PROGRESSIVE FATIGUE DAMAGE MODELING OF COMPOSITE CURVED STRUCTURES USED IN OFFLOADING HOSES

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Abstract

Carbon fiber reinforced plastics (CFRP) have been used for manufacturing curved structures, which are applied in several equipment due to its high specific stiffness and strength. Recently, improvements in pultrusion and filament winding process allow the use of curved profile to manufacture coil and rings in equipment such as offloading hoses. In this research, a progressive fatigue damage modeling is proposed in order to simulate the fatigue behavior of unidirectional curved structure made of carbon fiber composite materials. In fact, a three-dimensional, non-linear, finite element model considering a central section of the hose was developed to simulate curved composites like coils and rings. A radial compressive displacement was applied in opposite direction to the fixed region. Kinetic theory of fracture (KTF) was used into the model to simulate the progressive fatigue damage. The failure analysis was carried out using the Multi-Continuum Theory (MTC). Using the proposed procedure, coils and rings fatigue life could be estimated. Therefore, this progressive fatigue damage modeling is an effective tool to predict failure in unidirectional curved composite structures used in offloading hose under fatigue.

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1. Introduction

Hoses made with vulcanized rubber are frequently used in offshore systems and represent a economically viable solution for oil transfer. The reliability of these hoses throughout their life affects the operational availability and environmental safety. Accordingly, the ability to resist loads and fatigue strength become subjects of interest. Due the high strain and its complex structure, the hoses are difficult to analyze with respect to the stress and strain field generated in different load cases [1]. Some studies establish a methodology for calculating the design life of the components with similar characteristics to hoses, such as high performance tires [2], elastomeric components [3], rigid and flexible risers [4]. However, little is known about the hoses behavior throughout its life and how to increase their performance under dynamic conditions.

As use of the composite materials, the fatigue analysis in this structures has great importance. Several studies on fatigue of composite materials have been developed in search find what your actual performance and prediction life in complex structures. One of the main applications of use composites in structures to optimize of the fatigue life occurs in turbine blades. Mahfouz et al. [5] conducted analyzes to predict life of turbine blades subjected to cyclic loadings imposed by environmental conditions, checking the damage to the structure. Gözcü et al. [6] establishes as turbine blade design criterion the use of fatigue analysis, and checks the use of composite materials to reduce fatigue damage to this structure. Bhuiyan et al. [7] developed a physics-based model material is fatigue based on the kinetic theory of fracture is incorporated in the structural model to predict structural-level composite fatigue life.

This work show a initial study to development of a physics-based model material of an offloading hose using carbon fiber composite material for the curved structure used as spiral. The model was developed using finite element analysis in a hose with 20 inch of internal diameter.

2. Simulation Method

With the exception of nearly perfect axial loading, fatigue failure is primarily a matrix-dominated event for polymer-matrix composites. Fatigue damage initiates with the accumulation of microcracks in the polymer. This microcrack accumulation process is the most rapid during the early stages of fatigue life, and eventually these microcracks coalesce and form a macrocrack which leads to ultimate catastrophic failure of the composite. Therefore, an accurate fatigue prediction for composite materials requires a modeling approach that calculates the microcrack accumulation during each loading cycle.

For the case of a fiber-reinforced polymer (FRP) composite material, the fatigue failure mechanism can be modeled with the Kinetic Theory of Fracture (KTF). Since the stresses in the polymer matrix of FRP composites are not the same as the stresses in the composite itself, a methodology for determining matrix stresses from the composite level stresses is required in order to apply KTF to the polymer. The fatigue model used here utilizes the MultiContinuum-Theory (MCT) to extract these polymer matrix stresses from composite stresses. The Kinetic Theory of Fracture (KTF), which describes bond breaking and bond healing as the thermally activated process, captures the relevant physics of polymer matrix fatigue [7].

Unidirectional composites exhibit two separate modes (or processes) of fatigue failure in the plane of the lamina: off-axis and on-axis. Each process must have its own activation energy and activation volume, as the physics of microcrack accumulation are different for the two types of cracking. In addition, the effective stress definitions will be different. In this section, we define the effective matrix stress for both off-axis and on-axis loading. Off-axis is used when cracking parallel to fibers for unidirectional composites occurs. Effective stress σ_{eff} is determined by matrix failure criterion in the form of transversely isotropic invariantes of the matrix stress tensor, calculated using MCT. On-axis oading failure results from matrix cracks that arrest at the fiber/matrix interface. Effetive stress is determined by tensile matrix stress normal to the fibers.

The equation 1 was used in the model to predict fatigue life of the composite structure. This equation can be integration to compute the damage evolution with time:

$$\frac{dn}{dt} = (n_0 - n)\frac{kt}{h}\left[exp\left(-\frac{U_b - \gamma_b \sigma_{eff}(t)}{kT}\right) - exp\left(-\frac{U_h}{kT}\right)\right], \qquad n(0) = n_i \tag{1}$$

Where, n_0 is the inicial damage parameter, n is the damage parameter that represented the percentage of microcrack density relative to the microcrack density at failure, k is the Boltzmann's constant, t is the time, T is the absolute temperature, h is the Planck's constant, U_b and U_h are the energy barrier for bond breaking and bond healing, γ_b is defined as an activation volume that corresponds roughly to the volume of material participating in the activated process. U and γ are calibrated using elastic material

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properties, static strength data, and two lamina-level fatigue curves (a longitudinal failure curve and an off-axis fatigue curve).

This process has been implemented in the commercial plugin Autodesk Simulation Composite Analysis 2015 (ASCA) which works with the finite element software Abaqus^{TM}. The hose are complex structure and loaded with cliclic load imposed by environmental condictions, as wind, wave and current. A structural model of the central sections of the hose has been developed as show in Figure 1. The main components of the hose used were rubber layers, reinforcement plies and the spiral. The load-bearing component is the wire spiral with mechanical properties to crushing, which is continuously spiraled on the hose at a diameter, pitch and size specifics, in order to support structure of the hose, preventing collapse, obstruction or kink. The spiral was modeled as carbon fiber composite as a transversaly isotropic material. The other parameters of the finite element model and boundary conditions are more explained in [8]. The number cycles and the failure mode (longitudinal or transverse) are calculated only in spiral composite at ambient temperature (297.1 K). The spiral composite is the unique component that resists crush loading in this section hose. It was observed what the first element failed and the global failure of the structure.

Two steps were used in the simulations, the first step, the model was submitted to maximum radial load of 41 kN. In the second step, the model was submitted to cyclic load. A history load was used, being P_{max} and P_{min} equal to 15 and 45% of the minimum and maximum load, respectively. As the input file for the problem is executed, the composite stresses calculated by the finite element code are sent as an input to ASCA where the fatigue model is implemented.

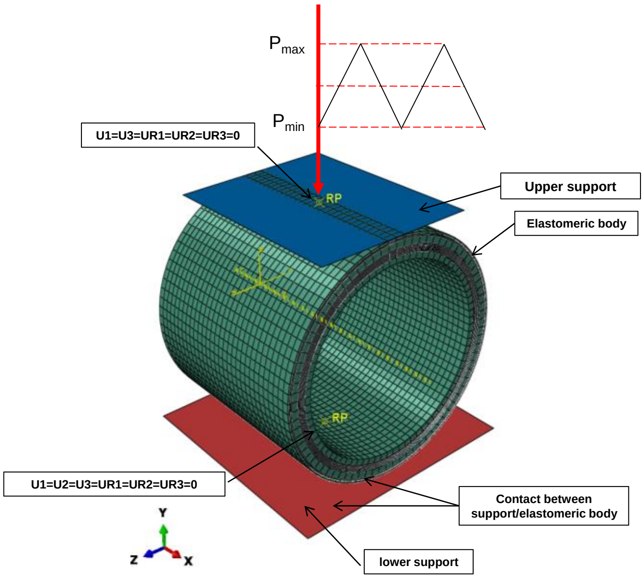

Figure 1. Details of the finite element model used to simulate the fatigue life.

3. Material properties

The fatigue methodology requires in-situ properties of the constituents, static strength two fatigue caracterizations curves. The mechanical properties of the carbon fiber/epoxy composite were obtained from [8] and show in Table 1. A micromechanical analysis to obtain the mechanical properties of the constituent was carried out.

Fatigue curves were used to characterization the behavior in fatigue of the material. The curves were obtained in Kawai et al. [9] to carbon/epoxy composite. The fatigue properties are compiled in Table 2. It was used two fatigue curves, one longitudinal fatigue curve (on-axis) and another with angle of loading 60° (off-axis) fatigue curve.

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Table 1. Mechanical properties values used as input in the model.

Mechanical properties	*Composite*	*Fiber (carbon)*	*Matrix (epoxy)*
ρ_c (g/cm³)	1.49	-	-
V_f (%)	61.3	-	-
E_{11} (GPa)	116.3	186.8	3.5
$E_{22} = E_{33}$ (GPa)	7.9	14.6	3.5
$\upsilon_{12} = \upsilon_{13}$	0.32	0.31	0.30
υ_{23}	0.37	0.23	0.30
$G_{12} = G_{13}$ (GPa)	4.05	16.6	1.3
G_{23} (GPa)	2.87	5.88	1.3
σ_{11}^T (MPa)	1878.1	-	-
σ_{22}^T (MPa)	59.0	-	-
σ_{11}^C (MPa)	937.0	-	-
σ_{22}^C (MPa)	213.0	-	-
τ_{12} (MPa)	68.3	-	-
τ_{13} (MPa)	67.7	-	-
τ_{23} (MPa)	67.0	-	-

Table 2. Fatigue S-N data for the carbon fiber/epoxy composite found in literature (f=10 Hz and R=0.1).

Stress (MPa)	*N (cycles)*	*Angle of Loading*
1655	61	0
1197	1741	0
1407	2520	0
1219	8930	0
1134	14810	0
1100	19950	0
1002	388600	0
1002	588200	0
79	47020	60
70	114300	60
70	168300	60

4. Results and discussion

The fatigue analysis of the hose section was performed after a static analysis. The effective stress σ_{eff} at the matrix has been used to calculate the fatigue loading cycle on the hose. Figure 2 shows the displacement vs number of cycles of the spiral used in hose section. The structure shows a displacement of 38.3 mm due the radial load in first cycle. A initial failure is observed between 1-2 milions of cycles when the displacement change compared to the initial cycles. It was observed a global failure in the structure between 2-3 milions of cycles. Because it is a failure with damage, simulation data was approached by a sigmoidal curve and dose-response equation with good agreement of the equation with the simulation data. It was generated the curve of the first order derivative curve where it was found that the peak of the curve is 2.63×10^6 cycles which shows the global failure of the section at that point.

A failure mode in the longitudinal direction of the fibers was evidenced in the first element. After the first element, others elements show failure modes in the longitudinal and transverse fiber direction ultil occur the global failure in the structure. The predominance of the failure mode in the longitudinal fiber direction shows that the spiral fails mainly caused by the load bending.

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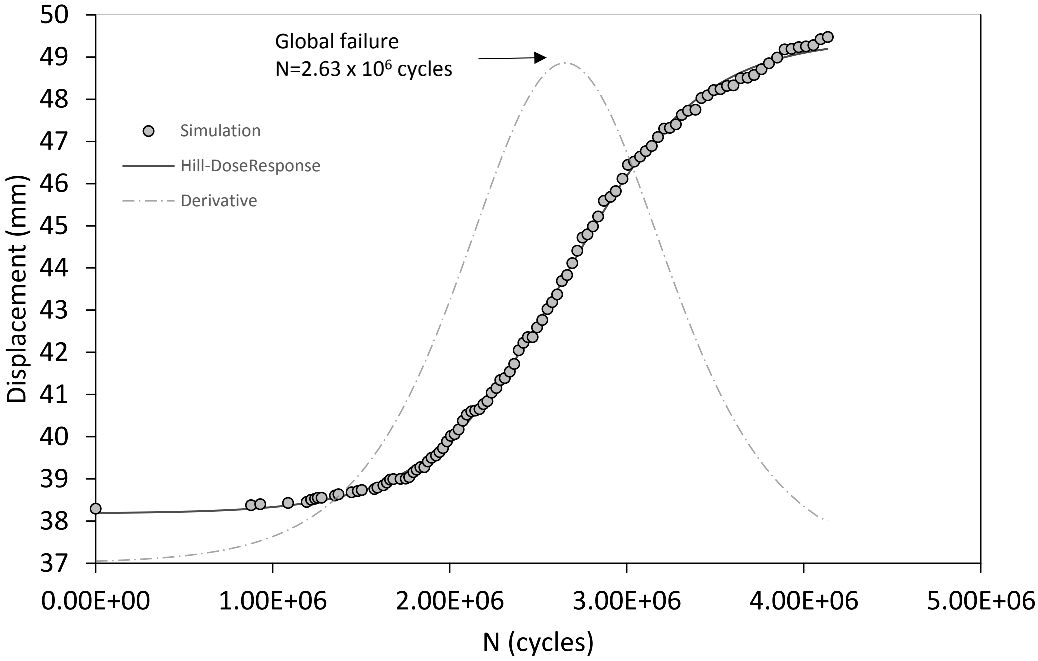
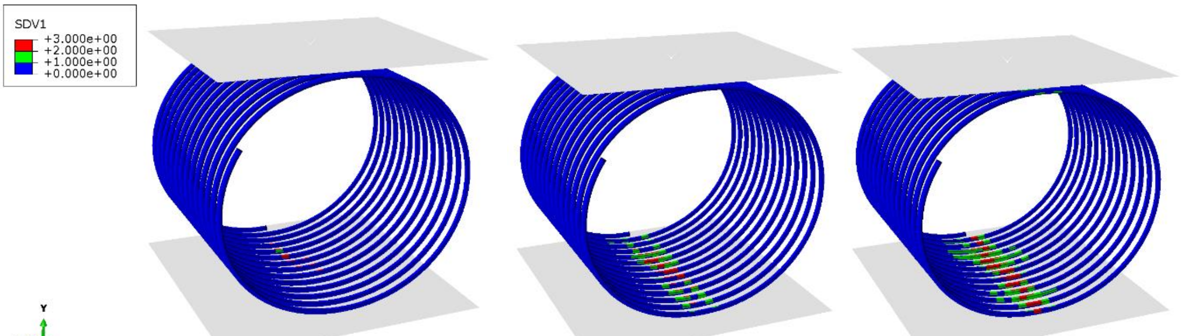


Figure 2. Displacement vs number of cycles.

Figure 3 shows the failure index of the spiral used in hose section using the MCT failure criteria with the failure index SDV1. It can observed that the initiation of matrix failure occurs in the region where the spiral tends to increase in diameter due to the radial load, being . In $1.59\times\ 10^{6}$ cycles same elements show failure. With increase load cycles, in $2.63\times\ 10^{6}$ the global failure of the structure occurs and in $3.01\times\ 10^{6}$ all turns of the spiral are failed.



Number of cycles=1.59×10^{6} Number of cycles=2.63×10^{6} Number of cycles=3.01×10^{6}

Figure 3. Propagation of progressive failure in spiral indicated by the failure index.

5. Conclusions

A progressive fatigue model of the hose offloading section of the curved structures has been developed with good results. A methodology for predicting fatigue life of complex structures, as curved composite for hose offloading was outlined. This methodology requires same characterization data and it was computationally efficient. Even after fatigue failure, the hose section does't show significant increase in the radial displacement. The spiral presented the first failure mode in the longitudinal direction of the fiber. This study was aimed to verify the fatigue life of curved profile applied to hose section with numerical analysis, but in future work should be carried out model validations with performing experimental tests.

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References

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[1] T. Lassen, A.I. Len and G. Imingen. Load response and finite element modelling of bonded offshore loading hoses. *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering – OMAE*. *San Francisco*. *USA*. June 8–13 2014.

[2] K.M. Jeong, H.G. Beom, K.W. Kim and J.R. Cho. Fatigue life prediction for radial truck tires using a global-local finite element method. *Interaction and Multiscale Mechanics*, 4:35-47, 2011.

[3] T. Zarrin-Ghalami and A. Fatemi. Multiaxial fatigue and life prediction of elastomeric components. *International Journal of Fatigue*. 55:92-101. 2013.

[4] F.C.M. Takafuji and C.A. Martins. Comparison of different approaches for fatigue damage accumulation in steel risers. *Proceedings of the 30th International Conference on Ocean, Offshore and Arctic Engineering*. *Rotterdam*. *The Netherland.* June *19-24* 2011.

[5] H. Mahfuz, M. Canino, T. Suzuki and F. Zhou. Design and fatigue analysis of composite turbine blades under ocean wave current loading. *Proceedings of the 20th International Conference on Composite Materials ICCM-20. Copenhagen. Denmark.* July 19-24 2015.

[6] M. Ozan Gözcü, T. Farsadi, Ö. Şener and A. Kayran. Reduction of fatigue damage equivalent loads in the wind turbine system through the use of off-axis plies in the spar caps of composite wind turbine blades. *Proceedings of the 20th International Conference on Composite Materials ICCM-20. Copenhagen. Denmark.* July 19-24 2015.

[7] F.H. Bhuiyan, D.J. Mavriplis and R.S. Fertig. Predicting Fatigue Life of Composite Wind Turbine Blades Using Constituent-Level Physics and Realistic Aerodynamic Loads. *Proceedings of the 57th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference. San Diego. USA*. January 4-8 2016.

[8] M.L.P Tonatto, R. Teles, M.M.C Forte, V. Tita and S.C Amico. Analysis of carbon fiber composite coil and ring for offloading hoses under crushing load via computational modelling. *Proceedings of the 20th International Conference on Composite Materials ICCM-20. Copenhagen. Denmark.* July 19-24 2015.

[9] M. Kawai, S. Yajima, A. Hachinohe and Y. Kawase. High-temperature off-axis fatigue behaviour of unidirectional carbon-fibre-reinforced composites with different resin matrices. *Composites Science and Technology*. 61: 1285–1302. 2001.

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