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Test Method

A triaxial tensile machine for three-dimensional membrane components: Experimental investigations and numerical simulations

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ABSTRACT

The use of fabric materials for inflated membrane structures has attracted considerable attention in recent decades due to light weight, high strength-to-weight ratio and excellent environmental stability. The load curtain of the catenary system for stratospheric membrane structures is a typical three-dimensional component with complex stress state, meaning that existing uniaxial and biaxial machines are not suitable to identify essential mechanical properties of this component. This paper focuses on the development of a new triaxial tensile machine and evaluation of mechanical properties of a three-dimensional load curtain component. The triaxial tensile machine with specific configurations could independently control five loads (X+/X-, Y+/Y- and Z). A series of cyclic experiments are carried out in terms of in-plane and out-of-plane angle combination.

It is found that experimental observations in the first cycle and subsequent cycles are distinctly different for three-dimensional membrane components. The force reduction in the first cycle is caused by plastic deformation during loading-unloading process. The stress state in subsequent cycles is approximately elastic due to the elimination of plastic deformation in the first cycle, indicating that cyclic experiments are suitable for identifying stable mechanical properties. The force differences between X+ and X- directions are related to stiffness difference between warp and weft directions. Moreover, the effects of Z force could result in asymmetrical X and Y forces, especially for small out-of-plane angle. Furthermore, a numerical model is developed for comparing with experimental results. The X and Y forces in terms of loading and unloading are in good agreement with experimental results, which could justify numerical methods.

1. Introduction

The utilization of fabric materials for inflated membrane structures has attracted considerable attention in recent years due to the capabilities of light weight, high strength-to-weight ratio and excellent environmental stability [1,2]. The inflated membrane structures can be used for large-span stadium roofs [3], dams [4] and stratospheric platforms [5,6]. To understand reasonable structural behavior under complex environmental conditions, basic mechanical properties in terms of load conditions are essential and indispensable [7,8].

The basic mechanical properties of fabric materials could be identified with uniaxial monotonic and cyclic tests that are suitable for characterizing ultimate strength/breaking elongation and stable elastic modulus/hysteresis hoop area, respectively [9]. For uniaxial monotonic mechanical properties, Penava et al. calculated Young's moduli of four different fabrics (cotton, wool, wool + lycra, PES) in seven directions oriented with a 15° increment and found that the maximum elastic moduli were in the warp and weft directions while the minimum value in the 45° direction [10]. Hu et al. proposed a modified energy method to determine yield stress of high-performance fabrics instead of traditional ultimate strength or deflection criteria [11]. Using uniaxial tensile properties to calculate structural behavior is not satisfactory compared with corresponding experimental results [12]. The possible reasons are the nonlinearity and large-deformation of composite materials during loading process. Therefore, cyclic tests are necessary to characterize stable mechanical properties. Kraft et al. concentrated on ratcheting strains of metallic fiber woven materials and revealed that energy losses did not attribute to plasticity, providing useful insight into the degree of non-recoverable wire sliding and frictional rubbing [13]. Kuo et al. developed an iso-phase approach to analyze composite elastic moduli which considered stress concentration and yarn undulation. It is obtained that a higher weaving yarn aspect ratio resulted in a lower modulus and that modulus reduction due to yarn undulation was more significant in weaving directions [14]. For elastic properties, elastic

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moduli evolution [15] and elastic limit [16] are typical values that tend to be approximately stable after certain cycles. In general, structural behavior determined with uniaxial cyclic properties are relatively better than those calculated with uniaxial monotonic properties. In fact, these structural behavior are still not satisfactory since inflated membrane structures are biaxially-tensioned [17,18]. In this case, Buet-Gautier et al. assessed mechanical behavior of fabric materials using a biaxial tensile device based on two deformable parallelograms, validating that mechanical properties of fabric materials were nonlinear due to weaving undulations and yarn contraction [19]. Galliot et al. focused on nonlinear biaxial tensile behavior of polyester fabrics in use for finite element analysis and showed that a revised material model significantly increased the accuracy of finite element predictions in comparison with standard orthotropic linear material models [20]. Moreover, Monticelli et al. estimated biaxial mechanical responses of a textile ribbon structure with a digital image correlation system for measurement of full strain field. This experimental investigation showed excellent mechanical performance of the ribbon structure at the maximum biaxial load level without visible damage [21].

On the whole, existing uniaxial and biaxial mechanical properties are essential for most inflated membrane structures, such as membrane roofs, dams and pavilions where basic mechanisms are restricted within uniaxial and biaxial conditions in relation to conventional applications and utilizations [22]. For stratospheric platforms, three-dimensional membrane components are employed to transfer and distribute car payloads [23]. The load curtain of the catenary system illustrated in Fig. 1 is a typical one which works in such a way that the car payload is transferred by the suspension cables to the load curtain and then distributed to the surface with this load curtain [24]. In this case, the area incorporating external surface and load curtain of stratospheric structures is a three-dimensional membrane component. The complex stress state due to external cyclic loads and periodic pressure variation could be revealed with triaxial tests. However, mechanical properties of these membrane components have not been well-addressed due to the absence of triaxial tensile machine. The lack of three-dimensional mechanical properties could limit the understanding of structural behavior and suitable utilization of this structure. This paper thus focuses on the development of a new triaxial tensile machine and characterization of mechanical properties of three-dimensional membrane components under different angle combination conditions.

The composition of this paper is organized as follows. The triaxial tensile machine, including configurations, functions and loading procedure is introduced in Section 2. A series of cyclic experiments concerning in-plane and out-of-plane angles are carried out to characterize typical mechanical properties in Section 3. The Section 4 develops a numerical model to compare with experimental results and understand detailed mechanical properties. Finally, basic observations and useful values are summarized in the Conclusions.

2. Triaxial tensile machine

2.1. General descriptions

The purpose to develop a triaxial tensile machine is to identify complex mechanical properties of three-dimensional membrane components. To perform tests with this machine, the basic principle is the independent control of three directions with a varying angle from 0° to 90°, i.e., in-plane (X and Y) and out-of-plane (Z) directions. For this reason, the main configuration of this triaxial tensile machine is composed of an in-plane biaxial tensile machine and an out-of-plane machine. The testing rig of the biaxial machine is utilized to fix four hydraulic press cylinders, position membrane specimens and work as the basis for the out-of-plane machine. Five independently-controlled directions are X+ and X-, Y+ and Y-, and Z+; these five directions are in line with real engineering applications to obtain suitable mechanical properties of three-dimensional membrane components.

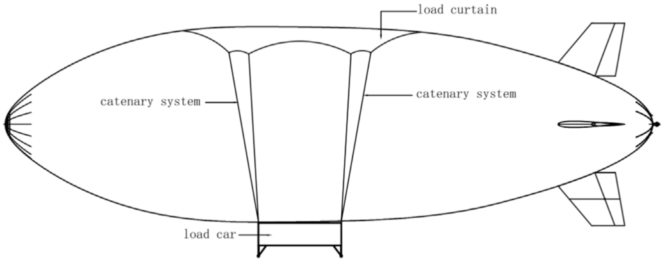

Fig. 1. Schematic diagram of the load curtain of the stratospheric membrane structures.

2.2. Configurations and working principle

The triaxial tensile machine can carry out experiments at any angle in three loading directions. The basic configuration is composed of translation mechanism, rotating mechanism, rolling screw, planetary reducer servo motor and load cells. To achieve efficient control, a program written in C++ is used to perform specific functions, which could ensure independent control of five arms and give feedback information with limited time lag. The high accuracy of experimental results is achieved with the real-time curves that are monitored and displayed with an interactive interface. The corresponding schematic diagrams and photos of the triaxial tensile machine are shown in Fig. 2. The equipment with related specifications are summarized in Table 1.

According to conventional standpoints, mechanical properties of fabric materials are nonlinear and dependent on specific loading procedures, such as uniaxial, biaxial and triaxial modes. In this paper, the working principle of this triaxial tensile machine is related to engineering utilizations in stratospheric membrane structures where loading sequence, angle combination and control scheme are critical steps. In detail, the loading sequence can consider material difference between warp and weft directions while angle combination and control scheme are used to measure complete experimental results for assessing complex mechanical properties.

2.3. Specific specimens

In general, suitable specimen types are necessary to obtain reasonable mechanical properties, such as rectangular/dumbbell specimens for uniaxial tensile tests and cruciform specimen for biaxial tests. As no research concerning mechanical properties of three-dimensional membrane components is available, an appropriate three-dimensional specimen is essential to obtain reasonable experimental observations and provide necessary guides for future study. For this purpose, five loading directions (four in-plane and one out-of-plane arms) are taken into consideration, see Fig. 3.

In detail, the out-of-plane arm (Z direction) with same membrane material is welded on the in-plane specimen with the welded length of 100 mm and width of 50 mm. Moreover, the length of 300 mm in Z direction is added for performing triaxial experiments. The dimensions and details of the in-plane cruciform and out-of-plane arm are illustrated in Fig. 3. A typical specimen with a given in-plane angle of 45° and out-of-plane angle of 60° is shown in Fig. 4.

3. Experimentation

3.1. Materials and specimen

The fabric material used in this study is the PVC-coated polyester fabrics (Ferrari F1302) that was produced in Serge Ferrari, France. The basic material properties are yarn of PES HT 1100/2200 Dtex, weight of 1350 g/m^2, total thickness of 1.02 mm and adhesion of 13 daN/5cm. The specific three-dimensional specimen composed of in-plane and out-of-plane parts is made with suitable cutting and welding. The in-plane