Marine Structures 50 (2016) 95–110

Contents lists available at ScienceDirect

Marine Structures

journal homepage: www.elsevier.com/locate/marstruc

Effect of metal inert gas welding on the behaviour and strength of aluminum stiffened plates

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ARTICLE INFO

Article history:
Received 20 August 2015
Received in revised form 17 June 2016
Accepted 13 July 2016

Keywords:
Aluminum stiffened plates
Metal gas welding
Heat affected zone
Residual stress
Buckling strength
Finite element analysis

ABSTRACT

This paper investigated the effect of a 3D simulated metal inert gas (MIG) welding induced heat affected zone (HAZ), residual stress and distortion fields on the behaviour of aluminum stiffened plates under compressive loading. A two-step, thermo-structural finite element model was developed for the simulation of the welding process and the model was verified using the available experimental results. The welding induced HAZ, residual stress and distortion were then studied for tee-bar stiffened aluminum plates of various geometries. The effect of these welding induced imperfections on the load vs. shortening curves, buckling mode, and the post-buckling behaviour of each stiffened plate geometry were investigated. It was found that welding induced tensile and compressive residual stresses ranged from 72 to 77% and 18–36% of the base metal yield stress, respectively. The width of the HAZ around the weld line increased as the plate slenderness increased. The reduction in buckling strength of the tee-bar aluminum stiffened plates due to the presence of the HAZ and residual stress was as much as 10% and 16.5% respectively.
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1. Introduction

Aluminum has been used to build ship structures since the mid-20th century with an increasing application in high-speed vessels in the past 20 years. In ship structures made of either steel or aluminum, stiffened panels, constructed through welding, are mainly used as ship hull girders and they are usually designed for axial compressive loads [1]. While welding induced residual stress and distortion are common in both aluminum and steel stiffened plates, the heat affected zone (HAZ) where the material strength sustains marked reduction due to welding is unique in aluminum stiffened plates. Analytical and experimental research showed that for aluminum stiffened panels, welding induced residual stresses and distortions, and yield strength reduction in the HAZ have substantial effects on the ultimate strength [2,3]. Finite element studies by Rigo et al. [3] showed that the effect of HAZ led to a 0–30% reduction on ultimate strength of angle-bar stiffened plates depending on their column slenderness. The reduction was minimal for high column slenderness, but increasingly significant as the stiffened plates became stockier. However, the slenderness typical of naval structures was not thoroughly studied. A numerical study conducted by Zha and Moan [2] showed that the reduction of the buckling strength due to HAZ was about 15% for AA6082-T6 and 10% for AA5083-H116 flat-bar aluminum stiffened plates failed by torsional buckling of stiffeners. Their parametric study revealed that over 90% of the reduction of strength was introduced by the presence of the transverse HAZ in nearby endplates. Their models were designed to buckle by the stiffener tripping mode; other models with other buckling

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http://dx.doi.org/10.1016/j.marstruc.2016.07.005
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modes were not included in the study. It should be pointed out that all aforementioned studies did not model the welding process and instead, constant HAZ widths were assumed in the finite element modeling regardless of the material thickness and welding parameters. In terms of residual stress, Zha and Moan [2] and Rigo et al. [3] found that the maximum reduction in buckling strength due to the presence of residual stresses was about 7% and 5%, respectively while the Ship Structure Committee [4] simply neglected the presence of residual stresses in the finite element modeling.

One major study on aluminum stiffened plates was conducted by Paik et al. [5] where 78 full-scale prototype aluminum stiffened structures constructed by metal inert gas (MIG) welding were tested under compression, which was followed by a finite element study. Using experimental results, the welding induced residual stresses, distortions and HAZ were approximated and categorized in three levels of “slight”, “average”, and “severe”. In the subsequent finite element study, they used one shell element representing the HAZ in the plate and stiffener. The welding process was not directly modeled but simplified average values of residual stresses, HAZ and distortions were assumed in the modeling. However, discrepancies between their experimental and finite element results were observed. Based on the regression analysis of the experimental and numerical results, they developed closed-form empirical limit state formulas for aluminum stiffened plates. For tee-bar aluminum stiffened plates the critical buckling strength was expressed as in Eqn (1):

$$\frac{\sigma_u}{\sigma_Y} = \frac{1}{\sqrt{1.318 + 2.759\lambda^2 + 0.185\beta^2 - 0.177\lambda^2\beta^2 + 1.003\lambda^4}} \le \frac{1}{\lambda^2} \tag{1}$$

where σ_u is the ultimate strength of the tee-bar aluminum stiffened plate, σ_Y is the yield stress of the aluminum, and β and λ are plate slenderness and column slenderness of the stiffened plate respectively.

Although there are methods by IACS [6] and Gordo and Soares [7] which can be used to determine the buckling strength taking into account the welding induced residual stresses for steel stiffened plates [8], whether they can be directly applied for aluminum stiffened plates remains a question due to the presence of HAZ. Two marine classification society rules, the DNV Rules of Classification of High Speed, Light Craft [9] and the ABS Guide for Building and Classing High Speed Naval Craft [10] apply an overall strength reduction to the yield stresses in the structure to account for HAZ and thus ignore the effect of HAZ on the buckling mode of the structure. While this makes design simpler, the penalty is presumably a heavier and more conservative structure. The Ship Structure Committee [4] suggested that the strength penalty for modeling the stiffened panel as all-HAZ material in place of a combined base/HAZ material model ranged from 10% to 30%. It recommended that modeling aluminum stiffened panels should explicitly consider the HAZ extent, location, and strength in place of applying a uniform reduction factor to the strength of the HAZ material.

In light of the above, this research was motivated to accurately characterize the welding-induced imperfections including residual stress and distortion fields as well as the HAZ in aluminum stiffened plates constructed by metal inert gas welding, and to evaluate the influence of these imperfections on the strength and behaviour of aluminum stiffened plates. Tee-bar stiffened plates with varying plate and column slenderness were considered in this study. A three-dimensional, two-step thermal-structural finite element model was developed to simulate the welding process and the model was verified with available experimental results. The model was then used to obtain aforementioned welding induced imperfections and generate the load vs. shortening curves of the aluminum stiffened plates under the compressive loading for each geometry. The effect of welding induced imperfections on the buckling strength, buckling mode and post-buckling behaviour of the aluminum stiffened plates were presented and discussed.

2. Numerical simulation

2.1. General

In this study, the ANSYS® program was used in the two-step thermal-structural nonlinear analysis. In the thermal analysis, the model was meshed with thermal elements and the time-dependent temperature distribution due to the moving heat source was obtained. In the subsequent structural analysis, the temperature field time history calculated from the thermal analysis was applied to the model as a series of thermal loads, where each load step represented an increment in the position of the traveling heat source along the weld path. The structural analysis of the model provided the residual stresses and distortions induced by the welding heat source.

The model consisted of a tee-stiffener and plate assembly with transverse frame plates welded at each end. A schematic view of the model is shown in Fig. 1. All materials were made of AA5083-H116, which is widely used in aluminum high speed vessels. The stiffener was connected to the plate by fillet welds deposited on both sides of the stiffener. The transverse frames were also joined to the stiffener and plate by fillet welds. The stiffener was initially attached to the plate by 10 mm long tack welds placed at both ends as well as in the mid-length of both sides of the stiffener shown as dotted lines in Fig. 1. The tack welds were also employed on both ends of the transverse frame plates. The welding sequence is shown in Fig. 1. After each of the first and second weld line, the stiffened plate was allowed to cool down for 30 min, and after each transverse weld line, the stiffened plate was allowed to cool down for 1 min. After the welding of all the weld lines was complete, the model was allowed to cool down to the room temperature. It is assumed in this study that a matching filler metal was used.

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