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Compression properties of multilayer-connected biaxial weft knitted carbon fiber fabric reinforced composites

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ABSTRACT

Three kinds of multilayer-connected biaxial weft knitted (MBWK) fabric reinforced composites are studied here, namely three-layer-connected, four-layer-connected, and five-layer-connected biaxial weft knitted fabrics. The compression properties of the MBWK fabric reinforced composites are characterized in the 0° and 90° directions by different carbon fiber volume fractions (V_f). Macro-fracture morphology and scanning electron micrograph (SEM) images are used to understand the deformation and failure mechanisms. Experimental results show that in the range of V_f, the structure of the reinforcement has significant effects on the compression properties of MBWK fabric reinforced composites. The major failure mode of the composites is shear failure, and the cracking of the composites focuses mainly on the delamination of the fabrics between the groups.

1. Introduction

Multilayer-connected biaxial weft knitted (MBWK) fabric is a special kind of non-crimp fabric (NCF). The MBWK fabric has a knit structure, which consists of high-performance fibers as stuffer warp and stuffer weft, and easily deformable 1 + 1 rib loops. MBWK fabric can be changed the layers of stuffer yarn according to the specific requirements. So far, the layers of stuffer yarn are up to 5 layers [1]. Thus, the fabric can be made the cloth of high and thick [2,3]. In MBWK fabric, the stuffer warp and stuffer weft are both exactly parallel and straight [4,5]. This kind of fabric not only gives full play to the characteristics of high-performance fiber with high strength and high modulus, but also fully utilizes the deformability of the knitting loop. This kind of arrangement endows the fabric with excellent mechanical properties and three-dimensional curved surface molding performance, which is unmatched by other fabrics [6,7]. In addition, composites reinforced with MBWK fabric exhibit a strong capacity for bearing external load, and high potential for lowering production costs, shortening the production cycle, and having a high property/cost ratio [8], which makes them attractive materials for use in high-performance composite parts. For these reasons, MBWK fabric reinforced composites are widely used in the fields of pilot helmets, aircraft wing covers, and car body manufacturing.

As with other composite materials, the structural parameters of the reinforcement determine and influence the performance of the composite. The deformation resistance and mechanisms of biaxial and triaxial NCFs under bias extension loading were experimentally investigated by Kong et al. [9]. They found that lowering the amount and line-tension of the stitches facilitated the tow sliding mechanism, reducing the deformation resistance of NCFs. Juan et al. [10] used the Micro-CT to analysis the internal deformed geometry of a non-crimp 3D orthogonal weave E-glass composite reinforcement. The aim is to observe, understand and quantify the effect of in-plane shear deformation on the composite reinforcement geometry, at mesoscale (i.e. unit cell level). A fiber bundle element model (FBEM) consisting of geometric, microscopic, and numerical submodels was proposed by Li and Bai [11] for the sheet forming of sheets of the MBWK fabric. E. Marklund et al. [12] used a multiscale approach to predict transverse tensile and transverse compressive

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strength of unidirectional non-crimp fabric (NCF) composites. Numerical analysis on fiber/matrix scale is performed to obtain the transverse strength of the fiber bundle to be further used in an analytical mesoscale model to predict the strength of the unidirectional NCF composite. Mattsson et al. [13] investigated the methodology for characterization of the internal structural parameters governing the performance of NCF composites and the methodology for determining the most typical geometrical parameters of composites using optical observations of cross-sections of manufactured laminates. Joki et al. [14] researched the nonlinear stress–strain response in glass fibre non-crimp fabric reinforced vinyl ester composite laminates subjected to in-plane tensile loading. The predicted behavior from using the model parameters were shown to be in good agreement with experimental results.

Thorough research has been undertaken for achieving good formability of MBWK fabrics on curved surfaces [15,16], yet composites reinforced with MBWK fabrics are often subjected to tensile, compression, and bending loadings [17]. With the development of the applications of the MBWK fabric reinforced composites, there is an urgent need to improve their damage tolerance and reliability. In recent years, researchers have further studied the compression properties of these composites [18–20]. Benson and Gregory [21] reported the results of an experimental characterization of a composite reinforced with four different knitted carbon fabrics and compared the results with conventional prepreg tape and uniweave fabric composites. Their experimental results indicated that high-quality knitted carbon fabrics could by produced by resin transfer molding (RTM) for aerospace-quality composites. Sun et al. [22] characterized the compressive behaviors of a multiaxial multilayer warp knitted (MMWK) fabric composite at various strain rates. At the same time, the compressive properties of a biaxial spacer weft knitted fabric reinforced composite were investigated by Liu et al. [23] at the quasi-static strain rate of 0.001/s and high strain rates from 700/s to 2200/s. Sun et al. [24] also reported the transverse impact behavior of a new kind of 3-D multi-structured knitted composite both in experimental and finite element simulation. In 2015, based on the representative volume element (RVE) model of single layer in MBWK fabric-reinforced composites, the elastic properties of MBWK fabric-reinforced composites have been developed and presented by Qi et al. [25]. Numerical predictions have compared to the results of tensile tests performed on composite samples. The percentage error of the numerical prediction results and the experimental results is less than 10%. At the same time, Wan et al. [26] researched a meso-structure model of MMWK composites from an elastic–plastic material model considering the strain rate effect for the components of the MMWK composite. The model is used to investigate the effect of the volume fraction of the knitting yarn on the dynamic in-plane compressive properties.

Analysis of variance (ANOVA) is a multivariate statistical method. It reflects the internal dependent relationship of a correlation matrix, according to the size of the correlation. Currently, this method is widely used in the analysis of composites. A one-way ANOVA of tensile strength was applied to analyze the relationship between fiber volume fraction (V_f) and tensile strength and two-way ANOVA analyzing method was used to deal with whether the carbon fiber volume fraction and the cutting direction have significant effect on the bending strength of the MBWK fabrics-reinforced composites by Qi et al. [27,28]. Their results showed that V_f had a significant effect on the tensile strength of MBWK fabrics reinforced composites. Song et al. [29] studied the effects of heat-accelerated aging on the tensile strength of three dimensional (3Dim) braided/epoxy resin composites. The results of two-way ANOVA analysis indicated that aging time had a significant effect on the tensile strength of these composites. Rapid evaluation of thermal aging of a carbon fiber (CF) laminated epoxy composite was reported by Fan et al. [30]. Their two-way ANOVA results indicated that aging time had a significant effect on the flexural strength of the composite whereas the aging temperature had no significant effect.

Currently, research into the mechanical properties of MBWK fabric reinforced composites has concentrated mainly on three layer-connected biaxial weft knitted fabric reinforced composites, but little research has focused on the mechanical properties of four-layer-connected or five-layer-connected MBWK fabric reinforced composites. To promote understanding of the relation between structural and compression properties of MBWK fabric reinforced composites, in this study, compression characterizations are conducted in the 0° and 90° directions of MBWK fabric reinforced composites with three-, four-, and five-layer-connected biaxial weft knitted fabric with different V_f s. Meanwhile, a two-way ANOVA of compression strength is used to analyze the relationship between V_f and compression strength. The influence of different numbers of connected layers on the compression performance of MBWK fabric reinforced composites is analyzed. Finally, compression failure mechanisms are proposed based on the macroscopic and microscopic fracture morphologies. This study provides a necessary basis for building essential constructs for future use of MBWK fabric reinforced composites in engineering applications.

2. Experimental and characterizations

2.1. Materials and preparation

In the experiment, the MBWK fabrics were made in the Institute for Composite Materials, Tianjin Polytechnic University, China. The weft yarns and the warp yarns are made of T300-3 K CFs which are knitted together by polyester yarns (PET DTY) with $1+1$ rib loops. The longitudinal section of the MBWK fabrics was showed in Fig. 1, in which Fig. 1(a) and (b) along 0°, Fig. 1(c) along 90°. The 0° direction is defined as the CF direction oriented along the weft direction, and the 90° direction orients along the warp direction. As can be seen from Fig. 1, the weft yarns and warp yarns were parallel and straight state respectively in the MBWK fabrics. So, the utilization of potential of the high strength and high modulus for the carbon were the more than 90%, while the corresponding plain woven fabric, but only about 70% [31,32]. Three different kinds of fabric reinforced composites are used in this research, namely three-layer-connected, four-layer-connected and five-layer-connected biaxial weft knitted fabrics, as shown in Fig. 2. The main process parameters of the MBWK fabrics were listed in Table 1. For the three-layer-connected biaxial weft knitted fabric, the upper and lower surface layers are composed of weft CF bundles and the middle layer is composed of warp CF bundles. The black lines are weft and warp carbon bundles. In the fabric, the angle between weft and warp carbon bundles is 90°. There is no interleaving between the weft and warp carbon bundles. These CF bundles are stitched together by the white lines which are made of polyester yarns (PET DTY) with $1+1$ rib loops. The thickness of the fabric is about 1.0 mm. The structure of the four-layer-connected biaxial weft knitted fabric differs from that of the three-layer-connected fabric, but all the yarns are the same. The first and fourth layers of the four-layer-connected fabric are composed of weft CF bundles and the second and the third layers are composed of warp CF bundles. There is no clear boundary between the second and the third layers. In the same plane, the two layers of warp CF bundles are bundled together to form twisted warp CF bundles. The thickness of the fabric is about 1.25 mm. The first and second layers of the five-layer-connected biaxial weft knitted fabric are composed of weft carbon fiber bundles, the third layer is composed of warp carbon fiber bundles, and the fourth and fifth layers are