during each assembly stage considering the above situations during the designing stage by exactly predicting welding deformation before the welding is done. Further, if the system that predicts whether welding deformation is equipped, it is possible to take measures to reduce deformation through FE analysis, helping in saving time for correcting work by arresting the parts which are prone to having welding deformation. For the FE analysis to predict the deformation of a large steel structure, calculation time, modeling, constraints in each assembly stage and critical welding length have to be considered. In case of fillet welding deformation, around 300 mm is sufficient as a critical welding length of the specimen as proposed by the existing researches. However, the critical length in case of butt welding is around 1000 mm, which is far longer than that suggested in the existing researches. For the external constraint, which occurs as the geometry of structure is changed according to the assembly stage, constraint factor is drawn from the elastic FE analysis and test results, and the magnitude of equivalent force according to constraint is decided. The comparison study for the elastic FE analysis result and measurement for the large steel structure based on the above results reveals that the analysis results are in the range of 80–118% against measurement values, both matching each other well. Further, the deformation of fillet welding in the main plate among the total block occupies 66–89%, making welding deformation in the main plate far larger than the welding deformation in the longitudinal and transverse girders.

Keywords: Residual stress; Welding distortion; FE-analysis; Angular distortion

1. Introduction

When a large steel structure is made by welding, design dimension may not be satisfactory at the final stage if welding deformation cannot be accurately predicted during the assembly stage, leading to cutting or adding the components. Such additional works need a separate modification process, which takes a lot of time and causes productivity decrease. Therefore, it is of utmost importance to decide components' dimensions during each assembly stage, considering the above situation during designing, to exactly predict welding deformation before welding is done. For the FE analysis to predict the deformation of a large steel structure, calculation time, modeling, restriction in each assembly stage, and critical welding length have to be considered.

There are broadly three methods to predict welding deformation in a large steel structure; i.e., thermal elastic–plastic analysis, inherent strain method, and equivalent force method. Thermal elastic–plastic analysis (Ha, 2011; Ha and Yang, 2010) is a method to predict welding deformation and residual stress by performing heat distribution and elastic plastic

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stress analysis that occur along with the movement of heat source for the welding. With these methods, even for the case of a coupon-size specimen, a huge amount of time for modeling and analysis are consumed (Ikushima, 2014). If the analysis subject is large, the analysis may not be possible due to the excessive time consumed and shortage of memory capacity of the computer. Recently, a study method to analyze welding deformation has progressed by accelerated explicit method. Accelerated explicit method (Ninshu, 2015; Shibahara and Ikushima, 2010) drastically reduces time for analysis and memory so that residual stress and welding deformation are predicted within a short time. However, it is at its initial stage and further study would be needed in order to apply accelerated explicit method and to apply this method universally.

A welding deformation prediction method by elasticity analysis was studied in order to resolve the issue of calculation time and the capacity of computer for thermal elastic–plastic analysis. The representative methods are the inherent strain method and equivalent force method. Inherent strain method (Kim et al., 2015a; Park et al., 2014) is a method to predict residual stress and deformation by drawing inherent deformation, which is the source of residual stress and deformation through the thermal elastic–plastic analysis and elasticity FEM with drawn inherent deformation as load. For that, reliable inherent deformation distribution from thermal elastic–plastic analysis technique and many analysis results need to be made as a database. Meanwhile, equivalent force method (Park et al., 2002a; Deng et al., 2012) is a method of predicting welding deformation by calculating equivalent force from the welding deformation in the experiment, focusing on the prediction of welding deformation. Though these methods need to establish "D/B" by performing a large amount of experiment, it has a merit of measuring deformation from the experiment conditions that are used in the actual site.

In applying welding deformation prediction method, research on external constraint and critical welding length is required in order to predict more accurate welding deformation. The magnitude of external constraint is changed according to the assembly stage and a component's geometry, and these factors affect the dimension of welding deformation. Therefore, the research on the effect of external constraint (Park et al., 2002b; Kim et al., 2015b) on the welding deformation was initiated by Sato (Sato and Terasaki, 1976), but it could not be applied to predict welding deformation. Some researchers managed applying constraint degree to draw welding stage that could minimize welding deformation (Tsai et al., 1999). According to research results, welding deformation largely occurs if welding is done on the welding joint which has a small constraint. In this study, the effect of external constraint according to type of deformation was implemented by constraint degree.

It is necessary to have a concept critical welding length in order to draw consistent experiment results when equivalent force method that calculates equivalent force from the deformation is used. Critical welding length is a welding length that generates constant welding deformation regardless of welding length. In existing research (Tsuji and Ogawa, 1976), critical welding length was reported to be around 300 mm. This length can be applied on fillet welding and bead-on-welding. However, according to results obtained from this study, the critical welding length of butt welding was far longer than that by fillet welding and bead-on-welding.

In this study, the relationship between the degree of external constraint and equivalent force by assembly sequence was investigated to predict the welding deformation of large steel structure more accurately, and critical welding length that affects the dimension of welding deformation was discussed. An automatic modeling module was developed so that the results could be easily implemented in the analysis of welding deformation for large steel structure, and then reliability was validated by comparing the FE analysis results and actual measurement of welding deformation for the steel structure of a large-sized ship block.

2. Mechanical modeling

2.1. Equivalent load method

In case of predicting the welding deformation of large steel structure by a thermal elastic–plastic analysis, modeling for welding is difficult and a huge analysis time and computer memory having a large capacity are needed even if the size of the analysis model is small as in the coupon specimen. Therefore, in this study, the analysis for the welding deformation that occurred by a complex thermal elastic–plastic behavior among the predication methods for the welding deformation of a large steel structure was not directly performed, but equivalent force method that calculated welding deformation through elastic FE analysis using equivalent force from the welding deformation by experiment was used. Table 1 show in comparison between equivalent forces method and inherent strain method. The equivalent forces method use mechanical forces (force/moment) but inherent strain method, strains. So, inherent strain method need fine mesh and a lot of modeling time.

Equivalent force methods are broadly categorized into three; i.e., longitudinal deformation, transverse deformation, angular distortion (Park et al., 2002a), and welding deformation are predicted by elastic FE analysis by calculating equivalent force from measured welding deformation during experiment using Eq. (1). At this time, the relation between equivalent force (P_L, P_T, and M) and welding deformation (δ_L, δ_T, and θ) can be expressed linearly as in Eqs. (1a), (1b) and (1c).

Table 1
Comparison between equivalent forces method and inherent strain method.

	Equivalent forces method	Inherent strain method
Input parameter	Force/moment	Strains
Modeling time	100 (standard)	120 (needed fine mesh)
Input time	100 h (standard)	200 h (calculate strains)
Computing time	100 h	100 h
Stress filed	x	0
Deformation	0	0