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Effect of geometric and material discontinuities on the reeling of pipelines

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ABSTRACT

The winding and unwinding of a pipeline onto a large diameter reel as practiced in the reeling installation method, induces bending strains of 1–3% followed by straightening, and reverse bending. The operator must ensure that such plastic deformations are sustained free of local buckling or rupture in the line. Such failures are for example precipitated by pipeline discontinuities in wall thickness and yield stress as they act as stress risers, lead to localized deformations severe enough to result in local buckling. The effect of such discontinuities is studied using a large-scale nonlinear finite element model that simulates the reeling/unreeling of a pipeline. Nonlinear kinematic hardening is used to capture the elasto-plastic behavior of the material imposed by the bending/reverse bending history. Discontinuities in wall thickness and yield stress are shown to result in sharp local changes in curvature that extend over 3–4 pipe diameters accompanied by severe local straining and ovalization. The extent of the disturbance is governed by the bending strain imposed by the ratio of pipe to reel diameter. It can be reduced by an increase in the applied tension but at the expense of additional ovalization of the pipeline. It can also be reduced by increasing the pipe wall thickness but with the consequent increase in costs. A parametric study of the effect of such discontinuities demonstrates that for some combinations of process parameters, the disturbance can lead to local buckling either during winding or unwinding. It is concluded that a modeling framework such as the one presented should be used to generate a design protocol for reel-installed pipelines.

1. Introduction

One of the most efficient methods for installing pipelines offshore involves winding several kilometers of linepipe onto a large diameter reel mounted on a sea going vessel. The vessel travels to the offshore installation site where the pipeline is unwound and installed on the sea floor [21]. Having the pipes welded at the spooling base on land, combined with the continuity of the unwinding process and the resultant speed of installation make reeling more efficient and cost effective than the J- or S-lay methods. It is thus increasingly preferred for many pipeline, flowline, and riser projects that involve pipe diameters less than 16 inches. As a consequence of significant increase in demand, the reeling vessel fleet, which was born in the 1970s with the Chickasaw and Apache vessels [21], has undergone a huge expansion with many larger, more powerful and versatile new vessels such as the Apache II [1], Deep Blue [12], Seven Oceans [28], Seven Navica [29], Deep Energy [13] and several more that are under construction.

A significant difference between a reeled pipeline and one installed by J-lay or S-lay is that the winding/unwinding process plastically cycles the pipe. Winding a pipe of diameter D onto a reel radius ρ, as shown in Fig. 1a, results in a bending strain of

$$\varepsilon = \frac{D}{(2\rho + D)}. \tag{1}$$

For example, winding a 12.75 in. pipe on to a 324 in. (8.23 m) radius reel induces a bending strain of 1.93%. On unspooling, the line is first straightened and bent once more to a second radius on the ramp shown in Fig. 1b, before it is straightened again and reversed bent to end up at zero moment and curvature as shown in Fig. 1c. The two plastic bending cycles introduce changes to the mechanical properties (e.g., [27,33,26] and the cross sectional geometry of the pipe (e.g., [22,14,6,24] that can affect its integrity and performance during installation and operation.

One of the potential limit states of the process is bending-induced local buckling (e.g., [16,17,23,9,8]. This is avoided by appropriate choice of pipe D/t and back tension applied during

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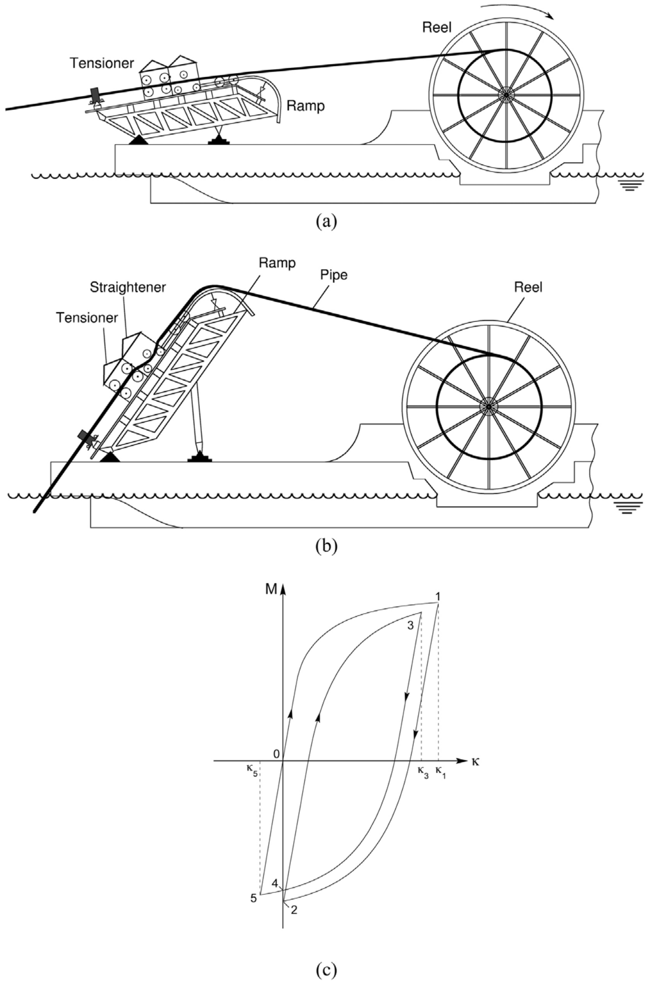

Fig. 1. Schematics showing (a) winding and (b) installation reeling vessel ramp positions. (c) Moment-curvature history induced by the process (winding [0–1], unwinding straightening [1–2], bending over ramp [2–3], straightening [3–4], reverse bending and unloading [4–5–0]).

spooling and unspooling (e.g., [4,30]. Girth welds and the associated heat-affected zones require special attention, as they tend to have somewhat different mechanical properties, and can also be flaw sensitive. Consequently, girth welds tend to received special consideration (e.g., [15,20]. In addition, variations in material yield stress between different strings of pipe and some variation along the length of a given string are unavoidable (see [3,32]. Furthermore, thickness discontinuities due to designed changes in pipe wall thickness are common. For example, in some projects thickness discontinuities result from the introduction of a thicker wall section to act as a buckle arrestor [31]. When such pipe discontinuities are reeled, they cause localized bending, ovalization and straining that can result in local buckling and, in extreme cases, rupture of the line [4,11,30,19].

This paper presents the results of a study that examines the local effects of discontinuities in pipe geometry and mechanical properties and the potential of buckling and failure. The problem is studied using a large-scale finite element framework, developed within the code ABAQUS, that includes the appropriate material, geometric and contact nonlinearities so that the effect of reeling and unreeling in the neighborhood of discontinuities can be captured (see also [25,26]. The effect of wall thickness and yield stress discontinuities of different amplitudes on the local behavior of the pipe is considered by varying the main problem parameters such as the back tension, the reel radius, and the pipe D/t.

2. Analysis

2.1. Finite element model

A 3-D model of the complete wind/unwind history is developed within the nonlinear code ABAQUS. The reel is represented as a circular rigid surface with a radius ρ. A 160*D* long section of pipeline is connected to the reel as shown in Fig. 2. The other end of the pipeline is placed between rollers that prevent vertical but allow horizontal motion of the line. A constant tension force (*T*) is applied on the LHS and the line is wound by applying incrementally a rotation, ϕ, to the reel. The pipe is unwound by reversing the direction of rotation until ϕ is back to zero while the level of the back tension is maintained.

The pipe consists of a 20*D* long starter section, a 20*D* long "test section", and a 120*D* trailing section. The the test section has a discontinuity at mid-length marked with the symbol "∨"in the figure. The pipe is assumed to deform symmetrically about the plane of bending so only half of the cross section is modeled. The whole structure is modeled with S4 shell elements. Of main interest are the stresses and deformations induced by the wind/unwind process by the discontinuity to its neighborhood. To capture this with accuracy, a finer mesh is adopted for the test section with 16 elements around the half circumference and 20 elements per diameter along the length. The other two sections have the same circumferential mesh distribution but only one element per diameter axially. The two mesh densities were arrived at from convergence studies.

The reel is modeled as an analytical rigid surface. Contact with the deformable pipe is modeled using a strict "master-slave" algorithm of ABAQUS, with the reel surface as the master and the pipe as the slave surface. The contact is frictionless but "finite sliding" is

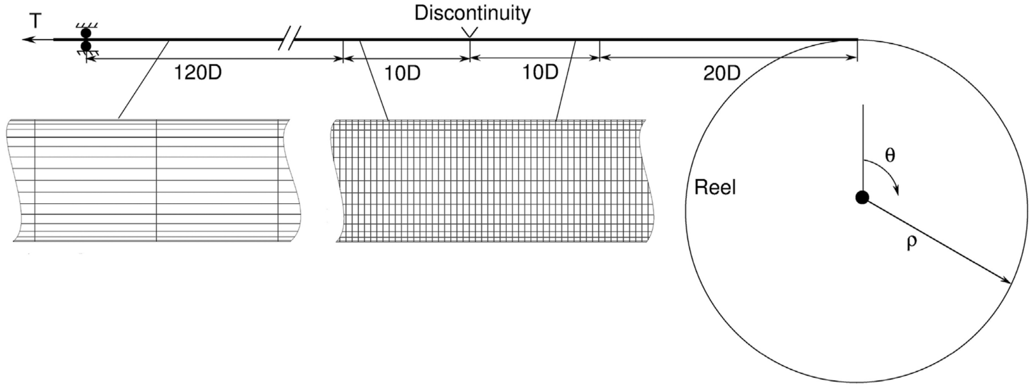

Fig. 2. Geometry of the reel/pipeline finite element model.