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Liner wrinkling and collapse of bi-material pipe under bending

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ABSTRACT

Lining internally a carbon steel pipe with a thin layer of corrosion resistant material is an economical method for protecting offshore tubulars from the corrosive ingredients of hydrocarbons. In applications involving severe plastic bending, such as in the reeling installation process, the liner can detach from the outer pipe and develop large amplitude buckles that compromise the flow. This paper outlines a numerical framework for establishing the extent to which lined pipe can be bent before liner collapse. The modeling starts with the simulation of the inflation process through which the two tubes develop interference contact pressure. Bending the composite structure leads to differential ovalization and eventually separation of part of the liner from the outer pipe. The unsupported strip of the liner on the compressed side first wrinkles and at higher curvature buckles and collapses in a diamond shaped mode. The sensitivity of the collapse curvature to the various parameters of the problem is studied, and amongst other findings the onset of collapse is shown to be very sensitive to small geometric imperfections in the liner. It is also demonstrated that bending the pipe under modest amounts of internal pressure can delay liner collapse to curvatures that make it reelable.

1. Introduction

In many offshore applications carbon steel pipe is lined internally with a thin layer of a corrosion resistant material in order to protect it from corrosive ingredients in hydrocarbons it carries during its operation. The most widely used product is assembled by inserting a slightly undersized tubular liner inside the carbon steel pipe and then mechanically expanding both so that the two tubes end up in interference contact with each other (exact steps followed differ to some degree between manufacturers – e.g., Butting Brochure; Rommerskirchen et al. (2003), de Koning et al. (2003), Montague (2004)). In offshore operations the carbon steel pipe carries most of the usual loads of internal and external pressure, tension and bending while the thin liner (2–4 mm) protects the line from corrosive ingredients in the hydrocarbons. However, in cases that involve significant plastic bending of the composite structure, such as in the reeling installation method or in lines susceptible to lateral buckling on the sea floor, the liner can detach from the outer pipe and develop large wrinkles and buckles that compromise the flow. A viable alternative is to use pipe with metallurgically "bonded" liner, commonly known as *clad pipe*, however this comes at a significant increase in cost.

Motivated by this challenge, significant efforts have been undertaken by industrial and academic researchers aimed at establishing the extent to which lined pipe can be safely plastically bent, identifying the main factors that influence liner buckling, and finding ways of delaying it. To this end, several full-scale bending experimental programs have been undertaken during the last several years. Those reported in the open literature include a series of bending results from Gresnigt and co-workers (e.g., Focke (2007), Hilberink et al. (2010, 2011), Hilberink (2011)), bending of heated lined pipe by Cladtek (Montague et al. (2010), Wilmot and Montague (2011)), repeated bending over circular shoes (Tkaczyk et al., 2011), full-scale reeling simulations by Subsea7 and Butting (e.g., Toguyeni and Banse, 2012) and others. Less developed are complementary analytical/numerical efforts reported by the same teams apparently due to the challenges of the problem. The most thorough study of the problem is due to Vasilikis and Karamanos who used FEs to analyze lined pipe under pure bending. They first considered the purely linearly elastic version of the problem (Vasilikis and Karamanos, 2010) and more recently (2012) the more realistic elastic–plastic version (See also recent results in Yuan and Kyriakides, 2013).

Collectively these efforts have contributed to the following state of current understanding of the problem. Bending to curvature levels that correspond to those seen by reeled pipe results in significant plastic deformation of both the carrier pipe and liner. Concurrently the composite structure develops Brazier-type (1927) ovalization of its cross section. This in turn can result in loss of contact and partial separation of the liner from the steel pipe. At some level of deformation, the separated section of the liner buckles into a wrinkling mode, commonly seen in pure bending of single pipe (e.g., see Ju and Kyriakides (1991, 1992), Corona et al. (2006), Kyriakides and Corona (2007), Limam et al. (2010)). As is

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common to plastic buckling of shells, wrinkling is followed by a second instability that leads to collapse of the liner in a diamond-type buckling mode (e.g., see references above and for the related plastic buckling under axial load see Tvergaard (1983), Yun and Kyriakides (1990), Kyriakides et al. (2005), Bardi and Kyriakides (2006), Bardi et al. (2006), Kyriakides and Corona (2007)).

The aim of this study is through numerical modeling to add clarity to the sequence of events that lead to liner failure, understand the major factors that influence it, and evaluate several of the methods for delaying failure that are being considered. The main expansion processes through which today's lined pipe is manufactured involve a certain amount of cold forming. This introduces changes to the mechanical properties of the two constituents, leaves behind residual stresses as well as the interference contact stress. Invariably, these changes influence the liner instabilities but to date have been mostly neglected as they tend to complicate the modeling. In the present effort this will be corrected by first simulating the mechanical expansion thus locking in the initial state. Expanded models are subsequently bent taking the structure first through liner separation from the carrier pipe, liner wrinkling, and finally liner localized collapse. The models developed will be used to study these aspects parametrically.

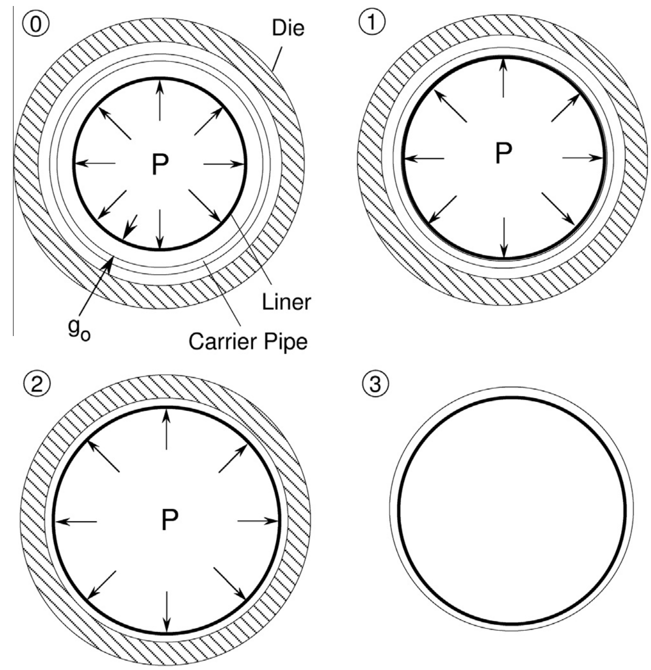

Fig. 1. Schematic representation of the expansion process through which lined pipe is manufactured (Butting brochure).

2. Modeling

2.1. Manufacture of lined pipe

Lined pipe consists of a carbon steel carrier pipe with a thin inner layer of corrosion resistant alloy liner. The two tubes are typically expanded together using one of several methods currently in the market, come into contact and remain so after unloading (e.g., Butting Brochure; Rommerskirchen et al. (2003), de Koning et al. (2003), Montague (2004)). The objective is that the finished bilayer composite ends with some interference contact pressure between the two components (often called "mechanical bonding"). The products in the market today have significant similarities but also some differences. In this study we will concentrate on the expansion process followed by Butting.

For 4–16-inch products the carrier pipe is seamless and is produced by the *plug* or *mandrel* piercing processes (e.g., see Ch. 3 Kyriakides and Corona, 2007). The 2–4 mm corrosion resistant liner (e.g., SS321, SS316L, alloy 625, alloy 825) is most often formed into a continuous longitudinally welded tube from coil. Special care is given to the metallurgical quality and integrity of the weld while also shaping its outer surface to conform to the circular shape of the steel pipe. The finished tube, cut to approximately 12 m length, is placed inside the carrier pipe whose inner surface is previously sandblasted and cleaned. A small gap (g_o) is allowed between the two pipes for ease of insertion. The two concentric pipes are then enclosed inside two semi-circular stiff dies with an ID that will result in the required final diameter of the composite (image ⓪ in Fig. 1). Hydraulic pressure is then applied to the liner causing it to expand and come into contact with the steel pipe as shown in image ①. The pressure is further increased expanding both pipes until the outer surface comes into contact with the stiff die as shown in ②. The pressure is then released causing both pipes to contract. The higher yield stress steel pipe tends to spring back more than the stainless steel liner and this results in interference contact between the two as shown in image ③.

The process was modeled both analytically and numerically treating the system as axisymmetric. Fig. 2 shows results from the FE model based on the parameters of what we designate as the *base case* given in Table 1. Fig. 2a shows the calculated pressure-radial displacement (P-w) response. Here the pressure is

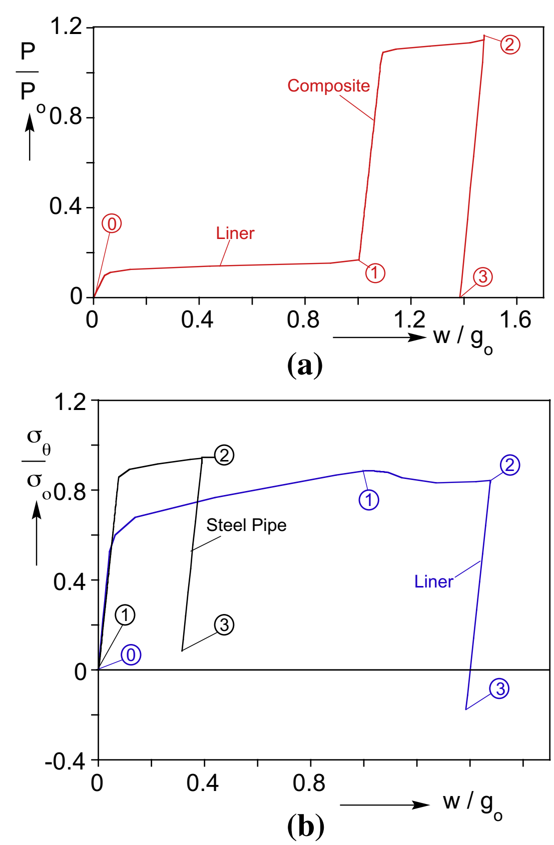

Fig. 2. (a) Pressure-radial displacement response of bi-material structure during hydraulic expansion and (b) corresponding stresses-displacement responses.

normalized by the yield pressure of the steel pipe, P_o, based on its yield stress and final dimensions; the radial displacement of the liner, w, is normalized by the initial gap g_o. Thus, between ⓪