Tensile Performance and Crack Propagation of Coated Woven Fabrics Under Multiaxial Loads

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ABSTRACT: The tensile performance of coated woven fabrics under multiaxial loads is examined in the present study. Two groups of experiments were conducted to investigate the influences of the configuration of the fabric specimen and the loading speed on the multiaxial tensile properties of the fabrics. The configuration of the specimen for the multiaxial tensile tests is identified as gear-shape with large arm widths. A loading speed of lower than 20 mm/min is suggested to obtain the tensile properties of the coated woven fabrics under multiaxial loads. The tensile performances of coated woven fabrics under uni-, bi-, and multiaxial loads were compared. We found that the tensile performances under bi- and multiaxial loads are much better than those under uniaxial loads. Therefore, for the application of the coated woven fabrics in lightweight structures, biaxial or multiaxial loading conditions will be necessary. Experiments on the specimens with an initial crack in the center under multiaxial loads show that, by comparison with other loading directions, the tensile properties in warp direction of the coated woven fabrics play an important role in the failure performance and crack propagation under multiaxial loads. To eliminate the dependence on the mechanical properties in warp direction, the balance of the two principle directions of coated woven fabrics should be improved. J Appl Polym Sci 113: 3388–3396, 2009

Key words: poly(vinyl chloride) (PVC); mechanical properties; multiaxial; tensile; crack propagation

INTRODUCTION

Lightweight structures, such as tension structures and air-supported structures, have been used widely in the past 30 years. Coated woven fabrics as roof materials used in these kind of structures play an important role in the application of lightweight structures. As a kind of flexible material, coated woven fabrics have virtually no bending stiffness. To sustain a shape, the coated fabrics must be in tension. Mechanical properties in tension are therefore very important to establish the material properties for structural design, installation, and maintenance.[1]

The common method to evaluate the tensile performance of coated woven fabrics is by tensile tests under uni- or biaxial loads. It is well known that the stress–strain curves of coated woven fabrics under uni- and biaxial loads are nonlinear, anisotropic, and inelastic.[2–5] It is also known that, under biaxial loads, the tensile responses are affected dramatically by the stress ratios between the two principle directions of woven fabrics.[6] However, in the real service of membrane structures, coated fabrics would experience complicated stresses, not only from the prestressing of the structure but also from the natural environments, such as temperature, snow, rain, wind, or other sudden attacks. All of these stresses come from different directions. Therefore, it would be interesting to explore the tensile properties of coated fabrics under multiaxial loads.

Further to the stress–strain behaviors, the failure of the coated woven fabrics is also a key issue in tensioned membrane structures. It is known that most of the failure of tensile structures results from the propagation of cracks or defects, which are initiated in the stress concentration areas of the membrane surface. The authors of some studies[7–9] have concentrated on the crack propagation of coated woven fabrics under uni- and biaxial loads. They found

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TABLE I
Specifications of PVC-Coated Polyester Woven Fabrics

Weave pattern	Yarn count (Tex)	Yarns density (ends/cm) × (picks/cm)	Mass (g/m^2)	Thickness (mm)	Breaking strength (warp/fill) (N/5 cm)
Panama	111.11	12 × 12	850	0.80	3500/3000

that, because of the anisotropic properties of coated woven fabrics under uni- or biaxial loads, the failure strength with a crack in the center was anisotropic whatever the initial length and orientation of the crack or the loading state was. Then, it would also be interesting to know the crack propagation of coated woven fabrics under multiaxial loads.

This study focuses on the experimental investigation of tensile performance of coated woven fabrics under multiaxial tensile loads. Factors such as specimen configuration and loading speed, which could affect the correct interpretation of testing results, were investigated. The tensile performance of coated woven fabrics under uni-, bi- and multiaxial loads was included for the purpose of comparison. Finally, the failure performance and the crack propagation of coated woven fabrics under multiaxial loads with a crack in the center were analyzed.

FACTORS INFLUENCING MULTIAXIAL TENSILE TESTS

All of the tests were performed on a multiaxial testing machine developed by University of Minho in Portugal.[10] The machine consists of four pairs of loading jaws uniformly distributed circumferentially.

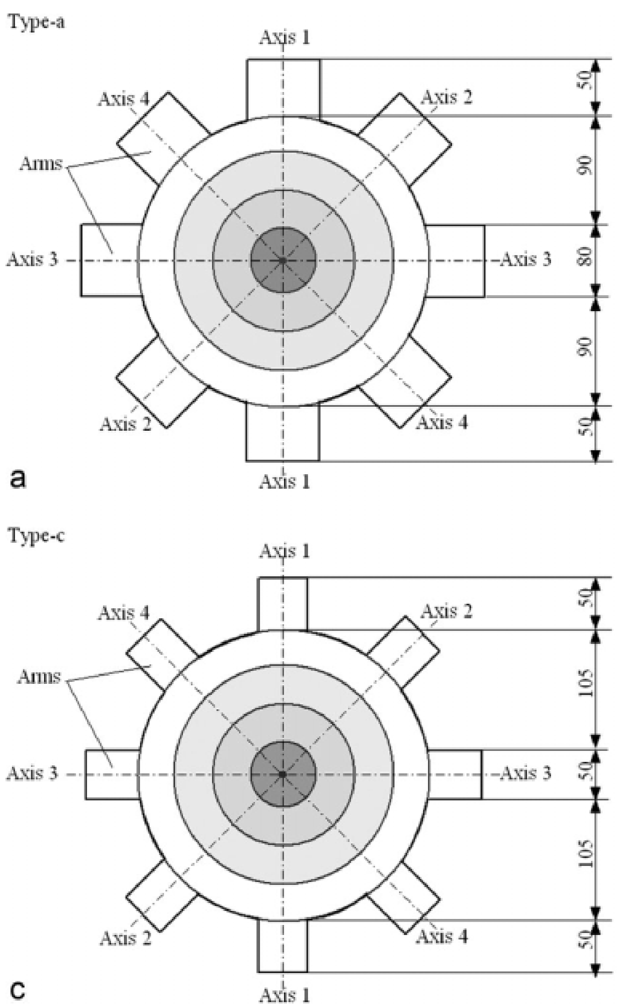


Figure 1 Configurations of the specimens for multiaxial tensile tests. (a) Type A; (b) Type B; (c) Type C; (d) Type D.

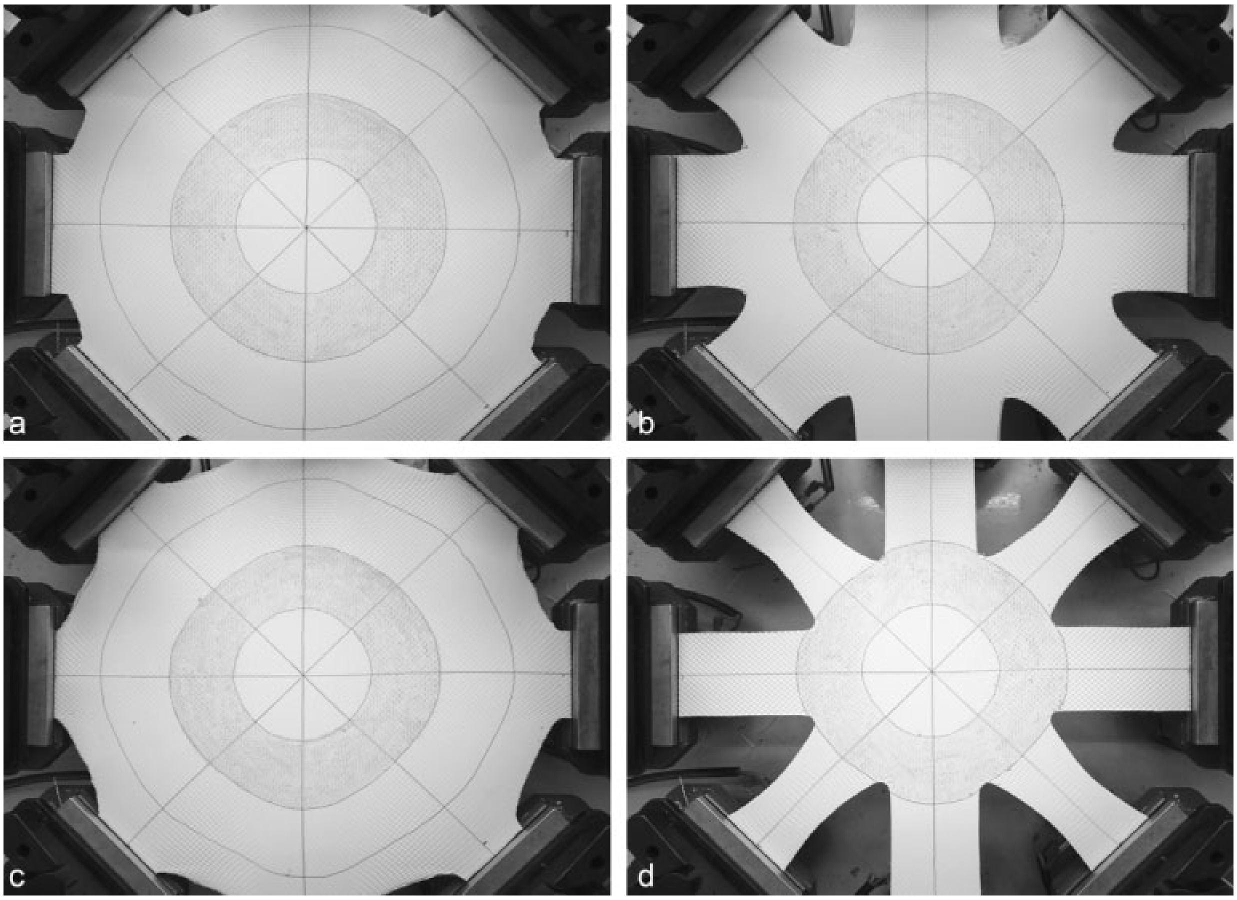


Figure 2 Strain distribution under multiaxial tensile loads. (a) Type A; (b) Type B; (c) Type C; (d) Type D.

The original distance between a pair of two jaws is 260 mm. The loading mode is constant rate of extension (CRE) and the loading speed is 5–100 mm/min. Poly(vinyl chloride) (PVC)-coated polyester woven fabrics were used as the samples in the study. Table I lists the specifications of the samples.

The influence of two key factors on the testing results were studied, i.e., the configuration of the testing specimens and the loading speed.

Four types of specimen configuration, as illustrated in Figure 1, were chosen: gear-shape with short arms for Types A and C, and cross-shape with long arms for Types B and D. The width of the arm was 80 mm for Types A and B and 50 mm for Types C and D. The chosen configurations were so chosen that they had been commonly used in biaxial tensile testing.[11–13] To record the distribution of the strain in the specimens, a series of homocentric circles were drawn on the top surface of the specimens. For these set of tests, the loading speed was 5 mm/min.

Four typical loading speeds (ν = 5, 20, 50, and 100 mm/min) were chosen to investigate the influence of this factor on the fabric behavior under multiaxial tensile load. For the whole tests, the specimens were placed where the two principle directions, warp and fill directions, of the PVC-coated woven fabrics were paralleled to the axes 1 and 3, respectively. For each test, three specimens were tested.

Configuration of the specimen

To observe the strain distribution on the specimens with different arm widths, images were taken during the multiaxial tensile tests and shown in Figure 2. It can be seen that, for specimens of Types A and B, the strain distributions along the four loading directions are quite uniform. However, for Types C and D, the homocentric circles on the specimen show somehow rhombohedral. The phenomenon indicates that the strain distribution is more uniform on the specimen with a large arm width of 80 mm (Types A and B) than that with a small arm width of 50 mm (Types C and D). Therefore, specimen with large arm widths is suggested for multiaxial tensile tests.

Further study on specimen configuration is to examine the effects of the shape with different arm lengths, i.e., gear-shape and cross-shape. Figure 3 shows the stress–strain response of specimens in four loading directions with different configurations.

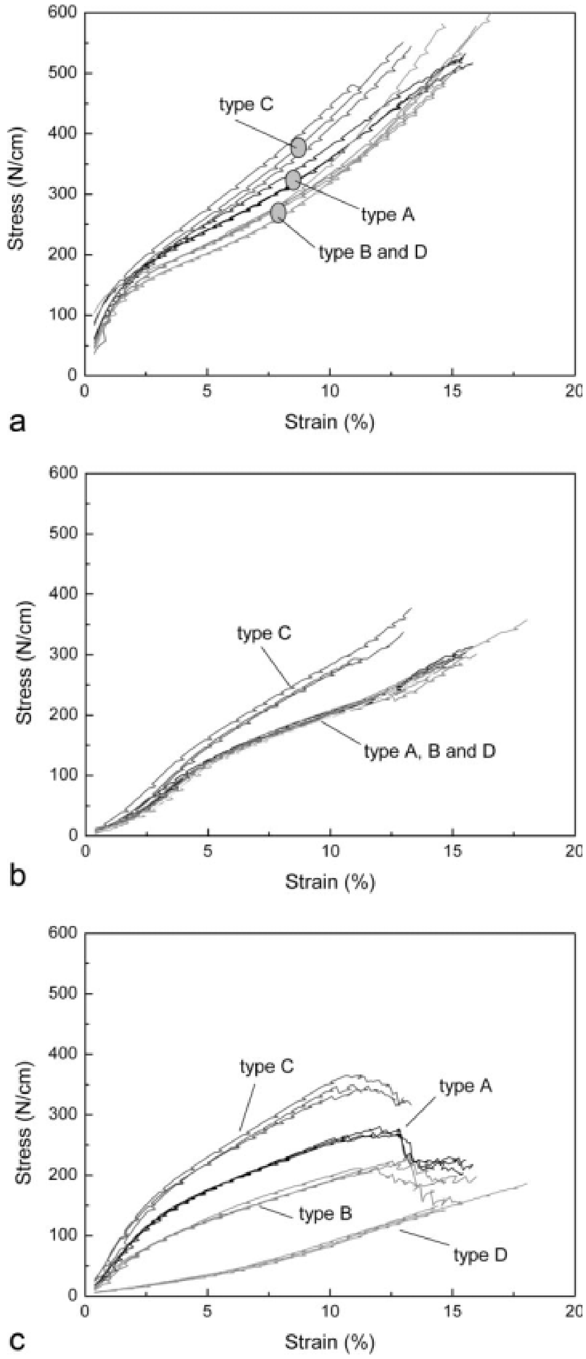


Figure 3 Tensile responses of different specimen configurations (Types A, B, C, and D). (a) Axis 1 (warp direction, 0°); (b) Axis 3 (fill direction, 90°); (c) Axis 2 or 4 (bias direction of ±45°).

Because the loading curves in axes 2 and 4 are almost the same, only the results of axis 2 are given in Figure 3(c). From Figure 3, it can be seen that in axis 1 (warp direction, 0°) there is a little difference between tensile performances for Types C, A, B, and D. In axis 3 (fill direction, 90°), the tensile performances on the specimen of Type C are different from the others. Even greater differences can be observed when examining the tensile performances in axis 2 or 4 (bias direction of ±45°) on four types of specimen shape. By comparing Types A and B (arm width = 80 mm) or Types C and D (arm width = 50 mm), it is seen that the slope of tensile curves in earlier loading stage on gear-shape specimens (Types A and C) is much greater than that on cross-shape ones (Types B and D). On the specimens with cross-shape (Types B and D), the multiaxial tensile performance in axis 2 or in axis 4 depends mainly on the uni-axial tensile performance of the coated woven fabrics in ±45° direction due to the existence of the long loading arms unless the strains in the specimen center were detected. Then, the interaction effect of the four loading directions in specimens of Types B and D (cross-shape) is less than that in specimens of Types A and C (gear-shape). Therefore, experiments on specimens of cross-shape (Types B and D) cannot give a reasonable response since the interaction effect between the four loading directions has been eliminated dramatically. Therefore, the specimens of gear-shape (Types A and C) are suggested for the multiaxial tensile tests.

Finally, it could be concluded that, to perform multiaxial tensile tests on coated woven fabrics, the configuration of Type A (gear-shape with large arm widths) is preferable. Therefore, in the following of this study, only the specimens of Type A are used.

Loading speed

Figure 4 shows the tensile performances in each loading direction under multiaxial loads. It can be seen that the tensile performances in each loading direction are affected dramatically by the loading speed. With the increase of loading speed, the breaking strength in axis 1 (warp direction, 0°) and axis 3 (fill direction, 90°) decreases obviously and the elongation at break declines dramatically. From Figure 4, it can also be noticed that when loading at a higher speed of 50 or 100 mm/min the nonlinear tensile response of coated woven fabrics at lower stress, especially in axis 1 (warp direction, 0°) and axis 2 or 4 (bias direction of ±45°), has been neglected. The nonlinearity of the tensile response can only be obtained veritably at a lower loading speed ($\nu \leq 20$ mm/min).

Therefore, for the multiaxial tensile tests loading speeds lower than 20 mm/min are recommended.

TENSILE PERFORMANCE UNDER UNI-, BI-, AND MULTIAXIAL LOADS

It would be interesting to see the difference of tensile performance of coated woven fabrics under different testing methods, i.e. under uni-, bi-, and multiaxial tensile loads. For this purpose, uni-, bi- (with stress ratio = 1 : 1), and multiaxial tensile tests were conducted on the same sample, of which the

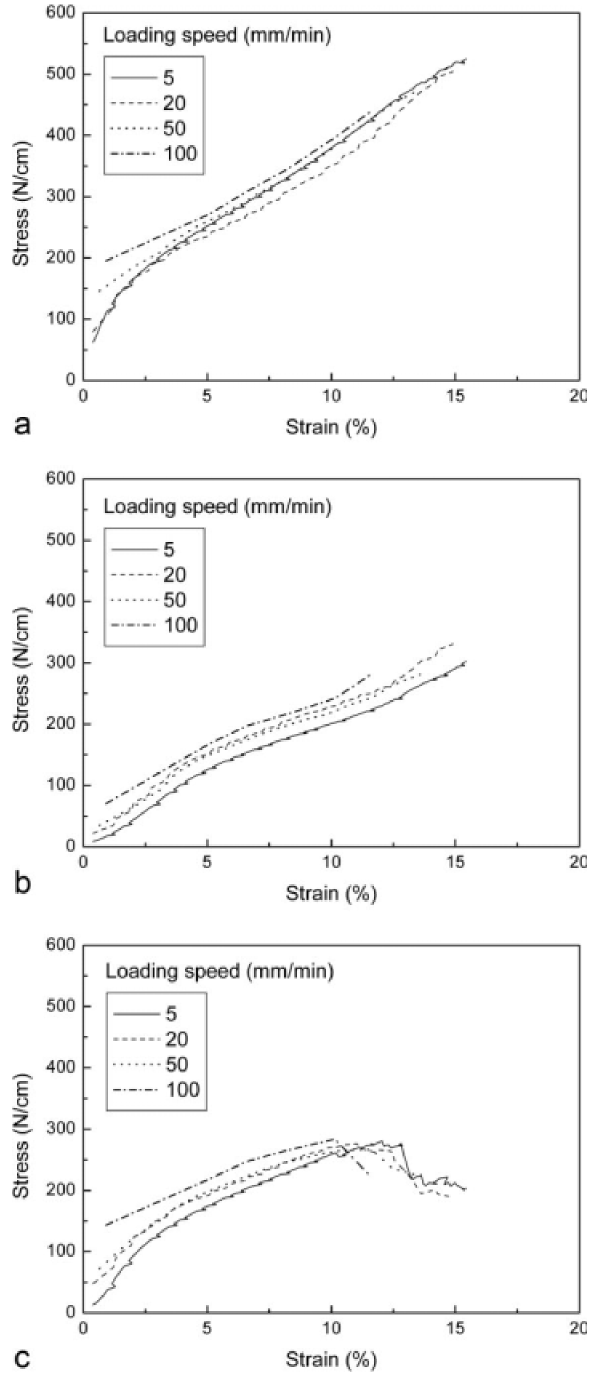


Figure 4 Multiaxial tensile responses at different loading speeds. (a) Axis 1 (warp direction); (b) Axis 3 (fill direction); (c) Axis 2 or 4 (bias direction of 45°).

specifications are listed in Table I. To facilitate the comparison of testing results, the configurations of specimen were carefully determined. For multiaxial tests, the specimen configuration of Type A was used. The configurations of the specimens used for uniaxial tests (strip specimens) and biaxial tests (cruciform specimens) were consistent with the multiaxial configuration. The configuration of the strip specimen for uniaxial tests was 260 mm (length) × 80 mm (width) and the configuration of the cruciform specimen for bi-axial tests was 260 mm (length in warp direction) × 260 mm (length in fill direction) with same arm widths of 80 mm for the two perpendicular directions. For all the tensile tests, the loading speed was 5 mm/min.

The tensile performance of PVC-coated woven fabrics in different loading directions under uni-, bi-, and multiaxial loads are shown in Figure 5. Uni-w,

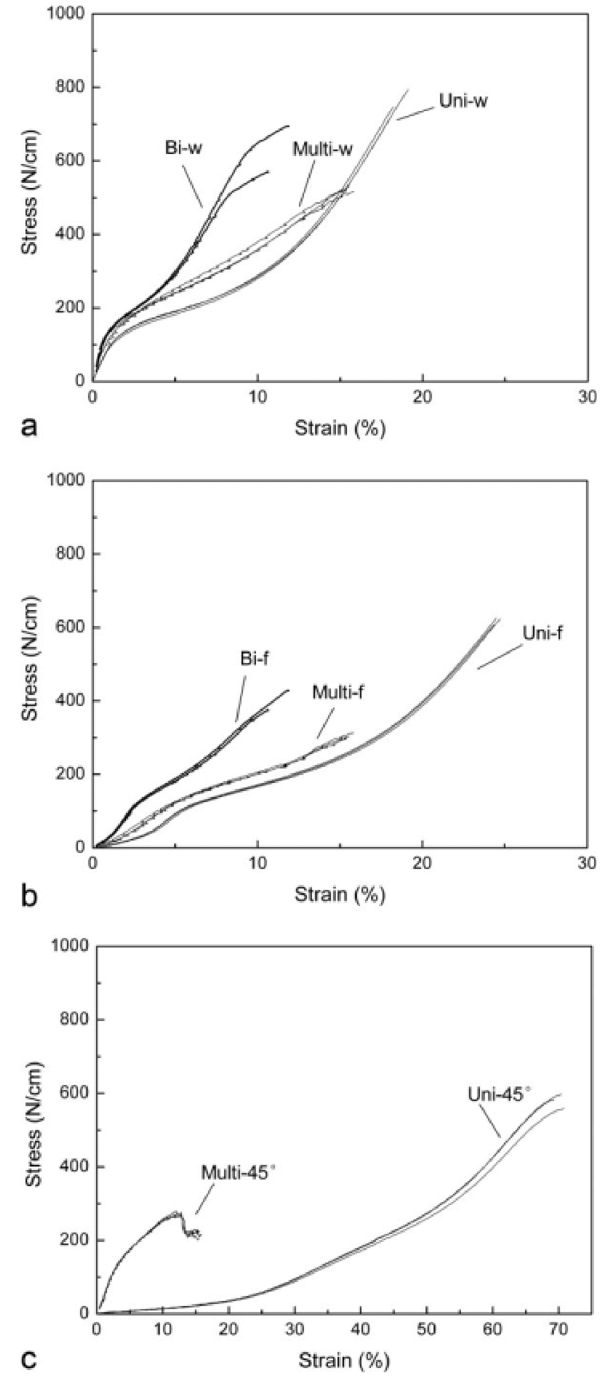


Figure 5 Stress–strain behaviors under uni-, bi-, and multiaxial tensile loads. (a) Warp direction, 0°; (b) Fill direction, 90°; (c) ±45° direction.

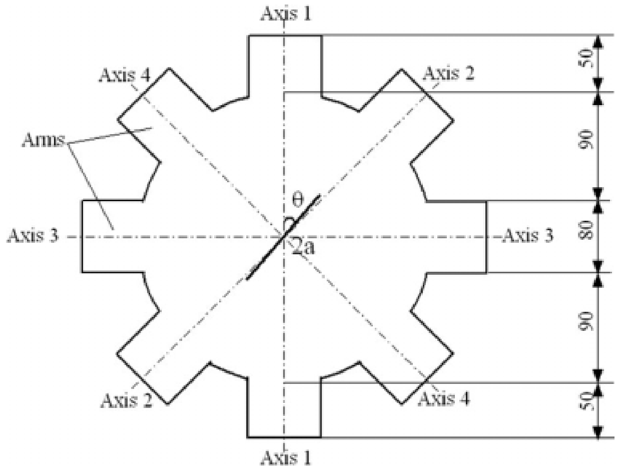


Figure 6 Specimen with a crack in the center for multiaxial tensile tests.

Bi-w, and Multi-w mean the stress–strain curves in warp direction under uni-axial, bi-axial, and multiaxial loads, respectively. Correspondingly, the postfix "-f" and "-45" mean the fill direction and the ±45° direction.

From Figure 5, it can be seen that the stress–strain behaviors in each loading direction are affected significantly by the testing methods:

1. In warp direction, at the earlier loading stage with stress lower than 50 N/cm, there is a little difference between the tensile curves under uni-, bi-, and multiaxial loads. However, with the increasing of tensile stress, great differences may be observed. It shows that under bi- and multiaxial loads, the Young's modulus is greater than that under uni-axial load.
2. In fill direction, there is great difference between the stress–strain behaviors under uni-, bi-, and multiaxial loads. The Young's modulus under uni-, bi-, and multiaxial loads is 131.1, 335.8, and 208.0 MPa, respectively. Under biaxial loads, the modulus in fill loading direction is much higher than that under uni- or multiaxial loads.
3. In ±45° directions, the whole tensile curves are totally different under the uni-axial and multiaxial loads. The modulus (565.3 MPa) under multiaxial loads is almost 30 times greater than that (19.3 MPa) under uniaxial loads.

Comparing the tensile failure performance of the specimens under uni-, bi-, and multiaxial loads, we noticed that the tensile strength and elongation at break in each loading direction (warp, fill and ±45° directions) under uni-axial loads was always greater than those under bi- and multiaxial loads. We also noticed that in warp and fill directions, the elongation at break under biaxial loads was the lowest one. In ±45° direction, the elongation at break under multiaxial loads is much smaller than that under uniaxial loads.

In general, it could be concluded that under bi- and multiaxial loads, the tensile performances are much better than those under uniaxial loads. These phenomena tell that as a result of the special structures (orthotropic and plain woven), the tensile

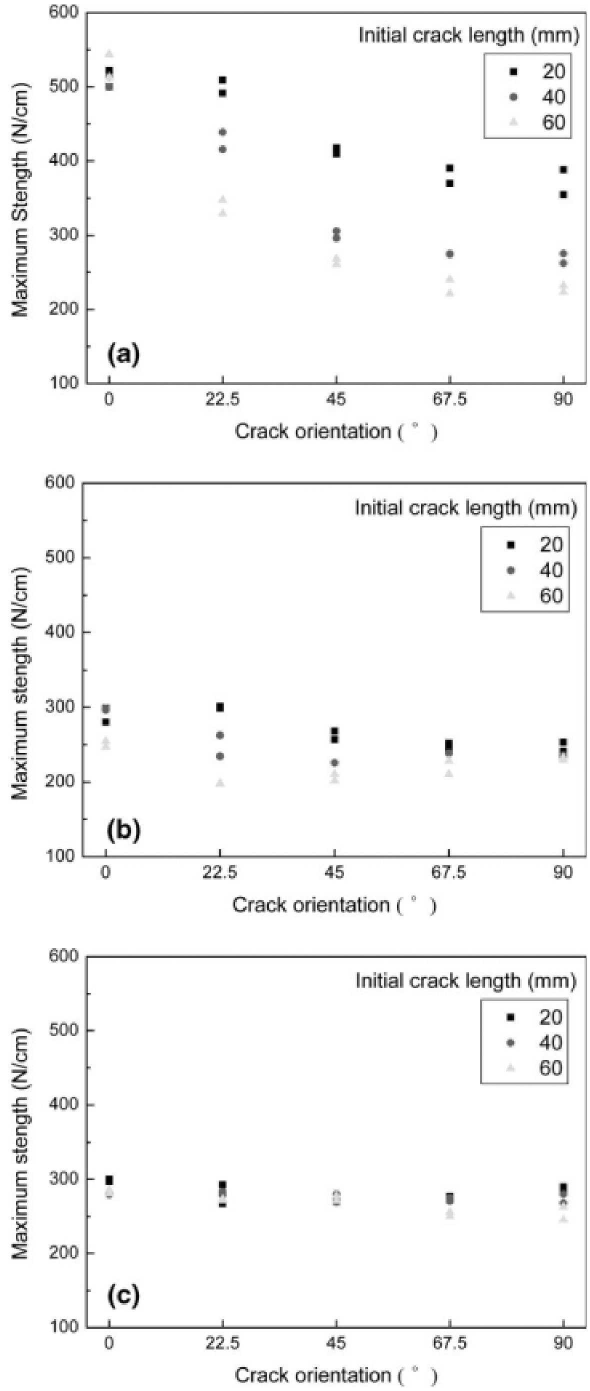


Figure 7 Effect of crack on the tensile strength of specimen. (a) Axis 1 (warp direction); (b) Axis 3 (fill direction); (c) Axis 2 or 4 (bias direction of 45°).

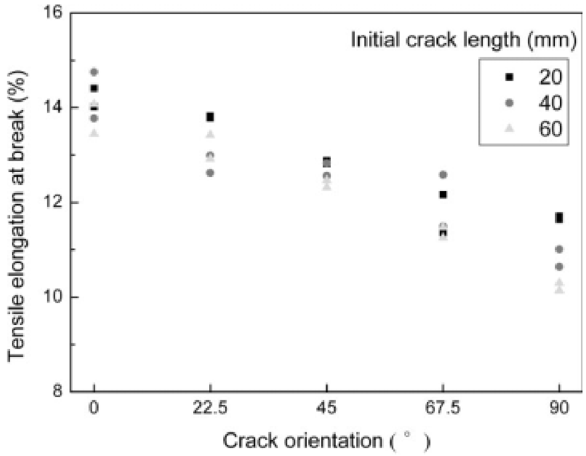


Figure 8 Effect of crack orientation in elongation at break.

performance of coated woven fabrics are benefiting from the interactions of warp yarns, fill yarns and coating material of coated woven fabrics when loading under bi- and multiaxial conditions. Then, during the application of the coated woven fabrics in lightweight structures, bi-axial or multiaxial loading conditions are necessary.

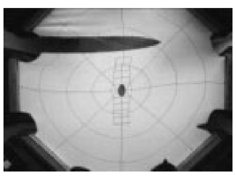
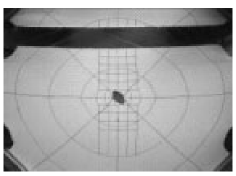
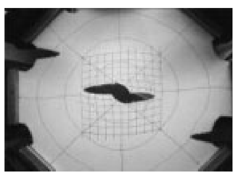
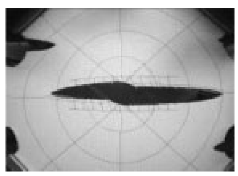
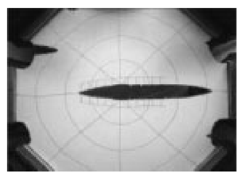
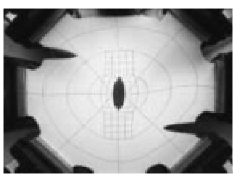
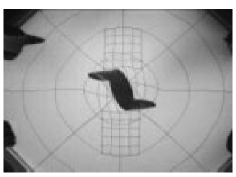
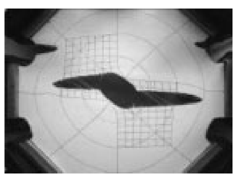
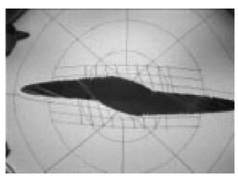
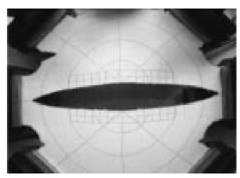
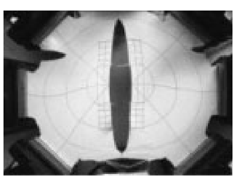
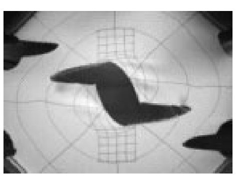
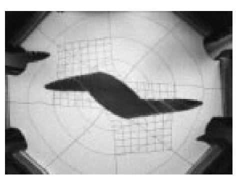
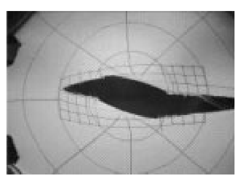
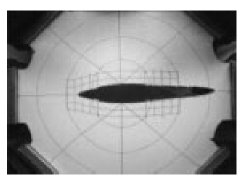
FAILURE PERFORMANCE AND CRACK PROPAGATION UNDER MULTIAXIAL LOADS

To investigate the failure performance and the crack propagation of the coated woven fabrics under multiaxial loads, experiments were conducted with a crack in the center of the specimen, as shown in Figure 6. Initial crack with three different lengths (2a = 20, 40, and 60 mm) and five different crack orientations (θ = 0°, 22.5°, 45°, 67.5°, and 90°) were prepared. The loading speed was 5 mm/min and three samples were tested.

It has been shown previously in Figures 3 and 4 that the tensile strength in axis 1 (warp direction) is much greater than those in other directions when there is no crack in the multiaxial specimen. From Figure 7, it could be noticed that with an existed crack, the maximum strength in axis 1 (warp direction) drops more significantly than that in other axes (in fill or 45° loading directions) as the initial crack length and the crack orientation increase. It is interesting to observe that, in axis 2 or axis 4 (45° direction), the effect of the initial crack length and crack orientation on the tensile strength is hardly noticeable. Then, it can be summarized that the tensile property and the crack propagation under multiaxial loads are dominated by the mechanical properties in warp direction of coated woven fabrics.

From Figure 8, it can be seen that with the increase of crack orientation, the elongation at break decreases. However, the initial crack length has almost no effect on the elongation at break. As the crack orientation turns from 0° (warp direction) to 90° (fill direction), the decrease of elongation at break accords with the decrease of the tensile

TABLE II
Crack Propagation in Multiaxial Tensile Specimens

Initial crack length (mm)	Crack orientation (°)				
	0	22.5	45	67.5	90
20					
40					
60					

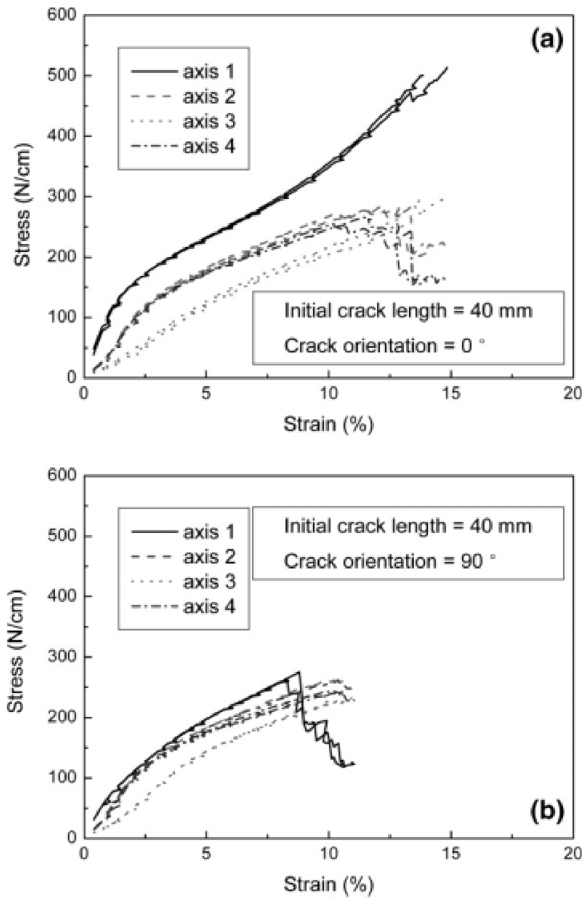


Figure 9 Typical failures in axis 1 (warp direction). (a) Brutal failure; (b) Progressive failure.

strength in warp direction. This emphasizes the importance of tensile properties in warp direction when crack propagation happens on coated woven fabrics under multiaxial loads.

The images of crack propagation of the specimens with a crack in the center under multiaxial loads are shown in Table II. Under multiaxial loads, the crack propagation or tensile failure occurs always in warp direction. Although the orientation of crack is 0° with an initial length of 60 mm, the crack propagation occurs in the fill direction and the failure is still in the warp direction. According to Bigaud,[7] under biaxial tensile loads, the failure in either warp or fill directions depends on the crack orientation and the loading ratios of two loading directions. However, under multiaxial loads with CRE loading mode in each direction, the failure tends to happen in the direction with a higher modulus, i.e., the warp direction of the coated woven fabric (see in Fig. 5).

Because the mechanical property in warp direction of multiaxial specimens dominates the failure of crack propagation under multiaxial loads, the failure mode in warp direction is much more important than other directions for the failure of coated woven fabrics with a crack. When there is a crack in the center of the specimen, two failure modes in axis 1 (warp direction) could be noticed: brutal failure and progressive failure. For example, when initial crack length is equal to 40 mm, at the condition of crack orientation = 0° the failure mode in warp loading direction is brutal failure, shown in Figure 9(a), and at the condition of crack orientation = 90°, the failure mode in warp loading direction is progressive failure, shown in Figure 9(b). Figure 10 shows the failure modes in warp direction according to different initial crack lengths and crack orientations. As the initial crack length increases from 20 to 60 mm, the failure mode in warp direction is developing into progressive failure from brutal one, except when the crack orientation is 0° (along the warp direction). This failure mode development trend under multiaxial loads fits with that of under biaxial tensile tests.

Therefore, it can be concluded that to improve the performance of coated woven fabrics under multiaxial loads and to reduce the dependence of performance on one principle direction (for example, warp direction), it is important to eliminate unbalanced mechanical properties in the two principle directions of coated woven fabrics.

CONCLUSION

The factors that might affect the tensile experiments of coated woven fabrics under multiaxial loads have been investigated. To achieve the tensile response of coated fabrics under multiaxial tensile loads, the configuration of Type A (gear-shape with large arm widths) is recommended. The loading speed has certain effect on the tensile failure performance and on the tensile response. When performing multiaxial tensile tests on coated fabrics, a loading speed lower than 20 mm/min is suggested.

The comparisons of the tensile results under uniaxial, biaxial, and multiaxial loads show that the tensile

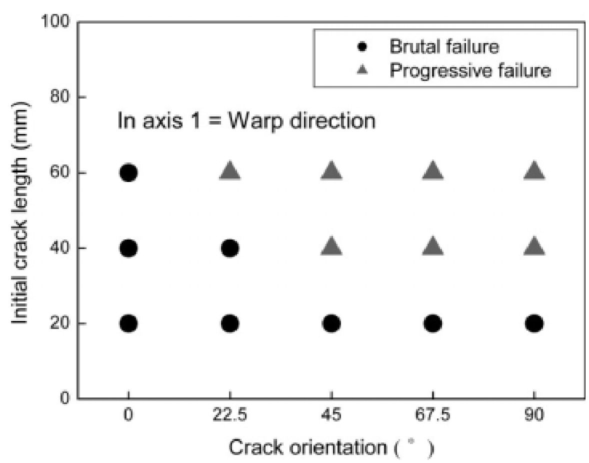


Figure 10 Multiaxial tensile failure modes in warp direction.

properties of coated woven fabrics are affected by the loading conditions. When loading under biaxial or multiaxial tensile conditions, the tensile performance of coated woven fabrics can reach the highest level for its application in lightweight structures.

On the basis of the experimental results of the specimens with a crack in the center under multiaxial loads, one can see that the tensile properties in warp direction of the coated woven fabrics play an important role in the tensile failure and crack propagation under multiaxial loads. The elimination of the unbalance of the mechanical properties in the two principle directions of the coated woven fabrics will benefit the mechanical performance of coated woven fabrics.

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