Applied Ocean Research 79 (2018) 7–19

Contents lists available at ScienceDirect

Applied Ocean Research

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

Investigation on structural behavior of ring-stiffened composite offshore rubber hose under internal pressure

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ARTICLE INFO

Keywords:
Stiffened composite rubber hose
Single carcass
Stiffener
Rebar
Failure pressure

ABSTRACT

Ring-stiffened composite offshore rubber hose of single carcass is commonly used for offshore oil transfer. Common hose dimensions are length of 10.7 m and nominal diameter of 500 mm. The nominal burst pressure is 7.5 MPa, equal to five times rated working pressure of 1.5 MPa. The hose carcass is composite cylindrical tube made of rubber, reinforcing fiber cords and steel spiral stiffener that provides radial stiffness. In hose design, the burst pressure shall be determined to verify its pressure bearing capacity. In this paper, a nonlinear finite element hose model is created with commercial software ABAQUS and validated to predict its structural behavior under internal pressure. The large deformations, interactions between components and nonlinear material properties of hyperelastic rubber and fibers are considered. Stresses of stiffener, radial and axial deformation and load in reinforcement plies are obtained. A bulging phenomenon amid two stiffeners is found, which indicates the confine effect of stiffeners. Failure pressure is jointly determined by the strength limit of polymer cords and steel stiffener. The influence of different fibers and rubbers on hose pressure-deformation response are compared. The results demonstrate good accordance with requirement of specification. The finite element model can predict hose failure pressure and provide guidance for reliable hose design in practice.

1. Introduction

Offshore floating rubber hose of single carcass is used for oil transfer in offshore oil field, such as conveying crude oil from floating production storage and offloading (FPSO) to export tanker. The hose floats on sea surface by integrated floatation foam under working conditions. It is also widely used in single point moorings which are particularly suited to the handling of large tankers at offshore locations [1]. The composite rubber hose is manufactured with prescribed length due to the dimension limitation of vulcanizing tank. Northcutt presents an overview of composite hose in offshore development [2]. It is an economical and feasible solution for hydrocarbon transfer.

The hose construction is depicted in Fig. 1 and Fig. 2. The geometric parameters are listed in Table 1. It is a composite structure with complex cross section. All of its structural parts are bonded together by rubber vulcanization. Interlayer bonding will prevent gaps and relative slip between layers. The hose has a typical single carcass composed of rubber, rubberized cord fabric (or named cord-rubber reinforcement) plies and a spiral stiffener. The steel end fitting comprises the flange, annular ribs and nipple. The annular ribs assist the binding steel wires to anchor various structural layers on the nipple. The nipple can transmit axial loads and bending moments from flange to hose body. The inner lining is made of oil inert nitrile butadiene rubber. The lining provides sealing capacity and protects the reinforcement layers from oil corrosion. The reinforcement plies are composed of cords embedded in elastomeric matrix, namely rubberized cord fabric, as shown in Fig. 3. The fabric is made of nylon or polyester cord, which includes numerous filaments. They are arranged at crossed +/- θ angles with respect to longitudinal hose axis, withstanding internal pressure and axial load. The angle-ply reinforcement plies are designed to achieve maximum strength and flexibility with minimum axial elongation.

In this paper, the nominal hose bore diameter is 500 mm and the rated working pressure is 1.5 MPa. As shown in Fig. 4, the steel helix wire is continuous without intermediate welding, embedded in the rubber between two reinforcement layers. The wire diameter is 12 mm with a pitch of 50 mm. The helix is wound at an angle nearly close to 90° relative to hose longitudinal axis. It increases radial stiffness of cross section and prevents ovalisation of hose section due to vacuum or bending. The floatation jacket is closed-cell foam, giving buoyancy over the entire hose length. Finally, a reinforced elastomeric layer with

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https://doi.org/10.1016/j.apor.2018.07.007
Received 4 April 2018; Received in revised form 6 June 2018; Accepted 13 July 2018

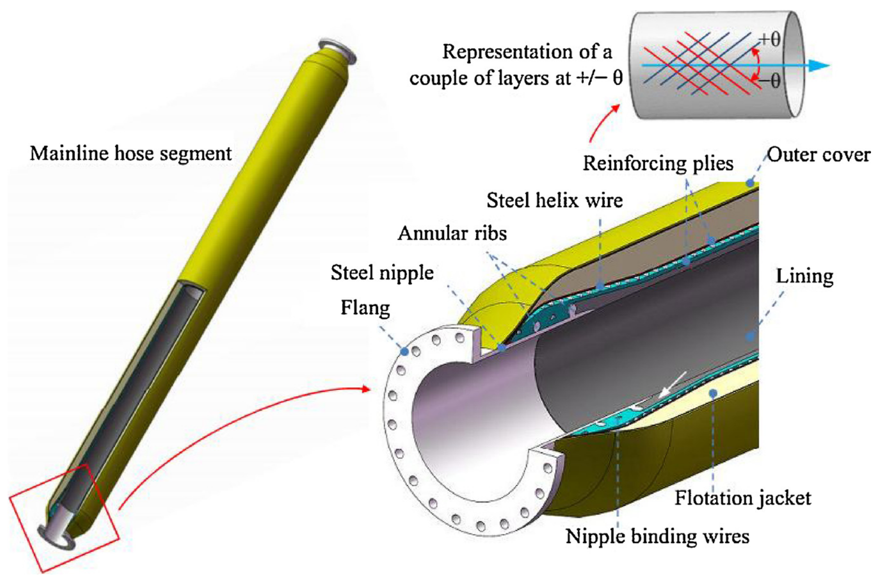

Fig. 1. Components of stiffened composite hose.

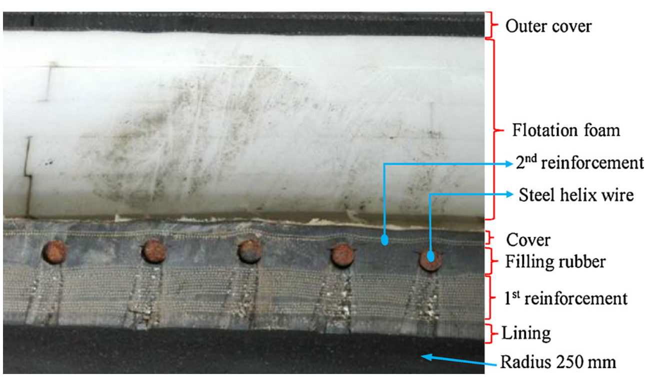

Fig. 2. Layout of composite hose body (longitudinal profile).

Table 1
Geometric parameters of the analyzed model.

Parameter	Value	Parameter	Value
Nominal inner radius (mm) r_0	250	Mean helix radius (mm)	284.6
Outer radius (mm)	294.4	Helix wire diameter (mm)	12
Number of plies in 1st and 2nd reinforcement layer	14; 2	Pitch of helix (mm)	50
Winding angle φ (°) of reinforcement layers	+45°/-45°	Length of the model (mm)	150

gridding cloth named cover, is laid on the floatation, making hose resistant to abrasion, weathering and sea water.

In offshore hose industry, engineers usually refer to two standards for hose structural design and verification, i.e. OCIMF 2009 [3] and API 17 K 2010 [4]. OCIMF 2009 provides technical requirements to ensure the satisfactory performance of elastomer reinforced, smooth bore, oil suction and discharge hose commonly used at offshore moorings. The performances of various materials like rubber, cords and steel are specified. It offers procedures and acceptance criteria of kinds of prototype tests, like burst, torsion and tensile test. API 17 K applies to a wider range of bonded flexible pipe than OCIMF 2009. It gives requirements for the design procedure, material selection, manufacture, testing of bonded flexible pipes. Particularly, it specifies the permissible utilization factors of bonded flexible pipe layer. The API 17 K standard requires an accurate determination of the load response in the hose wall. But sufficient design details about theoretical calculations or numerical simulations are not available in these guidelines. The ultimate bearing capacity analysis of single carcass floating hose under internal pressure and tension loads is few in published literature. Some researchers have carried out significant work on the structural behavior of marine hoses. Vinnem et al. [5] reported several large oil spills on the Norwegian Continental Shelf due to loading hose rupture. This fact implied the importance of safety and reliability of hose.

There is limited literature about analysis of stiffened composite rubber hose under internal pressure. Zhou et al. [6] theoretically analyzed the stresses of stiffened composite rubber hose under internal pressure less than 3.0 MPa, using orthotropic elasticity method. But the influence of stiffeners on hose response is not considered. Tonatto et al. [7] conducted burst test for double carcass offloading hose to validate the two-dimensional axisymmetric finite element models. The models consider plane stress state, whereas three stress components are neglected. Gonzalez et al. [8] proposed a numerical and an analytical model to calculate the stresses and strains in each component under 1.0 MPa internal pressure. But the steel helix was reduced to a spatial beam. Other researchers conducted analysis on unstiffened composite hose and pipelines subjected to internal pressure. Based on anisotropic elastic theory, Gu et al. [9] presented the analytic solutions of stresses and elastic deformations of steel wire wound reinforced rubber hose under internal pressure. The theory cannot consider nonlinear material properties. Zheng et al. [10] and Bai et al. [12] conducted theoretical and experimental investigation on short-term burst of plastic pipes reinforced by cross helically wound steel wires or thermoplastic pipe reinforced by aramid fibers. The experimental results of Bai [12] are used in this paper for validation of finite element model.

Some research work focused on other mechanical behavior of composite hose, such as fatigue durability, crush and torsion. Lassen et al. [13] carried out experimental work with respect to extreme load resistance and fatigue durability analyses on bonded steel reinforced rubber loading hoses. The findings are referable for hose engineers. Lassen et al. [14] presented extreme load capacity assessments and a fatigue life prediction methodology for bonded rubber loading hoses, subjected to repeated reeling. Tonatto et al. [16] implemented failure and damage analyses numerically and experimentally to predict crush behavior of the hose section. Gao et al. [17] numerically calculated the stresses and strains of hose and material utilization factors under torsion.