Ocean Engineering 128 (2016) 81–93

Contents lists available at ScienceDirect

Ocean Engineering

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

Progressive inelastic deformation of a girth-welded stainless steel pipe under internal pressure and cyclic bending

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ARTICLE INFO

Keywords:
Pressurized girth-welded stainless steel pipe
Weld-induced residual stresses
Cyclic bending
Ratcheting
Cyclic plasticity constitutive model
Finite element analysis

ABSTRACT

This study aims to characterize numerically the ratcheting behavior of a girth-welded straight stainless steel pipe in combined action of internal pressure and cyclic bending loading. Finite element (FE) thermal simulation of the girth butt welding process is first performed to identify weld-induced residual stresses. Three-dimensional (3-D) elastic-plastic FE analyses incorporated with the cyclic plasticity constitutive model capable of describing the cyclic plastic performance are next conducted to scrutinize the local (circumferential strain) and global (cross-section diameter change) ratcheting responses of the girth-welded stainless steel pipe under internal pressure and cyclic bending, which take the residual stresses and plastic strains obtained from the preceding thermal simulation as the initial condition. The analytical results demonstrate that welding residual stresses in combination with the internal pressure have significant effects on the hoop strain rate and the in-plane and out-of-plane diameter changes, and the degree and shape of the ovalization which occurs during the multiaxial ratcheting are dependent on the applied loads.

1. Introduction

Pressurized steel pipes which are the most basic elements in offshore pipelines are subject to cyclic loading induced by extreme weather, earthquake and wave, etc. One of the major concerns on these pipes is ratcheting. In a component under a primary load with secondary cyclic stressing that exceeds the elastic limit of the material, progressive accumulation of plastic strain occurs, which is called ratcheting even though the origin of the cyclic permanent strain accumulation remains not completely known (Taleb and Cailletaud, 2011). The inelastic strain accumulation combined with the fatigue damage during cyclic loading may result in reduction of the fatigue crack initiation life and thus the fatigue life of the component (Rahman et al., 2008). Ratcheting leads to larger in-grain misorientation in microstructure compared to fatigue, which is attributed to the larger accumulated plastic strain during ratcheting (Paul et al., 2015). Ratcheting is therefore one of the most critical structural problems to be investigated in a pressurized piping component subjected to cyclic loading. In most piping networks, connection of the pipes is mainly implemented by girth welding. In a girth-welded steel pipe, the presence of unavoidable welding residual stresses is well known (Karlsson and Josefson, 1990; Brickstad and Josefson, 1998; Yaghi et al., 2006; Deng and Murakawa, 2006; Lee and Chang, 2011a, 2014; Lee et al., 2013a), which are induced as a result of plastic strains caused by solidification, phase transformation and circumferential shrinkage during welding. Weld-induced residual stresses increase the vulnerability to stress corrosion cracking, fatigue damage and brittle fracture (Withers, 2007). It is also well recognized that mechanical behavior of a girth-welded pipe under monotonic loading is significantly affected by welding residual stresses (Lee and Chang, 2011b, 2013a, 2013b; Lee et al., 2013b, 2014a), i.e. the girth weld-induced residual stresses cause premature yielding and loss of stiffness and eventually lead to deterioration of the load-carrying capacity. However, the residual stress effect on the ratcheting response of a girth-welded steel pipe subjected to internal pressure and cyclic loading remains unclear.

In last three decades, a large number of research works have been dedicated to understand the cyclic plastic behavior. Along with the experimental studies (Hassan and Kyriakides, 1992, 1994a, 1994b; Hassan et al., 1992; Portier et al., 2000; Taleb and Hauet, 2009; Paul et al., 2012; Song et al., 2014; Taleb et al., 2014) which have provided useful information for the uniaxial/multiaxial ratcheting characteristics, various constitutive models capable of simulating the cyclic plastic response as accurate as possible have been developed (Armstrong and

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http://dx.doi.org/10.1016/j.oceaneng.2016.10.027
Received 17 March 2016; Received in revised form 29 July 2016; Accepted 13 October 2016
Available online 20 October 2016
0029-8018/

Nomenclature

b	material constant
c_k	material constant
f	yield function
k^*	initial size of elastic domain
m	material constant
n	unit normal vector to yield surface at current stress point
p	accumulated plastic strain
$\dot{p}$	accumulated plastic strain rate
H	plastic modulus
Q	saturated constant value of isotropic hardening
R	isotropic hardening variable
α	back stress tensor
α'	deviatoric back stress tensor
$\dot{\alpha}'$	deviatoric back stress increment tensor
$\bar{\alpha}'_k$	asymptotic value of the kth back stress
$\dot{\varepsilon}^p$	plastic strain increment tensor
σ	stress tensor
σ'	deviatoric stress tensor
$\dot{\sigma}'$	deviatoric stress increment tensor
γ_k	material constant
φ	material constant
$\dot{\lambda}$	plastic multiplier

Frederick, 1966; Chaboche and Rousselier, 1983; Nouailhas et al., 1985; Burlet and Cailletaud, 1986; Chaboche, 1986, 1991, 2008; Ohno and Wang, 1993; Corona et al., 1996; Jiang and Sehitoglu, 1996; Abdel-karim and Ohno, 2000; Bari and Hassan, 2000, 2002; Kang et al., 2002; Chen and Jiao, 2004; Kang and Kan, 2007; Kang and Liu, 2008; Abdel-Karim, 2009; Feigenbaum et al., 2012; Lee et al., 2014b; Do et al., 2015), most of which have generally been limited to the materials level. It has been demonstrated that the ratcheting response of a material has a significant dependence on the stress history, which in a pipe relies on the external load and the geometry (Hassan et al., 1998). Considering all these parameters experimentally is cost prohibitive and impractical. Thus, finite element (FE) simulation based on cyclic plasticity constitutive model should be employed to analyze the global (diameter change) and local (circumferential strain) ratcheting responses of a pressurized pipe for different cyclic loading patterns and configurations. For the structural ratcheting behavior of piping components such as straight pipes, elbows and branch pipes, many studies have been conducted (Chen et al., 2013). Nevertheless, a small number of research works so far have dealt with simulation of the plastic response of a straight piping component under cyclic bending and internal pressure. Hassan et al. Hassan et al., (1998) incorporated an improved constitutive model, which consists of the Armstrong-Frederick kinematic hardening rule (Armstrong and Frederick, 1966) and the Drucker-Palgen plastic modulus equation (Drucker and Palgen, 1981), into ANSYS FE package and validated the modified code by replicating the four-point displacement controlled cyclic bending tests of straight stainless steel pipes at constant internal pressure and correlating the analytical results with the experimental measurements. Gao et al., (2006) performed ratcheting simulations of pressurized straight low carbon steel pipes under cyclic quasi-three point bending, which involved bending moment gradients and shear loads through the pipe length, by using ANSYS program into which the Ohno-Wang model and the modified Ohno-Wang models were incorporated. The effects of bending load, internal pressure and loading history on the multiaxial strain accumulation were discussed. But, only hoop ratcheting strains were examined at various positions. Rahman et al., (2008) evaluated the performance of several constitutive models in simulating the structural ratcheting responses of straight pipes of alloy steel 4130 under combined curvature-symmetric cyclic bending and internal pressure against the measured local and global ratcheting responses. They claimed that the model parameters should be refined to improve the cyclic plasticity modeling. However, they focused on the performance evaluation of the constitutive models and hence limited load and structural parameters were employed in their investigation. Zakavi et al., (2010) used the Armstrong-Frederick model with isotropic/kinematic hardening rule to anticipate the circumferential ratcheting strains of pressurized straight carbon and stainless steel pipes subjected to simulated seismic bending moment. The FE results were compared with those obtained from the experiments and the capability of the combined hardening model was evaluated. From the literature review, it seems that ratcheting responses for internally pressurized piping components under cyclic bending have not been fully investigated. Moreover, as for the ratcheting analysis of a girth-welded steel pipe subjected to internal pressure and cyclic bending, very limited works have been reported to date due to the truly complex analysis procedure involved in welding and subsequent cyclic loading problems and therefore deserves special attention. Actually, Lee et al., (2004) evaluated the thermal ratcheting of welded cylindrical structure using inelastic analysis that employed the Chaboche-Rousselier nonlinear combined hardening model (Chaboche and Rousselier, 1983). They assumed the residual stress distribution at the welded joint according to the UK R6 procedure using axisymmetric FE model. However, the residual stresses are by no means axisymmetric, i.e. they vary spatially along the circumference due to the moving arc and welding start/stop effects (Lee et al., 2013a; Lee and Chang, 2014). Thus, the exact assessment of the residual stress effect on the ratcheting behavior could not be achieved.

This study attempts to scrutinize the ratcheting responses of a girth-welded straight stainless steel pipe under cyclic bending and internal pressure through the numerical simulation. The following approaches are taken in the present investigation: first, thermal simulation of the girth butt welding process is first conducted to obtain weld-induced residual stresses by using a sequentially coupled three-dimensional (3-D) thermo-mechanical FE analysis model developed by the authors; second, a cyclic plasticity constitutive model which can simulate the multiaxial ratcheting behavior is presented and verified against the test data, and third, parametric comparative studies in which the ratcheting responses of the girth-welded stainless steel pipe exposed to internal pressure and cyclic bending are explored taking the residual stresses and plastic strains as the initial condition are carried out by using a 3-D elastic-plastic FE analysis method which incorporates the cyclic plasticity model as the material constitutive equation. The ratcheting behavior of the pressurized steel pipe in cyclic bending without considering the residual stresses is also investigated in order to clarify the relevance of weld-induced residual stresses to the cyclic responses.

2. FE thermal simulation of the girth butt welding process

FE thermal simulation of the girth butt welding process should first be performed to attain weld-induced residual stresses and plastic strains, which are required input to the mechanical model for analyzing the effects that the residual stresses have on the ratcheting responses of the pressurized girth-welded stainless steel pipe under cyclic bending. Welding process is essentially a coupled thermo-mechanical process. The thermal histories strongly affect the stress fields, whilst the mechanical fields have a weak influence on the temperature profiles. Therefore, in this work, a sequentially coupled 3-D thermal-mechanical FE analysis model able to precisely capture the 3-D feature of welding residual stress distribution in the girth-welded stainless steel pipe, which was developed by the authors (Lee and Chang, 2014) based on the in-house FE-code (Lee, 2005) and its accuracy was confirmed