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# Effects of on-axis and off-axis tension on uniaxial mechanical properties of plain woven fabrics for inflated structures

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ABSTRACT

The use of enhanced plain woven fabrics for aerospace engineering needs essential and accurate mechanical parameters for analyzing structural behavior and performing numerical simulations. The uniaxial tensile tests are direct and effective approaches to investigate these mechanical properties. This study focused on uniaxial monotonic and cyclic mechanical properties of an enhanced plain woven fabrics URETEK 5893 in on-axis and off-axis tension. For uniaxial monotonic mechanical properties, an improved method to determine yield stress was proposed and digital image correlation (DIC) technique was utilized to investigate detailed breaking mechanism. It is found that yield stresses were stable in each loading direction and typical yield stresses in the warp, weft and 45° directions were 5.56 MPa, 8.84 MPa and 1.96 MPa, respectively. Moreover, the breaking mechanism in terms of strain propagation process was identified. For cyclic mechanical properties, approximate stable ratcheting strain and elastic modulus were investigated. Nonlinear ratcheting strain was more sensitive near 45° than other directions. Moreover, Poisson ratios in three directions were obtained with DIC technique and the maximum Poisson ratio existed in the 45° direction. The comparisons between experimental and theoretical elastic moduli showed that the best agreement existed in the warp and weft directions and the accuracy of using the theoretical equation to calculate elastic modulus was dependent on material linearity.

In general, this study could provide basic observations and useful values for understanding mechanical properties of plain woven fabrics in use for inflated membrane structures.


## 1. Introduction

The utilization of composite materials in building, mechanical and aerospace industries has attracted considerable attention in recent decades due to enhanced chemical resistance, excellent thermal properties and good dimensional stability compared to traditional materials [1]. Among different types of composites, plain woven fabrics can offer advantages over unidirectional fiber reinforced composites. For example, good resistance to chemical exposure and long life-cycle are suitable for mechanical industry [2]. High strength-to-weight ratio could meet the demands of aerospace engineering [3]. Moreover, compared with homogeneous polymers (such as ETFE foil [4] and FEP foil [5]), material properties could be changed by adjusting geometric parameters of fabric and/or fiber materials. These material properties suggest that plain woven fabrics could have widespread potential applications as engineering materials. Plain woven fabrics are produced by mechanically bonding two or more fiber yarns in a specific architecture [1]. The fabrication procedure involves interlacing two series of yarns normal to each other known as warp and weft. From the mechanical properties perspective, uniaxial tensile mechanical properties are indispensable for understanding mechanical mechanism and providing essential material parameters for simulating structural behavior. For this reason, yield stress and breaking mechanism form uniaxial monotonic tensile tests [4] and stable ratcheting strain and elastic modulus from uniaxial cyclic tests [6] are fundamental mechanical properties.

For uniaxial monotonic mechanical properties, Soliman et al. investigated Young's moduli of fiber reinforced polymer composites under on-axial and off-axial tension [7]. Penava et al. calculated Young's moduli of four different fabrics (cotton, wool, wool

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+ lycra, PES) in seven directions. They found that the maximum elastic moduli were in the warp and weft directions while the minimum value was in the 45° direction [8]. Davidow et al. proposed a practical method to determine yield stress of wood-plastic composite materials using energy dissipation method instead of traditional ultimate strength or deflection criteria [9]. Generally, none of these methods was accepted by the scientific community due to complexity and nonlinearity of composite materials [10], showing that a proper design required to consider specific experimental conditions. For breaking mechanism, Perie et al. employed the digital image correlation (DIC) method to assess breaking mechanism of a C/C composite and pointed out that this method was useful for analyzing experimental results of a plane shear characteristics [11]. Lisle et al. estimated material properties of satin balanced glass/epoxy woven fabric ply with infrared thermography (IR) technique and found that IR technique could determine damage scenario of composite laminates [12,13]. In general, these methods with acceptable experimental observations are alternative approaches for estimation of breaking mechanisms of plain-woven fabrics [14,15].

For uniaxial cyclic mechanical properties, approximate stable ratcheting strain and elastic modulus could be achieved with the dissipation energy of the materials. Kraft et al. concentrated on ratcheting strain of a metallic fiber woven structure and revealed that energy losses in the material did not attribute to plasticity, providing useful insight into the degree of non-recoverable wire sliding and frictional rubbing [16]. Montesano et al. addressed ratcheting strains under elevated temperatures and confirmed that ratcheting strain related to creep was minimal throughout the duration of cycling [17]. Moreover, Tohgo et al. further investigated fracture process (ratcheting evolvement) of CFRP cross-ply laminates under on-axis and off-axis cyclic loads [18]. For elastic moduli, elastic moduli evolution [19], loading-unloading secant moduli [20] and elastic limit [21] were typical factors and it is concluded that elastic modulus could reach stable value after certain cycles.

In fact, there is no consistent methods and experimental protocol as plain woven fabrics exhibit nonlinearity and depend on loading conditions, such as uniaxial monotonic and cyclic tensions. The inconsistency between various methods could result in large discrepancy when utilizing these material parameters for simulating structural behavior. Based on conventional standpoints, uniaxial monotonic and cyclic mechanical properties are fundamental parameters for estimating breaking mechanism and analyzing structural behavior [22,23]. Therefore, uniaxial mechanical properties are indispensable for understanding new and enhanced materials in use for aerospace engineering, such as air tube [24], air beam [25] and air ship [3]. In this case, the URETEK 5893 is an enhanced fabrics compared with its previous products, URETEK 3216 [26] and URETEK 5876 [27]. The material properties are believed to be improved but no detailed parameter values are available. To evaluate critical parameters for understanding basic mechanical properties, uniaxial tensile tests are necessary but unavailable because of its newness.

This paper focused on uniaxial mechanical properties of enhanced plain woven fabrics URETEK 5893. Uniaxial monotonic tests in 3 on-axis and off-axis directions were used to determine yield stress with an improved method. Breaking mechanism and Poisson ratio were estimated with the DIC technique. Furthermore, uniaxial cyclic tests in 7 on-axis and off-axis directions were carried out to estimate ratcheting strain and elastic modulus. The composition of this paper was organized as follows. Uniaxial monotonic and cyclic experiments with specific considerations and experimental conditions were detailed in Section 2. Mechanical parameters were determined from experimental results with suitable methods in Section 3. Then, parameter analysis and comparisons were done for further understanding of mechanical properties. Finally, useful observations and values were summarized in the Conclusions.

## 2. Experimentation

### 2.1. Materials and specimens

The materials used in this study was the 0.21 mm plain woven fabrics URETEK 5893 from Special Aircraft Research Institute in China. Standard rectangular specimen was utilized for identifying cyclic elastic modulus and ratcheting strain due to small strain [6]. The use of rectangular specimens for investigating yield stress and ultimate strength required modification as the breaking was often found at the gripped ends [4]. In this case, modified rectangular specimens with twisted clamp were used to avoid breakings at the gripped ends [28]. Therefore, modified rectangular and regular rectangular specimens were used for uniaxial monotonic and cyclic tests. The detailed dimensions of the two specimens were illustrated in Fig. 1.

### 2.2. Equipment

Mechanical tests were carried out on a single axis servo-hydraulic test machine UTM 400 (see Fig. 2) with computer control and acquisition. Specimens were clamped at the gripped ends with a fixed distance between the grips and were preloaded with 1.0 N

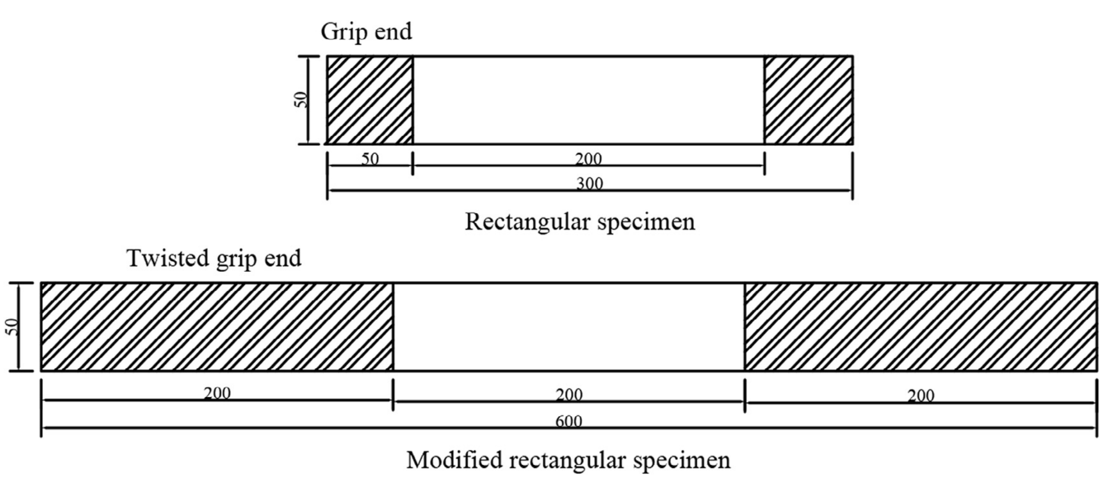


**Fig. 1.** Dimensions of regular and modified rectangular specimens (Unit: mm).