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A modified material model describing the load-deflection behavior of air-supported fabric structure with decreasing stress

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ABSTRACT

Air-supported fabric structures are often used as formwork for constructing concrete shells. However, the load-deflection responses of these quick deployment structures are difficult to be simulated by current material models because the decreasing stress can cause the change of the elasticity. In this study, a new modified material model is developed which can improve the ability of accurately predicting the dynamic behaviors of air-supported fabric structures under vertical load. Uniaxial and biaxial tensile tests are performed to understand the mechanical property of the fabrics, which is used to construct the modified material model. Two parameters are used and adjusted to describe the changing characteristics of the orthotropic elastic moduli. This modified material model is then incorporated in to the finite element simulation software, which is then compared with a vertical loading experiment on a large-scale fabric structure. The cycle of loading/unloading curves of biaxial tensile tests demonstrates that elastic moduli do decrease with the stress during unloading procedure. Compared with the vertical loading experiment, the modified material model can significantly increase the accuracy in contrast with three conventionally-used material models. This modified material model is expected suitable for predicting and analyzing the responses of PVC-coated polyester fabric structures especially dealing with the decreasing stress in fabrics.

1. Introduction

Inflatable fabric structures are known as temporary medical facilities, disaster-relief shelters, and military applications due to their advantages of lightweight, quick deployment, and low storage volume. Internal pressurized air prestress the fabric so it can carry compressive stress produced by loads. These environmentally friendly and sustainable constructions are also used to form large closed spaces, such as the gym or the waste-disposal site, which are known as air-supported fabric structures. Recently, another related technology by using air-supported fabric structures as formwork for constructing concrete shells are getting a lot of attention again, as shown in Fig. 1. This concept was started by Wallace Neff in 1942 [1] and grew during the 1970s and 1980s [2–4]. Using blower fans, the fabric formwork is fabricated to the proper shape that a concrete shell structure is supposed to be. Then, a special spray mix of concrete is applied to the interior surface of the fabric formwork to create a concrete shell. Apparently, precise deformation control of the fabric formwork is crucial in the construction of concrete shell. However, less requirements with deformation control for past applications result in the lack of design criterion of air-supported fabric structures, especially material models for predicting. In addition, huge volume and low inflation pressure will make convergence analysis very difficult for inflatable fabric structures [5,6], which poses number of challenges since the air-supported fabric structure has seen less study.

Vertical load is one of the main focuses in the design of lightweight structures, especially the inflatable fabric structures. The load-deflection studies on inflatable fabric structures using shell theory began in the 1960s. Fichter [7] developed a linearized shell theory to analyze the deformation of linearly elastic inflated beams and columns. With the development of the finite element analysis method, Molloy et al. [8] used the finite element method and shell theory to examine mechanical behavior of a pair of fabric arches leaning against each other under snow and wind loads. Plaut et al. [9] employed the linear thin-shell theory of Sanders [10] to study the deflections of a fabric arch under snow and wind loads by considering the effect of initial membrane stresses with Rayleigh-Ritz method. In order to improve the computational efficiency in the finite element method, other works addressed the development of Timoshenko beam theory for the load-deflection analysis of the inflatable fabric beams. Wielgosz and Thomas [11]

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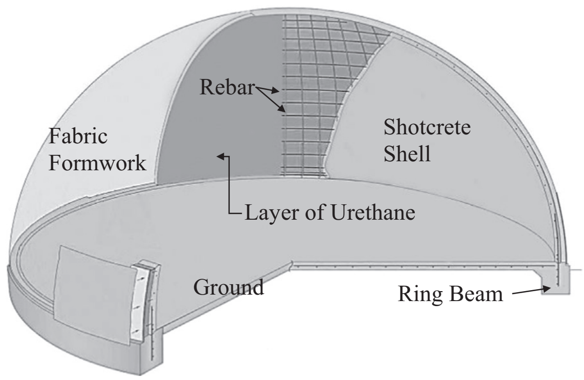

Fig. 1. Schematic cutaway of a concrete shell constructed following an inflated fabric formwork.

brought a Timoshenko's beam-based theory in a specialized beam finite element to calculate the deflection of pressurized fabric beams. Then the theory was developed by Thomas and Wielgosz [12] to predict inflated tubes. Davids et al. [5] developed a Timoshenko beam element which involved pressure effects and wrinkling to simulating the response of pressurized fabric tubes with geometric nonlinearities. Davids and Zhang [6] then employed the element to predict the load-deflection of inflated tubes which were compared with experiments. Davids [13] presented a 9.5-m-span semicircular arch experiment as comparison with the theory to examine the loading behavior of pressurized fabric arches. While the use of Timoshenko beam finite element is attractive for improving the computational efficiency, it is still not as accurate as shell or membrane finite element analysis.

With the development of properties testing methods on fabrics, a number of prior studies embedded the elastic properties tested by those methods in the membrane finite element to quantify the load-deflection response of inflatable fabric structures, which had good agreements with experiments and good computational efficiency. The torsion tests of inflated fabric tubes by Turner et al. [14] indicated that the assumption of linear elastic response in tension was reasonable for the same coated woven polyester fabric. Malm et al. [15] integrated the material parameters obtained by the torsion test in a three-dimensional membrane finite element specimen to obtain, and the prediction was validated by the bending test results of fabric beams. Later, Brayley et al. [16] used bending experiments and torsion material tests to evaluate the load-displacement response of inflated tubes. Guo et al. [17] established a three-dimensional membrane finite element model with linear elastic moduli obtained by uniaxial fabric tensile tests to analyze the load-displacement behavior of air-inflated frame consisting of arches and coupling beams. However, those elastic properties are not able to describe the strain-stress non-linear characteristics of the fabrics under vertical load, which is fine for inflatable tubular structures but not for those large or complex inflatable structures.

Since fabrics are non-isotropic and non-linear materials and the vertical load is the main factors influencing the change in the stress state, the reliability of numerical predictions on load-deflection responses depends on the accuracy of material models. Based on plane stress orthotropic assumptions, Bögner and Blum [18,19] develop a reasonable method to measure the elastic moduli in warp and fill directions of fabrics by using biaxial tensile tests. This method can obtain the variation of the elastic moduli for different stress ratios of the warp stress to the fill stress. Minami [20] presented a similar multi-linear method by forming the material response surface with three dimensional stress-stress-strain curves. On these basis, Galliot and Luchsinger [21] proposed a non-linear material model describing the biaxial tensile behavior of the fabrics by formulating the elastic moduli in warp and fill directions as a linear function of a normalized stress ratio. However, this material model did not take the effects of stress levels on elastic moduli into account while Davids [13] has noticed that the elastic moduli could be very different for various stress levels. Thus, it is not appropriate to bring this material model in membrane finite element to predict the load-deflection response of air-supported fabric structure, especially when the stress in fabrics is decreasing under the action of applied vertical load.

The objective of this paper is to develop a modified material model for accurately predicting the load-deflection response of air-supported PVC-coated polyester fabric structures. Due to the complex interaction between warp and fill yarns in fabrics, the elastic moduli change with the stress ratios and the stress levels simultaneously during modelling. The structure of this paper is organized as follows: Section 2, uniaxial and biaxial tensile tests are performed to test the elastic properties of the fabric for constructing material models, then three conventional material models are presented in details for developing the modified material model by addressing unloading cycle of biaxial tensile curves to analyze the effects of decreasing stress on the elastic moduli; Section 3, a large-scale experiment is performed to measure the response of air-supported fabric structures under vertical load, and an finite element model and design software is presented which is developed for membrane and cable structures and regarded as a relatively accurate method; Section 4, material models are integrated in the finite element software, and the predictions and performance are compared with the observations of the vertical loading experiment; Finally, Section 5 presents the conclusions.

2. Elastic properties measurement and material models

2.1. Material specifications

As a kind of composite materials, the PVC-coated fabrics for architectures are usually made up of a base cloth of plain woven yarns and coated surfaces of polyester. The polymeric surfaces protect the base cloth from damage, provide stability to the weave pattern and make the fabrics impermeable to water. Predominant material combinations are polyvinyl chloride (PVC) coated polyester yarns and polytetrafluoroethylene (PTFE) or silicone coated glass-fibre yarns [22]. Specimens in this paper are constructed with Duraskin B6915 membrane, which is a high-tech coated and multi-layer laminated fabric, made of polyester sulfone (PES) fabric and polyvinyl chloride and polyvinylidene fluoride (PVC-PVDF) surface. Also, Duraskin B6915 membrane is a bi-directional woven fabric consists of warp and fill yarns, and technical properties is shown in Table 1.

Values of stresses and elastic moduli are given per length [kN/m] and not per area. This is a common practice when working with fabric materials as the thickness of these materials is not well defined.

2.2. Uniaxial and biaxial tensile test

Uniaxial tensile tests following the MASJ [23] standard are carried out to measure the material properties of the Duraskin B6915 membrane. As shown in Fig. 2, longitudinal specimens of the Duraskin 6915 membrane are tested on a uniaxial test machine called Zwick/Roell Z100, and both ends of the specimen are loaded by an electro-mechanical drive. Tensile tests are displacement-controlled at a rate of 10 mm/min until the specimens are teared apart, and three effective

Table 1
Technical properties of Duraskin 6915 membrane.

Properties	Duraskin 6915
Weight [g/m^2]	1100
Total thickness [mm]	0.9
Yarn	1670 Dtex
Yarn counts warp/fill [yarns/m]	413.4/413.4
Tensile strength warp/fill [kN/m]	115/100