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Effects of plate configurations on the weld induced deformations and strength of fillet-welded plates

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ABSTRACT

The objective of this work is to access the importance of an accurate prediction of the weld induced residual stresses and distortion based on numerical simulations and experiments, and to investigate the compressive longitudinal ultimate strength of fillet-welded steel-plated ship structures. The distortions and residual stresses are calculated by a nonlinear thermo-elasto-plastic (TEP) approach considering a range of plate dimensions. The calculations are validated with an experimental program on the effect of welding. The calculated pattern of residual stresses is used to calibrate the size of the idealized model of the residual stress distribution. The obtained ultimate strength is compared with the results of some simplified methods as well as the International Association of Classification Societies (IACS) Common Structural Rules (CSR). The effects of plate and column slenderness on the ultimate strength of the stiffened plates are also included.

1. Introduction

Welding technology is nowadays widely used in ships and offshore structures. Welding methods that involve the melting of metal at the site of the joint are prone to shrinkage as the heated metal cools. Residual stresses and distortion are then introduced by the shrinkage. Welding distortion has negative effects on the accuracy of assembly, external appearance, and various strengths of the welded structures [1,2]. Non-uniform heat distributions, plastic deformations and phase transformations occur on the material being welded. These changes generate different residual stresses patterns for weld region and in the heat affected zone (HAZ) [3]. The residual stress may result in failure mechanisms such as fatigue, brittle fracture, stress corrosion cracking, and creep cracking [4,5]. Gannon et al. [6] investigated the effect of welding-induced residual stress and distortion on ship hull girder ultimate strength and revealed that the residual stresses reduced the ultimate strength of the stiffened plate by 11% with a consequent reduction in hull girder ultimate moment of 3.3%. Therefore, it is of great significance to accurately predict the thermal and structural responses of the welding operations, and to evaluate the strength capacity of the welded structures.

Over the past several years, numerical analysis such as finite element analysis (FEA) has been widely used to investigate the distribution of distortion and residual stress in welded structures. Mandal and Sundar [7] proposed a mathematical model to estimate the welding shrinkage in a butt joint. The model used in their analysis was based on the assumption that the plate undergoing welding is made up of a TEP zone and a fully elastic zone. Michaleris and Debiccari [8] performed TEP

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finite element analysis for welding simulation to predict the welding distortion. They claimed that their approaches were proven consistent to experimental and empirical data. Heinze et al. [9] investigated the gas metal arc welding (GMAW) of 5 mm thick S355J2+N steel numerically and experimentally. The influences of mesh density and continuous cooling transformation (CCT) behaviours on welding distortion were investigated by a validated numerical simulation and their modal analyses.

The welding condition, the properties of the structure and their interactions have significant influences on the thermal and structural responses (temperature history, distortion, and residual stress) in welded structures. The effect of constraints in the form of tack weld to minimize the angular distortions in one-sided fillet welding was analysed by Mahapatra et al. [10]. Gannon et al. [11] concluded that the welding sequence did not have a significant influence on the distribution pattern of the longitudinal residual stress but it did affect the peak values. Chen et al. [12] developed models and techniques to predict the corresponding structural responses of welded ship plates. Parametric studies based on numerical results were performed for different parameters including welding speed, plate thickness, heat input, and heat source type. More recently Fu et al. [13] discussed the effects of mechanical boundary conditions on the distribution of residual stress and deflection for T-joint welds. Adak and Guedes Soares [14] investigated the effects of three different restraints on the weld induced residual stress field and deformation in a high-strength butt-joint steel plate. Numerical and experimental studies on temperature and distortion patterns in butt- and fillet-welded plates were carried out in Ref. [15]. A two-dimensional parametric relationship of residual stress in fillet-welded plates was developed based on 12 case studies accounting for various plate thicknesses and welding sequences.

It has long been recognized that the ultimate compressive strength decreases due to the presence of welding-induced residual stress and distortions [16]. When a plate has a very high elastic buckling stress, it happens that the unstable failure does not occur before the development of a certain degree of plastic deformation. This phenomenon obviously changes the critical stress. Guedes Soares and Gordo [17,18] derived the equations to assess the strength of plates subjected to uniaxial and biaxial compressive and lateral pressure loads, including both effects of initial distortions and residual stresses. An approximate procedure was proposed to describe the load shortening curves for stiffened plates directly from mathematical expressions and showed the effect of residual stresses [19,20].

Based on the previous research on the distortion and residual stress calculations, the objective of this work is to investigate the compressive longitudinal ultimate strength of fillet-welded steel-plated ship structures. The distortions and residual stresses are calculated by the nonlinear finite element method (FEM). The calculated results are compared with some simplified methods in terms of the ultimate strength of the stiffened plates. The effects of plate and column slenderness are analysed and discussed at the end.

2. Welding experiments

Specimens for fillet welding were designed and fabricated, in order to investigate the characteristics of the temperature distribution as well as the mechanical behaviour generated in single-pass fillet welding. K-type Agilent 34307A thermocouple wires were used to measure the temperature histories of the plate specimens during the welding process. The thermocouple probe accuracy is 1.0 °C, and the probe vendor specifies accuracy of 1.1 °C. The thermocouples were welded to the plate specimens by Thermocouple Welder.

To investigate the temperature distribution, 8 points were selected for the measurements. As shown in Figs. 1 and 3 points with 15, 25 and 35 mm away from the weld centreline, respectively, were selected on each side of the top surface of the plates. There were 2 more points on both sides of the stiffener locating at 25 mm above the plate surface. Agilent 34970A data acquisition/switch unit (see Fig. 2) were used to record the temperature data of the selected points.

The lengths and breadths of the plates are both 500 mm, 5 specimens with different plate thickness and stiffener width and thickness are studied, as shown in Table 1. The conditions of the gas metal arc welding (GMAW) process are listed in Table 2. One side of the stiffener is welded firstly, and the other side is welded in the same direction after a short interval. The arc efficiency is estimated as 0.6 for the GMAW welding process. Fig. 3 displays the welded plate in the cooling stage. Fig. 4 illustrates two different types of welding sequences.

3. Numerical simulation

3.1. Heat source model

Goldak et al. [21] combined two semi-ellipsoids and proposed a new heat source called three-dimensional (3D) double ellipsoidal heat source as shown in Fig. 5. They calculated the temperature field of a plate by FEM using the proposed moving heat source and had shown that the 3D model could overcome the shortcomings of the previous two-dimensional (2D) Gaussian model in order to predict the temperature of the weld joints with deeper penetration.

To define the moving heat source in the FEA, local coordinate systems are established in different time steps, as the origins of the local coordinate system move along the welding direction from one time step to the next. For a point within the first semi-ellipsoid located in front of the welding arc, the heat flux equation is described as: