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Subsea FRP pipeline performance in external pressure: Failure and external pressure-induced buckling

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Abstract. The Subsea pipelines are subjected to high hoop stresses due to the hydrostatic pressure. When the internal pressure of the liquid has a higher value than the external hydrostatic one, there is a balance of the tensile and compressive stresses. However, during the offshore installation, the subsea pipelines are empty and the compression due to the hydrostatic pressure of the sea is predominant. High compressive stresses in FRP pipelines can cause failure or buckling. In the present work, an investigation of the external pressure-induced failure and buckling is carried out. Analytical formulae and results are provided and discussed.

1. Introduction

In the last decade FRP materials are often used in offshore applications as pipelines conveying oil or oil products, or as wrapping materials to strengthen corroded joints of steel pipelines. Although the FRP pipelines have superior strength than the carbon steel ones, their light weight is a shortcoming for offshore applications because of the high buoyancy. However, nowadays weights are hanged along the pipelines (Figure 1) that help their installation.

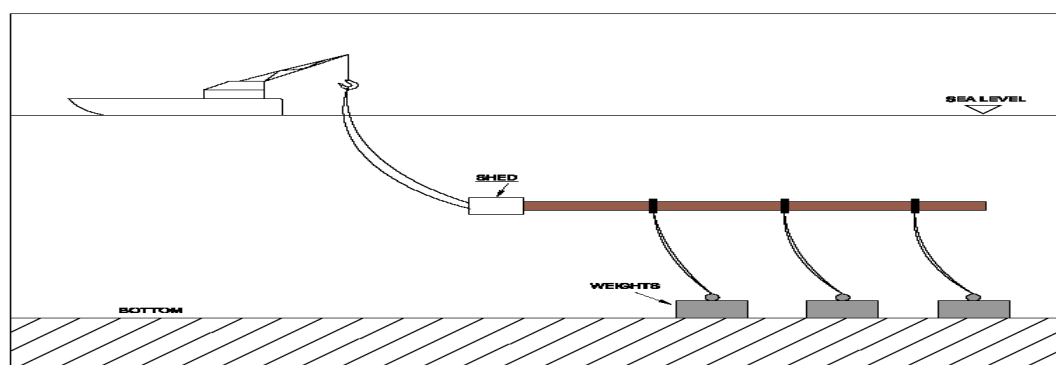


Figure 1. Installation of subsea FRP pipelines



During the installation process the subsea pipelines are empty. Therefore, they are subjected to high hydrostatic pressure that causes compressive hoop stress. Apart from failure, the external pressure may cause buckling [1-4].

Since FRP materials are anisotropic, the calculation of the hoop stresses and especially the critical buckling pressure is much more difficult than the ones in carbon steel pipelines. Although the global and local buckling has been investigated extensively for steel structures and components [5-8], there are not many works on buckling of multilayered FRP materials. Generally, only few monographs [9] and papers [10-13] have been published on composite materials in piping applications.

In the present work the hoop stress of multilayered FRP pipelines under external pressure are calculated. With the aid of Tsai-Wu failure criterion [14-16], the capacity of subsea E-Glass/Epoxy [17] pipelines is provided for several stacking sequences of the laminated material. Practical nomographs [9] for estimating the critical external pressure causing buckling are derived with the aid of a formula borrowed by the ref. [18] for the same pipelines.

2. Formulation of the problem

2.1 Failure analysis

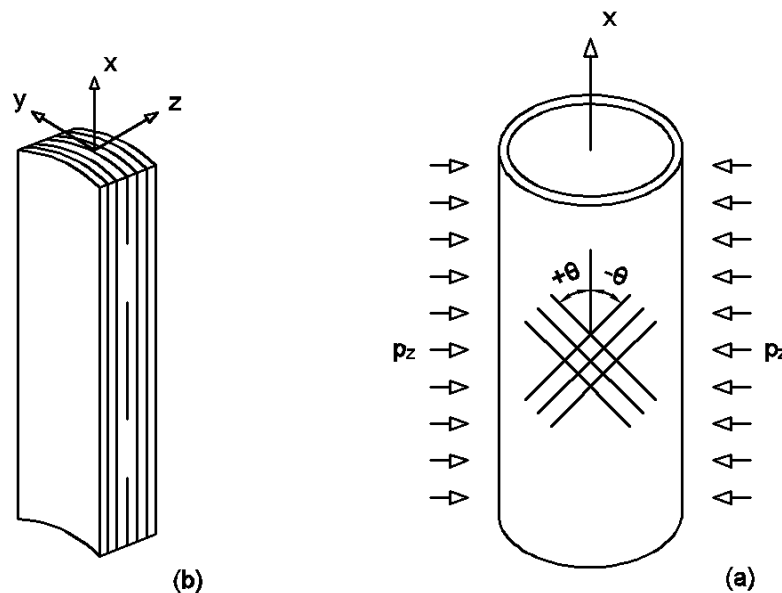


Figure 2. Geometry of the problem

The long pipe under consideration (Figure 2) with diameter D , thickness h , stacking sequence, is subjected to external pressure p_z . The first check to ensure its tolerance for this kind of loading should be based on failure analysis. The maximum allowable external pressure satisfying the selected failure criterion can be determined by the procedure shown in Figure 3.

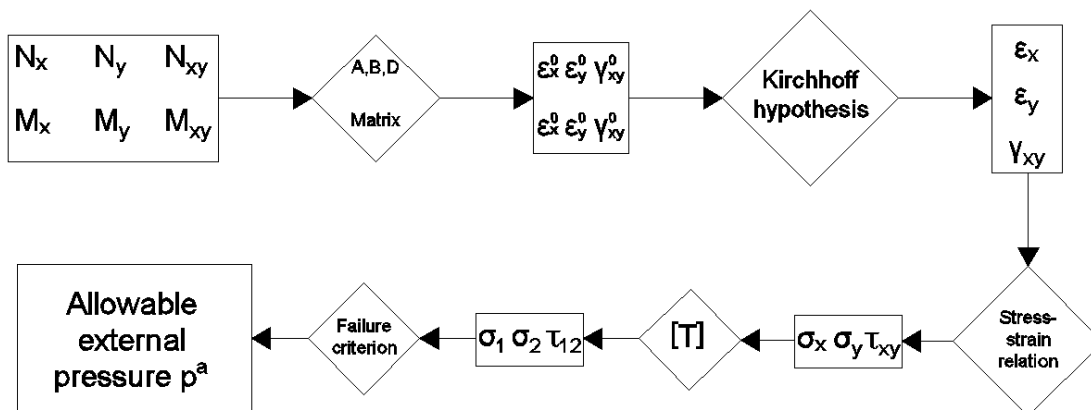


Figure 3. Procedure for estimation of allowable external pressure p^a

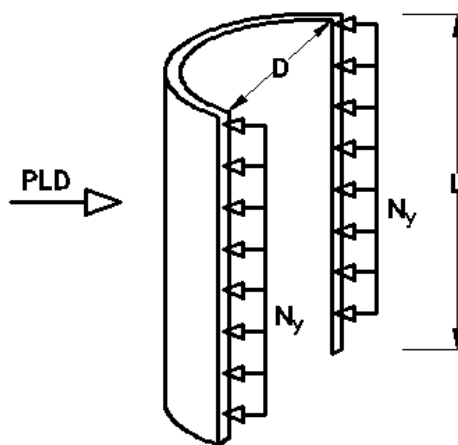


Figure 4. Equilibrium of a half pipe

In order to determine the external forces acting to the pipe’s wall, the equilibrium equation of the half pipe shown in Figure 4 should be used:

$$2N_y L = pDL \tag{1}$$

or

$$N_y = \frac{1}{2} pD \tag{2}$$

Because of the absence of external loads in directions x and x_y , N_y is the only load acting on the laminate. Therefore:

$$N_x = 0 \tag{3}$$

$$N_{xy} = 0 \tag{4}$$

$$M_x = 0 \tag{5}$$

$$M_y = 0 \tag{6}$$

$$M_{xy} = 0 \tag{7}$$

Taking into account above equations as well as the inverse ABD matrix, it can be written:

$$\varepsilon_x^0 = a_{12} N_y \quad (8)$$

$$\varepsilon_y^0 = a_{22} N_y \quad (9)$$

$$\gamma_{xy}^0 = a_{26} N_y \quad (10)$$

$$\kappa_x^0 = b_{21} N_y \quad (11)$$

$$\kappa_y^0 = b_{22} N_y \quad (12)$$

$$\kappa_{xy}^0 = b_{26} N_y \quad (13)$$

Therefore:

$$\varepsilon_x = \varepsilon_x^0 + z \kappa_x^0 \quad (14)$$

$$\varepsilon_y = \varepsilon_y^0 + z \kappa_y^0 \quad (15)$$

$$\gamma_{xy} = \gamma_{xy}^0 + z \kappa_{xy}^0 \quad (16)$$

With the aid of Eqs (14)-(16), the stress-strain relation provide the stresses σ_x , σ_y , τ_{xy} for every ply:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = [\bar{Q}_{ij}(\theta)] \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \quad (17)$$

Using the matrix $[T(\theta)]$, the principal stresses σ_1 , σ_2 , τ_{12} can be obtained by the following well known equation:

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} = [T(\theta)] \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} \quad (18)$$

Using Equation (18), the Tsai-Wu failure criterion for every ply yields the allowable value p^a of the external pressure. Since the Tsai-Wu is a second order algebraic equation, we are going to obtain two values of p^a for every ply. From the derived different values of p^a , the minimum one should be adopted in order to cover all cases.

2.2 Buckling model

A long pipe with mean diameter D is made by a multi-layered laminate with stacking sequence $[\pm\theta]$. According to ref. [18], the critical buckling pressure can be estimated by the relation:

$$p_{cr} = 3 \left[\frac{A_{ani} D_{ani} - B_{ani}^2}{A_{ani} (D/2)^3 + 2B_{ani} (D/2)^2 + D_{ani} (D/2)} \right] \quad (19)$$

In the above equation the parameters A_{ani} , B_{ani} , D_{ani} can be obtained by the following matrix equation:

$$\begin{bmatrix} A_{ani} & B_{ani} \\ B_{ani} & D_{ani} \end{bmatrix} = \begin{bmatrix} A_{22} & B_{22} \\ B_{22} & D_{22} \end{bmatrix} - [L_1]^T [L_2]^{-1} [L_1] \quad (20)$$

where,

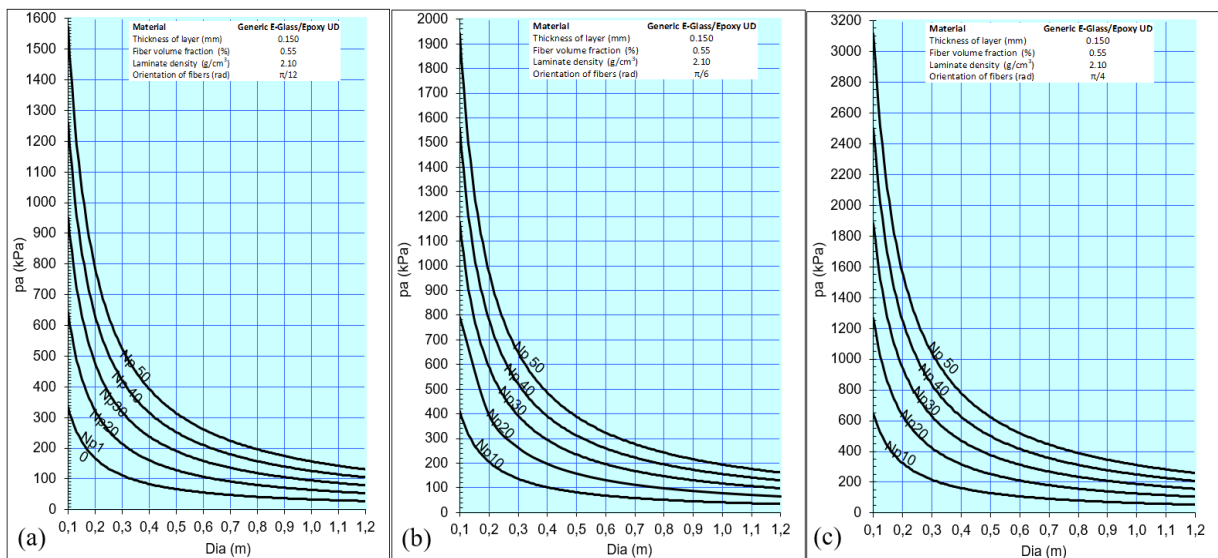
$$[L_1] = \begin{bmatrix} A_{12} & B_{12} \\ A_{26} & B_{26} \\ B_{12} & D_{12} \\ B_{26} & D_{26} \end{bmatrix} \tag{21}$$

$$[L_2] = \begin{bmatrix} A_{11} & A_{16} & B_{11} & B_{16} \\ A_{16} & A_{66} & B_{16} & B_{66} \\ B_{11} & B_{16} & D_{11} & D_{16} \\ B_{16} & B_{66} & D_{16} & D_{66} \end{bmatrix} \tag{22}$$

3. Results and discussion

Taking into account the model for external pressure, the allowable external pressure p_a has been estimated for pipes made by E-Glass/Epoxy (Figure 5). In the following diagrams are demonstrated the allowable values p_a for pipes of diameter: $Dia= 0.10 \text{ m} - 1.20 \text{ m}$ constituting by plies of thickness 0.150 mm , fiber orientation $\theta = \pm 15^\circ, \pm 30^\circ, \pm 45^\circ, \pm 60^\circ, \pm 75^\circ$ for number of plies $NP=10 - 50$.

Using the buckling model for external pressure, the critical pressure P_{cr} have been estimated for pipelines made by E-Glass/Epoxy (Figure 6). In the following curves, p_{cr} is demonstrated for pipes of diameters $Dia= 0.10 \text{ m} - 1.20 \text{ m}$ constituting by plies of thickness 0.150 mm , fiber orientation orientation $\theta = \pm 15^\circ, \pm 30^\circ, \pm 45^\circ, \pm 60^\circ, \pm 75^\circ$ number of plies $NP=10, 20, 30, 40, 50$.



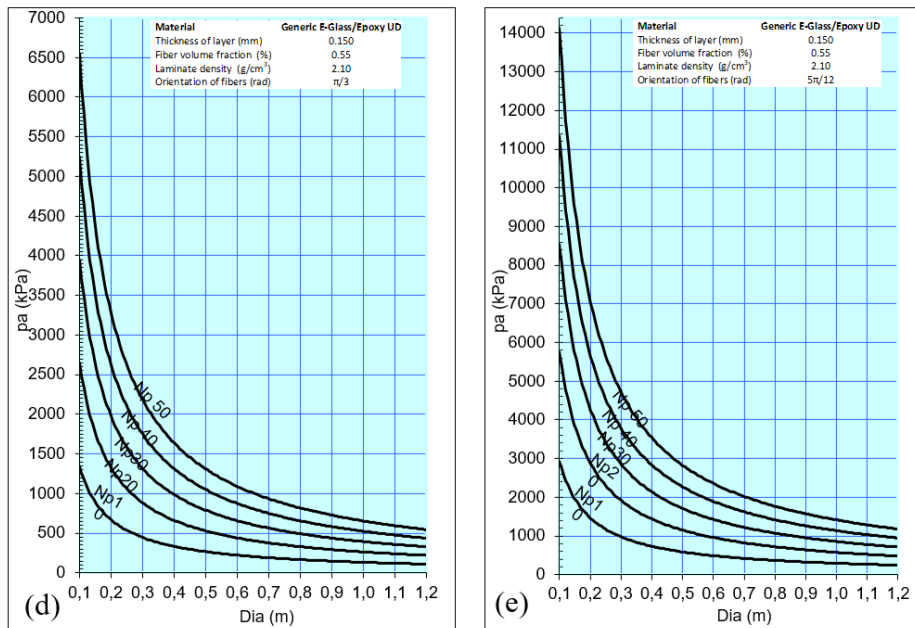
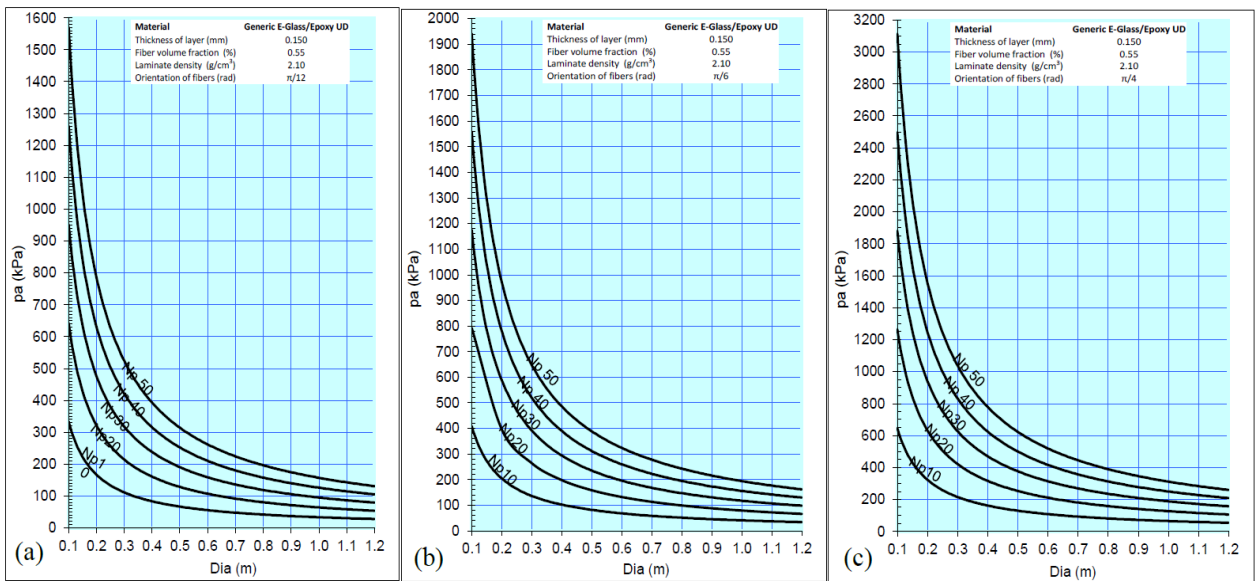


Figure 5. Bending allowable external pressure for FRP pipelines made by E-Glass/Epoxy



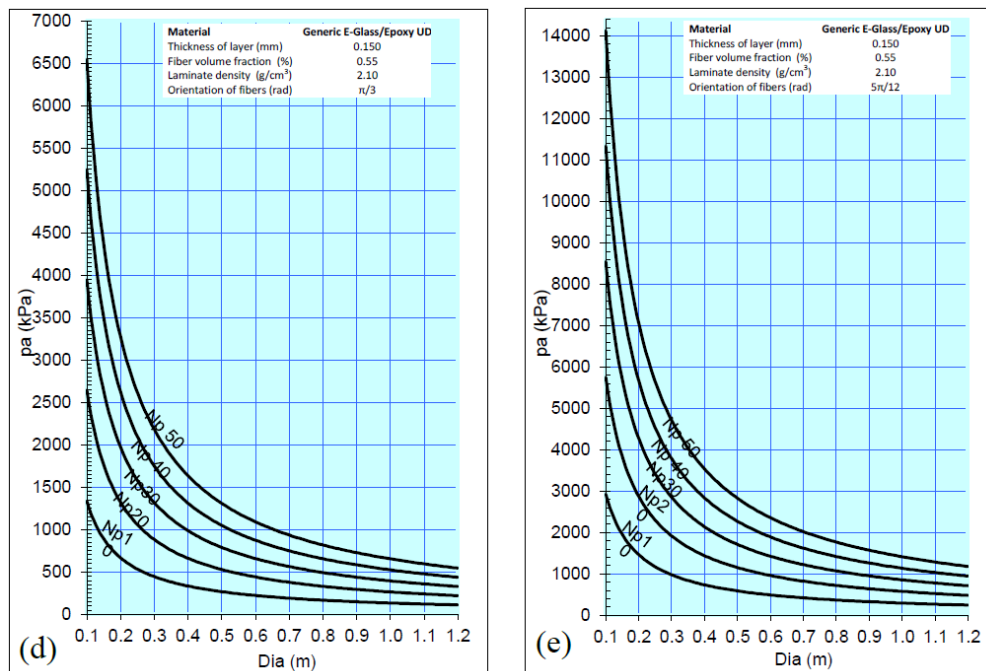


Figure 6. Critical external pressure for FRP pipelines made by E-Glass/Epoxy

4. Conclusions

1. In the present work, the external pressure-induced failure and buckling of subsea FRP pipelines is analyzed.
2. With the aid of the classical lamination theory for stresses of anisotropic materials, and a buckling model borrowed by the bibliography, theoretical tools for designing purposes are proposed.
3. Unlike existing commercial software packages, the proposed analytical models are advantageous because they provide accurate results.
4. Implementation of the model on typical multilayered FRP pipelines made of E-Glass/Epoxy material has been carried out and useful nomographs for quick estimation of the performance of FRP subsea pipelines are provided.

References

- [1] Bai Y and Bai Q 2005 *Subsea pipelines and risers*, Elsevier.
- [2] Reddy D V and Swamidas A S J 2014 *Essentials of offshore structures*, CRC press.
- [3] Flügge W 1973 *Stresses in shells*, Springer-Verlag.
- [4] Timoshenko S P and Gere J M 2009 *Theory of elastic stability*, Dover publications.
- [5] Kollar L and Dulacsha E 1984 *Buckling of Shells for Engineers*, Wiley.
- [6] Jullien J F 1991 *Buckling of Shell Structures on Land in the Sea and in the Air*, CRC Press.
- [7] Smirnov A L and Tovstik P E 2001 *Asymptotic Methods in the Buckling Theory of Elastic Shells*, World Scientific Publishing Company.
- [8] Litle W A 1964 *Reliability of Shell Buckling Predictions*, The MIT Press.
- [9] Pavlou D G 2013 *Composite Materials in Piping Applications*, Destech publications.
- [10] Pavlou D 2020 *Inner flow-induced buckling of FRP catenary risers*. Journal of Offshore Mechanics and Arctic Engineering. **142**(6), 1-28.
- [11] Pavlou D 2019 Curved fibre-reinforced-polymer risers: inner-flow-induced dynamic instability analysis. Proceedings of the Institution of Civil Engineers : *Maritime Eng*, **172**(4), 133-147.
- [12] Pavlou D 2018 Design aspects of joints, supports and U-shaped expansion loops for pipelines

- made of composite materials. "Science and technologies of pipeline transportation of oil and oil products, **8**(5), 522-29 (in Russian).
- [13] Pavlou D 2018 Flow-Riser Interaction in Deep-Sea Mining: An Analytic Approach for Multi-Layered FRP Risers. In ASME 2018 37th *Int Conf on Ocean, Offshore and Arctic Engineering* - vol **7B: Ocean Eng** ASME Press, ISBN 978-0-7918-5127-2.
- [14] Reddy J N 2004 *Mechanics of laminated composite plates and shells*, CRC press.
- [15] Tsai S W and Wu E M 1971 A general theory of strength for anisotropic materials, *J Compos Mater* **5**, 58-80.
- [16] Kollár L P and Springer G S 2003 *Mechanics of composite structures*, Cambridge University Press.
- [17] Berenberg B <http://composite.about.com>
- [18] Rasheed H A and Karamanos S A 2008 Stability of tubes and pipelines, in: *Buckling and Postbuckling Structures*, edited by Falzon B.G. and Aliabadi M.H., Imperial College Press.