Construction and Building Materials 164 (2018) 672–681

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Experimental and numerical study on nonlinear mechanical properties of laminated woven fabrics

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HIGHLIGHTS

- To perform biaxial tests on laminated woven fabric under various stress ratios.
- To characterize the material nonlinearity through stresses-moduli response surface.
- To formulate the biaxial elastic modulus in full cubic polynomials in stress sector.
- To implement and validate the nonlinear numerical computation method.

ARTICLE INFO

Article history:
Received 9 September 2016
Received in revised form 18 November 2017
Accepted 2 January 2018

Keywords:
Laminated woven fabric
Material nonlinear analysis
Stresses-moduli response surface
FEM analysis

ABSTRACT

This article presents a nonlinear analysis to explore mechanical properties of the membrane structures made of laminated woven fabrics by numerical simulation and experiments. Stresses-moduli response surfaces are created with the data of stress-strain curves measured from the biaxial test. To apply this method into finite element method (FEM) analysis, complete cubic polynomials of these surfaces are obtained and created the nonlinear material model under user defined subroutine UMAT of ABAQUS. A cruciform specimen is analyzed adapting the nonlinear model, which is subjected to biaxial tensile under the condition of stress ratio of 1:1, 1:2, 2:1, 3:1, 1:3, 0:1 and 1:0. It is shown that the results of nonlinear material model agree well with experimental results.

1. Introduction

The woven fabrics are usually manufactured by using base cloth and functional layers, one of which is coated layer and the other one is laminated layer. Their mechanical properties depend mainly on the base cloth and their yarn properties. The functional layers can protect the base cloth from the weather ageing caused by ultra-violet radiation, chemical corrosion etc. As the woven fabrics have various attractive characteristics like lightweight, high-strength, ease of handling, high-adaptability, they are widely used in engineering practice like civil, aeronautical and aerospace industries. In the field of building and construction, tension membrane structures are significant type of long-span structures, such as Shanghai Expo'2010 Axis canopy roof [1,2]. For aerospace engineering, gasbags of landing and decelerator of re-entry manufactured by woven fabrics are also extensively utilized in accordance to inventory data [3]. In fact, the woven fabrics can be used to manufacture common envelope due to its lightweight. And it plays primary role in manufacturing the envelope of common LTA (lighter than air) airship and stratospheric airship which is an important research platform to investigate near space [4].

For fabric membrane structures, their design parameters involving maximum strength, deformation and safety factor, are dependent on the structural response of fabrics subjected to various loadings. And they exhibit strongly nonlinear mechanical behaviors due to complexity of micro-structure of the woven fabrics. So far, many mechanical models of woven fabric have been established, and they can be generally summarized as visco-elastic, visco-plastic and elastic models. The mechanical model is chosen according to the type of fabrics and the analysis end target [5].

A plenty of theoretical elastic models of the woven fabrics have been developed, but most of those models are only based on results of uniaxial tensile test, which inevitably lack enough accuracy to obtain the corresponding design parameters of woven fabrics. Although some of those models based on biaxial tensile test can provide partly reasonable results, many difficulties still need

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https://doi.org/10.1016/j.conbuildmat.2018.01.004
0950-0618/

to be discussed, such as the application of elastic constants calculated in different load radios and the adaptability of those models on the fabric through all the loading phases.

The investigation of mechanical properties of fabrics has been carried out for many years. Peirce et al. [6] presented the first theoretical model to describe mechanical response of fabrics. Although many imperfections existed in this model, their work largely established the comprehension for mechanical properties of fabrics in future studies. Consequently, several fabric models based on the Peirce model have been developed by researchers [7].

Luo [8] compared the same coated fabric under uniaxial and multi-axial tensile testing and found that coated fabric demonstrates anisotropic properties under uniaxial tensile condition, and the same fabric rather behaves more isotropic under multi-axial tensile loads. Ambroziak and Kłosowski [9] carried out uniaxial and biaxial tensile tests to identify the immediate elastic nonlinearity of PVC-coated fabrics for structure design and the material model could be applied to FEM analysis directly. In addition, the author found that the elastic constants determined from uniaxial tests results are accurate enough for engineering calculations. Zhang [10] carried out biaxial tensile testing to analyze the biaxial cyclic behaviors at different stress ratios, and they found that loading history on the mechanical properties of PTFE-coated fabric is obvious, and different constitutive constants should be conducted in different design stages. Dinh et al. [11] based on the uniaxial and biaxial tensile tests data proposed a new elasto-plastic model for coated fabric, and presented a numerical analysis method implemented by Abaqus user material subroutine and validated with the data obtained from biaxial tensile testing. Chen et al. [12] carried out uniaxial and biaxial tensile testing of fabrics for airship envelops, calculated the elastic constants according to experimentation data, and it was found that elastic constants should be determined for specific loading conditions and stress distributions depending on the project's demands. Galliot [13] investigated the biaxial mechanical properties of coated woven fabrics used in inflated and tensile structures, and they used ANSYS to create a nonlinear model and to numerically simulate the inflated pre-stressed structures. Kato et al. [14] proposed a constitutive formula for coated fabrics based on the fabric lattice model. Ambroziak [15] analyzed PVC-coated Panama fabric with a user-defined HOOKLW subroutine by MSC.Marc system with elastic constants from uniaxial tensile tests. Biaxial tensile behaviors of fabrics were assumed to be orthotropic plane stress for a specific stress ratio while their elastic properties can be varied with respect to the stress ratios to present the interaction between warp and weft yarns. They considered the material nonlinearities of yarns and coatings and crimp interchange between warp and weft in their formula.

However, only some simple material models have always been used in the numerical calculations. The main reason for this imbalance is that too many parameters have to be considered leading to increase of computation time. Thus, the achievements cannot be efficiently used in the numerical calculation of membrane structures. For some traditional building materials, as method of partial coefficient can be used to obtain reliability of structures, it can still be extensively utilized is in structure design. Since the mechanical properties of coated fabrics are still not revealed very clearly, method of safety factor is also popular to fabric structure design.

Simplified linear material models have been developed by Galliot [13], Ambroziak [15], and Blum, Bögner [16] for a number of commercial software. But these models only allow simple treatment of mechanical response of fabrics due to accuracy limitations. This is because the actual response of fabrics witnessed is highly nonlinear behavior being dependent on stress ratios, which are more complex than described by elastic constants in the stiffness matrix.

The most recent attempt to describe the fabric behavior is based on response surfaces, which directly links the measured strains to the applied stresses through three dimensional representations. In order to obtain the biaxial tensile results for such response surfaces, Bridgens and Gosling [17] presented a new test protocol: the specimen was firstly pre-stressed for several hours, then increased the load by 10% higher than the test load in order to remove most of the residual strains as the second stage and finally biaxial test was performed on specific loading regime to test the entire response of the fabric. The experimental results were plotted via a three dimensional coordinate stress–stress–strain. According to these data, response surfaces were fitted by using various methods. The correlation between numerical model and experiments was very good.

In recent years, the studies on the mechanical properties of Laminated Woven Fabrics were always based on biaxial tensile tests, and proposed the elastic constants under certain stress ratio or response surface of stresses-strain for the structural analysis. But no relevant research on the elastic constants in stresses space, thus, it is necessary to obtain deeper understanding in the mechanical properties of fabrics. This paper attempts to discuss this problem and to propose a numerical analysis method for fabric based on stresses-moduli response surface.

In this paper, it presents an experimental study on tensile properties of a typical laminated fabric Uretek3216LV under biaxial cyclic loading, and a numerical approach for the tensile behaviors of laminated fabrics subjected to any three dimensional stress state. The objective of this article is to explore the tensile behavior of the fabric and to investigate the mechanical responses under biaxial tensile loading by using experimental and analytical approaches. The biaxial tensile tests are carried out under various stress ratios in accordance to the testing protocol proposed by Bridgens [17]. According to test data, a stresses-moduli response surface of this laminated fabric is created, and a nonlinear model modified by ABAQUS user material subroutine using complete cubic polynomials of response surface is applied to the fabric. The numerical simulation stress-strain curves are compared with the results of biaxial tests.

2. Biaxial tensile test

2.1. Specimens and setup

Membrane material named as Uretek3216LV is a type of high-tech multi-layer laminated fabric and consists of three layers: helium barrier, load carrier and thermal bonding layer. The load carrier is composed of Vectran HT fiber plain weave fabric. Vectran is a high-performance thermoplastic multifilament yarn spun from Vectra® liquid crystal polymer (LCP, Celanese). The fabric is woven into 200 denier Vectran fiber bundles composed of 40 Vectran filaments. To meet strength requirement, 22 bundle counts per centimeter are laid in the warp and fill directions. The areal density of plain weave fabric is 106 kg/m^2 and its tensile strength is 882.9 N/cm [18].

The biaxial tests were performed to several cruciform specimens with their arms aligned to the warp and weft directions of the fabric, according to the geometry depicted in Fig. 1(a). The effective cantilever length of each specimen 160 mm and its crossing area of cruciform is 160 × 160 mm^2. The slits should be cut in same arrangement in each arm of one specimen in order to obtain a homogeneous tensile stress in the center of the specimen even for large deformations as shown in Fig. 1. The slits in the arms were thought to be beneficial to form a uniform stress distribution in the crossing area of one specimen [4,13,18]. In addition, as compared with the straight corner or triangular corner, the rounded arc cor-