Mechanical Properties of Coated Plain Weave Fabrics under Biaxial Loads

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It is necessary to acquire the mechanical properties of advanced plain-weave fabrics as design parameters for application to ultra-light structures. In this study, biaxial tensile experiments of cruciform specimens with an open hole were conducted to evaluate the strength of coated plain-weave fabrics composed of specific high-tensile-strength fibers. Uniaxial tensile tests of strip specimens were also carried out to obtain the fundamental uniaxial properties of the fabrics. The results of these tensile tests show that the open-hole tensile strength of the fabrics under biaxial loading is approximately equal to the strength under uniaxial load irrespective of biaxial load ratio, and warp directional strip specimens exhibit higher strength than weft directional specimens in spite of the same density of yarn in both directions. There is a partial contribution of misalignment of the weft yarn in the membrane to the loss of strength in the weft direction. The results of observations by microscope and single-yarn tensile tests reveal that the strength difference in warp and weft directions is caused by the degradation of the weft yarn by heating in the polymer film coating process coupled with yarn misalignment.

Key Words: Coated Weave Fabrics, Biaxial Strength, Cruciform Specimen, Airship

1. Introduction

Recently, the development of high-performance membrane materials has been conducted using high-strength fibers such as polyarylate and PBO (poly-p-phenylenebenzobisoxazole). Many of these membrane fabric materials are coated with polymer films to improve tolerance against ultraviolet radiation, moisture absorption, airtightness and so on. Several applications of flexible membranes are being planned in the field of aerospace engineering. Presently, stratospheric airships and deployable space structures constructed using membrane materials have been proposed.

One of the key technologies of the stratospheric platform project in JAXA (Japan Aerospace Exploration Agency) is how to realize extreme weight reduction in airships, for which high-strength membrane fabrics have been developed.1) Coated plain-weave fabrics have anisotropic and nonlinear properties that are mostly dominated by the characteristics of the fabric. It is important for designing the membrane structures to understand deeply the anisotropy and nonlinearity of the high-strength membranes. Acquisition of the strength of the coated fabrics under biaxial loading is required, especially to properly evaluate the strength of the airship skin for the purpose of effective weight reduction and safety design.

The strength of a coated plain-weave fabric depends on the tensile direction, and the high directional dependency of the strength is critical in some cases. Understanding the mechanism of anisotropy of coated fabrics is essential for evaluating the biaxial strength. Peirce2) formulated on plain-weave fabrics using a simple geometrical model based on the fabric structure without mechanical consideration, and showed relationships between the crimp of fibers and distortion of the fabric. Olofsson3) and Huang4) proposed mechanical formulations in consideration of fiber bending stiffness without giving respect to the elongation of fibers. Kawabata et al.5,6) analyzed mechanical properties based on the tension balance of warp and weft yarns while ignoring the bending effect, and compared experimental results that were obtained using cruciform biaxial specimens. They also took into account the radial compressive stiffness of the yarns. Gasser et al.7) analyzed not only plain-weave fabrics, but also satin fabrics using the Finite Element Method (FEM), and numerical calculations were reported to be in good agreement with experimental results. Kuwazuru et al.8) proposed the FEM analysis of the mechanical behavior of plain-weave fabrics with complex geometrical boundary conditions.

Though the researches mentioned above are very important for explaining the mechanical properties of fabrics, the effects of coating on the mechanical properties of widely-used coated fabrics had not yet been researched. Recently, experimental and analytical studies on membrane fabrics including the effects of coatings have been developed. Minami et al.9,10) and Szostkiewicz et al.11) conducted numerical calculations and biaxial tensile experiments with cruciform specimens of coated fabrics, and reported good agreement between the calculated and experimental results. Influences of defects such as cracks on the strength of coated fabrics were also investigated using uniaxial tensile tests with strip specimens and biaxial tensile tests with cruciform
specimens.\textsuperscript{12–14} In these studies, FEM was also conducted to examine the failure mechanism of coated fabrics with defects. However, most of the investigations have been focused on conventional fabrics, and the study of membranes consisting of novel high-strength fibers is still insufficient.

In this study, the strength properties of coated plain-weave fabrics composed of polyarylate fiber, VECTRAN (Kuraray Co., Ltd.), were evaluated. Biaxial tensile tests with cruciform membrane specimens were conducted to obtain the strength properties of the coated fabrics. In addition to biaxial tests, uniaxial tensile tests using strip specimens were conducted to obtain the fundamental uniaxial properties of the fabrics. The results of these experiments show the influence of biaxial tensile loads on the strength of the coated high-strength fabrics. Microscopic observations and tensile tests of yarns in the coated fabrics were conducted to evaluate the damage to the yarns after weaving, which has a significant impact on the biaxial strength of the membrane fabric.

2. Experimental Procedures

2.1. Material system

The material system used in this study was coated polyarylate fiber (VECTRAN) plain weave. It was developed as an ultralight membrane material for stratospheric platforms. VECTRAN plain-weave fabric is characteristically strong and stiff, and an EVAL (Kuraray Co., Ltd.) film layer and polyurethane coating are applied to prevent gas leakage and as a protective layer, respectively. The area density of polyurethane coating are applied to prevent gas leakage and as a protective layer, respectively. The area density of the coated fabric is 198 g/m\textsuperscript{2}. The line density of the warp and weft yarns in the fabrics is 200 denier, and the weave density is 34 yarns/in in both directions. The angle between the warp and weft yarns is not necessarily a right angle, and ranges from 87 to 93° because of difficulty in manufacturing. Misalignment in case of non-coated fabrics is insignificant because the angles between the warp and weft yarns are not restrained by coatings. However, the yarns in coated fabrics are adhered by the coating materials, and the angles between the warp and weft yarns become restrained by the adhesive effect. These misalignments are considered to affect the mechanical properties of the membrane fabrics. In this study, the \(x\)-direction and \(y\)-direction indicate the direction of warp yarn and perpendicular direction to \(x\)-direction, respectively, and the membrane specimens are cut out on the basis of \(x-y\) coordinates.

2.2. Biaxial tensile experiments

A planar biaxial testing machine having orthogonal \(x\)- and \(y\)-axes, and two pairs of hydraulic cylinders placed horizontally on each axis diagonally is utilized (shown in Fig. 1). The loads generated in the hydraulic cylinders are transmitted to the chucks to hold the cruciform specimen’s arms. The hydraulic pressure of each pair of opposing hydraulic cylinders is servo-controlled independently, so that the load ratios \(F_x : F_y\) are arbitrary controlled using closed-loop circuits,\textsuperscript{15} where \(F_x\) and \(F_y\) correspond the loads in the direction of the \(x\)- and \(y\)-axis, respectively. Displacements of the arms of the opposing hydraulic cylinders are equalized using a pantograph-type link mechanism,\textsuperscript{16} and hence the center of the cruciform specimen is constantly kept at the center of the testing apparatus during biaxial tensile testing. The load capacity of the testing machine is 50 kN (tensile), and 20 kN load cells were used to measure loads in this paper.

Biaxial tensile tests were conducted to evaluate the influence of biaxial load ratio on the strength of the membrane fabrics. The cruciform specimen configurations used in this study are shown in Fig. 2. An open hole (3.5-mm diameter) exists at the center of the membrane specimen. Four arms of the cruciform specimen were attached to the four grips of the biaxial testing machine, and applied biaxial loading with constant biaxial load ratio for each test. Sandpaper was adhered to the steel plates at the grips to prevent slippage of the membrane specimen’s arms. The distance between opposed grips was 180 mm. The crosshead speed in the direction of the main axis was 9.4 kN/min, and that in the direction of the other axis (< 9.4 kN/min) was determined by the biaxial load ratio. It is noted that \(y\)-axis of the cruciform specimens did not coincide with the weft yarn direction due to a slight misalignment of weft yarns, though the \(x\)-axis coincided with the warp yarn direction.

2.3. Uniaxial tensile experiments

Uniaxial tensile tests of the coated membrane fabrics were conducted to compare the results of the biaxial tensile tests. Configurations of the uniaxial strip specimens are shown in Fig. 3. The uniaxial strip specimens were cut out in directions parallel to the \(x\)- and \(y\)-axis. The longitudinal direction of the \(y\)-directional specimen was not parallel to the warp direction due to a misalignment of the weft yarns. In addition to the uniaxial specimens mentioned above, uniaxial specimens parallel to the weft yarns were prepared, and
uniaxial tensile tests in the direction of the weft yarns were also conducted. Specimens with widths of 60 mm (Fig. 3 (a) and (b)) were examined for the strength of the membrane fabric, and specimens with widths of 30 mm (Fig. 3 (c)) were examined for the relationships between load and elongation. The width, length and diameter of the open hole in the uniaxial strip specimens (shown in Fig. 3(b)) were determined in accordance with the configurations of the biaxial cruciform specimen shown in Fig. 2. The loading conditions for the 60 mm-wide specimens (Fig. 3 (a)) were a tensile speed of 9.4 kN/min and the distance between the grips was 180 mm. Elongation of 30 mm-wide specimens was measured using a digitized servo hydraulic material testing machine (Instron Corp., load capacity: 100 kN) and a non-contact video extensometer (Shimadzu Corp., the model: DVE-201). For the measurement of elongation, the tensile speed was 200 mm/min, grip distance was 260 mm, and the target distance for the non-contact video extensometer was 190 mm.

2.4. Tensile experiments on yarn fibers

The mechanical properties of the coated fabrics are strongly dominated by the properties of the yarn in the membrane materials. Tensile tests were conducted on single yarns to acquire their mechanical properties. Three types of yarn, raw yarn before weaving, and warp yarn and weft yarn in the coated fabrics, were evaluated. The warp and weft yarns were sampled from the coated fabrics after peeling off one side of the membrane coating. The configurations of the yarn specimens were a length of 200 mm and the distance between the grips was 180 mm. Both ends of the yarn specimen were attached by steel-plate clamps, and the cross-head speed was 300 mm/min. The rated capacity of the load cell (Kyowa Electronic Instruments Co., Ltd., model: LTZ50KA) used in the yarn tensile test was 500 N.

2.5. Microscopic observations

Cross-sections of the membrane, face of weaving fabric after peeling off one side of coating, and yarns sampled from the coated fabrics were observed using a digital video microscope (Keyence Corp., model: VH6300). Specimens for the observation were sampled from untested materials. Warp and weft yarns were drawn from the coated fabrics in the same manner as the yarn specimens for tensile tests.

3. Results and Discussion

3.1. Uniaxial tensile properties

Typical load-strain curves of the x- and y-directional strip specimens (Fig. 3 (c)) are shown in Fig. 4. These curves indicate the difference in elongation depending on the tensile directions. Strengths of the coated fabrics in the direction of the x- and y-axis were 0.626 kN/cm (average of six specimens) and 0.450 kN/cm (average of three specimens), respectively. The strength of the membrane material is also dependent on the tensile direction.

The influence of specimen width on strength was also evaluated. x- and y-directional strengths of 30 mm- and 60 mm-wide specimens are shown in Figs. 5 and 6. In Fig. 5, narrow specimens (width 30 mm) are stronger in the x-direction than wide specimens (width 60 mm). The degradation in the strength of the wide specimens is about 9% in Fig. 5, and this is assumed to be caused by a slight misalignment in the attachment of material to the testing machine due to the wide width of the specimen and horizontal attachment on the biaxial testing machine. A uniaxial testing machine was used to apply a vertical tensile load on the narrow specimens. The y-directional strength of the wide specimens proved to be stronger than that of the narrow specimens (Fig. 6). Misalignment of the weft yarns in the y-direction supposedly caused degradation of the narrow specimen strength, because the ratio of yarns discontinued at the edges on both sides of the narrow specimens is larger.
than that of the wide specimens. A photograph of the x- and y-directional specimens after tensile tests is shown in Fig. 7. The x-directional specimen, in which the warp yarns were aligned with the tensile axis in parallel, broke perpendicular to the tensile axis. On the other hand, the y-directional specimen, in which the weft yarns were misaligned with the tensile axis, broke in a staircase pattern. Misalignment between the weft yarns and the tensile axis for the y-directional specimens created shear stress in the gauge area, which supposedly caused the staircase-pattern.

Tensile tests of strip specimens with and without a hole (Fig. 3 (a) and (b)) were conducted to evaluate the effect of the open hole on the strength of the coated fabrics. Results of the tensile tests are shown in Fig. 8. In the results, strength is defined as the failure load divided by the width of the specimen. Figure 8 shows degradation in the strength of x- and y-directional specimens due to the existence of the hole. The strength loss rate was about 15%, though ratio for the hole width a 3.5 mm diameter in the 60 mm-wide specimen was about 6%. Minami9) analyzed fabrics with a rectangular hole using FEM analysis in consideration of the crimp, and explained that fibers around the hole were subjected to higher load than fibers away from the hole. Though the open hole in the coated fabric specimens in this study was not rectangular, it is assumed that the fibers around the circular hole were also subjected to a higher load. Thus, the strength loss rate of the open-hole specimens is higher than the ratio of the hole diameter when compared to the specimen width.

3.2. Strengths under biaxial loading

Tensile tests of the cruciform specimens with a 3.5 mm-diameter hole (Fig. 2) were carried out under biaxial loading conditions. Biaxial failure properties for nine biaxial loading ratios were acquired. The average failure loads of five specimens (biaxial loading ratio 1:1 and 1:0) and three specimens (other biaxial loading ratios) are respectively plotted in Fig. 9. The results of the uniaxial strip specimens with the 3.5 mm-diameter open hole are also plotted with triangular marks (△) in Fig. 9. A photograph of the cruciform specimen after the biaxial tensile test is shown in Fig. 10. Failure in the tensile test occurred at the open hole immediately after the load hit maximum value; the cleavages extended to the width of the arms (60 mm) and biaxial load dropped to nearly zero. Cleavage ran through the center of the specimen in both x- and y-axis directions under load ratios neighboring 1:1, as shown in Fig. 10. Cleavage ran through in one direction, x- or y-axis direction, under load ratios neighboring 1:0 or 0:1.

In Fig. 9, the x-directional tensile strength of the cruciform specimens ($F_x : F_y = 1:0$) is nearly equal to that of the strip specimens, and the y-directional arms of the cruciform specimen had little affect on x-directional uniaxial strength. Open-hole strength in the case of x-directional load being larger than y-directional load ($F_x > F_y$), is almost independent of the y-directional load and equal to the strength of the uniaxial strip specimens. Biaxial strength in the case of x-directional load being smaller than about 60% of the y-directional load ($F_x < 0.6 F_y$) is also independent of x-directional load. Nevertheless, the biaxial strength rises slightly in the region where x-directional load is between 60 and 100% of the y-directional load ($0.6 F_y < F_x < F_y$).
Strength under the biaxial loading of coated fabrics is totally independent of the biaxial loading ratios, but y-directional strength under load ratios neighboring 1 : 1 rises slightly.

The results of the biaxial tests show that the biaxial strength of open-hole specimens is approximately constant irrespective of the biaxial loading ratio. The failure starts at the edge of the hole where a higher tensile load is applied to the yarns in the membrane materials. There is no force perpendicular to the circular hole at the portion of the yarns tangent to the open hole, like a free edge, and therefore the open-hole strength is approximately independent of the biaxial load ratio.

### 3.3. Effect of weft yarn misalignment

The y-directional strength of the membrane fabric is lower than the x-directional strength. One of causes of the low strength in y-direction is considered to be the misalignment between the tensile direction (y-direction) and the weft yarn direction, which is a maximum of $3^\circ$. To evaluate the affect of the weft yarn misalignment, uniaxial tensile tests were conducted with specimens set at angles of 0 and $3^\circ$ between the tensile direction and the weft yarn. Specifications of the specimens were a 60 mm width and 260 mm length, and each had a 3.5 mm-diameter hole, as shown in Fig. 3 (b). The results of the experiment, as shown in Fig.11, reveal that $3^\circ$ misalignment causes a degradation of about 20% in the open-hole uniaxial strength.

The affects of weft yarn misalignment on the tensile strength are approximated analytically. Weft yarn can be divided into two parts when it is misaligned with the tensile direction as shown in Fig. 12. One part is a group of yarns with both ends attached to the grips, and the other part is a group of yarns with only a single end attached to the grip (hatched part in Fig. 12). The yarns with a single end attached to the grip do not contribute significantly and lead to degradation of the strength. For calculating loss in strength, it is assumed that the yarns with the single end attached to the grip do not contribute to the strength, the 3.5 mm-diameter hole is sufficiently small compared to the 60 mm width, and the strength is proportionate to the ratio of the yarns with both ends attached to the grips. The width not contributing strength $A$ in Fig. 12 is described as follows:

$$ A = 180 \tan \theta $$  
where $\theta$ is the angle between the weft yarn direction and the tensile direction. The strength loss rate is assumed to be proportionate to the rate of the non-effective width $A$ as compared to the whole specimen width 60 mm, and thus strength ratio $D$ as compared to the specimen without misalignment of the weft yarns is described as follows:

$$ D = (60 - A) / 60 $$  

Experimental and analytical results on the strength ratio with $\theta = 3^\circ$ are shown in Table 1. Table 1 indicates that analytical approximation is in good agreement with the experimental results. The degradation of strength due to misalignment of the weft yarns can be explained by the discontinuity of the weft yarns at the free edges of the uniaxial specimen.

Open-hole strengths in the $y$-direction, weft direction and warp ($x$) direction are compared in Table 2. The misalignment of weft yarns to the tensile axis is distributed in the range of $\pm 3^\circ$ in the $y$-directional specimens, which were cut perpendicular to the warp ($x$) direction. The average strength of the $y$-directional specimens is smaller than that of the weft directional specimens, which were cut parallel to the weft yarns (Table 2). Warp ($x$) and weft directional tensile strengths are quite different, though the density of a single yarn and the number of yarns in unit width are the same in the warp and weft specimens. Table 2 implies that the reason for less strength in the $y$-direction as compared to that in the $x$-direction is not merely misalignment of the weft yarns.

### Table 1. Degradation of open-hole strength due to misalignment of weft yarns.

<table>
<thead>
<tr>
<th>Misalignment of weft yarn $\theta$</th>
<th>0°</th>
<th>3°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average strength (experiment) kN/cm</td>
<td>0.387</td>
<td>0.322</td>
</tr>
<tr>
<td>Strength ratio (experiment)</td>
<td>1</td>
<td>0.83</td>
</tr>
<tr>
<td>Strength ratio $D$ (analysis)</td>
<td>1</td>
<td>0.84</td>
</tr>
</tbody>
</table>
3.4. Crimp of yarns and adhesion bonding of fabrics and coatings

Crimp and degradation of the yarns are believed to lead to the difference between x- and y-directional strengths of the coated fabrics. The crimps in the yarns are caused by the crossover of warp and weft yarns (Fig. 13). Photomicrographs of warp and weft directional cross-sections are shown in Fig. 14. This figure indicates that the weft yarn is more undulated than the warp yarn.

The front face of the fabric after peeling off the surface coating is shown in Fig. 15. This figure shows that the yarns in the fabrics are untwisted. Dark regions on the front face of the fabric in Fig. 15 represent the bonded points where polyurethane coating adheres to the fabric. There was much more residual resin of the removed coating on the weft yarns than on the warp yarns (Fig. 15). Yarns sampled from the fabrics are shown in Fig. 16. The sampled yarns also indicate much resin remaining adhered to the weft yarns. The reason for better adhesion to resin on the weft yarns is a large crimp in the yarns, which creates a large contact area between the coatings and the yarns. The coating process was applied under the conditions of compression and a high temperature of more than 150°C. The large contact area between the weft yarns and heated polyurethane sheet leads to degradation of the weft yarns due to the high temperature, to which the warp yarns are not subjected. The degradation of the weft yarns could lower weft directional stiffness and strength as compared to warp directional stiffness and strength.

3.5. Mechanical properties of fiber yarns

The results of the tensile tests of warp and weft yarns sampled from the coated fabrics are shown in Figs. 17 and 18, respectively. The elongations of raw yarns are also plotted as reference data in both figures. Five denier single filaments are bundled up as a 200-denier yarn specimen. Thus, the yarn specimen had to be attached carefully to avoid loosening some single filaments since the yarns were not twisted. Though several specimens for the tensile test broke at the chuck, many specimens broke at a point far from the chucks without fibers pulling free. The data for the specimens that broke at the chuck are not included in Figs. 17 and 18. The number of specimens for the raw yarns and the sampled warp yarns is three in Figs. 17 and 18. However, six specimens of sampled weft yarns were tested, as plotted in Fig. 18, to compensate for the large fluctuation in the results of weft yarns.

The strength of the yarn specimens sampled from coated fabrics was lower than that of raw yarns because the yarns were damaged due to peeling off the coatings, which affects the strength. The stiffness of the raw yarn and sampled warp yarns were almost the same, as can be seen by comparing the slopes of the curves in Fig. 17. However, the stiffness of the sampled weft yarns was lower than that of the raw yarns (Fig. 18). The stiffness of sampled weft yarns is reduced as the result of heat deterioration during contact with the hot resins of the coatings, as shown in Fig. 16. It is believed that the large fluctuation in failure load of the sampled weft yarns was be induced by severe damage caused when the coating and weft yarns were peeled for sampling.
4. Conclusion

In this study, the strength of a coated polyarylate plain-weave fabric, which is one of the candidate materials for stratospheric platform main structures, was evaluated at room temperature. The effects of biaxial loading on the strength of the membrane fabrics were obtained through the use of cruciform specimens with an open hole. The fundamental uniaxial mechanical properties of fiber yarn and coated fabrics were also obtained for comparing properties under biaxial loading. Fabrics and yarns that had been coated with different processes.

The results of the experiments, the mechanical properties of the coated membrane fabrics were clarified. Uniaxial tensile strength of the membrane in the weft direction is lower than that in the warp direction, and opening a hole on the strip specimens caused a substantial reduction in strength in the uniaxial tensile tests. The open-hole strength of the fabrics under biaxial loading was approximately independent of the load ratio and equal to that under uniaxial loading, though the strength was slightly higher when the load ratio was near equi-biaxial. The dependency of strength on tensile direction was caused by misalignment of the weft yarns and heat deterioration of the weft yarns during the coating process.

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