



BUCKLING PROPOGATION IN CORRODED PIPE LINES CONSIDERING THICKNESS AS A RANDOM VARIABLE

Bantupalli Sravan Teja

Dept. of Civil, Pydah College of Engg. Visakhapatnam, (India)

ABSTRACT

Propagation pressure for offshore intact and corroded pipelines is calculated by Rigid Plastic Analysis based on average thickness and using thickness variation. For generating thickness it is assumed that the thickness follows uniform distribution. Further the same work is carried out using normal distribution and is found that the results can be used for any random thickness variation. Fourier Approximation is made to the thickness generated using uniform distribution to resemble practical situation. Application of using thickness variation is checked for corroded pipe and is found that it is applicable to small angular extent of corrosion with small relative depth of corrosion and large angular extent of corrosion for any relative depth of corrosion.

I. INTRODUCTION

Pipelines are widely applied means to transport oil and natural gas, which are essential fuels for the world's economy. As exploration and discoveries are moving into deeper waters, pipe lines too are being installed in ever increasing depths. Pipeline design requires dimensioning pipelines and selecting appropriate material properties, which can guarantee the pipe's ability to withstand environmental, functional and accidental loads imposed on the structure during construction, installation and operating conditions. In deepwater, pressure containment no longer remains the dominating failure mode. Its importance is superseded by local buckling and buckling propagation. Local buckling arising from external over pressure alone is called collapse . This over pressure is the maximum during installation when the pipeline is empty and not subject to any internal pressure. Design against collapse is governed by the maximum water depth the pipe will experience. Local Buckling could also occur due to a combination of external pressure, axial and bending loads. During installation, together with the external pressure load which is investigated in collapse, the pipe line is subject to bending when it takes on a catenary shape and tension from the loading vessel to maintain required shape . The combination of the three loads aggravates the local buckling problem when compared to collapse alone.

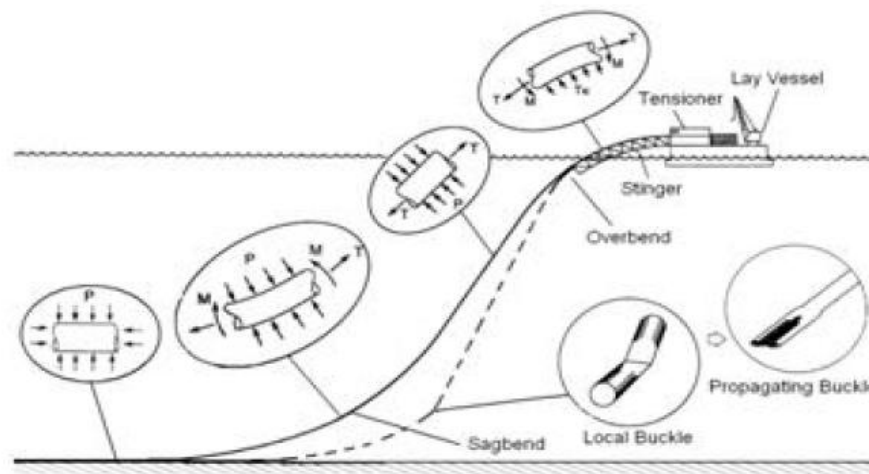


Fig .2 Buckling of an offshore pipeline during laying process (Kyriakides.S, Corona.E, 2007)

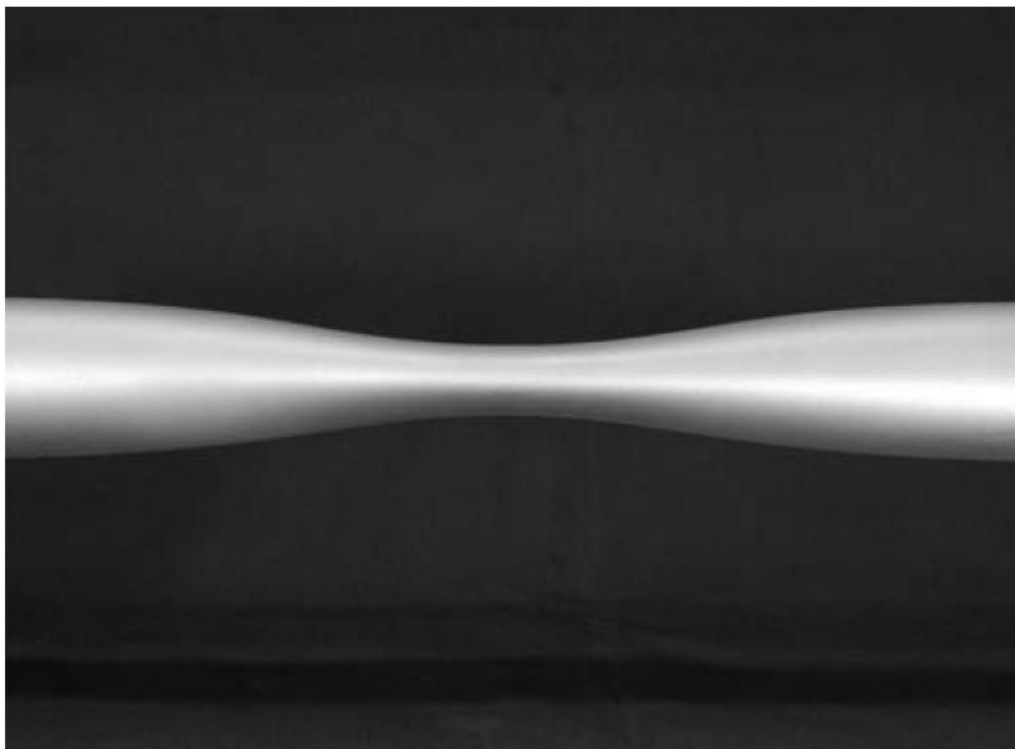


Fig 1 Collapse of an offshore pipeline (Kyriakides.S, Corona.E, 2007)

In deep waters, the most stringent requirements are dictated by buckling propagation. This phenomenon initiates upon formation of a local buckle during installation or operation and propagates along the pipeline to a point where the external pressure is less than the pipeline's propagation pressure. There will be a gradual change from unbuckled region to the buckled region as shown in Fig . During operation buckle may form due to dropped object or impact by an anchor or so. The schematic diagram of this is shown in below fig.. The buckling propagation pressure is the lowest pressure required to propagate a buckle under steady-state or quasi-static conditions. Design to resist this failure mode requires exorbitant values of wall thickness which would

render projects far too costly. This failure mode is therefore controlled by inserting buckle arrestors. These thicker sections of pipe limit the buckle's travel by preventing it from crossing over.

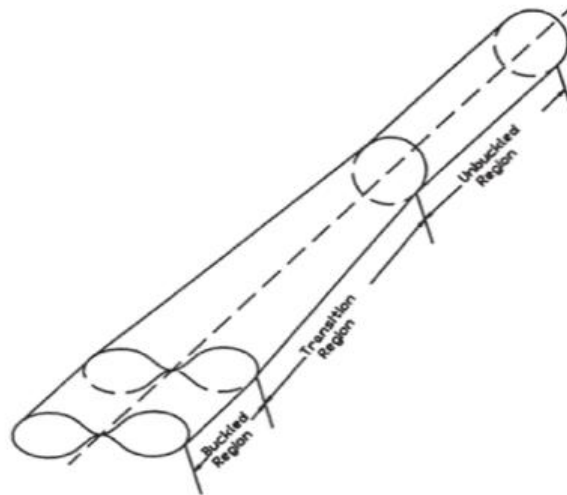


Fig .3 Schematic diagram of Propagating buckle (Michelle S. Hoo Fatt, 2001)

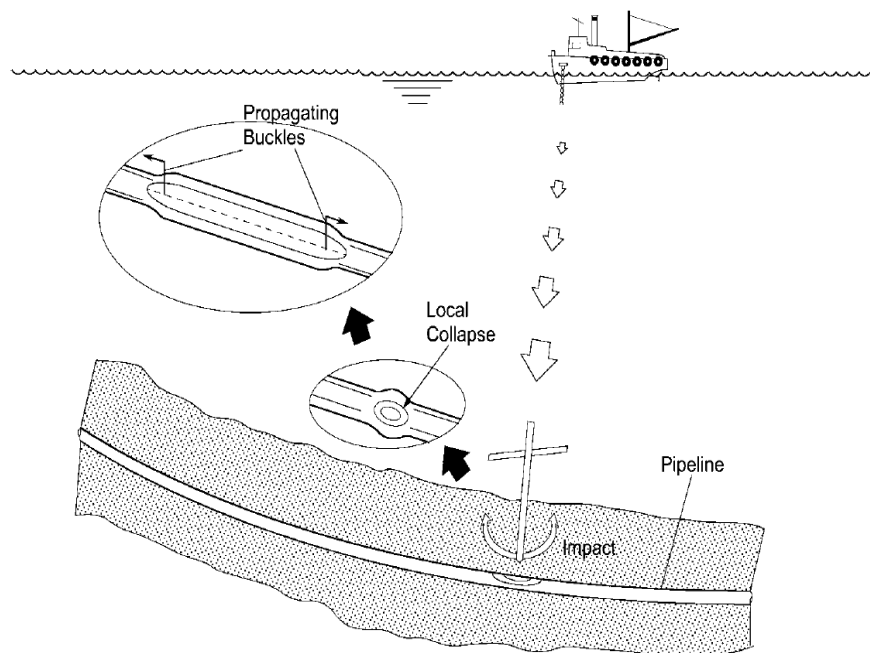


Fig 4 Buckling propagation in a pipeline due to impact by an anchor (Kyriakides.S, Corona.E, 2007)

II. PROBLEM DESCRIPTION

Pipeline consist varying thickness around circumference and along longitudinal direction as discussed previously. Analyzing such a problem is very complicated. So, in this study the thickness is considered as constant along the length of the pipeline. This simplifies the problem from three dimensional to two

dimensional. Corrosion is also considered as uniform along the length of the pipeline. Detailed description of corroded pipe is given in section .

III. INTACT PIPE

As explained earlier in seamless pipe inside surface is generally smooth as surface of the piercer cylinder used to pierce through billet is smooth. But the outside surface is irregular due to uneven heating and rolling. This results in thickness variation in cross section and along the length. To simplify the problem same thickness variation is assumed at all cross sections. Solutions obtained from such assumption will yield conservative estimates of failure load. The pipeline is assumed to be in a state of plane strain. Cross-sections in the pipeline perpendicular to the longitudinal axis of the pipeline remain plane. The pipeline is considered to be composed of ring elements. Stresses in a ring element of the pipeline do not interfere with the deformation of the adjacent ring elements. Therefore, one can analyze the deformation of the ring element to approximate the collapse of the pipeline.

IV. CORRODED PIPE

The corroded pipeline is modeled as a non-uniform, infinitely long cylindrical shell with a cross-section as shown in Fig 2.1. The non-uniform shell is divided into two regions. Region 1 has a thickness of $t - c$ and is subtended by an angle of 2β where t is the average thickness of the shell, c is the thickness reduction and β is the angular extension of the non-uniformity. Region 2 has a thickness of t with angular extension of $2(\pi - \beta)$. The thickness is symmetric about the circumferential neutral surface of the shell in both Regions 1 and 2.

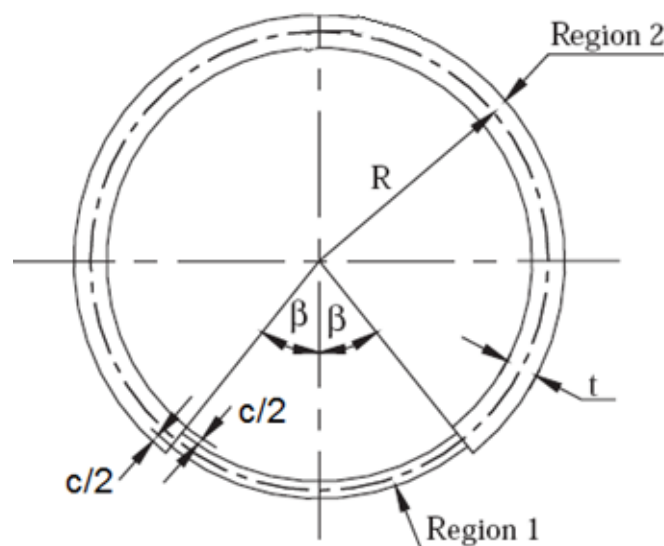


Fig. 5 Cross section of corroded pipe

In order to simplify the problem, the corroded region is assumed to be the same throughout the entire length of the pipeline. All other assumptions are same as that of the intact pipe.



Rigid plastic analysis is used to find the propagation pressure in both intact and corroded pipes. In the analysis, the material of the corroded pipeline is idealized as perfect, rigid plastic. Four plastic hinges are used to approximate the collapse mechanism of the corroded pipeline. Plastic work dissipated in the pipeline is calculated from a ring collapse mechanism due to circumferential bending at the four plastic hinges. For the intact pipe the mode of buckling is anti-symmetric. In corroded pipe both symmetric and anti-symmetric modes are possible. For both symmetric and anti-symmetric modes, the principle of virtual work and upper bound theory are used to find the buckle propagation pressure.

When small angular deformation $\Delta\phi$ is given as shown in fig 6, the change in angle between the lines joining the plastic hinges at each hinge can be found using the geometry of the figure. According to energy theorem, external virtual work is equal to plastic energy dissipated in pipe.

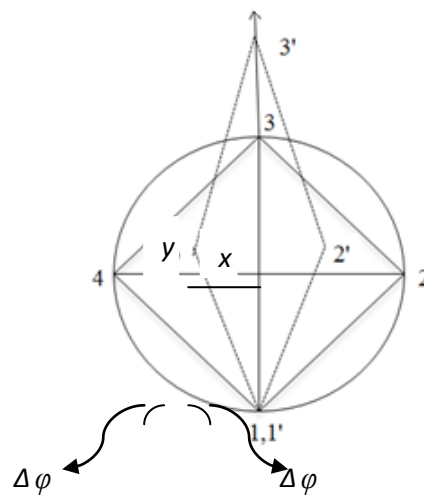


Fig. 6 Deformed shape of intact pipe

In mathematical form

$$P\Delta A = \sum M_i |\Delta\theta_i| \tag{3.1}$$

where

P is external pressure,

ΔA is change in area enclosed by lines joining plastic hinges ,

M_i is plastic moment at hinge i ,

$\Delta\theta_i$ is change in angle between lines joining plastic hinges at hinge i ,

θ_i is initial angle between lines joining plastic hinges at hinge i ,

θ_i' is final angle between lines joining plastic hinges at hinge i .

Initially the lines joining hinges are at right angles. So,

$$\theta_1 = \theta_2 = \theta_3 = \theta_4 = \frac{\pi}{2}$$



From the geometry of the Fig.3.2

$$\theta_1' = \theta_1 - 2\Delta\varphi \Rightarrow \Delta\theta_1 = 2\Delta\varphi$$

$$\theta_3' = \theta_1' = \theta_1 - 2\Delta\varphi = \theta_3 - 2\Delta\varphi \Rightarrow \Delta\theta_3 = 2\Delta\varphi$$

$$\theta_2' = \theta_4'$$

$$2\theta_2' + 2\theta_1' = 360$$

$$\theta_2' = 180 - \theta_1' = 180 - [\theta_1 - 2\Delta\varphi]$$

$$= 180 - 90 + 2\Delta\varphi = 90 + 2\Delta\varphi$$

$\Delta\theta_2'$ is the difference between θ_2' and θ_2 , $\Delta\theta_2' = \Delta\theta_4'$ (from Fig. 3.2)

$$\Delta\theta_2' = \theta_2' - \theta_2 = -2\Delta\varphi$$

$$\Delta\theta_2' = \Delta\theta_4' = -2\Delta\varphi \text{ and } \theta_1' = \theta_3' = 2\Delta\varphi \tag{3.2}$$

$$\text{Plastic moment, } M = \sigma_0 \frac{t}{2} \frac{t}{2} = \sigma_0 \frac{t^2}{4} \tag{3.3}$$

where, σ_0 is the average flow stress given by

$$\sigma_0 = \frac{1}{\varepsilon_{avg}} \int_{\varepsilon_y}^{\varepsilon_{avg}} \sigma d\varepsilon$$

where, $\sigma = E\varepsilon$ for $\varepsilon < \varepsilon_y$

$$= \sigma_y \left[\frac{En}{\sigma_y} \varepsilon + 1 - n \right]^{\frac{1}{n}} \text{ for } \varepsilon > \varepsilon_y$$

Substitute σ in σ_0 and integrate



$$\begin{aligned} \sigma_0 &= \frac{1}{\varepsilon_{avg}} \int_{\varepsilon_y}^{\varepsilon_{avg}} \frac{\sigma_y \left(\frac{nE}{\sigma_y} \right)}{\left(\frac{nE}{\sigma_y} \right)} \left[\frac{En}{\sigma_y} \varepsilon + 1 - n \right]^{\frac{1}{n}} d\varepsilon \\ &= \frac{1}{\varepsilon_{avg}} \frac{\sigma_y^2}{nE} \frac{1}{1 + \frac{1}{n}} \left[\frac{En}{\sigma_y} \varepsilon + 1 - n \right]^{\frac{1}{n} + 1} \\ &= \frac{\sigma_y \varepsilon_y}{\varepsilon_{avg} (1+n)} \left\{ \left[\frac{En}{\sigma_y} \varepsilon_{avg} + 1 - n \right]^{\frac{1}{n} + 1} - \left[\frac{En}{\sigma_y} \varepsilon_y + 1 - n \right]^{\frac{1}{n} + 1} \right\} \\ \sigma_0 &= \frac{\sigma_y \varepsilon_y}{\varepsilon_{avg} (1+n)} \left\{ \left[\frac{En}{\sigma_y} \varepsilon_{avg} + 1 - n \right]^{\frac{1}{n} + 1} - 1 \right\} \end{aligned} \tag{3.4}$$

Strain can be calculated as

$$\varepsilon = \frac{\partial u}{\partial x} + z \frac{\partial^2 w}{\partial x^2} \approx z \frac{\partial \theta}{\partial x} \quad \because \text{Angular extension is neglected}$$

$$\varepsilon = z \frac{\Delta \theta}{2t}$$

The extreme strain

$$\varepsilon_{\max} = \frac{t}{2} \frac{\Delta \theta}{2t} = \frac{\Delta \theta}{4}$$

The average strain is obtained as

$$\varepsilon_{\text{avg}} t = 2 \left(\frac{1}{2} \times \frac{t}{2} \times \varepsilon_{\max} \right) = \frac{\Delta \theta}{8} t$$

$$\varepsilon_{\text{avg}} = \frac{\Delta \theta}{8}$$



$$\sigma_0 = \frac{8\sigma_y \varepsilon_y}{\Delta\theta(1+n)} \left\{ \left[\frac{En}{\sigma_y} \left(\frac{\Delta\theta}{8} \right) + 1 - n \right]^{\frac{1}{n}+1} - 1 \right\}$$

Here, at all the hinge points, $\Delta\theta=2\Delta\phi$ is the same, thereby making σ_0 same at all the hinges. Hence their corresponding moments are also the same.

Normalized propagation pressure : Normalized propagation pressure is defined as ratio of propagation pressure of corroded pipe to that of the intact pipe. It is denoted by the symbol η .

$$\eta = \frac{P_P}{P_{PI}}$$

where P_P is the propagation pressure of corroded pipe.

P_{PI} is the propagation pressure of intact pipe.

V. RESULTS USING THICKNESS VARIATION

Initially thickness is generated assuming that it follows uniform distribution between allowable tolerances. In this formulation the constant (average) radius is used. But in reality radius also changes, to demonstrate this, in next formulation radius is also considered as variable. The same procedure is repeated again by assuming the variables (thickness and radius) follow normal distribution. Then finally a Fourier approximation is made to the thickness developed using uniform distribution to represent the thickness as a function of θ (circumferential position). Then by using this $t(\theta)$ propagation pressure is calculated. Detailed explanation about these procedures, their application to the problem previously considered and comparison is given in subsequent sections of this chapter. As mentioned in Table 1.1, DNV code allows $\pm 12.5\%$ variation from average thickness for $t \geq 10$ mm. In the present case as $t = 18.29$ mm, thickness can vary from 16.004 mm to 20.576 mm. Assuming that thickness follows uniform distribution between these limits, t is generated. A brief description of the procedure is given below.

Cumulative distribution function of the uniform distribution is

$$C = \int_a^t \frac{1}{b-a} dt$$

Where a and b are upper and lower limits of the distribution respectively and C is cumulative distribution function which varies from 0 to 1. In the present case

$$a = 16.004 \text{ mm}$$

$$b = 20.576 \text{ mm}$$

On integrating Eqn(5.1) and rearranging the terms

$$t = C(b-a) + a$$

Case 1 (Using Random t and average R)



By taking required number of terms, C can be divided into corresponding number of intervals between 0 and 1, and for each C corresponding t can be found using Eqn(5.2) and is shown in Fig.5.1. Then the square of the average thickness in Eqn(3.5) is replaced by average of squared thickness. In other words, the average thickness is replaced by its Root Mean Square (RMS) value. Here radius is treated as constant and average R is used.

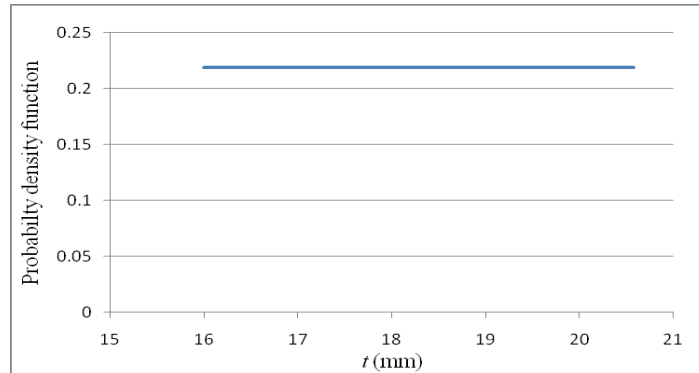


Fig. 5.1 Thickness variation using Uniform Distribution

VI. OBSERVATIONS

1. Propagation pressure decreases with increase in both β and c/t values. But the rate of decrease is slow with increase in β when compared to that of c/t .
2. As the angular extension of corrosion increases Anti-Symmetric mode dominates. This phenomenon is expected as β reaches 180° the pipe is again an intact pipe with reduced thickness throughout which buckles in Anti-Symmetric mode only.
3. Present values are compared with the values published by Jianghong Xue (2005). Small difference is observed because in the present work, the average flow stress is taken different at different hinges which is more accurate.
4. With increase in angular extension of corrosion the propagation pressure decreases. For higher depth of corrosion (c/t value) the decrease in propagation pressure is very rapid

VII. CONCLUSIONS OF WORK

1. For all values of β normalized propagation curves approximately follows the line joining the points (0, 1) and (1, 0). The mathematical equation of the line can be represented as " $\eta + c/t = 1$ ". By using this equation an approximate value of propagation pressure can be found out.
2. The minimum required number of readings to find the propagation pressure accurately is 360 for both intact and corroded pipe line.
3. Average radius of the middle surface can be taken as constant when thickness is considered as random.
4. For any given thickness variation of a corroded pipe Fourier approximation can be made and propagation pressure can be found using the propagation pressure formula for intact pipe by replacing t^2 by $\frac{1}{2\pi} \int_0^{2\pi} [t(\theta)]^2 d\theta$.

5. Calculating propagation pressure using thickness variation is especially useful for practical purpose where the angular extension and relative depth of corrosion is small like pitting corrosion and for the case when the angular extension of corrosion is large like erosion.
6. As the difference between propagation pressures calculated using normal distribution and using uniform distribution is very small, calculation of propagation pressure using thickness variation can be applied to any real situation even though it is checked here only for uniform distribution.

VIII. SUGGESTION FOR FUTURE WORK

1. Unsymmetric corrosion can be considered and applicability of using thickness variation for calculating propagation pressure can be studied which is more realistic
2. Three dimensional models of thickness variation can be formed and effect on buckling propagation pressure can be studied

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