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Numerical buckling analysis of an inflatable beam made of orthotropic technical textiles

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ABSTRACT

This paper is devoted to the linear eigen and nonlinear buckling analysis of an inflatable beam made of orthotropic technical textiles. The method of analysis is based on a 3D Timoshenko beam model with a homogeneous orthotropic woven fabric. The finite element model established here involves a three-noded Timoshenko beam element with C^0-type continuity for the transverse displacement and quadratic shape functions for the bending rotation and the axial displacement. In the linear buckling analysis, a mesh convergence test on the beam critical load was carried out by solving the linearized eigenvalue problem. The stiffness matrix in this case is generally assumed not to be a function of displacements, while in the nonlinear buckling problem, the tangent stiffness matrix includes the effect of changing the geometry as well as the effect of the stress stiffening. The nonlinear finite element solutions were investigated by using the straightforward Newton iteration with the adaptive load stepping for tracing the load–deflection response of the beam. To assess the effect of geometric nonlinearities and the inflation pressure on the stability behavior of inflatable beam: a simply supported beam was studied. The influence of the beam aspect ratios on the buckling load coefficient was also pointed out. To check the validity and the soundness of the results, a 3D thin-shell finite element model was used for comparison. For a further validation, the results were also compared with those from experiments at low inflation pressures.

1. Introduction

Finite element (FE) analyses of inflated fabric structures present a challenge in that both material and geometric nonlinearities arise due to the nonlinear load/deflection behavior of the fabric (at low loads), pressure stiffening of the inflated fabric, fabric-to-fabric contact, and fabric wrinkling on the structure surface. In addition to checking fabric loads, the finite element model is used to predict the fundamental mode of the inflated fabric beam. In general, the FE analyses of thin-walled structures can be almost performed by many robust FE package such as ABAQUS and ANSYS. However, in reality, the built-in shell and membrane elements are not very suitable for describing the inflatable structure applications with an orthotropic fabric. The shell elements are quite rigid, while membranes are too flexible. This leads to the need for the numerical models with a specific element appropriates for inflated fabric structures.

In the reviewed literature, only the inflated tensile structures have been addressed and, the response of an inflated lightweight structure to service loads has been examined. Papers in this category generally assume homogeneous isotropic and orthotropic material properties for the inflated structure and employ the membrane or thin shell theory to determine the structural response.

In earlier work, Libai and Givoli [1] derived the equations governing the incremental state of stress in an orthotropic circular membrane tube. The membrane in this study was taken to be hyperelastic and was not specified in detail. The changes in loading, including uniform internal pressure and longitudinal extension, are regarded as small perturbations on the initial homogeneous state of stress. The approach was based on the linearization of the equations about a known homogeneous reference state. The rectangular elements with Hermite cubic shape functions were used in conjunction with the variational principles. Wielgosz and Thomas [2–4] developed an inflatable beam finite element and

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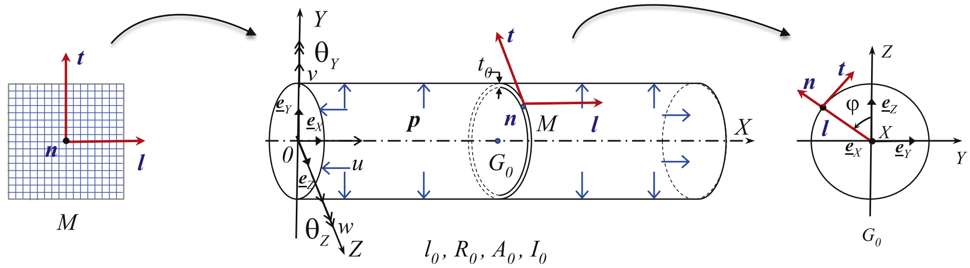

Fig. 1. HOWF inflatable beam.

used it to compute the deflection of hyperstatic beams. The element used is a membrane one. Then, Bouzidi et al. [5] described two finite elements for 2D problems of inflatable membranes: axisymmetric and cylindrical bending. The elements built with the hypothesis of large deflections, finite strains and with follower pressure loading. The numerical solution is obtained by solving directly the optimization problem formulated by the theorem of the minimum of the total potential energy.

Also, by employing membrane elements and experimental results, Cavallaro et al. [6] showed that pressurized tube structures differ fundamentally from conventional metal and fiber/matrix composite structures. This study led to a note that while the plain-woven fabric appeared to be an orthotropic material, the fabric does not behave as a continuum, but rather as a discrete assemblage of individual tows, whose effective material properties depend on the internal pressure of the beam, weave geometry and the contact area of interacting tows.

Suhey et al. [7] presented the finite element model of an inflatable open-ocean-aquaculture cage using membrane elements with assuming that the material is anisotropic. The authors used nonlinear elements to model the tension-only behavior of the fabric material in order to calculate the magnitudes of the deflection and the stress at the onset of wrinkling. The results were verified by the modified conventional beam theory [8,9].

Le van and Wielgosz [10,11] obtained the numerical results with a beam element developed from the earlier work of Fichter [12] and the 3D isotropic fabric membrane finite element. In their approach, the governing equations were discretized by the use of the virtual work principle with Timoshenko's kinematics, finite rotations and small strains. The linear eigen buckling analysis were carried out through a mesh convergence test using the 3D membrane finite element computations. Last recently, Apedo et al. [13] investigated linear and nonlinear finite element solutions in bending by discretizing nonlinear equilibrium equations obtained from his previous analytical model in which a homogeneous orthotropic fabric was considered.

In inflatable structures, with the arising of the local buckling that leads to the formation of the wrinkles, nonlinear problems pose the difficulty of solving the resulting nonlinear equations that result. Problems in this category are geometric nonlinearity, in which deformation is large enough that equilibrium equations must be written with respect to the deformed structural geometry. Few works have dealt with buckling analysis of inflated structures. By means of the total Lagrangian formulation developed by Le van and Wielgosz [10,11], Diaby et al. [14] proposed a numerical computation of buckles and wrinkles appearing in membrane structures. The bifurcation analysis is carried out without assuming any imperfection in the structure. In consideration of an inflatable beam, Davids and Zhang [15] developed a quadratic Timoshenko beam element based on an incremental virtual work principle that accounts for fabric wrinkling via a moment-curvature nonlinearity. However, in these studies, the materials were assumed to be isotropic.

This paper is devoted to the linear eigen and nonlinear buckling analysis of simply supported inflatable beam made of orthotropic technical textiles. The method of analysis is based on a 3D Timoshenko beam model with a homogeneous orthotropic woven fabric (HOWF). The finite element model established here uses a three-noded Timoshenko beam element with C^0-type continuity for the transverse displacement and quadratic shape functions for the bending rotation as well as the axial displacement. The effects of geometric nonlinearities and the inflation pressure on the stability behavior of inflatable beam are assessed: a simply supported beam is studied. The influence of the beam aspect ratios on the buckling load coefficient are also pointed out. A 3D thin-shell finite element model is then utilized for comparison. Finally, the obtained results are also compared with experimental results.

2. Governing equations

In this section the governing equations of a 3D Timoshenko beam with a HOWF are briefly presented. The Green-Lagrange strain measure is used due to the geometrical nonlinearities.

Fig. 1 shows an inflatable cylindrical beam made of a HOWF. l_0, R_0, t_0, A_0 and I_0 represent respectively the length, the fabric thickness, the external radius, the cross-section and the moment of inertia around the principal axes of inertia Y and Z of the beam in the reference configuration which is the inflated configuration. A_0 and I_0 are given by

$$A_0 = 2\pi R_0 t_0, \tag{1}$$

$$I_0 = \frac{A_0 R_0^2}{2} \tag{2}$$

where the reference dimensions l_0, R_0 and t_0 depend on the inflation pressure and the mechanical properties of the fabric [16]:

$$l_0 = l_\phi + \frac{pR_\phi l_\phi}{2E_t t_\phi}(1-2\nu_{lt}) \tag{3a}$$

$$R_0 = R_\phi + \frac{pR_\phi^2}{2E_t t_\phi}(2-\nu_{lt}) \tag{3b}$$

$$t_0 = t_\phi - \frac{3pR_\phi}{2E_t}\nu_{lt} \tag{3c}$$

in which l_ϕ, R_ϕ, and t_ϕ are respectively the length, the fabric thickness, and the external radius of the beam in the natural state.

The internal pressure p is assumed to remain constant, which simplifies the analysis and is consistent with the experimental observations and the prior studies on inflated fabric beams and arches [8–12,14,15,17–20]. The initial pressurization takes place prior to the application of concentrated and distributed external loads, and is not included in the structural analysis per se.

M is a point on the current cross-section and G_0 the centroid of the current cross-section lies on the X-axis. The beam is