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Finite element analysis of cyclically-loaded steel pipes during deep water reeling installation

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ABSTRACT

Thick-walled steel pipes during their installation in deep water are subjected to combined loading of external pressure and bending, which may trigger structural instability due to excessive pipe ovalization. In the case of reeling installation method, prior to deep-water installation the pipe is subjected to cold forming associated with strong cyclic bending on the reel, resulting in the development of initial ovalization and residual stresses, which may affect the pipe structural performance. Using advanced material models and finite element tools, the present study examines the effect of cyclic loading due to reeling on the mechanical behavior of thick-walled seamless steel pipes. In particular, it examines the effects of reeling on cross-sectional ovalization and the corresponding material anisotropy and, most importantly, on pipe resistance against external pressure and pressurized bending. The results show that cyclic bending due to the reeling process induces significant anisotropy and ovalization on the pipe. It is also shown that the mechanical resistance of reeled pipes is lower than the resistance of non-reeled pipes, mainly because of the resulting cross-sectional ovalization at the end of reeling process.

1. Introduction

Pipe reeling is an efficient installation method suitable for steel pipes of diameter up to 16 in. Kyriakides and Corona (2007). The reeling method, shown in Fig. 1, allows for controlled onshore girth welding of a long pipe segment, which is spooled onto a large diameter reel. The reeled pipe is loaded on a reeling vessel, in order to be transported, deployed and installed offshore. Once the offshore installation location is reached, the pipe is installed in deep water by unspooling as the vessel moves, with the configuration shown in Fig. 1 (Kyriakides and Corona, 2007).

The repeated "excursions" of the pipe material into the plastic range during the reeling process ovalize the pipe cross section, causing permanent (residual) stresses, influencing the pipe material mechanical properties and affecting the structural performance of the reeled pipe. In particular, the pipe experiences large strains when it is spooled onto the reel, often in the range of 2%, which requires that the pipe is mechanically straightened out before its installation. The five consecutive steps of reeling process are show in Fig. 1 and are discussed in a later section.

The effects of reeling-induced imperfections and their importance in terms of the structural strength and stability of the steel pipe have been studied by Brown et al. (2004), who examined the definition of the minimum reelable pipe thickness. Manouchehri et al. (2008) reported the effect of the reeling installation method on the strength limit states. The interaction between residual stresses and fracture behavior of the pipe has been examined by Zhang et al. (2004), while Sriskandarajah and Rao (2015) focused on the prediction of residual ovality due to reeling process.

Upon unreeling and straightening, the pipe is installed in deepwater, where buckling under external pressure constitutes a fundamental limit state for the design of offshore pipelines, and the corresponding failure is commonly mentioned as "collapse" (Kyriakides and Corona, 2007), associated with a flattened "dog-bone" shape of the pipe cross-section. Moreover, at the sagbend region (Fig. 1) the pipe undergoes significant bending in the presence of high external pressure (Corona and Kyriakides, 1988; Karamanos and Tassoulas, 1991), which accentuates ovalization of the pipe cross section resulting in pipeline collapse. Experimental and numerical studies on the collapse pressure of reeled offshore pipes have been reported in (Pasqualino et al., 2004; Pasqualino and Neves, 2010), aimed at examining the effect of reeling-induced ovalization on pipeline performance in terms of external pressure resistance.

The effect of reeling-induced plastic deformations on pipe

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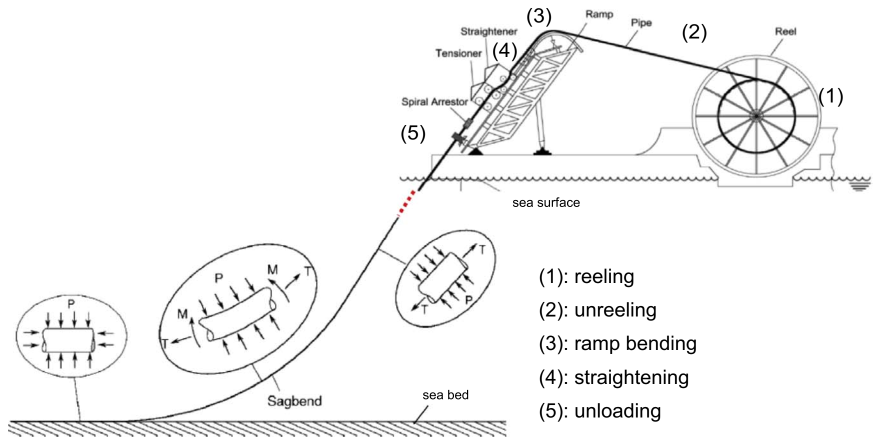

Fig. 1. Typical reeling pipeline installation vessel (Kyriakides and Corona, 2007).

material properties has been investigated during the last decade. Martinez and Brown (2005) examined the evolution of pipe properties during the reeling process. Bawood and Kenny (Dawood and Kenny, 2013) reported simulation results of the pipe mechanical response during reel-lay installation. In the work of Meiwes et al. (2014a, 2014b), small and large scale reeling tests are reported, simulating the reeling process and examining its influence on the mechanical properties of the pipe material. The effect of low temperatures on the reeling installation has been examined by Heier et al. (2013), whereas, the effect of geometric and material discontinuities at adjacent pipe segments on pipe mechanical behavior during reeling has been examined by Kyriakides and Liu (2014).

In the present study, motivated by the reeling process, the effect of cyclic bending on the mechanical response of thick-walled seamless pipes under combined loading conditions is examined using an efficient finite element model. The pipes under consideration are 12-inch-diameter seamless pipes with thickness ranging from 0.6 in to 0.937 in, which are typical for deep water applications. To describe steel material behavior, a cyclic-plasticity material model is employed, introduced by the authors elsewhere (Chatzopoulou et al., 2016). The model is based on von Mises plasticity and the nonlinear kinematic hardening rule, appropriately enhanced to account for the yield plateau at initial yielding and the Bauschinger effect. The constitutive model is numerically implemented and inserted within the finite element model using a material user-subroutine. The finite element analysis is based on a generalized two-dimensional model, capable of describing accurately cross-sectional ovalization, which is the major failure mode in the case of pressure and pressurized bending of relatively thick-walled pipes in a rigorous and accurate manner. A parametric analysis is also conducted with emphasis on the effects of cyclic bending due to reeling on the ultimate capacity of the pipe under external pressure and bending.

2. Numerical modeling

2.1. Finite element modeling description

A quasi two-dimensional model is developed in the general-purpose finite element program ABAQUS/Standard, which describes the cross-sectional deformation of the pipe under generalized plane-strain conditions. This allows for the simulation of pipe cyclic bending due to reeling, and the external pressure and bending application in a continuous multi-step analysis procedure. The present study focuses on relatively thick-walled steel pipes, which are expected to fail primarily due to cross sectional ovalization (collapse), so that localized buckling phenomena (pipe wall wrinkling) are not dominant and, therefore, this two-dimensional analysis approach is adequate for the purpose of the present analysis. In the analysis a "half pipe" model is considered, accounting for symmetry with respect to the yz-plane (Fig. 2) and bending is applied about the x-axis of the pipe cross-section. An in-house user-defined material subroutine (UMAT) is used for the description of the material behavior under severe plastic loading conditions, presented in the subsequent Section 2.2. The pipe is discretized using four-noded, reduced-integration generalized plane-strain continuum finite elements, denoted as CPEG4R in ABAQUS/Standard. In Fig. 2 the finite element model, the applied boundary conditions and the finite element mesh are depicted; five elements are employed through pipe thickness. Cyclic bending loading is applied first in five consecutive steps, followed by the application of external pressure and bending in subsequent analysis steps.

2.2. Constitutive modeling

An accurate simulation of material behavior under reverse (cyclic) loading conditions is of major importance for the accurate modeling of the reeling process and the reliable prediction of pipe capacity. During cyclic bending due to reeling/unreeling, the material behavior is characterized by two main features: (a) the yield plateau of the steel stress-strain curve upon initial yielding, (b) the Bauschinger effect under reverse plastic loading. Both features need to be taken into account in the constitutive model.

In the present study, the elastic-plastic behavior of the steel pipe material is described through a Von Mises plasticity model with nonlinear kinematic hardening initially introduced as reported in (Chatzopoulou et al., 2016). The Von Mises yield surface is given by the following equation:

$$F = \frac{1}{2}(\mathbf{s} - \mathbf{a})\cdot(\mathbf{s} - \mathbf{a}) - \frac{k^2}{3} = 0 \tag{1}$$

where $\mathbf{s}$ is the deviatoric stress tensor, $\mathbf{a}$ is the "back stress" tensor and k is the size of the yield surface. The value of k is a function of the equivalent plastic strain ε_q representing material hardening, so that $k = k(\varepsilon_q)$. The evolution of the back stress tensor is given by the following expression:

$$\dot{\mathbf{a}} = C\dot{\boldsymbol{\varepsilon}}^p - \gamma \mathbf{a}\dot{\varepsilon}_q \tag{2}$$

where C, γ are nonlinear kinematic hardening parameters, calibrated from appropriate material testing results.

To represent the aforementioned main two features of steel