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Wrinkling and collapse of mesh reinforced membrane inflated beam under bending

Qiang Tao, Changguo Wang *,[1], Zhiming Xue, Zhimin Xie, Huifeng Tan

Center for Composite Materials and Structure, Harbin Institute of Technology, Harbin 150080, China

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ABSTRACT

A novel concept of mesh reinforced membrane (MRM) is proposed in this paper. The tensile collapse mechanism of MRM is elucidated based on three obvious deformed stages. An improved Shell-Membrane model is used to predict the wrinkling and collapse of MRM inflated beam which is verified by a non-contact experiment based on the digital image correlation technique. Further the wrinkling details including the wrinkling evolution, pattern, shape, stress distribution are simulated to evaluate the functions of MRM for loading-carrying capacity of inflated beam. Pressure resistant performance of inflated beam was studied at last. The results revealed that MRM shows a great improvement on the collapse moment of inflated beam. MRM contributes to restrain wrinkling evolution by changing the transfer path of loadings which results from dispersing stress distribution and changing wrinkling pattern. The results show good references to the wrinkling control and the improvement of load-carrying capacity of inflated beam.

1. Introduction

Membrane inflated beams are the major load-carrying components of the space inflatable structures due to their outstanding properties, mainly are: light weight, low lunching costs, and ease of deployment and storage [1]. Typical examples include inflatable wings, solar sails, truss structures and inflatable antennas [2–4] etc. Load-carrying capacity of membrane inflated structures is the major concerned issue. The main failure mode of membrane inflated structures is buckling. The buckling process of inflated structure generally starts from a local wrinkle and ends up with an overall buckling, and thus the effects of wrinkles on the deformed behaviors of inflated beams have to be accurately considered in the analysis of load-carrying capacity [5].

Membrane wrinkling may significantly affect the performance and reliability of the membrane inflated structures, and thus has been a research topic of continued interests. A lot of research work related to wrinkling and collapse of the inflated beams or arches has been already published [6–8]. In 1926, Brazier [6] derived a collapse bending moment for an unpressurized isotropic shell by minimizing the strain energy per unit length of a shell. Wood [7] extended Brazier's expression for the case of taking internal pressure into consideration and modified the expression for orthotropic materials. Veldman [8] combined a few of the collapse moments described abovementioned and proposed the collapse moment of cylinders made of orthotropic film material. Veldman revealed that the new model showed a better correlation with the test results than the existing models.

Researchers also developed some analytical approaches and experiments to study the bending behavior of inflated beam [9–16]. Davids [9,10] focused on the development of a Timoshenko beam finite element for the nonlinear load-deflection analysis of pressurized fabric beams including the internal pressure effect and local fabric wrinkling. Apedo [11] and Nguyen [12] proposed a 3D Timoshenko beam with a homogeneous orthotropic woven fabric. The model took into account the geometric nonlinearities and the follower force resulting from the inflation internal pressure. Lampani [13] numerically simulated bending wrinkling behavior and deployment process. Wang [14] analyzed modal behavior of wrinkled membrane inflated beam. Distinctions can be depending on whether the material is regarded as a shell or as a membrane, whether it concerns isotropic or anisotropic material, whether the beam is pressurized or not and whether it is an analytical or empirical expression. Walker [15] and Cook [16] experimentally researched performance of inflatable tubes combined with tape spring reinforcements.

Maintaining shape stability and increasing load-carrying capacity are essential for application of inflated structure. Researchers make several attempts about these (as depicted in Fig. 1). Yoo et al. [17] studied the wrinkling control of inflated booms using SMA wires. SMA wires have achieved good effects on

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* Corresponding author.
E-mail addresses: taoqiang@hit.edu.cn (Q. Tao), wangcg@hit.edu.cn (C. Wang), tanhf@hit.edu.cn (H. Tan).

[1] AIAA member

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Nomenclature

CCD	Charge-Coupled Device
DIC	Digital Image Correlation
E_1,E_2	Young's modulus in the 1 and 2 direction
F_w^{KM},F_{coll}^{KM}	The wrinkling load and collapse load for Kapton® membrane inflated beam
F_w^{MRM},F_{coll}^{MRM}	The wrinkling load and collapse load for mesh reinforced membrane
Inflated beam	
GFT	Glass Fiber Tape
KM	Kapton® Membrane
l_ϕ,l_0	Length of inflated beam in the natural and reference configuration, respectively
M_w,M_{coll}	The wrinkling moment and collapse moment
MRM	Mesh Reinforced Membrane
p	internal pressure
r_ϕ, r_0	Radius of inflated beam in the natural and reference configuration, respectively
t_ϕ, t_0	Thickness of inflated beam in the natural and reference configuration, respectively
W	Structure weight of inflated beam
α	The modified factor for the improved Shell-Membrane model
δ	The enhancement rate of specific load
η	The specific load
ν_{12}, ν_{23},ν_{31}	Poisson's ratio in Cartesian coordinates for an orthotropic material
θ_w	The wrinkling angle
ω	The specific pressure

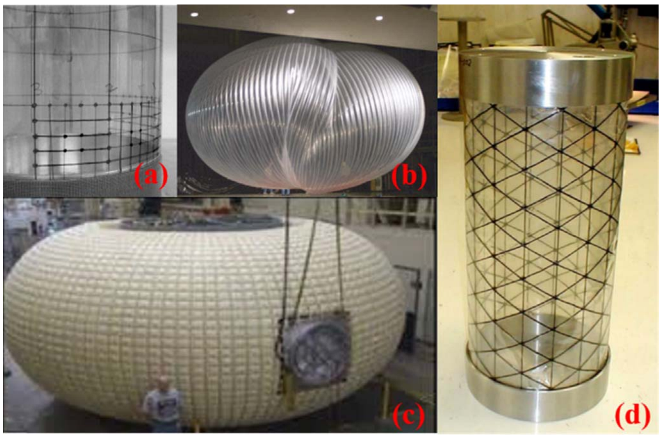

Fig. 1. Several attempts about maintaining shape stability and increasing load-carrying capacity of inflated structures: (a) wrinkling control of inflated booms using SMA wires; (b) pumpkin balloons constrained by stiff meridional tendons; (c) inflatable habitat reinforced by woven fabric webbings; (d) carbon-reinforced isogrid inflatable booms.

the shape and wrinkling controls of membrane structures [18,19]. Wang [20] proposed a novel control strategy to control the wrinkling deflection and improve the bending performance of an inflated beam using SMA wires by experimental and numerical studies. In addition, several novel applications such as carbon-reinforced isogrid inflatable booms [21], pumpkin balloons [22], and inflatable habitat reinforced by woven fabric webbings [23] were found in literatures. The mechanism of SMA wires to the wrinkling control is through the recovery force generated by the electrically driven SMA wires to remove the wrinkles and improve the bending performance of the inflated beam. Carbon-reinforced isogrid inflatable booms were developed to increase load-carrying capacity of booms by utilizing carbon-reinforced isogrid structure outside the inflatable booms. Carbon-reinforced isogrid structure itself has good bending performance. Pumpkin balloons and inflatable habitat reinforced by woven fabric webbings were designed to improve the ultimate pressure so as to maintain shape stability. Stripes or woven fabric webbings were attached to the membrane surface. These reinforced materials would bear the loads together with membrane. Inspired by abovementioned attempts, mesh structure may guide us to control the wrinkles and enhance load-carrying capacity of inflated beams by adding the mesh on the surface.

In this paper, a novel concept of mesh reinforced membrane (MRM) is proposed at first. An improved Shell-Membrane model is then used to predict the bending-wrinkling behavior of the inflated beam comprised of MRM, which is verified by the non-contact experiments based on the digital image correlation (DIC) technique. The numerical simulation is performed to predict the wrinkling details, including the wrinkling evolution, pattern, shape and so on in the end.

2. Wrinkling and collapse loads

2.1. Mesh reinforced membrane inflated beam

In this section, a novel concept of mesh reinforced membrane (MRM) inflated beam is proposed at first (as shown in Fig. 2). Similar to the concept of laminated composite material, MRM is composed of two components: the mesh and the membrane. The mesh materials can be glass fiber tapes (GFTs), Kevlar strips, carbon fiber strips and other similar tapes or strips materials. The membrane materials can be selected to meet the corresponding requirements. Meanwhile, the mesh patterns can be designed and tuned to show various types such as rhombus, triangle, mixed triangle, hexagon and rectangle.

In this paper, an inflated beam comprised of MRM is fabricated. The mesh material is GFT produced from DuPont, and the membrane material is Kapton® membrane (KM). Hexagon mesh is selected in this paper. Here, this type of inflated beam is named as MRM inflated beam (both 8 GFTs along the helical direction and longitudinal direction). For comparison, a pristine KM inflated beam is also fabricated.

2.2. Natural and reference configurations

The inflated structures are mainly made of flexible membrane materials with near-zero bending stiffness. The membrane

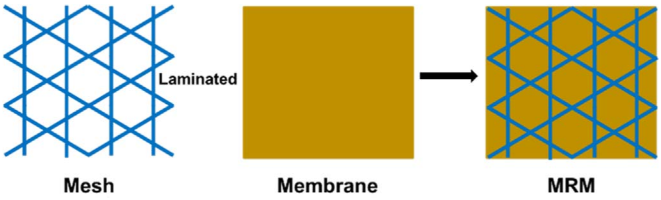

Fig. 2. The concept of mesh reinforced membrane (MRM).