Journal of Constructional Steel Research 149 (2018) 41–52

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Effect of sequence and stiffener shape on welding distortion of stiffened panel

Saeed Shadkam [a], Eslam Ranjbarnodeh [b],*, Mehdi Iranmanesh [a]

[a] Faculty of Marine Technology, Amirkabir University of Technology, Iran
[b] Faculty of Mining and Metallurgical Engineering, Amirkabir University of Technology, Iran

ARTICLE INFO

Article history:
Received 8 November 2017
Received in revised form 20 June 2018
Accepted 6 July 2018
Available online xxxx

Keywords:
Welding distortion
FE simulation
Elastic method
Stiffened panel
SM490A steel
Sequence

ABSTRACT

Welding is extensively used in industries for the assembly of different products including ships, automobiles, trains, bridges etc. Welding distortion is usually a source of dimensional imprecision in assembly and higher manufacturing costs. So, it is of crucial importance to predict and minimize welding-induced distortion by improving the quality of the welded structure. The purpose of this research is to reduce the distortion in large ship panels. The study uses two methods. First, distortion prediction by thermal elastic plastic FE analysis is employed to estimate the inherent deformations of different SM490A steel welded joints. Then, the welding process of a large ship panel is elastically analyzed on the basis of the theory of inherent strains. The elastic analysis reveals some distortions on the edge and inside of the panel. The distortions can be minimized by changing welding sequence of panel stiffeners to symmetrical welding of type B and changing shape to L-stiffener as well as changing stiffener material to the SM570.

1. Introduction

Welding technology is a joining mechanism extensively used in the assembly of different products including ships, automobiles, trains, and bridges. For instance, assembly process in ship construction essentially includes joining large blocks that are composed of fully welded thin plates. Distortion frequently happens during the construction of these blocks due to different reasons like cutting and welding. Welding-induced distortion pushes up the manufacturing costs. Though complete removal of distortion is practically impossible, the blocks can be manufactured precisely enough to overcome the relevant problems during assembly. So, it is of crucial importance to quantitatively predict and control distortion during assembly of large welded structures. Weld-related distortions not only affect the dimensions of the welded parts but also clearly impact their performance. The correction of distortion is very time-consuming and eventually impairs the quality of the weldments. To ensure manufacturing correctness, it is necessary to launch a precision management system to monitor the manufacture of thin-walled structures. Precision management of products is a matter of crucial importance to ship construction industry. In general, there are two ways to reach the objective of precision management: close control through minimizing the changes during assembly, and precise planning at design stage. If buckling and distortion components can be predicted for thin and large panels before welding, it can play a significant role in improving the manufacturing precision.

Watanabe and Satoh studied the buckling behavior of the welded thin plates [1]. Nomoto et al. investigated variables controlling buckling distortion during welding process by experimental and numerical methods [2]. Ueda et al. used an extended plate buckling finite element (FE) analysis to calculate radial distortion in fillet welds. They also examined the influences of welding sequence and externally applied forces on the radial distortion [3]. In a series of experiments on a ship panel, Wang et al. calculated welding-induced distortion in weldments done by MAG welding. They concluded that the input heat plays a significant role in distorting the plates [4]. Deng et al. integrated thermal elastic plastic (TEP) FE method and elastic FE method to predict welding-induced distortion. They showed the usefulness of these methods for thin plates. Finally, they examined the effect of such parameters as input heat, welding process, welding sequence, plate thickness, and stiffeners spacing on the induced distortion [5]. To be able to readily predict the welding-induced deformations for large plate structures and joints, Liang et al. proposed a simple and highly efficient method for estimating inherent deformations of common joints by an FE analysis method [6]. Wang et al. used elastic FE method based on the theory of inherent deformations to calculate welding-induced out-of-plane distortions. Then, they used linear heating to reduce the induced buckling and bending [7]. In 2013, Murakawa et al. predicted the distortion induced in a large panel using the elastic FE method based on the theory of inherent deformations. They used linear heat to reduce out-of-plane distortions and found it very useful [8]. In 2016, Zeng et al. studied the

---

* Corresponding author.
E-mail addresses: saeedshadkam@aut.ac.ir (S. Shadkam), islam_ranjbar@aut.ac.ir (E. Ranjbarnodeh), imehdi@aut.ac.ir (M. Iranmanesh).

https://doi.org/10.1016/j.jcsr.2018.07.010
0143-974X/© 2018 Elsevier Ltd. All rights reserved.

thermal elasto-plastic analysis, FE models of multi-pass butt welds, and T-type fillet welds to obtain the inherent strain distribution in a 5A06 aluminum alloy cylindrical structure [9]. In 2017, Wang et al. found that welding sequence would intensively influence the final dimensional accuracy via straightening in fitting procedure and updated stiffness of current main welded structure [10].

Despite the published works in this field and to the best knowledge of authors, computational tools are used for this prediction, which has been the subject of many investigations. So, the present study uses an elastic-plastic thermal FE method for estimating the inherent deformations for various welded joints derived from a large welded model. Then, the elastic FE method is used on the basis of the calculated inherent deformations to predict welding distortion in a large welded model. At the same time, the effects of applied welding sequence, shape and the material of the applied stiffener are studied on final welding-induced distortion.

2. Mathematical model and FE analysis

Distortion in welding can be predicted by two methods: TEP analysis in which welding process is solved as a non-linear transient problem, and inherent strain method in which distortion is obtained from elastic analysis and the inherent strains are assumed as the main strain. Both methods have their own advantages and disadvantages. The advantage of the latter method lies in calculation time, but its main drawback is that welding details and conditions cannot be fully considered. The concept of inherent strain [16] is very close to inherent stress and inherent force. If the constraints are very weak, the inherent strain will become inherent deformation; otherwise, it will turn into stress. Simply talking, the integration of these two methods forms the basis for FE simulation of the welding process.

2.1. Thermal elastic plastic analysis

Research shows that welding-induced distortion can be effectively and readily predicted by developing practical methods. Distortion in assembly process is induced by non-linear phenomena including non-linear material (TEP behavior of weldment and base metal) and non-linear geometry (large deformation). Hence, these non-linear problems should be precisely considered to make a precise prediction of welding-induced distortion. The present paper strived to find an effective method for the prediction and estimation of welding-induced distortion based on existing studies and non-linear problems of this kind. TEP transient method is a feasible choice for predicting welding-induced distortion in small and medium-size structures. In this analysis, a thermal source can be modeled by Goldak's double ellipsoid thermal model [18]. But, most researchers use Gaussian normal distribution to simulate GMAW. Thus, the present paper used Gaussian thermal model as expressed by Eq. (1):

$$q(x) = \frac{3 \cdot Q_{arc}}{\pi r_a^2} \cdot \exp\left(-\left(\frac{r(x)}{r_a}\right)^2\right) \tag{1}$$

where Q_{arc} is input heat in watts (W) expressed as Eq. (2), r_a is Gaussian thermal source in meters, and $r(x)$ is distance from thermal source center in meters.

$$Q_{arc} = \eta UI \tag{2}$$

where Q_{arc} is input heat in watts, η is welding arc effective coefficient, U is arc voltage in volts, and I is welding current in amperes.

2.2. Elastic analysis

TEP method is not a feasible method for analyzing welding-induce distortion of large, complex structures because its weld mechanics severely suffers from non-linear problems for which a considerable calculation power is needed. But, inherent strain method is an alternative method for predicting welding-induced distortion in large structures. Since inherent strain method can readily predict welding-induced distortion by FE elastic analysis, it is much more practical and effective than transient TEP method.

2.2.1. The theory of inherent strains

The mechanical behavior during welding is very complex. Overall, there are five types of strains in welded parts: elastic, plastic, thermal, creep, and phase transformation. The elastic strain is reversible and is removed as the part cools down. But, the others are the inherent strain of the part. The inherent strains are known as the main cause of distortion and residual stresses. They depend upon such factors as plate thickness, input heat, welding velocity, and joint type. In general, the strains induced in a welded structure are calculated by the following equation [10].

$$\varepsilon_{total} = \varepsilon_{elastic} + \varepsilon_{plastic} + \varepsilon_{thermal} + \varepsilon_{creep} + \varepsilon_{phase} \tag{3}$$

$$\varepsilon_{total} - \varepsilon_{elastic} = \varepsilon_{plastic} + \varepsilon_{thermal} + \varepsilon_{creep} + \varepsilon_{phase} = \varepsilon_{inherent} = \varepsilon^* \tag{4}$$

According to Eq. (3), inherent strain equals the sum of plastic strains and thermal strains. But, the thermal strain is negligible in gas welding and is ignored. So, the amount of inherent strain equals the amount of plastic strain in each direction.

2.2.2. The theory of inherent deformations

The inherent strains can be directly applied to elastic model, but it is very time-consuming in the sense that it is very difficult to apply these strains as initial strain to the elastic model and to all nodes. The theory of inherent deformation has been introduced with the assumption that there is an inherent amount of deformation along the section perpendicular to the weld line in a welded structure. This deformation can be a substitute for the inherent strains. So, the method produces four inherent deformations for each cross section including longitudinal shrinkage, transverse shrinkage, longitudinal buckling, and transverse buckling. The welding-induced deformations including longitudinal and transverse compression and radial distortion are often created by longitudinal and transverse inherent strains (ε_z^* and ε_x^*, respectively). The amount of inherent deformation is obtained by integration of the inherent strain over the cross section perpendicular to the weld line averaged on thickness (h) [12].

$$\delta_L^* = \frac{1}{\mathrm{h}} \iint \varepsilon_z^* dydz \tag{5}$$

$$\delta_T^* = \frac{1}{\mathrm{h}} \iint \varepsilon_x^* dydz \tag{6}$$

$$\theta_L^* = \frac{12}{\mathrm{h}^3} \iint \left(\mathrm{y} - \frac{\mathrm{h}}{2}\right) \varepsilon_z^* dydz \tag{7}$$

$$\theta_T^* = \frac{12}{\mathrm{h}^3} \iint \left(\mathrm{y} - \frac{\mathrm{h}}{2}\right) \varepsilon_x^* dydz \tag{8}$$

where δ_L^* is longitudinal compression, δ_T^* is transverse compression, θ_L^* is radial distortion or buckling in longitudinal direction, and θ_T^* is radial distortion or buckling in transverse direction.

2.2.3. Description of elastic analysis process

Elastic simulation is a suitable method for thin plate structures. Welding-induced distortion can be simulated by the application of inherent strains at each stage of production to a welded joint according to a certain welding sequence. In elastic FE method, a plate-shape 4-node element was used to stimulate the welded parts. In general, the residual plastic strains are distributed in the vicinity of the welded point