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Analytical prediction for lateral buckling of tensile wires in flexible pipes

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ABSTRACT

The development of oil and gas fields in deepwater challenges the design of flexible pipes due to high pressures, temperatures and dynamic loads. Amongst the known failure modes, lateral buckling of tensile armor layers in flexible pipes has attracted extensive interest for its complicated mechanisms. The present paper addresses lateral buckling behavior of tensile armor wires in flexible pipes when armor annulus is flooded. Based on the thin curved beam theory, a single armor wire is modeled on a cylindrical surface without considering the effect of friction and bending through a system of six order nonlinear differential equations. Then, by applying a perturbation technique, analytical solutions are obtained which reveal a series of potential lateral buckling modes. An estimate for the lateral buckling is obtained under conditions given herein. Case studies are performed comparing the proposed model with the results obtained through a numerical program and alternative analytical model available in the literature.

1. Introduction

Flexible pipes are tubular composite structures widely employed in offshore oil and gas field development especially when the offshore industry has moved into deeper water in the last decades. A typical unbonded flexible pipe, as depicted in Fig. 1, is composed of a number of layers with specific functions. Among these layers, the tensile armors, which conventionally consist of helically wound steel wires with quasi-rectangular cross section, bear most of the tensile load and convert part of it into radial loads and displacements, twist and elongation.

Under scenarios typically found during deepwater installation or some phases of its service life, such as well shut down operations, the flexible pipe bore may be empty or with very small internal pressure. These conditions may generate significant longitudinal compressive loads on the flexible pipes due to the hydrostatic end-cap effect [4]. Such compressive loads, mainly supported by the tensile armor layers, may cause buckling in either radial or lateral directions.

The radial buckling mode, also known as ”birdcage”, is characterized by large localized radial dislocation. To date, extensive research has been conducted in an effort to investigate the mechanism of this failure mode [3,14,19]. Studies have shown that the radial buckling mode to some extent can be prevented by the application of anti-birdcage tapes over the tensile armor layers [1]. Nevertheless, the risk of buckling in the lateral direction has arisen, which was first discovered by Petrobras in 1999 during a jumper installation at a water depth about 1700 m, demonstrating that the conventional method to avoid buckling by reinforcing the anti-birdcage tapes had found a limit. The lateral buckling mode is often observed under the combined effect of axial compression and repeated bending when the outer sheath is damaged, i.e., in the wet annular situation, since the lateral support generated by

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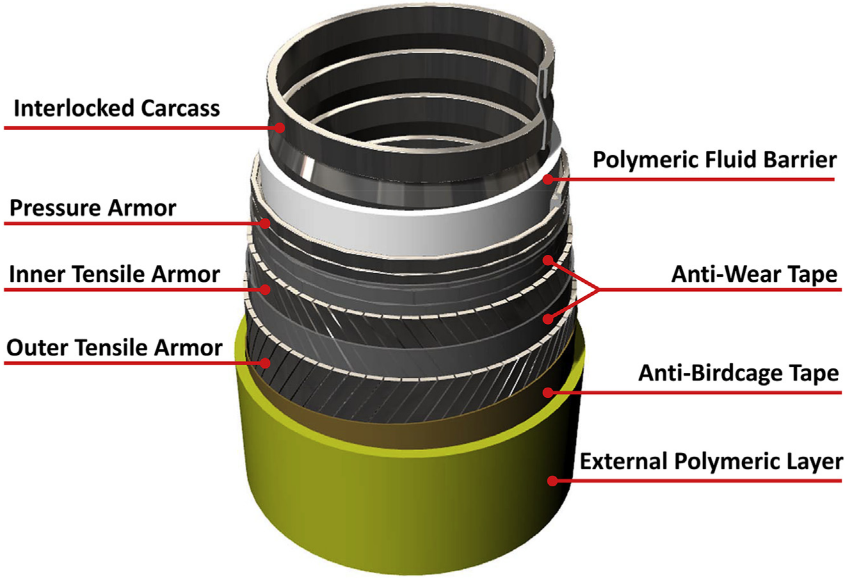

Fig. 1. Typical unbonded flexible pipe.

frictional forces is substantially reduced.

To date, considerable effort has been made by industrial and academic research groups to improve the understanding of this failure mode. Ref. [2] summarized the experimental methodologies for the prediction of lateral buckling including DIP (Deep Immersion Performance tests), pressure tank tests, and mechanical tests. The influence of armor annulus state (dry or flooded) on lateral buckling mechanism is discussed. Ref. [5] reproduced the lateral buckling mode through mechanical tests at atmospheric pressure by applying monotonic compressive load combined with a significant number of bending cycles. The compressive strength loss was observed when bending cycles were applied. However, no details about the applied load and characteristics of pipes tested were reported. Further experimental study regarding lateral buckling was carried out by Ref. [18] during the qualification of flexible pipes for water depths up to 3000 m, but again no details were published, curtailing reproducibility of the results.

Based on finite element analysis (FEA), Ref. [4] discussed the importance of torsional resistance on armor wires lateral buckling, considering that armor wires may have some free space to rotate when the pipe is subjected to axial compressive loads. Besides, the mechanical behavior of armor wires in straight pipe withstanding monotonic compressive loads was studied by Refs. [8], [22] and [23]. The studies showed that the buckling modes highly depend on frictional forces and radial resistance from high strength tapes and external water pressure. Moreover, a finite element model with periodicity conditions was developed by Ref. [6], which is applicable for the analysis of lateral buckling. It was observed that the transverse deflections of armor wires are stabilized during post-buckling stages due to lateral contact between neighboring wires.

In addition, Ref. [16] presented a finite element methodology addressing the mechanical behavior of armor wires under longitudinal loads and bending. Analyses were performed to investigate the response of an axially compressed armor wire subjected to either monotonic or cyclic bending. The results demonstrated that the cyclic bending had a negative effect on the lateral buckling capacity. Furthermore, this FE model was updated by Ref. [24] including the effect of anti-birdcage tape on end rotation. It was claimed that the application of anti-birdcage tape may resist pipe twist and delay the lateral buckling process. Moreover, Ref. [9] presented a consistent system of differential equations describing the mechanical behavior of a long and slender beam on a torus surface. On this basis, subsequent works regarding lateral buckling were carried out, whence the effect of bending, radial expansion, boundary condition, initial imperfection, as well as frictional resistance on lateral buckling was investigated [10,11,12].

Although considerable research has been conducted through experimental and numerical approaches, few analytical models were proposed to identify the underlying mechanisms of this failure mode. An analytical model to access the stability limit of flexible pipe under axisymmetric loading was developed by Ref. [7] on the basis of perturbation methods by establishing an eigenvalue problem. Ref. [20] developed an analytical model for simulating the buckling and post-buckling behavior of armor wires based on a total strain energy approach. The results were calibrated by a series of DIP and pressure chamber tests, however, no details were presented. Ref. [16] proposed analytical formulations to estimate the lateral buckling limit of a single armor wire under compression and monotonic bending. Nevertheless, since the full magnitude of friction is assumed available in the transverse direction and the effect of cyclic bending is not considered, the buckling limit is overestimated. Moreover, by ignoring the effect of friction, another analytical model was presented by Ref. [17] to evaluate the lateral buckling limit of a single armor wire on straight cylindrical surface assuming harmonic transverse deflection. This model was found to be on the conservative side as compared to experimental results due to the absence of frictional resistance. More recently, an empirical model was proposed by Ref. [13] to evaluate the lateral buckling limit, again, without considering the effect of friction and bending.

This paper aims at investigating the mechanisms of tensile armor wires lateral bucking when the annulus is flooded, thus