Marine Structures 54 (2017) 50–72

Contents lists available at ScienceDirect

Marine Structures

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

Nonlinear finite element analysis of failure modes and ultimate strength of flexible pipes

Dong-Hyun Yoo [a], Beom-Seon Jang [b,*], Ki-Ho Yim [c]

[a] Department of Naval Architecture and Ocean Engineering, Seoul National University, Seoul, South Korea
[b] RIMSE, Department of Naval Architecture and Ocean Engineering, Seoul National University, Seoul, South Korea
[c] Offshore System R&D Department, Daewoo Shipbuilding & Marine Engineering Co., Ltd., Seoul, South Korea

ARTICLE INFO

Article history:
Received 1 November 2016
Received in revised form 26 February 2017
Accepted 30 March 2017

Keywords:
Flexible pipe
Ultimate strength
Failure modes
Nonlinear FE analysis

ABSTRACT

Designs of flexible pipe utilized in offshore dynamic riser applications need to be subjected to strength assessment over the entire length in relation to the dynamic motion of the connected floater. Such assessment includes many uncertain factors including soil properties, internal pressure, ocean metadata and others. Failure of flexible pipe, moreover, leads to serious financial loss and environmental degradation. Thus, flexible pipe failure modes and safety need to be evaluated in terms of ultimate strength under various loads. Ultimate strength assessment of flexible pipe is quite complicated and time-consuming compared with that of a steel catenary riser, due to the composite materials, geometric complexity and the contact mechanism between layers The material nonlinearity and large deformation, moreover, render stable convergence of nonlinear analysis to a solution problematic. This paper proposes practical and stable methods of ultimate-strength assessment using 8-layered and 5-layered 3D FE models subjected to axial tensile and compressive loads, respectively. In the 5-layered model, four inner layers (carcass, pressure sheath, pressure armour, and anti-friction tape) are replaced by one equivalent pressure layer which plays a role of withstanding pressure applied together with the axial compression. It aims to improve the convergence of nonlinear analysis by simplifying the interactions between layers. For each analysis, the failure mechanisms and the interactions between layers are investigated in detail with incremental loading. The effect of initial imperfection, i.e. ovalizations are also examined. In the compressive strength analysis, the influence of various external pressure are additionally studied.

1. Introduction

Flexible pipe consists of several layers that have different functions, materials and geometries. As recent offshore projects have become larger and deeper, the demand grows for new flexible pipe designs that can withstand high internal pressure and large bending curvature. Such new-design development needs to be supported by exhaustive assessment of structural integrity in terms of yield strength, ultimate strength, fatigue strength, and other parameters. The previous studies on the structural behavior of flexible pipe can be classified into analytical and numerical approaches. All of them utilize overall

* Corresponding author.
E-mail address: seanjang@snu.ac.kr (B.-S. Jang).

http://dx.doi.org/10.1016/j.marstruc.2017.03.007
0951-8339/

elastic stiffness curves that are based on the elastic behaviors of each layer and the stick-slip behavior caused by the mechanisms of contact between layers.

In their analytical model, Feret and Bournazel [1] formulated governing equations for the behavior of flexible pipes under axisymmetric loads and evaluated the stresses in tensile armour layers on the basis of a simplified solution for the helical tendons. However, the results are not valid when the layers are not in contact. A similar analytical model was provided by McNamara and Harte [2].

Kebadze [3] also investigated the behavior of flexible pipes under axisymmetric loads, but with respect to various applications of kinematic models for each layer. The research proposed the use of the kinematics of the thin tube for isotropic layers, which approach was adopted in Refs. [4] and [5].

Many investigators have studied the structural behaviors of the carcass and pressure armour using orthotropic models (e.g. Bahtui et al. [4]; Harte and McNamara [6]; Kebadze [3]; Neto et al. [7,8]; Ren et al. [9]; Sævik [5]; Sousa [10]; Sousa et al. [11,12,13]). Their uses of the elastic modulus in the relevant constitutive equations, however, are different slightly. Sousa et al. [11] and Neto et al. [7], for example, employed the equivalent modulus differently from the other studies.

The experimental research on the behavior of flexible pipes is abundant. Most of it, though, has described only the experimental results without treating detailed design data for each layer (e.g. material properties, thicknesses, radius, sectional area, shapes of sections, laying angles, etc). Witz [14], by contrast, provided detailed product data as well, which information has been utilized in many comparative studies [3,9,10]. The papers presented the relevant structural behaviors as subject to tension, torsion, bending, and bending with internal pressure, and also compared several institutions' analytic predictions with the experiment results.

Numerical models formulated using commercial software (e.g. ANSYS®, MARC®, ABAQUS®) or specialized FE tools (e.g. BFLEX) have been suggested. Sousa [10] and Sousa et al. [11] used ANSYS® for their FE analyses, taking into account material nonlinearity, geometric nonlinearity, and the contact mechanism between layers. For the carcass and pressure armours, they employed an equivalent shell model. Bahtui et al. [4] proposed nonlinear FE analysis methods using ABAQUS® with the explicit method. They utilized orthotropic models for the carcass, and compared their numerical results with analytical results respecting tension, torsion, and bending. Similarly, Ren et al. [9] investigated the tensional behavior of the 2.5 in flexible pipe provided in Ref. [14]. Sævik [5] developed a specialized FE tool, named BFLEX, that reflects the actual shapes of all layers. The stresses in tensile armour layers are compared with experimental results.

In addition to the elastic stiffness analysis required for global dynamic analysis or the assessment of the stresses of each layer, ultimate-strength analysis is necessary in order to estimate the safety margin against failure under excessive loads. In one relevant study, Neto et al. [7] predicted the wet collapse and burst of flexible pipes, to which end they developed and compared a 2D equivalent FE model, a full 3D FE model, a 3D ring model, and analytic models. They found that small carcass and pressure armour laying angles does not affect the radial-structural response. And although the equivalent shell model shows a tendency to underestimate the Von Mises stress up to yielding, it provides good predictions of radial displacement and ultimate strength with respect to pressure. Recently, Sousa et al. [13] tested the strengths of high-strength tape and compared the results by FE analysis.

A full 3D FE model which accounts for all actual geometric shapes even for carcass and pressure armour using 3D solid elements can be conceived. Such a model can be valid for simple elastic analysis that considers only the contact mechanism. However, with the full 3D solid FE model, guaranteeing robust convergence in ultimate-strength analysis, wherein material nonlinearity and severe geometric nonlinearity induced by large deformation have to be carefully taken into account, is difficult. Normally, much trial and error is necessary before a final failure can be obtained. Another prohibitive factor of this full 3D model's application to an actual development process is the huge computational time and cost.

In this research, two simplified FE models are used for ultimate strength assessment of flexible pipe of 2.5 inch. ANSYS® mechanical [14] is used for the analysis. The validity of the method is supported by comparing the axial stiffness with those of analytical models in Witz [14]. Layers of complex geometries such as carcass and pressure armour which seriously deteriorates the convergence of analyses are replaced with respective equivalent layers that show similar structural behaviors. First, full-layered 3D FE model is used to evaluate the ultimate tensile strength. The resultant radial deformation is negligible and the convergence of nonlinear analysis is relatively good even if the FE model contains all layers. The analysis results are verified by comparing with an analytical model which is modified suitable to a prediction of structural behavior beyond yield strength.

Next, an ultimate compressive strength analysis is carried out using 5-layered model. When the model is subjected to high axial compressive force, the tensile armour layers get to expand radially. Then, the polymeric layers wrapping them end up yielding, and a large radial deformation occurs suddenly. This phenomenon is called a radial buckling or bird-caging failure. Since ultimate compressive strength analysis involves complex interactions between layers and large deformations, this analysis doesn't converge well. Therefore, a much simpler FE model is introduced. Radial buckling is mainly related to tensile armour layers and outer polymeric layers, and the inner layers scarcely contribute to this failure mode. Thus, these inner layers can be replaced with one equivalent layer. The 2D FE model is used to find circumferential elastic modulus of the equivalent layer. This simple model is called a 5-layered model. The validity of the model is also proved by comparing its axial stiffness with that of the 8-layered model and other references. For ultimate compressive strength analysis, the effect of external pressure is also investigated.

This paper proceeds as follows. First, the properties of the 2.5 in. flexible pipe are introduced. Then, the 8-layered and 5-layered models are introduced. After that, the analytic method is explained briefly. Next, the axial stiffness values of the FE