Engineering Structures 168 (2018) 384–398

Contents lists available at ScienceDirect

Engineering Structures

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

Theoretical analysis of reinforcement layers in bonded flexible marine hose under internal pressure

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ARTICLE INFO

Keywords:
Marine hose
Reinforcement
Theoretical

ABSTRACT

This paper portrays the results of analytical study on reinforcement layers of bonded flexible marine hose under internal pressure. Based on the anisotropic laminated composite theory, a complete theoretical solution is chosen to elaborate on the mechanical behaviour of the convoluted reinforcement layers. The developed method aims to set up a unified mathematical approach which can be suitable for arbitrary multi-layers composite of synthetic fibers in reinforcement structure. Comparative case studies are made to verify the accuracy of the method which are in agreement with the published results of four layered filament-wound composite pipe. An extended case study on a typical fourteen-layered reinforcement structure is carried out for investigating the variations of stresses and strains. Furthermore, considering the practical application in offshore engineering, parametric analysis on different known conditions, verification with experimental and numerical results are applied. Failure analysis on Tsai-Hill failure criterion are also proposed to analyze the capability of practical reinforcement layers in bonded flexible marine hose.

1. Introduction

Bonded flexible marine hose, which is frequently used in the field of offshore engineering, plays a significant role in connecting platform to shuttle tankers for oil transfer at the sea surface, see Fig. 1. A hose assembly is approximately 10–12 m in length composed of reinforced fiber, vulcanized rubber and steel end fitting. In order to present as a flexible, feasible offshore system, a marine hose is comprised of multiple layers which can provide large flexibility to withstand global bending moment and internal pressure. Since the hose is considered as bonded structure, relative displacements between various layers are not allowed due to elastomeric vulcanization, except for double carcass hoses which allow relative displacement between the carcasses. The sectional components of typical marine hose's structure is shown as follows, see Fig. 2.

The basic layers of a marine hose include carcass, liner, reinforcement layers and a steel helical wire embedded into rubber layer. Among these components in Fig. 2, reinforcement layers and steel helical wire are of vital significance. Reinforcement layers, which are also called cords or plies, are made of plentiful synthetic fibers configurated with a fixed winding angle in each layer. In a typical marine hose structure, more than 10 reinforcement layers are applied with opposite winding angles between adjoining layers [1,2]. These composite layers have many potential advantages over structures made of conventional materials. Because of highly anisotropic material properties, this kind of specific structure can resist large internal pressure and increase axial stiffness. Meanwhile, the steel wire can also guarantee the structural reinforcement by intensifying the bending stiffness of the hose and preventing its transversal section from crushing [1].

The bonded flexible marine hoses have been used in industrial sector for several decades due to well-rounded product development capabilities. However, there is a conspicuous dichotomy between industrial application and academic research. A great deal of practical issues related to scientific problems are still knotty to be clarified. Hence, in recent years, so as to verify the structural design, basic guidelines are used, such as API 17 K [3] and OCIMF [4]. Moreover, some studies have been carried out to simulate the mechanical behaviour of marine hose because of the deficiency of these guidelines, such as fatigue stress and failure analysis. Northcutt [5] developed an experimental research of bonded flexible riser, bonded flexible pipeline and bonded floating export hose. The survey showed a series of results of marine hose such as the axial and bending stiffnesses. Lassen et al. [6] proposed both experiment work and fatigue life analysis considering extreme load resistance and fatigue durability. A finite element

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https://doi.org/10.1016/j.engstruct.2018.04.061
Received 28 November 2017; Received in revised form 11 April 2018; Accepted 16 April 2018

Nomenclature

z	axial coordinate
θ	circumferential coordinate
r	radial coordinate
$\boldsymbol{\sigma}$	stress tensor
$\boldsymbol{\varepsilon}$	strain tensor
$\boldsymbol{u}$	displacement vector
$\boldsymbol{C}$	elastic tensor
t	tangential coordinate in local frame
b	binormal coordinate in local frame
n	normal coordinate in local frame
$\boldsymbol{C}'$	elastic tensor in local frame
ε_0	axial strain constant
γ_0	twist constant per unit length
E	elastic modulus
G	shear modulus
ν	Poisson's ratio
ϕ	winding angle

model was also built up by Lassen et al. [7] in comparison with the previous test results. Summarized of several work above, Gonzalez et al. [1] applied an analytical model [8] developed for bonded flexible pipes and proposed a numerical method based on a specific finite element model which considered continuum and rebar finite elements. Correlation between models were fine. Furthermore, Tonatto et al. [2] proposed a parametric analysis on finite element models with axisymmetric and 3D elements of a double carcass floating hose, experimental tests were also performed to validate the numerical results.

Among the limited publications in marine hoses field, it is apparently acknowledged that there are few studies concentrating on the theoretical analysis of marine hoses. The discussion could not be resolved because no one was able to answer the crucial questions in a form in which they could be pursued productively. In other words, with no decision of determining the priority of research method, the flexible marine hose, which exhibits a complex mechanical behaviour, is in need of starting from a simple question focused on its basic layers, then moving forward with a gradual research process. This will allow the feasibility of a theoretical solution and obtain credible results which can be the substantial reference for further study such as using the composite elastic theory or analytical model proposed by Batista et al. [8]. Moreover, theoretical method has its key advantage which is more efficient while implementing the parametric analysis. By contrast, although an axisymmetric model may be simple, it is still inconvenient to use finite element models to analyze parametric effects since starting a series of new calculating processes would cost more time, which is inappropriate for ongoing investigation.

Accordingly, considering all aspects mentioned above, this paper initially focuses on the mechanical behaviour of reinforcement layers, and a solution of at least 10-layered composite structure is therefore in need of taking into account. If the proposed problem can be solved analytically without excessive approximation, it can be served as a fundamental solution for further developed investigation including other layers, so as to make overall and complete comparisons with other published finite element and experimental results.

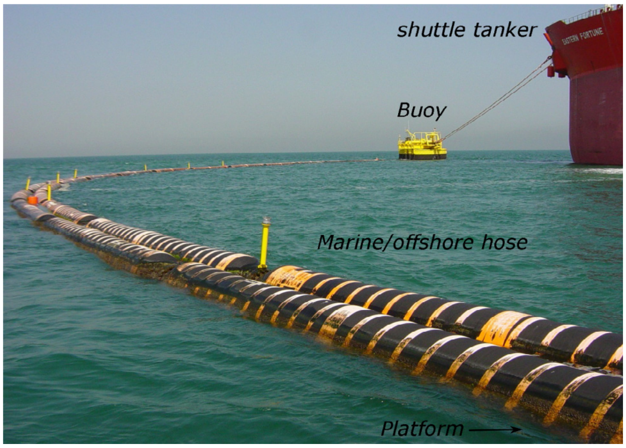

Fig. 1. Application of marine hose in offshore engineering.

In the present paper, a unified theoretical method which can be suitable for arbitrary multi-layers composite of reinforcement structures in offshore hoses is established. Based on an existing model without any modification, a pragmatic and systematic programming process of this mechanical problem is proposed in case the specific tests or studies of any appropriate N-layered reinforcement structure are in demand. By comparative analysis with published results, validity of the proposed analytical method is confirmed. Moreover, parametric analysis including comparison with other numerical results and failure analysis are also investigated. Since the method is implemented by a fast programming process which does not require repeating calculating processes for each parametric case, these post-processing results can be exported efficiently compared to other methods. The obtained data of reinforcement layers in offshore hoses are of paramount importance for further investigation and design in offshore engineering.

2. Model assumption & parameterization

The material status of one vulcanized reinforcement layer is presented as follows, see Fig. 3a). A typical anisotropic material structure with consistent property in only one fixed direction can be obviously observed in the figure. Since the composite elastic model can be applied in the case, it is appropriate to choose reinforcement layers as the first objective among marine hose's layers to analyze.

Considering the reinforcement structure for marine hose's geometrical model separately, this part discusses mainly the process developing from engineering structure to mathematical model. Aiming at establishing the basic mathematical foundation, it is in need of concerning all mechanical equations at appropriate local frame. Due to specific structure of bonded flexible marine hose, which enables the pipe to behave at radial and circumferential directions with an explicit physical implication, it is essential to set up a mathematical description using cylindrical coordinate system. The diagrammatic sketch from engineering model to mathematical parameterization can be demonstrated as follows, see Fig. 3b).

In such a context, what is recognized as a cylindrical model can be validated in the following definition:

A subset $\Sigma \subset \mathbb{R}^3$ is a regular surface, if there establishes a map, satisfying the following form

$$\boldsymbol{\Sigma}(\boldsymbol{x}_\Sigma)\colon \mathbb{R}^3 \ni \boldsymbol{x}_\Sigma = \begin{bmatrix} z \\ \theta \\ r \end{bmatrix} \mapsto \boldsymbol{\Sigma}(\boldsymbol{x}_\Sigma) = \begin{bmatrix} z = z \\ y = r\cdot\sin\theta \\ x = r\cdot\cos\theta \end{bmatrix} \in \mathbb{R}^3 \tag{1}$$

where (z,θ,r) is local cylindrical frame while (z,y,x) represents the standard orthogonal basis. The vector form $\boldsymbol{\Sigma}(\boldsymbol{x}_\Sigma) = (z(z,\theta,r),y(z,\theta,r),x(z,\theta,r))$ can be used conveniently to study differential and integral calculus on the surface. Furthermore, it is emphasized here that the sequence of coordinate is deliberately designed using right-hand rule corresponding to another local frame (t,b,n) which will be introduced later.

With establishment of local frame on the layers's surface, then mechanical analysis can be implemented from its vectorial form.

Note that, throughout the past decade, some studies have been