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Analysis of flexural behaviour of reinforced thermoplastic pipes considering material nonlinearity

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ABSTRACT

Reinforced thermoplastic pipes (RTPs) are considered as prospective alternatives to traditional steel pipes in different offshore oil and gas applications due to their attractive properties. The spoolable versions of these pipes can be efficiently installed by the reel-lay method with relative ease. Nonlinear flexural behaviour of RTPs composed of a liner made of pipe grade polyethylene (PE), aramid fibre reinforced PE layers and a PE outer cover is modelled and analysed using finite-element analysis (FEA) considering the material nonlinearity. The pipe is modelled as a cylindrical shell in Abaqus/Standard. Numerical algorithms reflecting strain-dependent mechanical characteristics of PE are employed to perform simulations. Advantages of the proposed modelling approach are demonstrated with numerical examples. The minimum allowable bend radii of RTPs with different ply angles are determined. The effects of diameter-to-thickness ratios and the material nonlinearity on the spoolability of RTPs have been investigated. It is shown that the spoolability of RTPs can be improved by employing a certain two angle-ply reinforcing layer system, which could reduce the installation costs.

1. Introduction

With the rapid development of industries, the energy consumption has expanded in today's world. In 2008, the world's energy consumption grew to approximately 3.5×10^{11} GJ, and more than 70% of the total energy consumption was supplied by consuming the fuel from the oil and gas industry [1]. As an increasing number of offshore hydrocarbon reserves have been found, the offshore oil and gas production will play a significant role in the world's energy supply in the future. Offshore pipelines have been considered to be one of the most economical means of large scale oil and gas transportation. Among various types of offshore pipelines, reinforced thermoplastic pipes (RTPs) are now being widely considered as possible alternatives to traditional steel pipes due to their better corrosion resistance, high stiffness to weight ratio, and low maintenance costs. Recently, more than 500 km of RTPs have been installed in the Middle East and Southeast Asia [2]. The typical structure of an RTP consists of an inner liner, several structural reinforcing layers and an outer cover.

The liner and the cover, which are made from neat thermoplastic, protect the reinforcing layers from corroding due to the internal transported product and the external environment, respectively. Various thermoplastics such as polyethylene (PE), cross-linked polyethylene (PEX), polyamide (PA) and polyvinylidene fluoride (PVDF) can be used to manufacture the liner and the cover. Among different kinds of thermoplastics, it is common to employ PE for offshore applications as it is an established material in oil and gas production [3]. The use of other thermoplastics for more specialised fluid services is currently under development. Normally, the structural reinforcing layers consist of several angle-ply layers with winding angles of ±54.7°. Reinforcements in the reinforcing layers, which are the principle load-bearing components of an RTP, can be provided by using either high strength fibres (e.g. aramid or glass) or metallic (e.g. steel) wires or tapes. The current RTP products, which can be used as either flowlines or risers, are available in diameters ranging from 50 to 150 mm with a working pressure of up to 35 MPa [4]. Pipe grade PE (PE 80 or PE 100) and the aramid fibre reinforcements are currently utilised to manufacture commercial RTPs for the offshore oil and gas applications (e.g. RTPs made by Airborne and Pipelife) [5,6].

RTPs are also commonly considered as spoolable pipes which can be installed by the reel-lay method. The reel-lay method allows an RTP product to be manufactured onshore, packaged on a road transportable reel in a long continuous form and transported to the site of the pipeline. The installation is achieved by continuously unwinding the pipe from the reel and laying it on the seabed. The reel-lay method reduces labour costs during the installation phase

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because most of the welding, coating and testing are accomplished onshore [7]. In addition, it is the fastest installation method compared to other conventional installation techniques such as S-lay and J-lay methods. Consequently, in comparison to other conventional installation procedures, the reel-lay method provides considerable cost and schedule advantages including low installation costs, ease of storage and handling. The minimum allowable bend radius of a flexible pipe is an important design parameter when employing the reel-lay method. A better spoolability is desirable as the transportation and material costs during installation phase can be significantly reduced by spooling a pipe onto a smaller size reel [8]. However, it should be noted that overestimating the spoolability of a pipe may cause substantial damage to its material. At present, when packaging the pipe on the reel, it is common practice to define the minimum allowable bend radii of RTP products using an empirical approach [3]. The design of RTPs could be improved if more advanced analysis of their flexural behaviour is implemented. Based on this analysis, the minimum allowable bend radii of RTPs can be estimated more accurately.

Research on the flexural behaviour of long metallic and composite cylinders has been undertaken actively. As the reel-lay method is widely employed for installing traditional metallic pipes, a number of studies on the reeling of metallic pipes have been reported in the literature [9–11]. It has been shown that the minimum allowable bend radius of a metallic pipe could be limited by the elastic strain limit of the metallic material as the pipe may bend into the plastic range during the winding and unwinding process. Brazier [12] studied the flexural behaviour of a long metallic pipe subjected to pure bending. Due to the induced bending moment, an ovalisation occurs in the cross-section of the pipe resulting in a progressive reduction in its flexural stiffness, which is known as the Brazier effect. The pipe then buckles when the induced bending moment becomes larger than the critical moment. Kedward [13] extended Brazier's approach to thin-walled orthotropic cylinders and presented theoretical solutions which enable calculation of the critical moment for the pipes made from orthotropic materials. Chan and Demirhan [14] created a closed-form solution to determine the bending stiffness of laminated composite pipes. However, their work was shown to be appropriate to only small diameter pipes.

Rodriguez and Ochoa [15] conducted numerical studies to analyse the flexural behaviour of carbon fibre/epoxy and glass fibre/epoxy pipes. In their study, the failure of the pipes was characterised by the damage initiation in the composite layers and the progressive damage development was analysed. Their analysis indicated that, as expected, the epoxy-based composite pipes cannot be used as spoolable pipes as they fail easily in the brittle mode under bending. Xia et al. [16] developed analytical solutions to study the stress–strain response and deflection of filament-wound fibre-reinforced sandwich pipes subjected to pure bending. Yet, no failure modelling was performed in their study. Most recently, Ashraf et al. [17] presented numerical studies investigating the spoolability of RTPs made from Polyetheretherketone (PEEK) and AS4-carbon fibre-reinforced PEEK composites. Similarly to findings of Rodriguez and Ochoa's analysis, the spoolability of this RTP was rather limited. It failed at a large radius due to a matrix failure in the transverse direction in the fibre-reinforced layers.

Although the aforementioned studies provided effective methods to evaluate the minimum allowable bend radii of pipes, it should be noted that the mechanical behaviour of material has been assumed to be linear elastic. The mechanical behaviour of PE, which is now being widely used to manufacture RTPs, is nonlinear. As a result, the overall response of fibre-reinforced PE composites to loading could be also nonlinear [18]. Therefore, it is reasonable to presume that the spoolability assessment of current RTP products could be affected by the consideration of the nonlinear mechanical behaviour of PE. However, the effect of this material nonlinearity on the spoolability estimate of RTPs has not been discussed in the literature.

The ply angles of ±54.7° are commonly used to manufacture RTPs for offshore oil and gas applications in order to fully utilise the strength properties of fibre reinforcements in the reinforcing layers [3]. This ply angle is chosen based on the "netting analysis", which is valid when the hoop to axial stress resultant ratio is 2:1 in thin-walled composite vessels when they are subjected to internal pressure [19,20]. The two angle-ply reinforcement layer systems with different angles of the reinforcement orientation can also be successfully employed due to the balanced nature of this type of composite structure [17].

One objective of the current paper is to study the flexural behaviour of RTPs, which are considered to be made from PE and fibre-reinforced PE plies, using FEA modelling. The effect of the material nonlinearity of PE on the spoolability assessment of an RTP is investigated. The spoolability of RTPs with different diameter-to-thickness (D/t) ratios and ply angles (single angle-ply reinforcing layer systems and two angle-ply reinforcing layer systems) is also analysed.

2. Numerical model

In the present work, flexural behaviour of an RTP composed of an inner thermoplastic liner, aramid fibre-reinforced thermoplastic reinforcing layers and an outer thermoplastic cover is investigated. An FEA model of the RTP subjected to pure bending is developed to simulate its structural response. In this model, one end of the RTP is kept fixed while the other end is free to rotate. At the free end, kinematic coupling is used to link the degrees of freedom of the nodes of the cross-section to a reference point located at the neutral axis. The loading scenario of the pipe being rolled onto a reel is modelled by applying rotation 'θ' at the reference point. The induced moment is determined by calculating the reactive moment at the reference point. The bend radius, R of the RTP is determined as L/θ, where L is the length of the pipe. The geometry, boundary conditions and the applied rotation are shown in Fig. 1.

For FEA simulation in Abaqus/Standard, the 4-noded doubly curved general-purpose shell element S4 is used to model the RTP. This element is based on the first-order transverse shear theory of flexible shells and considered appropriate for studying cases with arbitrarily large rotations and displacements [21]. The shell middle surface is selected as a reference surface. A mesh

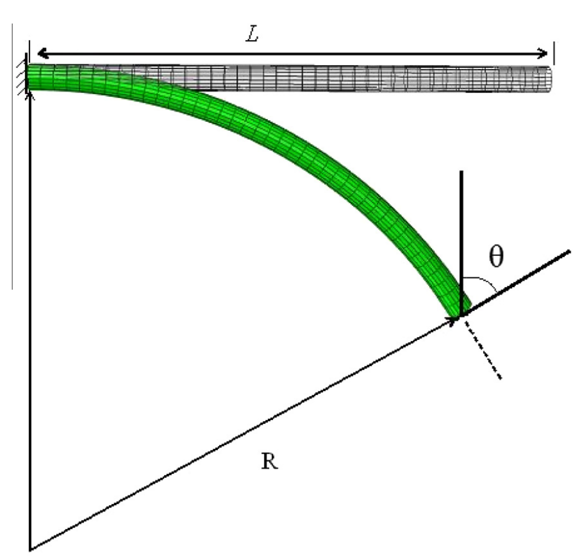

Fig. 1. Geometry, boundary conditions and applied rotation of the pipe.