Ocean Engineering 108 (2015) 594–605

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Numerical analysis of buckling failure in flexible pipe tensile armor wires

Xu Yang[a,*], Svein Saevik[b], Liping Sun[a]

[a] College of Shipbuilding Engineering, Harbin Engineering University, Chuanhai Building 904, 145 Nantong Street, Harbin, China
[b] Department of Marine Technology, Norwegian University of Science and Technology, O. Nielsens vei 10, 7491 Trondheim, Norway

ARTICLE INFO

Article history:
Received 12 July 2013
Accepted 10 August 2015

Keywords:
Flexible pipe
Tensile armor layer
Buckling failure
Finite element model

ABSTRACT

Flexible pipes may be exposed to high axial compression and bending during deep-water installation. As the compression force is mainly sustained by the tensile armor layers, this may result in localized lateral or radial buckling failure in these layers. In this paper, a finite element model was created to evaluate the critical instability load of tensile armor wires under external pressure and compression. The tensile armor wires are modeled by curved beam elements under loxodromic assumptions. Other layers' contribution was simplified by spring elements and equivalent beams. The buckling load capacity and associated failure modes are obtained. The results are also compared with the results based on 3D Euler beam elements and results published in the literature. Parametric analyses were further included with respect to external pressure, friction modeling and the influence of initial imperfections.

1. Introduction

Flexible pipes have been widely used as the offshore industry moves into deeper water area and harsher environments where a high level of bending deformation is expected. Fig. 1 shows the cross-section of a typical unbonded flexible pipe used in offshore applications. The pipe consists of several separate layers. Each layer serves specific function and purpose based on its different geometry and material properties. The layers interact with each other and generate the desired properties of the entire pipe. Essentially the flexible pipe relies on polymer layers to provide sealing or anti-friction and metallic layers to provide strength. Depending on the application, some of these layers may not exist while extra layers may be added. This technique allows large diameters, great lengths and high mechanical strength of the pipes. As seen from Fig. 1, the flexible pipe has a complex structure that introduces several challenges to structural analysis.

The tensile armor layers normally have two cross-wound layers of steel tendons which are designed to sustain the external tension, torsion and the axial force from end-cap pressure. In deepwater applications, especially during installation when pipe bore is empty, the pipes may be exposed to significant axial compression in combination with cyclic bending, which may result in local instability of the tensile armor layers. The armor wires may experience large lateral or radial movements, which finally results in buckling failure. The radial buckling mode is called ‘bird-caging’ because of the shape of armor wires, shown in Fig. 2. The anti-buckling tapes help to avoid this failure mode to some degree; however, lateral instability may still exist. There are two possible failure modes depending on the annulus condition: dry annulus condition and wet annulus condition. The dry condition applies when the external plastic layer is intact and then the external water pressure would provide extra support in terms of contact pressure and friction. The wet condition, applies when the external layer is damaged, where no pressure exists around the wires providing less contact pressure and friction resistance.

During the early stages of flexible pipe application, the lateral instability phenomenon was not paid much attention as most offshore projects were situated in shallow waters. It was first reported in late 90's at 1700 m of water depth (Tan et al., 2006). Bectarte and Coutarel (2004) discussed a methodology to predict instability based on laboratory tests and DIP testing (Deepwater Immersion Performance Test). However, no details about the characters of the flexible pipes, failure modes or loads were mentioned. Tan et al. (2006) summarized the results from pressure chamber testing and full scale offshore DIP testing. A model based on total strain energy and associated design criteria were provided, however, again with no details published. Due to the extremely high costs of DIP testing, research based on numerical simulations was highly encouraged. Vaz and Rizzo (2011) presented a finite element model to predict the critical load and post-buckling behaviors under axisymmetric loads. The wires were modeled as straight beam elements with springs supporting the

---

* Corresponding author.
E-mail addresses: yangxu87@gmail.com (X. Yang), svein.savik@ntnu.no (S. Saevik), sunliping@hrbeu.edu.cn (L. Sun).

http://dx.doi.org/10.1016/j.oceaneng.2015.08.011
0029-8018/

Symbol and characters

FE	Finite element
DOF	Degree of freedom
3D	3 dimensions
DIP	Deepwater immersion performance
MPC	Multi-point constraints
E	Young's modulus
W_i	Internal work
l	Element length
R	Radius
A	Cross sectional area
p	External pressure
P_{cr}	Critical load
F	Friction force
F_r	Radial force
f	Friction coefficient
m	Distributed moment
im	Initial imperfection parameter
s	slip distance
N	Contact force
G	Shear modulus
I_i	Cross section constants
X^i	Local curvilinear coordinates for armor wire
$\mathbf{u}$, u_i	Displacement vector and its components in direction i
$\mathbf{u}_p$, u_i	Prescribed displacement vector and its components in direction i
Z^i	Cartesian coordinates with origin in center of pipe
q_i, q_t	Distributed force about axis i and distributed tangential force
S_c	Contact area
c_n	Penalty stiffness parameter
σ, $\sigma_{rupture}$	Stress tensor and rupture stress of anti-buckling tape
w_{ip}	Prescribed torsion and curvature quantities about axis i
w_i	Torsion and curvature quantities about axis i related to relative displacement
β, β_i	Relative displacement vector or component about axis i
ψ	Polar coordinate angle defining helix position
θ_I, θ_0	Armor cross section rotation around local axis i and article angle
α	Lay angle of armor wire
w_i	Components of beam displacement
χ_i	Components of beam rotation
π	Potential energy of contact element

layers. It was demonstrated that the relationship between critical load, friction coefficients and external pressure is non-linear. Ostergaard et al. (2012b) presented a method based on curved beam equilibrium equations to investigate lateral instability. One single wire under compression and bend cycles was analyzed, and then the whole layer and influence of initial imperfections discussed (Ostergaard et al., 2012a). The friction, ovalization and contact force were ignored. Ostergaard et al. (2011) also considered the friction force in the armor wires to compare the results with experiments. However the contact force between inner layer and outer layer was not studied. Saevik and Thorsen (2012) presented a numerical method based on curved beam elements that can be used to predict lateral buckling. A single wire model was analyzed where friction and contact forces were included. The results were compared with analytical solutions and buckling modes were discussed.

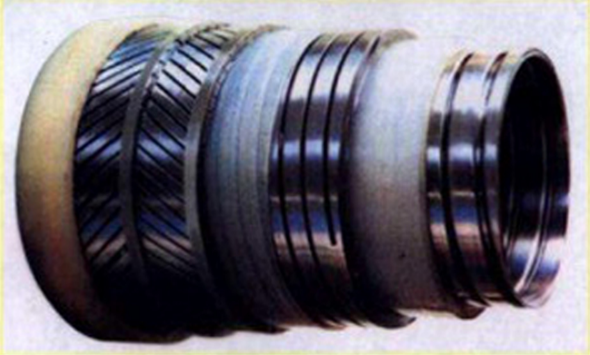

Fig. 1. Typical cross section of flexible pipe (Saevik, 2011).

Fig. 2. Birdcaging failure (Bectarte and Coutarel, 2004).

This paper presents a numerical model to predict the instability of tensile armor wires under axisymmetric compression and external pressure. Equivalent wires and curved beam elements are used to represent tensile armor layers (Saevik and Thorsen, 2012). A contact model has been applied to simulate the contact force between layers whereas spring elements are used to include the support from anti-buckling tape layer and pressure armor layer. Sensitivity analyses are conducted to optimize computation time with required accuracy. The influence of friction coefficients and external pressure of a 9.5 in. flexible pipe model is presented and the results are compared with the model created by ABAQUS (Vaz and Rizzo, 2011).

2. Methodologies

2.1. Basis and background for formulations

The finite element formulation of wires is based on the theory of thin curved rods. The earliest research can be traced back to linear theory of slender curved rods by Kirchoff (1859). The nonlinear formulation of thin curved rods was developed by Hay (1942) and generalized by Huang (1973). Washizu (1964) combined Green strain tensor, Hooke's law and Principle of Virtual Work to measure strain and stress. Saevik (1993) extended this formulation and developed a new finite element (FE) to simulate the behavior of one single wire exposed to a given curvature field. Later this element was further developed to include layer