



Inflation and bending of an orthotropic inflatable beam

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ABSTRACT

An inflatable beam is an airtight structure made of a soft technical fabric and subjected to an internal pressure which gives it a final cylindrical shape, a pre-stress in the membrane and a bearing capacity. Against all appearances, it is not a standard beam and it requires a specific formulation in order to take account of the internal pressure which plays a key role in its mechanical response.

This work deals with inflatable beams made of orthotropic materials. The first part of the paper is concerned with the inflation of the membrane tube, an important stage which is often neglected so far in the literature. As preliminaries of the bending problem studied in the next part of the paper, the constitutive law related to the inflated state of the tube – not the natural state – is investigated. It will be shown that the constitutive law related to the inflated pre-stressed state is not the same as the constitutive law related to the natural state. Expressions of the material coefficients involved in the former constitutive law will be established from the material coefficients defined on the natural reference configuration which are the only ones supposed to be known. The second part of the paper deals with the bending of the inflatable beam. The Timoshenko beam kinematics will be chosen because of the significant shear effect in the tube wall and the problem will be formulated in finite deformations in order to account for all the nonlinear effects, in particular the action due to the internal pressure which is a follower load. The nonlinear system of equations obtained will then be linearized around the pre-stressed configuration and will result in a more tractable linear system. The proposed formulation allows a comprehensive study of the influence of the internal pressure on the geometry and material properties of orthotropic inflatable beams. The analytical results will be compared with numerical results obtained from a nonlinear membrane finite element code.

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1. Introduction

Inflatable structures made of modern textiles have been used for several decades. Among their applications in space industry, there are deployable antennas, inflatable re-entry capsules and inflatable solar power sails, mainly made of isotropic fabrics. The inflatable technology is also widely applied to terrestrial structures, both in civilian and military fields. Today, large inflatable structures are built for sports centers, exhibition halls and storage shelters. The fabrics used in these types of structures are often made of warp and weft threads which ensure the mechanical resistance and a coating which ensures the airtightness. In comparison with conventional structures, the inflatable structures may present some advantages in some specific cases: they are light, easily foldable, easily to transport, deploy. Moreover, it is not very expensive to manufacture them and keep them deployed.

The pressurized membrane structures are often made of bearing components which take the shape of tubes or beams. Each

component is made of an airtight fabric and subjected to an internal pressure which gives it a final cylindrical shape, a pre-stress in the membrane and a bearing capacity. In the sequel, mention will be made of two types of reference configuration:

- (i) the *natural* configuration, where there is no external loads and the stress field is zero. The geometry and material properties are supposed to be known in the natural configuration. The membrane has no bearing capacity in this state;
- (ii) the *pre-stressed* configuration, where the membrane structure is subjected to the internal pressure only. The geometry and, as will be seen below, the material properties are different from those in the natural state. The bearing capacity of the structure should increase with the pre-stress, i.e. with the internal pressure.

Several works have been conducted in the literature to predict the behavior of an inflated tube subjected to bending loads. In these works, the reference configuration corresponds to the pre-stressed configuration of the inflated tube.

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The earliest analytical expressions for the load-deflection response and the collapse load of a cantilever pressurized membrane tube can be found in Comer and Levy's paper [1]. In this work, the usual Euler–Bernoulli kinematics was chosen and it was assumed that the tube is made of an isotropic linear elastic material. Later, Webber [2] extended Comer and Levy's theory [1] to the case of a tube subjected to bending and twisting, and succeeded in determining how a twisting moment modifies the deflection, the wrinkling load as well as the collapse load. Afterwards, Main et al. [3] improved Comer and Levy's theory of pressurized membrane tubes [1] by considering the effect of the bi-axial stress state on the wrinkling. Experiments were conducted on pressurized tubes with circular cross-sections and the results obtained were compared with those given by Comer and Levy's theory [1]. In another study, Main [4] took the orthotropic property of the fabric into account so as to enhance his previously developed theory. Suhey et al. [5] carried out numerical computations on anisotropic pressurized membrane tubes by means of membrane finite elements and validated their finite element model by comparing their numerical results with Main et al.'s theoretical results in [3,4].

When using the Euler–Bernoulli kinematics, the internal pressure does not appear in the expression of the deflection. In order to improve the previous formulations, many other authors preferred to use the Timoshenko kinematics which is more appropriate for thin-walled beams.

A major contribution in this formulation type is due to Fichter [6] who developed a theory for pressurized cylindrical membrane tubes made of isotropic membrane. His approach was based on the minimization of the total potential energy. After linearization, Fichter successfully derived the analytical equations for the bending problem of a pressurized membrane tube, exhibiting the very term of the internal pressure in the deflection expression.

Steeves [7] adopted a similar approach and proposed solutions in terms of Green functions. Wielgosz and Thomas [8,9] dealt with analytical solutions for inflatable isotropic beams and panels by establishing the equilibrium equations in the deformed state in order to incorporate the internal pressure in their formulation. They considered the internal pressure as a follower force which represents the strengthening effect on the bending and shear stiffnesses. Le van and Wielgosz [10] improved Fichter's theory [6] by using the virtual power principle in the context of the total Lagrangian formulation. They considered large displacements and rotations in order to take account of all the nonlinear terms in the kinematic and equilibrium equations, and proposed solutions for the bending and buckling of a pressurized isotropic membrane tube. Davids and Zhang [11] confirmed Fichter's results by considering the pressure work during the volume change in isotropic Timoshenko beams. On the basis of [10], Apedo et al. [12], Nguyen et al. [13] went further by developing a theory for pressurized membrane tube made of an orthotropic material. They first used a 3D kinematics and then linearized their formulation. The bending and buckling problems were investigated, and the results obtained show that it is essential to consider the fabric orthotropy in the computations.

In all the above-mentioned works, the reference configuration is the pre-stressed configuration, yet the material coefficients used in the constitutive law are those related to the natural configuration, which corresponds to the tube without internal pressure. On the other hand, studies on the behavior of fabrics used in pressurized membrane structures have shown that the fabric characteristics in the pre-stressed state differ from those in the natural state and depend on the internal pressure.

Cavallaro et al. [14] utilized finite element analysis to compute the load–displacement curve of a pressurized membrane tube subjected to four-point bending conditions and found that the mechanical response strongly depends on the internal pressure. Turner et al. [15] conducted torsion tests on pressurized membrane tubes subjected to different internal pressures with the aim of determining the shear

modulus of the fabric in the pre-stressed configuration. Their experimental results also reveal that the shear modulus depends on the internal pressure and the larger the pressure is, the larger the shear modulus. Later on, Davids and Zhang [11] realized four-point bending tests with the same fabric as in [15] and with different internal pressures. By taking the shear moduli in [15], these authors performed an inverse analysis upon the load–displacement and obtained Young's modulus. They noticed that Young's modulus of the fabric in the pre-stressed configuration increases with the internal pressure. A beam finite element was designed to compute the load–displacement response of the pressurized membrane tube and the input data used were the material coefficients in the pre-stressed configuration of the structure. A good correlation found between the numerical model and the experimental deflection indicated that it is essential to use the material coefficients related to the pre-stressed configuration. More recently, Kabche et al. [16] presented a complete procedure based on Turner et al.'s test [15] in order to quantify the fabric properties in the pre-stressed configuration, which are strongly dependent on the internal pressure. They also realized the same four-point bending test as Davids and Zhang [11] and made similar observations on the material coefficients related to the pre-stressed configuration.

Inflatable structures are usually made of coated woven fabrics, which mostly display an anisotropic and viscoelastic behavior. In most of the above-mentioned studies, coated fabrics are modeled – as commonly practiced in the field of tensile structures – as orthotropic membranes under the plane stress assumption. Accordingly, we will not deal here with fabrics but with orthotropic membranes and we will assume that the membrane obeys the Saint Venant–Kirchhoff orthotropic elastic law. Elaborate models of coated fabrics and comparison with experimental results are much more complex subjects and they will not be considered in this paper. Our aim is to propose a comprehensive analytical model for orthotropic inflatable beams including both the inflation and the bending stages. The paper is organized as follows:

- **Section 2** defines the problem of a pressurized membrane tube and points out that one should consider two distinct successive stages. The first is the inflation of the membrane tube, an important stage which is often neglected so far in the literature. The second stage is the bending of the pressurized membrane tube and it will be seen further that the results of this stage strongly depend on those acquired in the first stage.
- **Sections 3–5** are concerned with the inflation of the membrane tube. **Section 3** is a brief reminder of the analytical results given in [17] for the geometry of the inflated tube. As preliminaries of the bending problem studied in the next part of the paper, the constitutive law related to the *inflated* state of the tube – not the natural state – is investigated in **Section 4**. It will be shown that the tube *remains orthotropic* with respect to the inflated state. However, the material coefficients involved in the constitutive law are no longer the same. As far as the authors' knowledge, this is the first time a bridge is established between the material coefficients at the natural state and those at the pressurized state. The change of the material coefficients is numerically computed on different geometries of the tube and material properties of the membrane in **Section 5**. The values of the material coefficients for the membrane will be chosen of the same order as the coefficients found in the literature for fabrics. The numerical results obtained will be used in the bending stage of the tube.
- The last part of the paper – **Sections 6–9** – deals with the bending of the tube. As will be described in **Section 6**, the Timoshenko beam kinematics is chosen because of the significant shear effect in the tube wall and the problem is formulated in finite deformations in order to account for all the nonlinear effects, in particular the action of the internal pressure which is a

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