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Influence of the residual stresses and distortions on the structural behavior of girth-welded cylindrical steel members

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HIGHLIGHTS

- ▶ Structual behavior of girth-welded cylindrical steel members was investigated by FE method.
- ▶ The compression or bending behavior always involves local buckling near the girth weld.
- ▶ The local buckling alters the nature of the load–displacement response.
- ▶ The weld-induced imperfections should be considered in assessment of the structural behavior.

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ABSTRACT

The structural response of girth-welded cylindrical steel members is affected by the weld-induced residual stresses and distortions. This paper presents finite element analyses to clarify the effects of the girth weld-induced imperfections on the structural behavior of the cylindrical steel members with medium diameter-to-thickness ratio. Finite element modeling of the girth weld-induced residual stresses and deformations is first described. Nonlinear finite element analyses in which the behavior of the cylindrical steel members in pure compression and in pure bending is explored incorporating the girth weld-induced imperfections are next discussed. Results showed that the weld-induced residual stresses and distortions should be taken into account in assessment of the structural behavior of the girth-welded cylindrical steel members subjected to pure compression or pure bending since the weld-induced imperfections always induce local buckling near the girth weld, which alters the load–displacement behavior and diminishes the ultimate load-carrying capacity.

1. Introduction

The use of structural steel cylindrical sections as compression or bending members has drawn considerable attention from engineers and architects in the construction industry due to their aesthetic appearance and structural efficiency. In the realistic applications, girth welding of the cylindrical members is frequently required owing to the long geometry relative to the diameter and the wall-thickness. When two cylindrical sections are welded together, residual stresses and deformations are produced in the vicinity of the weld region as a result of plastic deformation caused by non-uniform thermal expansion and contraction in the welding process. The presence of welding residual stresses can be detrimental to the integrity and the service behavior of the welded members [1]. Particularly, when combined with service loads, welding residual stresses cause premature yielding and loss of stiffness and may lead to deterioration of load-carrying capacity. Moreover, welding deformations, i.e. weld distortions induced by circumferential shrinkage of the weld region has been founded to have significant effects on the buckling behavior of welded cylindrical shells [2]. Accurate estimation of magnitude and distribution of the weld-induced imperfections, and understanding their influences on the compression or bending behavior of girth-welded cylindrical steel members are therefore very important for the efficient design and safety.

The finite element method can be employed to simulate welding temperature field, welding residual stress field and welding deformation [3–8]. In the past, a significant amount of finite element models were proposed to predict welding residual stresses and deformations in girth-welded steel pipes [9–15], but these models were generally limited to the axisymmetric model. As demonstrated in the work by Lee and Chang [16], the axisymmetric model cannot reproduce the three-dimensional features in the girth welding process. In the available three-dimensional finite element analysis, limited works have been conducted due to the high computational cost [16,17–24].

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Many researchers have investigated the behavior of welded cylinders subjected to compression or bending considering the effects of weld-induced imperfections by experimental, theoretical and numerical methods. However, their works have been confined to cylindrical shell structures which normally contain several longitudinal and/or circumferential welded joints or cold-formed sections for the compressive behavior [25–30] and have been limited to cold-formed sections for the flexural behavior [31–34], and thus they have not considered the girth welding process.

As for the analysis of compression or bending behavior of girth-welded cylindrical steel members including the process in which the weld-induced residual stresses and distortions are produced, very little attempts have been made to date due to the truly complex analysis procedures involved in the welding and buckling. Actually, Lee et al. [35] assessed the buckling behavior of girth-welded circular steel tubes exposed to external couples by a FE method taking the weld-induced imperfections into consideration. However, quantitative evaluation of the effects that the girth weld-induced imperfections have on the bending behavior was not attempted. This paper presents finite element analyses which focus on the influence of the weld-induced imperfections on the structural behavior of a girth-welded cylindrical steel member with medium diameter-to-thickness ratio subjected to compression or bending. The base material used here is SUS304 austenitic stainless steel. Finite element modeling of the girth weld-induced residual stresses and deformations is first described. Nonlinear finite element analyses in which the behavior of the cylindrical steel member in pure compression and in pure bending is explored with and without considering the residual stresses and distortions in order to clarify the effects of the weld-induced imperfections are next discussed. Finally, the paper concludes from the discussion of the analysis results, and outlines future works.

2. Finite element modeling of the girth weld-induced residual stresses and deformations

Numerical modeling of weld-induced residual stresses and deformations needs to accurately take account of: (1) conductive and convective heat transfer in the weld pool; (2) convective and radiative heat losses at the weld pool surface; (3) heat conduction into the surrounding solid materials as well as the conductive and convective heat transfer to ambient temperature [1]. Moreover, one needs to account for temperature-dependent material properties and the effects of liquid-to-solid and solid-state phase transformation in the material.

In this study, the process of welding was simulated using three-dimensional thermo-mechanical finite element formulation based on the in-house finite element code developed by the authors [36], which has been extensively verified against numerical results found in the literature and experiments [16,37]. The solution procedure for welding residual stresses and deformations consists of two steps: a transient thermal analysis followed by a transient thermal–mechanical analysis. These two analyses are sequentially coupled since the thermal field has a strong influence on the mechanical field with little inverse influence [21] and therefore can be carried out in sequence. At the first step, a transient heat transfer analysis solves for the temperature field and its history associated with the heat flow of welding. Then, the resulting temperature history solutions are fed into the thermal–mechanical analysis as the thermal loading for the evolution of thermal stresses and deformations.

2.1. Thermal analysis

The heat transfer analysis is based on the heat conduction formulation with the moving heat source. The energy balance equation for the thermal analysis is given by:

$$\nabla(k\nabla T) + \dot{q} - \rho c \dot{T} = 0 \tag{1}$$

where T is the temperature, $\dot{T}$ is the rate of change of temperature, k is the thermal conductivity, c is the specific heat, ρ is the density, $\dot{q}$ is the rate of moving heat generation and ∇ is the spatial gradient operator.

According to the nature of arc welding, the heat input to the work piece can be divided into two portions. One is the heat of the welding arc, and the other is that of the melt droplets. The combined heat source model is employed to simulate the heat of the welding arc and the melt droplets [38]. The heat of the welding arc is modeled by a surface heat source with a Gaussian distribution, and that of the melt droplets is modeled by a volumetric heat source with uniform density. The heat of the welding arc is assumed to be 40% of the total heat input, and the heat of the melt droplets 60% of the total heat input [39].

During the thermal cycle, radiation heat losses are dominant in and around the weld pool; whereas, away from the weld pool convection heat losses are dominant. As for the boundary conditions applied to the thermal model, convection and radiation are both taken into consideration and their combined effects are represented by the temperature-dependent heat transfer coefficient, h [11].

$$h = \begin{cases} 0.0668T \ (\mathrm{W/m^2} \ \circ\mathrm{C}) & 0 < T < 500 \\ 0.231T - 82.1 \ (\mathrm{W/m^2} \ \circ\mathrm{C}) & T > 500 \ \circ\mathrm{C} \end{cases} \tag{2}$$

To account for the heat effects relevant to the molten metal of the weld pool, two methodologies are used: (1) the liquid-to-solid phase transformation effects of the weld pool are modeled by taking into account the latent heat of fusion, and (2) an artificially increased thermal conductivity, which is three times larger than the value at room temperature, is assumed for temperatures above the melting point, to allow for its convective stirring effect, as suggested in [15]. The latent heat, solidus and liquidus temperature are 260 J/g, 1340 °C and 1390 °C, respectively.

In the thermal analysis, the process of sequential weld filler deposition is simulated using a consistent filler activation/deactivation scheme. This scheme keeps track of the movement of the weld torch and updates the status of weld filler (deposited or not). For the weld filler that is not yet deposited at a given time, a value for thermal conductivity equivalent to that of air is assigned. This process is called filler deactivation. The deactivated fillers can be regarded as virtual fillers that are not actually present. After the weld filler is deposited, it is reactivated and the thermal conductivity is made to change from air value to that of the material used.

2.2. Mechanical analysis

The subsequent thermal–mechanical analysis involves the use of the temperature histories computed by the previous heat transfer analysis for each time increment as an input (thermal loading) for the calculation of transient thermal stresses and deformations. During the welding process, solid-state phase transformation is not considered because the metallurgical phase transformation does not occur in the austenitic stainless steel used in this work. Therefore, additive strain decomposition can be used to decompose the differential form of the total strain into three components as follows:

$$d\varepsilon_{ij} = d\varepsilon_{ij}^{e} + d\varepsilon_{ij}^{p} + d\varepsilon_{ij}^{th} \tag{3}$$

where $d\varepsilon_{ij}^{e}$ is the elastic strain increment, $d\varepsilon_{ij}^{p}$ is the plastic strain increment and $d\varepsilon_{ij}^{th}$ is the thermal strain increment. The elastic strain increment is calculated using the isotropic Hooke's law with temperature-dependent Young's modulus and Poisson's ratio. The