Marine Structures 42 (2015) 154–174

Contents lists available at ScienceDirect

Marine Structures

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

# Bending behavior modeling of unbonded flexible pipes considering tangential compliance of interlayer contact interfaces and shear deformations

Leilei Dong [a,*], Yi Huang [a], Guohai Dong [b], Qi Zhang [a], Gang Liu [a]

[a] *School of Naval Architecture, Dalian University of Technology, Dalian, China*
[b] *State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian, China*

ARTICLE INFO

*Article history:*
Received 27 December 2014
Received in revised form 23 March 2015
Accepted 25 March 2015
Available online 21 April 2015

*Keywords:*
Unbonded flexible pipe
Bending behavior
Tangential compliance
Shear deformation

ABSTRACT

Rigorous analytical formulations are given to describe the gross slip initiation and progression in tensile armor layers of unbonded flexible pipes. Then two mechanisms are thought to contribute to the decrease of layer stiffness before gross slip begins. The first one considers the micro-slip occurred at the interlayer contact interfaces. The relative displacement between an armor wire and the underlying layer is determined according to the theory of contact mechanics. Shear deformations of the supporting plastic layer are taken into account in the other mechanism where plane sections no longer remain plane. The results of bending moment-curvature relationship from the presented models are compared with the available test data and good correlations are found. The shear model is seen to describe the slip transition better than other models do.



* Corresponding author.
*E-mail address:* leilei.dong@dlut.edu.cn (L. Dong).

http://dx.doi.org/10.1016/j.marstruc.2015.03.007

## 1. Introduction

While flexible pipe behavior under axisymmetric loads is well understood [2,15,20,25,26,29,34], determination of various bending characteristics is still a challenging problem. The difficulty is mainly due to the presence of helical layers and the freedom of helical components to slide against surrounding layers. So many authors put substantial effort into the post-slip behavior modeling of flexible pipes [4,5,11,12,19,24,25,27,29,35], based on the assumption that the slip path of the armor wire follows either the strained helix (also known as the loxodromic path) or a geodesic curve.

Experimental results in terms of bending moment-curvature relationship generally show much smaller pre-slip bending stiffness and longer transition from the pre-slip to the full-slip stiffness than the analytical prediction [33], which implies that the pre-slip behavior of flexible pipes is not described adequately. In current stick-slip models, the pipe is simply modeled as a solid beam before gross slip initiates, i.e. plane sections remain plane during bending. Recently shear deformation in the multi-layer structure is identified as a potential source of the stiffness decrease in the stick regime [28]. However, it is believed that tangential compliance of interlayer contact interfaces is probably another mechanism which plays some part in the reduction of the pre-slip stiffness.

According to the theory of contact mechanics [10], micro-slip does occur between contacting bodies up to a certain limit value at which gross slip begins. The relative tangential displacement is accommodated in large part by elastic shear strain at the contact interface. This elastic behavior is characterized by tangential compliance. Analytical models considering the tangential compliance of contact interfaces can be found in the literature, mostly dealing with the analyses of spiral strands or cables [7–9,18,21]. The inclusion of tangential compliance is translated into a slowly decreasing cable flexural rigidity [7,18,21]. To our knowledge, the consideration of tangential compliance in flexible pipe analyses has not been performed.

The pre-slip behavior has a significant effect on the fatigue performance of dynamic applications of flexible pipes, such as a deep-water flexible riser. In global analyses the decrease of pre-slip stiffness can give larger curvatures compared with the current stick-slip models. This effect is even more pronounced if bending hysteresis is incorporated [30,31]. In addition, shear deformations will delay the gross slip initiation, hence reducing the stress in the stick domain at a given curvature [28]. Considering the slope parameter in the S–N curve, a small reduction factor in stress can have a great impact on the resulting fatigue life.

In this paper, more rigorous analytical formulations are firstly given to describe the gross slip initiation and progression of the armor wire. The effects of tangential compliance and shear deformations on the layer bending behavior are then taken into account. Comparative studies with respect to the available experimental data are further carried out and encouraging correlations are found.

## 2. Analytical model

### 2.1. Assumptions and definitions

The main assumptions and definitions used throughout the analysis are:

1. The slip path of the armor wire is assumed to follow either the strained helix or a geodesic curve. Both curves are considered as the limit curves for wire slip, and the actual path is probably somewhere in between. According to [23]; the transverse slip can be neglected when evaluating the dynamic bending stress. Hence, the strained helix assumption is employed in this study.
2. The wire slippage in its axial direction is only governed by the internal axial force and the available friction, i.e. the effect of cross-sectional shear forces is neglected. This assumption is, although not stated explicitly, usually made in the literature. Its accuracy will be examined later.
3. The radial component of the wire curvature in the deformed pipe can be approximated by that in the undeformed pipe, i.e. the effect of additional curvature from bending is neglected. This is a reasonable assumption as the radial curvature increment is normally less than 5% of its initial value [25].