OPTIMIZATION OF THE LAMINATE STACKING SEQUENCE FOR A FLEXIBLE SUBSEA PIPELINE OF PEEK/CF COMPOSITE

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Abstract. *One of the critical points of offshore production is the use of long subsea pipelines that withstand the functional, environmental and accidental efforts to which they are submitted. Also, considering the installation and transportation, the pipelines must present high flexibility and low specific weight. Thus, the use of high-performance composite materials proved to be an attractive and viable alternative. To meet the main launching methods currently used (Reel-Lay, S-Lay, and J-Lay), equipment of this nature must withstand high flexural efforts in its storage and transportation before installation. The present research was conducted to determine a fiber orientation sequence in laminate stacking that grants high flexibility and resistance to bending loading required by the storage and transportation (Reel-Lay method). The modeling was performed via finite element method using Abaqus™ software with the optimization process performed by Isight™ software. The material used is a carbon fiber reinforced PEEK composite produced by filament winding. In the studied bending loading case, the pipeline must be able to wind the reel of a certain radius. The orientation of the layers is the parameter to be optimized. Considering the composite manufacturing process, twelve possible orientations were considered in the optimization process (0° / ± 15° / ± 30° / ± 45° / ± 60° / ± 75° / 90°). An optimal stacking sequence was obtained and a critical reel-lay diameter was identified.*

1. INTRODUCTION

The upstream oil industry has reached unimaginable depths. For instance, 7000-meter-deep wells and 3000-meter-deep waters are already a reality. This advance creates even greater challenges for various engineering areas and requires optimized solutions, which in general adopts advanced materials or demands the development of new ones. The subsea pipelines are responsible for the interconnection between wells on the sea-bottom and the christmas tree pipeline, the extraction center which manages the oil pumping to the ship/platform. It is an extremely critical part of the process due to the highly aggressive conditions in which they are submitted, such as constant action of the ocean currents and platform movements. The high depths also require that the pipelines withstand high pressures under several hygrothermal conditions. Also, the pipeline must resist high bending stresses when the reel-lay storage process is used, as shown in Fig. 1.

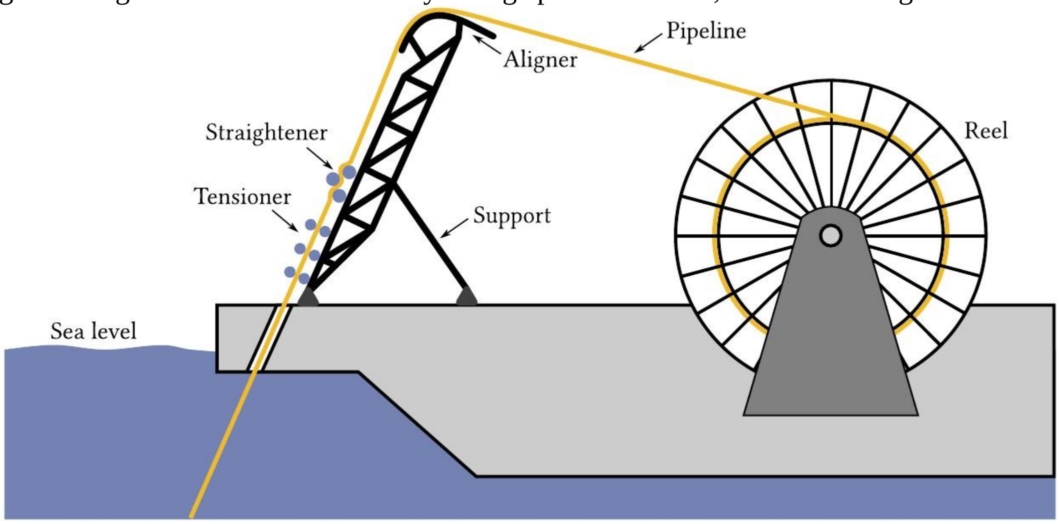

Figure 1 - Reel-Lay method schematic. Based on Hu et. al. [1].

The use of subsea pipelines made of composite materials is being adopted as a viable solution to improve their structural efficiency, much due to the reduced weight of the system and greater conformability of composite tubes, replacing metallic pipelines at deep extraction points [2]. For the application considered, positive aspects of polymeric-matrix composite materials are the lower specific weight, corrosion resistance, higher fracture toughness and the possibility to design the material according to specific conditions of usage. The material and the structure are designed in a unified process, for instance, the number of plies, their orientation, and fiber/matrix system can be chosen, which influences the final structure geometry, its inertia, and stiffness directly. The riser system as a whole need to be designed correctly to withstand mechanical stresses from different sources, such as intrinsic in-service, environmental, and accidental loads. The selection of an adequate production system is based on requirements such as environmental conditions, the number of risers, field depth and layout, production volume, and operating costs [3].

The present article aims to study the structural viability of the implementation of the Reel-Lay method on the process of storage and transportation of subsea pipelines made of composite materials via finite element simulations. The main goal is to optimize the laminate stacking sequence which allows the coiling of the tubes continuously on a reel having the smallest possible diameter. A simplified tubular model, developed in the software Abaqus™ was analyzed, along with an optimization routine using the software Isight™. The Hashin failure criterion (1980) was applied to evaluate the performance of the component, which emphasizes the probable onset of damage in a unidirectional laminated composite. The strength values adopted for the criterion were extracted from the literature.

2. MATERIALS AND METHODS

2.1. PEEK/CF composite laminate

The carbon fiber reinforced poly-ether-ether-ketone (PEEK/CF) composite was chosen due to its high mechanical and thermal resistance. The PEEK thermoplastic matrix is known for its excellent mechanical performance in comparison with other polymers, mainly due to its high fracture toughness, and for its high chemical and thermal resistance, with a working temperature of up to 260 °C [4]. The usage of the carbon fiber as a reinforcement grants the composite with improved mechanical and wear resistance, as well as thermal conductivity, allowing the implementation of such materials in high- performance applications, such as in the naval, automobilist, and petrochemical industries.

2.2. Finite element model description

The analyzed tube has an external radius of 85 mm and wall thickness of 10 mm. The numerical model consists of a pipeline section, aligned with the z-direction, submitted to a prescribed rotation in turn of the x-direction (Fig. 2).The rotation was applied in the tube edge via a simple linear analytical field considering small rotation angles, so that tan(θ) ~ θ. The rotation around the x-axis (rr_{xx}) is given by:

$$r_x = \frac{l}{r} \tag{1}$$

where l is the pipeline section length and r the reel-lay radius.

A local coordinate system (tt_1, tt_2, n) is adopted to describe the material orientation. The axis $tt1$ is aligned with z-direction, and axis n points to the pipeline center. The angle θ gives the material orientation with respect to the local coordinate system. The material coordinate system (1, 2, 3) has the third axis aligned with the n-direction, and the angle between 1 and tt_1 direction is θ. The model was created in Abaqus™ software and discretized using four-node quadrilateral shell elements (S4R), as can be seen in Fig. 2. For the laminate stacking, twelve layers with the same thickness were adopted, and the stacking direction is parallel to the direction 3. The laminate configuration was maintained as symmetrical.

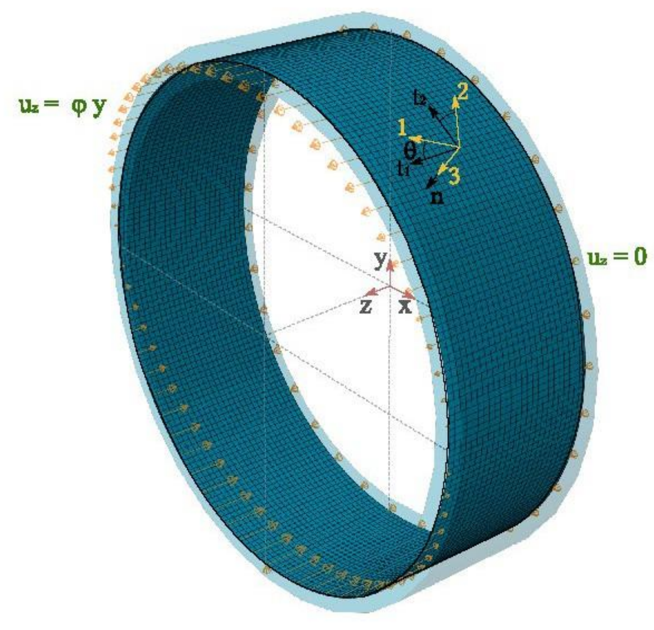

Fig.2 - Finite element model: geometry and boundary conditions and finite element mesh with S4R elements.

Material properties published by PEDERSON (2008) [3] was utilized as input in the model (Tab.1). The material was modeled as linear elastic and the composite ply is orthotropic.

Table 1 – Mechanical properties of a PEEK/CF composite lamina [5]. The direction 1 is parallel to the fiber direction and direction 2 belongs to the lamina plane.

Symbol	Material property	Value
E11	Young's modulus along direction 1 [MPa]	148296
E22	Young's modulus along direction 2 [MPa]	8825
E33	Young's modulus along direction 3 [MPa]	8825
Nu12	Poisson's ratio	0.342
Nu13	Poisson's ratio	0.342
Nu23	Poisson's ratio	0.350
G12	Shear modulus in 1-2 plane [MPa]	5377
G13	Shear modulus in 1-3 plane [MPa]	5377
G23	Shear modulus in 2-3 plane [MPa]	2976

Therefore, several reel diameters were analyzed to verify the structural feasibility of the application. The values of the curvature angles equivalent to the reel diameters are seen in Tab. 2.

Table 2 – Reel diameters and curvature angles analyzed

Reel diameter [m]	**10.0**	**10.5**	**11.0**
Prescribed rotation (r_x) [10^{-3} rad]	10.00	9.523	9.909

2.3. Failure Criteria

Because of the extremely aggressive environment in which subsea pipelines are submitted, and the difficulty of maintenance, a First Ply Failure methodology was adopted. This methodology is in agreement with the necessity of the high reliability of the components involved. The lamina failure is evaluated regarding the Hashin criterion. This criterion considers four types of mechanisms of damage onset: tensile stress in the fiber direction (direction 1), compression stress in the fiber direction, tensile stress along the perpendicular fiber direction (direction 2) and compression stress in the perpendicular fiber direction

Table 3 – PEEK/CF composite lamina failure stresses [3].

Symbol	Material property	Value
X1t	Tensile failure stress in fiber direction (direction 1) [MPa]	148296
X1c	Compressive failure stress in fiber direction (direction 1) [MPa]	8825
X2t, X3t	Tensile failure stress transverse to fiber direction (direction 2 and 3) [MPa]	8825
X2c, X3c	Compressive failure stress transverse to fiber direction (direction 2 and 3) [MPa]	0.342
S12, S13	Shear strength in 1-2 and 1-3 plane [MPa]	0.342
S23	Shear strength in 2-3 plane [MPa]	0.350

2.4. Determination of the laminate stacking sequence

The determination of the adequate laminate stacking sequence was performed using the software Isight™. This software generates an automatization routine, which allows the structure response of several simulations varying the model parameters until an objective is achieved, following an optimization algorithm. In this work, twelve different orientations were analyzed for each layer: 0; ± 15; ± 30; ± 45; ± 60; ± 75 and 90°, considering the manufacturing feasibility of the composite. The four Hashin failure criterion parameters were utilized as constraints in the analysis; in other words, when the critical value of any parameter reached a value equal or higher than 1 in any element, the configuration was deemed unfeasible. The objective parameter of the analysis was adopted as the minimization of the highest Hashin failure criterion parameter. The multi-island genetic algorithm (MIGA) optimization technique was chosen. A traditional genetic algorithm classifies each potential solution as an individual; individuals are then combined to form other improved individuals until the optimal global solution is achieved. MIGA divides the population of individuals into several “islands,” and the genetic operations are performed on each island separately, occasionally some chosen individuals migrate into other islands as the analysis progresses [7].

3. RESULTS

The optimization routine provided a [-45, 45,-45, 45, 45,-45]s stacking sequence as the optimized solution, regarding a minimum failure index for the Hashin criterion. This result is plausible since a 45° fiber orientation offers a fair balance between longitudinal and transversal resistance to the composite. The four Hashin criterion parameters distribution as a function of the thickness for the point with the highest failure index (points I and II in Fig. 3), considering the envelope, can be seen in Fig 4. The envelope consists of the highest value of the failure index along with the thickness direction. It can be noted that the indexes vary linearly with thickness and the most critical region is the external surface of the tube.

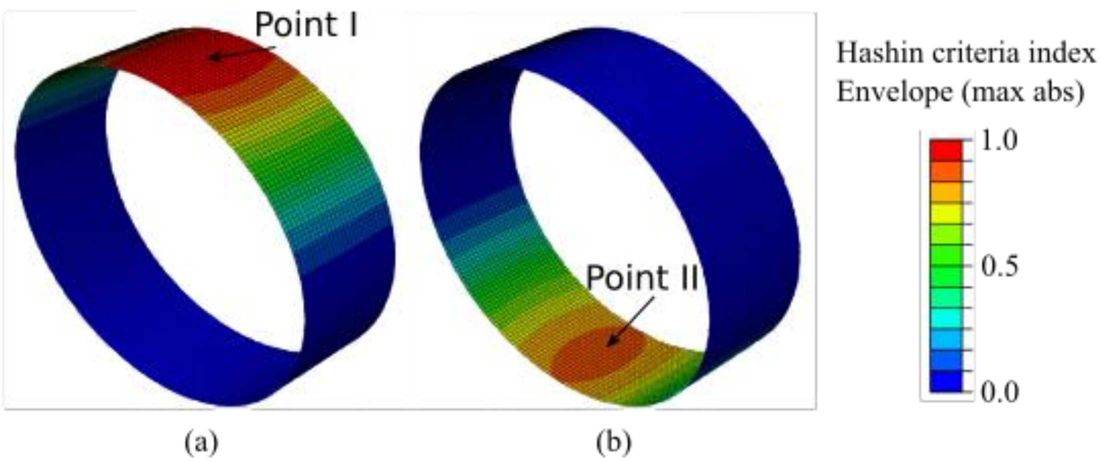

Figure 3 - Hashin criteria indexes for the critical diameter of 10.5 m. a) Criteria index for compression failure on transversal fiber direction (max at point I) b) Criteria index for tensile failure on transversal fiber direction (max at point II).

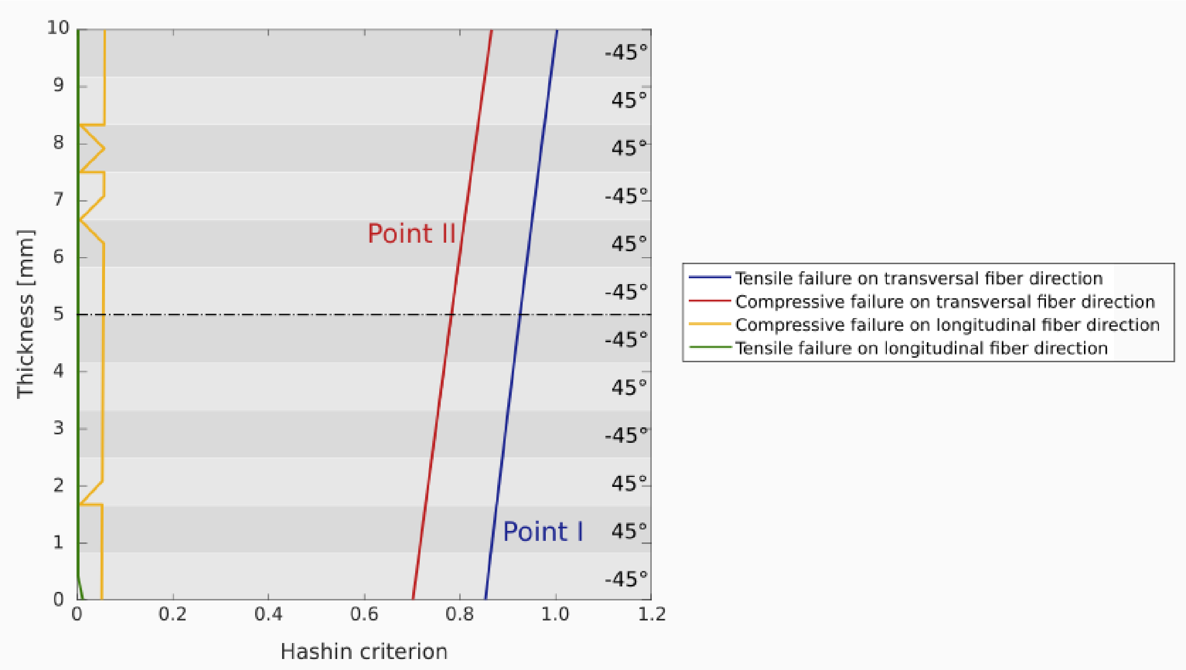

Figure 4 - Hashin criterion parameters of the composite along the thickness direction in the critical points for each criteria.

A minimum reel-lay diameter is an important design parameter to testify to the applicability of the composite pipelines as a solution. Table 4 summarizes the failure index for several reel-lay diameters. For diameters greater than 10.5 m, any stacking sequence has satisfied the failure criterion using the geometry constraints shown in Fig. 2.

Table 4 - Viability analysis considering twelve layers

Reel diameter [m]	10.0	10.5	11.0
Highest failure index (Tensile failure on transversal fiber direction)	1.180	1.003	0.975

4. CONCLUSIONS

The present article was dedicated to the study of a composite pipeline aiming its storage using the reel-lay method, which induces high bending loading in the material. The combined use of Isight™ and Abaqus™ software is a powerful tool for structural optimization. For the bending loading case studied, the computational tool led to a [-45,45,-45,45,45,-45]s laminate. A minimum reel-lay diameter of 10.5 m was found considering only the bending case. The results presented herein are preliminary. To approach a more realistic scenario, new analyses regarding other loading cases, e.g., axial and torsion, must be inserted in the optimization algorithm.

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REFERENCES

[1] X. Hu, M. Duan, P. Liu. Risk and Reliability Analysis of Deepwater Reel-Lay Installation: A Scenario Study of Pipeline during the Process of Tensioning. Natural Resources. 03. 156-163.10.4236/nr.2012.33020. (2012)

[2] R. Sérgio, M. Souza, A. Carlos, M. Dutra. Estudo de falhas em risers de fabricados em material compósito. Proceedings of 4º Congresso Brasileiro de Pesquisa e Desenvolvimento em Petróleo e Gás; October 21-24; Campinas - SP, Brasil. (2007)

[3] J. M. de Morais, Evolução da tecnologias de produção de petróleo em águas profundas. In: Petróleo em águas profundas: uma história tecnológica da Petrobras na exploração e produção Offshore. 1st edition: IPEA, Petrobras, p 139-214. (2013)

[4] P. Mallick. Fiber-Reinforced Composites - Materials, Manufacturing and Design; vol. 3. CRC Press. (2007).

[5] J. Pederson. Finite Element Analysis of Carbon Fiber Composite Ripping Using ABAQUS. Clemson University, All Theses. 512. https://tigerprints.clemson.edu/all_theses/512. (2008)

[6] Z. Hashin. Failure Criteria for Unidirectional Fiber Composites, Journal of Applied Mechanics, 47(2): 329–334. (1980).

[7] X. Hu, X. Chen, Y. Zhao, W. Yao. Optimization design of satellite separation systems based on multi-island genetic algorithm. Advances in Space Research, v.53, p. 870-876. (2014)

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