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CONSIDERATIONS ON THE PLASTIC BUCKLING OF BI-LAYERED CYLINDRICAL SHELLS

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Abstract. The mechanical behaviour of lined cylindrical shells under bending is analysed from an experimental and a theoretical standpoint. Attention is focused on the parameters that determine the resistance to shell ovalisation and liner wrinkling. This is attained by means of a simplified analytical approach which could provide guidance to safe and economic design of lined shells and the paper describes the results obtained so far during the research..

1 INTRODUCTION

Oil and gas industry is increasingly facing the need to transport large volumes of untreated and corrosive products over long distances from the well to the processing plant. In order to reduce costs, recourse is more and more being made to lined pipes, which consist of a carbon steel load bearing outer pipe, which provides the structural capacity, and a corrosion resistant alloy (CRA) liner, protecting the carbon steel outer pipe from the transported corrosive product. The liner is mechanically fitted inside the outer pipe. Currently there is inadequate information available with which to carry out analysis of the response of a lined pipe to the application of bending, axial loading and internal net pressure and the development in the manufacturing and use of CRA lined pipes has been essentially based on heuristic and empirical approaches. On the other hand very little guidance is available from design codes.

In the present work the variables that have an influence on the mechanical behaviour of lined circular shells under bending and determine the resistance to ovalisation and liner wrinkling are identified and discussed by means of a simplified analytical approach which could provide guidance to safe and economic installation of these elements.

2 THE MECHANICS OF CRA LINED PIPES

There are two forms of pipe that are internally protected by a layer of corrosion resistant alloy (CRA): the first one is commonly called ‘clad pipe’ and the second one is known as ‘lined pipe’. The clad pipe has a layer of CRA rolled onto the carbon steel plate prior to forming the pipe. The CRA material is metallurgically intermixed with the carbon steel at the interface of the two materials and thus forms a very strong bond. On the contrary, the lined pipe has the layer of CRA material formed from a thin sheet that is bonded to the inside of the carbon steel pipe by means of mechanical processes, as shown in Figure 1.

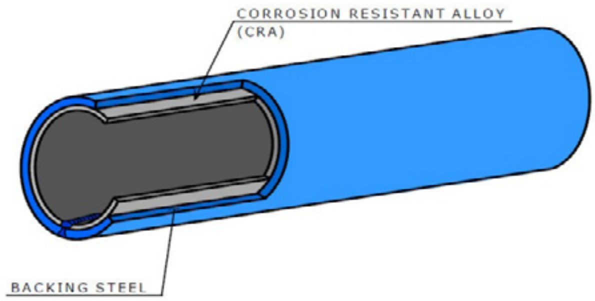

Figure 1: Sketch of a bi-layered pipe

The requirement for CRA pipes to be used for high temperature flow lines is that the pipe should be able to sustain bending deformations exceeding the material yield strain, without degradation of the CRA material and liner. Experience has shown that CRA clad pipe can sustain very large levels of bending strain whereas, on the basis of previous tests, the CRA liner in lined pipe has ‘wrinkled’, or developed local buckles at comparatively low levels of strain. This factor has limited the use of CRA lined pipe to pipelines that have low levels of temperature or which have been prevented from bending on the seabed.

However, from a theoretical standpoint there is still a certain degree of uncertainty about the variables that influence the mechanical behaviour of lined pipe during bending and the parameters that determine the resistance to pipe ovalisation and liner wrinkling. Therefore, a better understanding of the mechanics would allow a safer and more economic design of lined pipe and help to extend the field of use of the more cost-effective lined pipes in place of the clad ones.

2.1 The manufacturing method

The methods of manufacture of CRA lined pipe from various suppliers are generally similar, even if can vary in detail. The carbon steel pipe is received in a manufactured state and the inner surface is grit blasted to obtain a smooth clean surface. The CRA material is received in the form of a cold-reduced sheet wound into a coil. The sheet is cut to width and length and then formed into a cylinder by longitudinally welding the seam. The cylinder is subjected to heating to anneal the CRA and then fitted into the bore of the pipe. This operation is facilitated by manufacturing the CRA cylinder to a diameter less than the inside diameter of the pipe. The radial gap between the CRA cylinder and the bore of the pipe is controlled by the width of the CRA sheet cut from the coil and is decided purely on the basis of ease of fitting the CRA cylinder into the pipe joint. The inclusions of the radial gap is termed here as ’looseness of fit’.

The liner is expanded to the inner diameter of the pipe using a tool that is powered hydraulically and then the combined pipe and liner are expanded to a specified pressure applied to the tool. Following the expansion, the hydraulic pressure is reduced to zero and the tool is moved along the inside of the liner to expand the next section of the pipe and liner. The tool is about 3 m long so that four separate expansion operations are required for the usual 12.2 m pipe joint. The degree of expansion is generally such that the maximum hoop strain imposed on the carbon steel pipe is just less than the material yield strain.

Assuming that the CRA liner and the bore of the pipe are exactly the same, Figure 2 shows the increase of strain applied by the expansion tool. The strain-stress line for the carbon steel and the CRA follow their respective material properties up to the level of the strain specified by the hydraulic pressure applied to the expanding tool, shown by the vertical green line. When the pressure is reduced the carbon steel follows the same stress-strain line, back to A, as was followed during the initial expansion. The CRA material unloads along the elastic line but with an offset value of strain, to B. There is a residual hoop strain in the CRA which represents an ‘interference fit’ which causes a pressure between the outer surface of the liner and the inside of the pipe, i.e. the interface pressure. This pressure makes the pipe diameter to dilate a little and the liner diameter to contract a little until a common strain, somewhere between A and B is attained together with a common interface pressure. This interface pressure is the basis of the bonding of the liner with the pipe.

It may be noted from Figure 2 that the level of the interface pressure is purely a matter of the expansion strain and the respective material properties of the carbon steel and the CRA. However, as noted above, in order to assemble the CRA tube into the pipe bore, it is necessary to have looseness of fit. The radial gap is generally in the range of 3 mm to 4 mm.

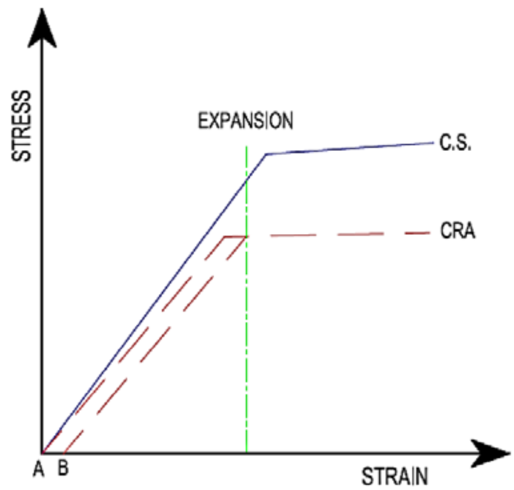

Figure 2: Diagrammatic representation of the manufacturing expansion process

Figure 3 demonstrates how the initial radial gap affects the manufacturing method. The liner effectively has an initial negative strain, compared to the zero strain of the bore of the pipe, at point A. The value of the negative strain is simply the radial gap divided by the radius of the CRA cylinder. The expanding tool first increases the diameter of the CRA cylinder until it contacts the bore of the pipe, see the dashed red line in Figure 3.

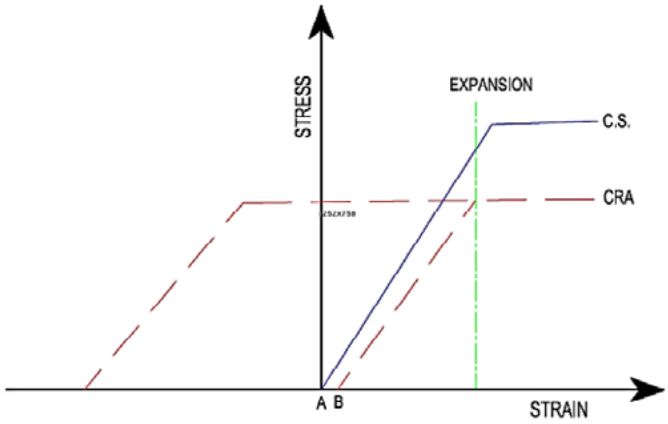

Figure 3: Diagrammatic representation of the expansion operation for an assumed level of looseness of fit

Then the combined pipe and liner is expanded by the tool up to the specified levels of strain, shown by the vertical green line. Removing the hydraulic pressure causes the liner and the pipe to reduce their respective hoop strains and an interference bond results, as in the case for no looseness of fit, although the presence of the initial radial gap can result in a lower interface pressure.

2.2 Local buckling of liner under bending

It has been observed during tests that if a lined pipe is subjected to bending, or combinations of axial forces and bending, the liner will develop wrinkles. An example of the form of the wrinkling, sometimes call ‘local buckling’, is shown in Figure 4.

Figure 4: Typical form of liner wrinkling following completion of test [1]

These localised deformations are typical of the patterns observed in lined pipes that have diameters ranging from 10-inch to 26-inch. The compressive strains at which such wrinkles are first observed in tests have generally been derived by means of finite non-linear modelling. In this manner the initiation of local deformations in the liner due to bending deformations, applied to the lined pipe at ambient temperature and pressure, and the development of these deformations into wrinkles are calculated, see Figure 5.

It can be pointed out that a comprehensive numerical modelling of such a phenomenon is rather complicated and requires, in principle, the involvement of plasticity, damage and coupling of different numerical techniques. However, in the past several studies have been conducted at the University of Naples on each of these topics (see refs. [2-7], [8-10] and [11-15], respectively) and a good understanding of the suitable theoretical and computational tools for the problem at hand is therefore available.

The primary loading applied to the model is a constant bending moment to replicate the conditions in the central region of bending tests. As a pipe subject to bending ovalises, the boundary conditions and load application methods must allow ovalisation to occur [16].

The wrinkling mechanism observed is as follows.

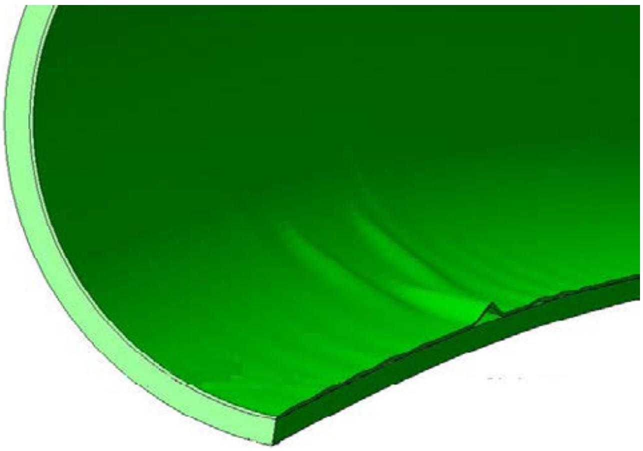

Figure 5: Example result from FE modelling, showing the liner wrinkling for bending strain =2.5%

During bending, ovalisation of the pipe and liner section occurs. The degree of ovalisation is related to the wall thickness of the section. This is primarily a geometric effect (independent of material properties) and the thin-walled liner, if it was unrestrained, would ovalise significantly. This results in a decrease in the contact pressure between the liner and pipe at the top and bottom sections of a pipe, furthest away from the neutral axis of bending, with an in-crease in contact pressure at the side. A necessary condition for wrinkling commencement is that the contact pressure reduces to zero along the compression face, although wrinkling does not necessarily occur immediately after zero pressure is attained.

It appears that the longitudinal stress levels also need to reach a critical value determined by the tangent elastic modulus from the stress strain curve. This reduces as the stress, and hence plastic strain, increases and it implies that at low strains wrinkling will not occur, even for an unsupported condition.

Very small initial imperfections are likely to have exceedingly large effects on reducing the bending strains at which wrinkling is initiated, given the well-known unstable nature of thin-walled cylinders when subjected to axial compression.

3 A SIMPLIFIED BUCKLING MODEL FOR COUPLED LAYERS

Results from basic studies of shell buckling have established that if a thin shell, such as the CRA liner, is contained within a relatively rigid boundary, the thin shell cannot buckle and develop deformations around its surface. That previous work has been presented as the theory of one-way buckling. It is concluded from this theory that the initial deformations, and later wrinkles, can occur in the liner only when the initial interface pressure has been reduced to zero and probably even when the relative radial movements of the liner and the pipe result in a gap between them, albeit the magnitude of the gap might be very small.

Following achievement of a level of axial bending strain at which the liner detaches from the pipe wall and causes a small gap between the liner and the pipe wall surfaces, the liner is free to buckle locally. In such conditions the critical stress is given by the following equation [18]

$$\sigma_{cr} = \frac{2Et_l}{D_l\sqrt{3\left(1-\nu^2\right)}} \tag{1}$$

where E is the Young's modulus, ν is the Poisson's ratio, t_l is the liner thickness and D_l is the liner diameter.

However, in the majority of practical cases the value given by equation (1) is greater than the CRA yield stress and so the local buckling needs to be calculated using the tangent modulus of the CRA instead of the elastic modulus [17]. In order to do so, an analytical description of the stress-strain relationship is required, such as the Ramberg-Osgood one

$$\varepsilon = \frac{\sigma}{E} + \left(\varepsilon_y - \frac{\sigma_y}{E}\right) \times \left(\frac{\sigma}{\sigma_y}\right)^{\beta} \tag{2}$$

σ_y and ε_y being the yield stress and the corresponding elongation, respectively. For most engineering cases it is $\beta \geq 5$.

Equation (2) gives the following expression of the tangent modulus

$$E_t \equiv \left(\frac{\partial \varepsilon}{\partial \sigma}\right)^{-1} = E\left(\frac{\sigma_y^{\beta}}{\sigma_y^{\beta} + \beta(E\varepsilon_y - \sigma_y)\sigma^{\beta-1}}\right) \tag{3}$$

and Figure 6 shows the calculated tangent modulus for a typical CRA obeying to a Ramberg Osgood material description.

By virtue of equation (3), equation (1) becomes

$$\sigma_{cr} = \frac{2E_t t_l}{D_l\sqrt{3\left(1-\nu^2\right)}} \tag{4}$$

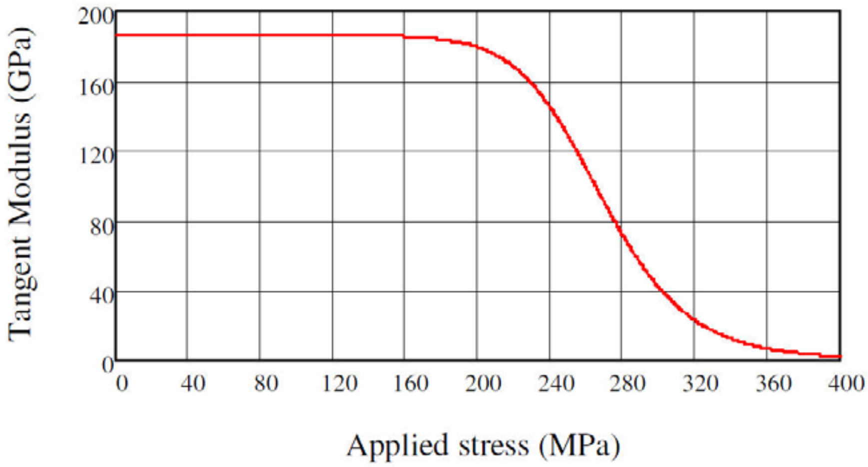

Figure 6: CRA material tangent modulus for a range of axial applied stresses

In order to analyse the detachment of the liner from the outer pipe it can be assumed that the pipe wall is a rigid surface and that all the radial deformations due to the applied axial bending strains occur only in the liner. In such a manner the ovality of the liner tends to be inhibited by the interaction of the liner with the inside of the pipe wall. However, by considering only the section of the liner at the bottom of the pipe, that is where the liner potentially could lift-off the pipe inner surface, a simplified understanding of the mechanism causing initiation of local liner deformations can be obtained.

The ovalising pressure p acting on the unit of area of the liner in the direction normal to the neutral axis, see Figure 7, can be expressed as [19]

$$p = \chi^2 E t_l y \tag{5}$$

where y is the distance from the neutral axis and the curvature, χ, is given by $\chi = M / EI$. M is the bending moment and I is the second moment of area of the composite section about its neutral axis.

Therefore, assuming a unit width of the liner at the bottom of the pipe, the equivalent pressure around the CRA tube that causes the liner to ovalise, for purely elastic material properties, can be described by

$$p = \frac{2 t_l \sigma_b \varepsilon_b}{D_l} \tag{6}$$

where σ_b is the maximum bending stress and ε_b is the bending strain.

The pipe/liner assembly must be loaded to levels of axial bending strain greater than the CRA and steel yield strains before the maximum bending conditions at the liner would enable separation of the liner and pipe surfaces. Thus, for the post-yield condition in the liner it is

$$p = \frac{2 t_l \varepsilon_b \left[\sigma_y + E_t \left(\varepsilon_b - \varepsilon_y \right) \right]}{D_l} \tag{7}$$

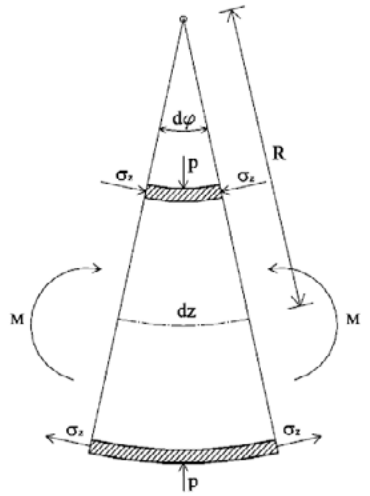

Figure 7: Axial stresses and resulting ovalising pressure

Finally, assuming that a separation is necessary between the liner and the pipe wall to enable the ignition of liner wrinkling, the equivalent radial pressure caused by the bending strain can be equated to the sum of the initial manufacturing interface pressure and the internal applied pressure and equations (4) and (7) suffice for an approximate evaluation of the problem.

Figures 8 and 9 show that the presented simplified approach has the same trend as the numerical model, but underestimates the rate of growth of the amplitude of the gap between the line and the pipe inner surface. Nevertheless, the simplified method provides confirmation of the mechanics underlying the initiation of lift-off and the growth of the gap between the liner and the pipe. Figure 10 shows plots of liner wrinkling strain versus outside diameter for experimental and calculated values.

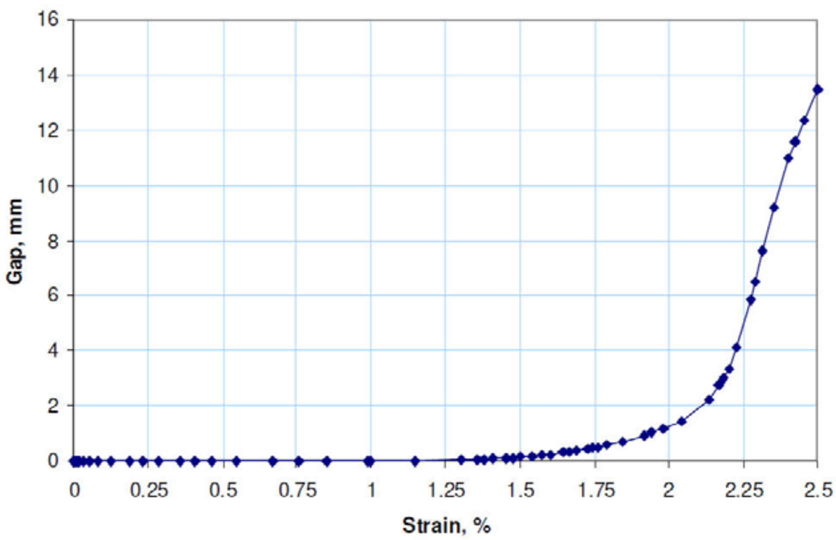

Figure 8: Plot from FE model of separation gap between liner and pipe surface for a range of strain values

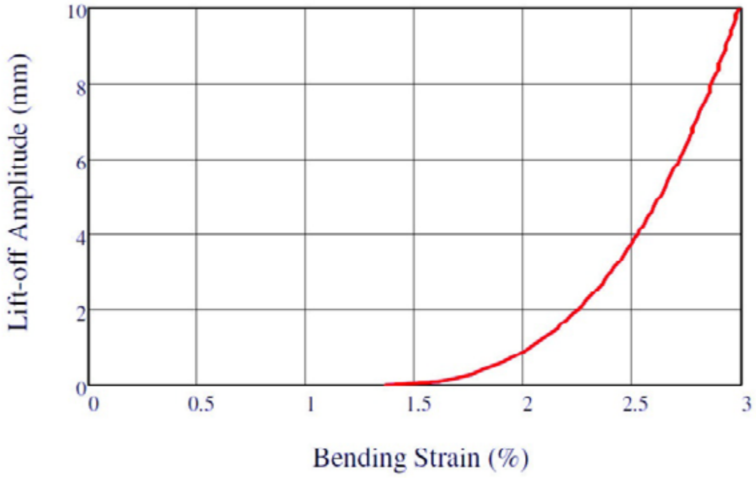

Figure 9: Development of a buckle on the liner vs. the increase in applied compressive bending strain

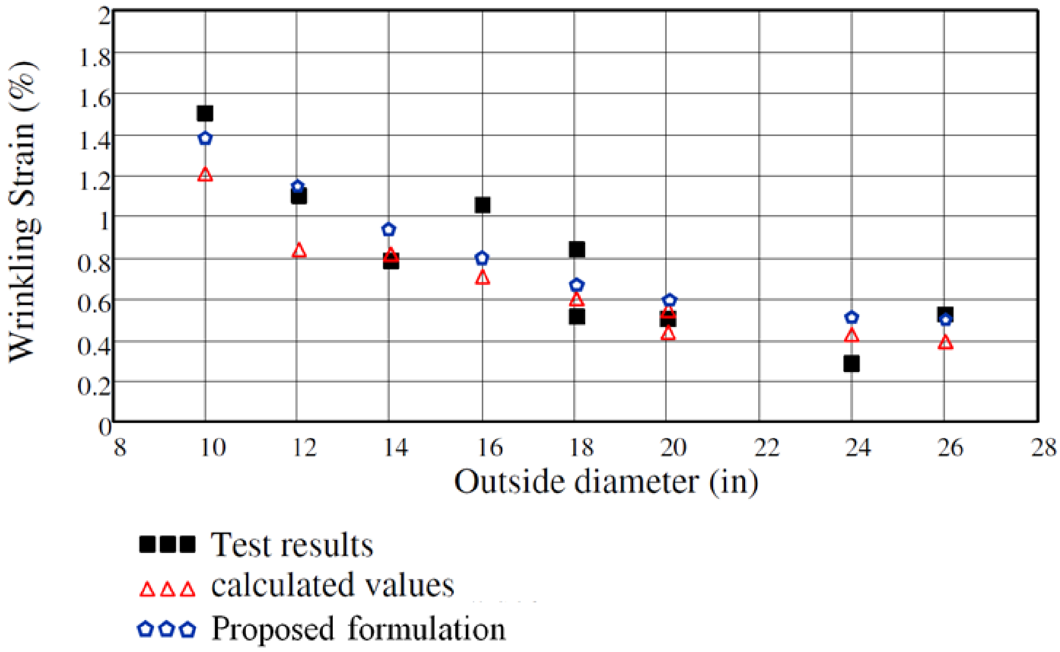

Figure 10: Plot of liner wrinkling strain versus outside diameter

4 CONCLUSIONS

From the proposed simplified analysis for a CRA lined pipe subjected to bending loads a few conclusions can be drawn.

First of all, at maximum compressive bending strain levels that are less than the CRA yield strain, the liner remains attached to the inside surface of the pipe wall, held there by the initial interface pressure. Additionally, at maximum bending strains greater than the yield strain of the liner material, the interface pressure is progressively reduced by increasing the maximum compressive bending strains; the curvature of the lined pipe under bending applies a ‘lift-off pressure’ which counters the interface pressure. Finally, further increase in the bending strains results in separation of the liner from the pipe wall at the bottom of the pipe.

Overall, it has been shown that a reasonable evaluation of the phenomenon can be attained by means of the illustrated formulae. Further theoretical investigation is currently underway at the University of Naples in the framework of a long term pipeline assessment programme [20-26].

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