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Failure analysis of thick composite curved tubes

Hamidreza Yazdani Sarvestani *, Mehdi Hojjati

Department of Mechanical and Industrial Engineering, Concordia University, Montreal, Quebec H3G 1M8, Canada

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ABSTRACT

In the present paper, a progressive failure analysis of thick laminated composite curved tubes subjected to pure bending moment is conducted proposing a novel high-order displacement-based method. The most general displacement field of elasticity of thick laminated composite curved tubes is developed employing a displacement approach of Toroidal Elasticity and the layer-wise method. Subsequently, the accuracy of the proposed method is verified by comparing numerical results obtained by the proposed method with finite element method (FEM) and experimental data. By employing the proposed method, a progressive failure analysis is performed using Tsai-Wu criterion. Finally, effects of lay-up sequences of thick composite curved tubes on stress distributions and failure sequences are investigated.

1. Introduction

Composite straight and curved tubes are used as primary load-bearing structures in many engineering fields such as aerospace, offshore and infrastructure industries. One such application is the cross-piece for helicopter landing gears. These structures usually are moderately thick and they are subjected to certain loads such as tension, torsion, shear and bending. The study on failure behavior of composite tubes subjected to mechanical loading is required to understand their design potentials. Composite curved tubes are much more difficult in analysis especially in a progressive failure analysis than isotropic tubes due to their anisotropy. Moreover, prediction of the state of stress and strain in different layers of laminated composite tubes is of theoretical interest and practical importance. An accurate evolution of stresses is essential for failure analysis and better design of structures. A large number of studies have been conducted to obtain stresses and perform failure analysis on composite straight tubes and curved beams [5–23].

1.1. Stress analysis

1.1.1. Isotropic curved tubes

Von Karman [1] found a theoretical explanation for higher flexibility of a curved tube in bending compared to a straight tube. A particular case of Von Karman problem, the so-called Brazier effect, is buckling analysis of straight or curved tubes [2]. Their works provided fundamentals for much of subsequent tube analyses. Boyle [3] used a nonlinear theory of shells to formulate the tube bending problem. Emmerling [4] determined a nonlinear deformation of elastic curved tubes subjected to bending loads. He also studied the pre-critical deformation of tubes based on the semi-membrane theory. Levyakov and Pavshok [5] investigated a thin elastic curved tube subjected to pure bending using finite element method. In addition, buckling behavior of curved tubes was analyzed and effects of geometrical parameters of tubes on the critical bending moment were studied. A stress analysis of composite curved tubes subjected to in-plane bending was performed based on finite curved elements [6]. A fifth-order polynomial and Fourier series were used to define displacement components. Kolesnikov [7] analyzed large pure bending deformations of homogenous, incompressible, isotropic and hyperelastic curved tubes with a closed cross-section. Equilibrium equations were reduced to ordinary differential equations based on membrane assumptions. Yudo and Yoshikawa [8] used a nonlinear finite element analysis to study the buckling phenomenon for straight and curved tubes under a pure bending moment. Effects of a cross-sectional deformation on elastic buckling moment were investigated considering the length-to-diameter ratio and the diameter-to-thickness ratio.

1.1.2. Orthotropic curved beams

Ting [9] and Chen et al. [10] investigated a cylindrical anisotropic circular tube subjected to pressure, shear, torsion and extensive loads for axisymmetric deformation of a homogeneous tube assuming stresses as a function of radial distance. Shear and radial stresses in curved beams were developed based on satisfying both

* Corresponding author.
E-mail address: h_yazd@encs.concordia.ca (H. Yazdani Sarvestani).

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equilibrium equations and static boundary conditions on surfaces of beams [11]. Dryden [12] obtained stress distributions across a functionally graded circular beam subjected to pure bending using stress functions. Free vibration analysis was performed on functionally graded beams with curved axis using a finite element method to discretize motion equations [13]. A first order shear deformation theory was used to study static and free vibration behavior of generally laminated curved beams [14]. Wang and Liu [15] presented elasticity solutions for curved beams with orthotropic functionally graded layers subjected to a uniform load on the outer surface by means of Airy stress function method. A mathematical model was developed to analyze mechanical behavior of laminated glass curved beams [16].

1.2. Failure analysis

Thuis and Metz [17] investigated effects of lay-up sequences on energy absorption of composite cylinders loaded in compression. Different failure modes for different laminates were observed. An energy based failure model was used to analyze the impact resistance of composite shells [18]. Effects of pressure and curvature on the impact response were investigated. In another work [19], ABAQUS finite element code was used to study composite laminates and shell structures subjected to low-velocity impact. Element type, impactor modeling method, meshing pattern and contact modeling were investigated to obtain an accurate solution. Ismail et al. [20] studied buckling failures of thin composite cylindrical shells under axial compressive loading. Initial geometric and loading imperfections were investigated to find out their effects on buckling failure. Romano et al. [21] performed a progressive failure analysis to study both post buckling and final failure of damaged composite stiffened panels subjected to compressive load. Damage locations and the reduction of the panel stiffness were studied. Mahdavi et al. [22] investigated different failure mechanisms of filament-wound tubes subjected to tensile forces. They obtained hoop and tensile strengths of tubes with a specific geometry and layer numbers. Chaudhuri [23] studied long thick composite cylindrical shells subjected to hydrostatic pressure. Effects of modal imperfections, transverse shear/normal deformation on propagation of fracture mode were analyzed. Tan et al. [24] performed experimental tests to investigate failure mechanisms of a quasi-isotropic CFRP laminate, containing a circular hole, under combined tension and shear or compression.

The above review shows that there is a need to work on stress and progressive failure analyses for thick composite curved tubes subjected to mechanical loadings. Although finite element methods are used for analyzing such structures, it is necessary to create a new model for structures when dimensions or lay-up sequences are changed. In response to this need for an alternative, rapid, and low computational cost method, the focus of this paper is to propose a method where inputs to obtain solutions are simple; i.e. one only needs to provide inputs of dimensions or lay-up sequences without a need to create a new model. The present work is devoted to develop a method that can provide stresses, strains and deformations for thick composite curved tubes subjected to pure bending moment with simple inputs. Displacement approach of Toroidal Elasticity (TE) and the layer-wise method are used. Comparison is made between results obtained for the proposed analytical method with experimental data and FEM. There is a good agreement of the developed method with experimental data and FEM. Practical lay-up sequences are considered to study their effects on stress distributions of thick laminated composite curved tubes. Finally, a progressive failure analysis using Tsai-Wu criterion is conducted to determine maximum bending moments and failure sequences of composite curved tubes.

2. Motivation

Conventional helicopter landing gears consist of two skids running along the main direction of the helicopter, and two parallel cross tubes connecting the skids together as seen in Fig. 1. Cross tubes of helicopter landing gears consist of both straight and curved tubes which support the weight of helicopters. Despite the numerous advantages of composite materials, they generally suffer from poor impact resistance, poor fracture toughness and poor delamination strength when used in the aforementioned applications. These problems are addressed using thermoplastic-matrix composites. Derisi [25] designed and manufactured thermoplastic composite straight tubes for helicopter landing gears. Another technique to solve for the drawbacks of thermoset-matrix composites, such as poor delamination strength, is using improved lay-up sequence design. Recently, a method for the stress analysis of thick composite straight tubes subjected to cantilever loading was developed [26,27]. Now, in order to provide some insight into the mechanical behavior of the curved part of composite helicopter landing gears, a simple-input displacement-based method is developed. Specifically, this method is used to evaluate stresses and perform a progressive failure analysis in thick laminated composite curved tubes.

3. Formulation

First, in Section 3.1, the displacement field for a composite curved tube with a single layer is derived using Toroidal Elasticity and the method of successive approximation. Then, in Section 3.2, by using the developed displacement field of single-layer composite curved tubes and layer-wise method, a new displacement-based method is proposed to analyze thick arbitrary laminated composite curved tubes. Note that the detailed derivations can be found in [28,29]. Here, necessary formulations are explained briefly.

3.1. Displacement field of single-layer composite curved tubes

Toroidal elasticity is a three-dimensional theory used for a elastostatic analysis of thick curved tubes. Here, a displacement approach of Toroidal Elasticity is chosen to analyze composite curved tubes. The governing equations are developed in three toroidal coordinate systems. The method of successive approximation is used to obtain the displacement field of single-layer composite curved tubes.

3.1.1. Governing equations in toroidal coordinates

A thick laminated composite curved tube with a bend radius R, mean radius R_1 and thickness h is subjected to a pure bending moment, M, as shown in Fig. 2a. Annular cross section is bounded

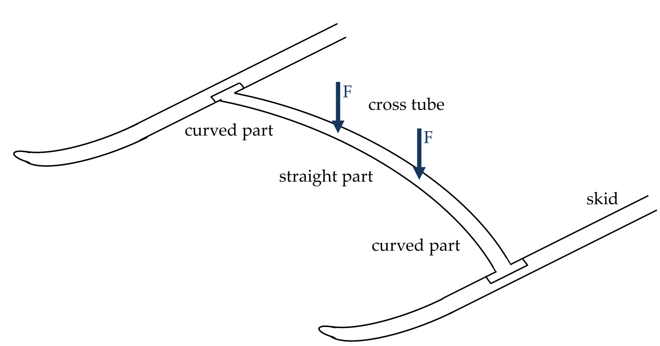

Fig. 1. Helicopter landing gear.