Tensile properties and meso-scale mechanism of multi-axial warp-knitted fabrics of various structural designs

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Received 1 March 2013; revised received and accepted 16 July 2013

Tensile properties tests of three kinds of multi-axial warp-knitted fabric, namely triaxial fabrics (-45°/90°/+45° and -45°/0°/+45°) and quadraxial fabric (-45°/90°/+45°/0°) have been studied along the orientations of 0°, 45° and 90°. Stress-strain curves are obtained. The whole tension processing has been observed through high-speed camera and the series of images is picked up to analyze the meso-scale mechanism of the extension and displacement of tows on oriented layers. The results indicate that the tensile properties of MWK fabric are closely related to the orientations of the layers, and stitching yarns incarnate significant effects on deformation procedures of fabrics.

Keywords: Mechanical behavior, Meso-scale mechanism, Multi-axial warp-knitted fabric, Oriented layers, Tensile properties

1 Introduction

Multi-axial warp-knitted (MWK) fabrics are prepared by using laying yarn system and stitching yarn system. All the non-crimp tows are aligned together along the warp (0°), diagonal (-45° \( \leq \theta \leq 45° \)) and weft (90°) to share the stress, so that the 90% of yarn capacity can be used\(^1\). Each single layer of the fabric has high degree of orientation to provide multi-directional in-plane mechanical properties. Thus, the mechanical performance of MWK fabric is well improved. In addition, the stitching yarns improve the integration and the strength of the fabric. Tensile strength of MWK fabric is enhanced sufficiently and becomes the typical mechanical features with the use of no-crimped tows. Due to the special manufacturing technique, various kinds of high performance materials can be processed into MWK fabric. The high production efficiency will also enhance industrialization. As a kind of textile reinforcement with distinguished mechanical properties, MWK fabrics have been extensively utilized in wide range.

Mechanical properties are extremely important for MWK fabrics. Kong \textit{et al.}\(^1\) studied the tensile extension properties and deformation mechanism of multi-axial non-crimp fabrics. They indicated that this kind of fabric has excellent mechanical properties. The amount, line-tension and location of the knitting stitches have obvious influence on the deformation resistance. Hu \textit{et al.}\(^2\) built up a uniaxial tensile model to predict the tensile properties of warp-knitted fabrics. The theoretical model is justified by the tests, and a good agreement between theoretical and experimental results is obtained. Luo \textit{et al.}\(^3\) studied the behavior of rib and Milano weft-knitted fabrics under biaxial tension. The final deformation along the wale and course directions is determined at different displacement ratios. The geometrical models are also established to predict the ultimate deformation. There is a good agreement with experimental results. Hou \textit{et al.}\(^4\) studied the tensile behavior of 3-D angle-interlock woven carbon fabric (3DAWF) under high strain rate tension from the viewpoints of experimental and finite element analyses. The results showed that the variety of failure morphologies exist in the different layers of 3DAWF. The stress waves are fluctuant and lead to irregular failure morphologies under high strain tension. Boisse \textit{et al.}\(^5\) investigated the phenomena at the elementary woven cell level and built a model to simulate the fabric sheet forming process. The results indicated that their experiment and simulation show a good agreement.

Textile fabric is considered as a kind of excellent reinforcement material for extensive utilization in the composites, due to its outstanding mechanical behavior. Onal\(^6\) compared the MWK fabric and woven fabric reinforced composites from the mechanical performance point of view and found that MWK fabric reinforced

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laminate have lower resin weight and more excellent flexural stiffness. Luo et al.\textsuperscript{7} studied the bi-axial tensile properties of bi-axial warp knitted PET/PVC flexible composites along the seven in-plane directions. They found that bi-axial warp knitted coated fabrics have a strong orthotropic behavior. Ramakrishna\textsuperscript{8} analyzed the models for predicting tensile properties of weft-knitted glass fibre fabric reinforced composites. The fracture strength of bridging yarns is estimated by investigating the strength. The experimental results show consistency with analytical procedures. Wu et al.\textsuperscript{9} investigated mechanical properties of warp-knitted fabric-reinforced composites. The results revealed that tensile strength and the modulus of warp-knitted fabric reinforced composites are greatly influenced by knitted structures and density of fabric. Peled et al.\textsuperscript{10} discussed the tensile properties of textile reinforced cement composites. The results indicated that the textile reinforcement with combination of a small bundle diameter fabric and a large size of loop developed best mechanical properties. Sugie et al.\textsuperscript{11} focused on the impact properties of CF/GF fibre hybrid multi-axial warp-knitted fabric composites. The result demonstrated that the energy absorption capability of this kind of fabric composites is closely related to the fracture mechanism.

In order to understand the tensile properties of MWK fabrics in depth, this study was undertaken to investigate the tensile properties and meso-scale mechanism of three kinds of MWK fabric samples made by using different structural designs, including two triaxial fabrics and a quadraxial one. The transformation in the configuration of the fabric structure during extension is revealed by image technology. Stress-strain curves are drawn and the failure modes and forming reasons are analyzed systematically.

2 Materials and Methods

2.1 Microstructures of MWK Fabrics

The triaxial fabrics (Triaxial Type I and Triaxial Type II) and Quadraxial Type which were consisted of continuous E-glass yarns with the same specifications were used. They were obtained from Jiangsu Jiuding New Material Co., Ltd. via Karl Mayer MultiAxial-2-CH. The specifications of the samples are described in Table 1. The three samples have the same ply density and are well stitched with the same standard of yarns in tricot or chain stitch pattern, keeping the stitching loads consistent, but ply layers, orientation of tows and weight different. It is worth mentioning that the third sample is much heavier than the earlier tow, since there is one more layer inserted in the fabric. On the other hand, though the stitching patterns are different, the stitching yarns have tiny influence onto the fabric weight; due to the fact that weight of stitching yarns can be ignored normally.

2.2 Tensile Test

The effective tensile extension zone of the specimen was kept as 200mm×25mm. The tensile tests were done using multipurpose material tester Instron 3385H along the different orientations. The Keyence high-speed camera was employed to record the digital videos and to take the still pictures in order to observe the deformation of fabrics during the tensile processes. The loading speed was kept at 5cm/min. The bottom end of the specimen was fixed and the top end of the specimen was clamped by the holder and allowed to move at the loading speed. The gauge length was 200mm. Three MWK fabrics were tested and the stress-strain curves were obtained. The experimental apparatus are shown in Fig. 1. Multipurpose material

<table>
<thead>
<tr>
<th>Sample</th>
<th>Description</th>
<th>Number of ply layers</th>
<th>Orientation of tows</th>
<th>Stitch pattern</th>
<th>Weight g/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triaxial Type I</td>
<td>Triaxial</td>
<td>3</td>
<td>-45°/90°/+45°</td>
<td>Chain</td>
<td>396</td>
</tr>
<tr>
<td>Triaxial Type II</td>
<td>Triaxial</td>
<td>3</td>
<td>-45°/0°/+45°</td>
<td>Tricot</td>
<td>396</td>
</tr>
<tr>
<td>Quadraxial Type</td>
<td>Quadraxial</td>
<td>4</td>
<td>-45°/90°/+45°/0°</td>
<td>Tricot</td>
<td>709</td>
</tr>
</tbody>
</table>

Fig.1 — Experiment apparatus
Results and Discussion

3.1 Mechanical Properties

All the tensile tests were carried out by using the multipurpose material tester Instron 3385H. The deformation of the three kinds of fabric samples was studied along the directions of 0°, 90° and ±45° separately. There were three specimens for every single orientation of each sample. The tensile curves obtained are shown in Fig. 2.

Stress-strain curves of Triaxial Type I (-45°/90°/+45°) sample are given in Fig. 2(a). The test result along the orientation of 90° shows that the specimen can bear stress up to 120MPa. The specimen fractures at 3.8% strain, which indicates that it can bear larger load but can abruptly fall. The curve reveals that ductility is absent along 90° direction. On the other hand, both specimens along 45° and 0° have more placid curves after attaining a peak value of stress and a larger displacement exist. The stress along the 0° direction is the smallest, and the stress loaded along 90° direction is found to be triple of it. All the three curves of different samples exhibit non-linear behaviors. According to Fig. 2(a) and the images, Triaxial Type I(-45°/90°/+45°) displays the highest failure load along the test orientation of 90° owing to the layer of 90° tows. Under the increasing load, 90° tows remain straight, compact and ordered arrangement. As the load becomes greater, 90° tows show phenomenon of bundling and simultaneously the failure load reaches its peak. On the other hand, the low modulus of the layer along 0° is because of the absence of 0° layer. The stress-strain curve of bias test has intermediate behavior. This situation is owing to the effect of stitching yarns. Stitching yarns fix the tows on bias layers and make them displaced hysteretically and slowly. However, since the tows along bias directions has angle with the test orientation, the tows on the bias layers could not develop the mechanical properties fully, therefore they could not bear as much load as the 90° tows can bear.

Stress-strain curves of Triaxial Type II (-45°/0°/+45°) sample are shown in Fig. 2(b). The sample along 0° bears highest stress and reaches its peak at 165 MPa. It fractures at nearly 5% strain. The sample along 45° direction shows intermediate behavior and it shows lengthy displacement process and breaks at the strain of 3%. It is indicated that the Triaxial Type II (-45°/0°/+45°) specimen along 0° has the highest Young’s modulus. Similar trend is observed for Triaxial Type II (-45°/0°/+45°) sample. The tensile test along 0° shows larger strength because of the existence of 0° tows and on the orientation of 90°, the specimen shows the weakest situation during

Fig.2—Stress-strain curves of (a) Triaxial Type I, (b) Triaxial Type II and (c) Quadraxial Type
the test along 0° owing to the deficiency of 90° tows. The test results of bias directions are found still intermediate with the same reason as mentioned for the tensile test of Triaxial Type I. In this test, both of the specimens along 0° and 45° are fractured suddenly, while the curve of 90° is maintained continuously under low load.

Stress-strain curves of Quadraxial Type fabric is also exhibited in Fig.2(c). Both curves along 0° and 45° have the similar trend. The curve along 90° has poor performance. The trend is mild, continuous and level consistent though it endures the stress within lower scale. The Quadraxial Type fabric having -45°/90°/+45°/0° shows excellent general performance. Though Quadraxial Type fabric has poorer performance in the test along 90° direction, it still can bear the stress of more than 20MPa steadily, which is higher than that in Triaxial Type I and Triaxial Type II. This is benefit from that it has tow layers along 90°, 0°, and ±45°. The relevant tow layer shows effects, no matter which direction it was tested. The mechanical properties of every layer could be brought into play adequately. Therefore, the Quadraxial Type fabric shows balanced performance.

Table 2 shows breaking strength and extension of the three fabrics in different directions clearly. It can be indicated that three kinds of samples have the same trend. It is observed that the breaking strength and breaking extension along the orientation of 45° are obviously higher than the ones along 0° or 90°; the sizes of the data of latter two directions depend on whether the corresponding yarn layer exists or not.

### 3.2 Photographic Analysis

During the tensile test, the integrated deformation was observed and recorded by Keyence high-speed camera. The utilization of this device could provide available imaging materials to reveal the meso-scale mechanism of the deformation. Several videos were recorded and series of continuous still images was picked up according to the times nodes.

The picked images of deformation process of Triaxial Type I(-45°/90°/+45°) are shown in Fig. 3. In Fig. 3(a) the tows along 90° which is perpendicular to test direction are away from each other stepwise. The stitch yarns are found broken in the whole tensile processing. The final image shows that the tows in both of the first and the third layers along -45° and +45° directions have displacement and the angle along 0° direction of the two layers becomes smaller. Along the tensile direction at 45° [Fig. 3(b)], the tows along 90° are away from each other gradually with the load increasing, as shown in the first four images. The angle of the tows along 45° direction and the ones along 90° becomes smaller, while the angle of the tows along -45° direction and the one along 90° is larger. It can be noticed that the fabric is fractured abruptly and exhaustively. It is obvious that the stitch yarn begins to fracture under the load [Fig.3(c)], and the situation becomes worse with the load increasing. The tows along both -45° and 45° are disperse, as shown in final image, while the fibres along 90° show bundling and play a role of main force to bear the load.

The picked images of deformation process of Triaxial Type II(-45°/0°/+45°) are shown in Fig. 4. In the test along 0° [Fig. 4 (a)], tows on the orientation of test play a major role in bearing load, though some of 0° tows are fractured from the first deformation as the load is increased. Tows along -45° and +45° nearly are totally collapsed under the high load. The final image presents confused situation. In Fig.4(b) for the test along 45°, the extension of the specimen appears at the first deformation and becomes more obvious in the future. After a large deformation, stitching yarns begin to break up and get worse just as displayed in the image. Finally, the specimen is fractured with the incompact 0° tows. The warp tows do not perform as mighty as in the test along 0° direction, but are just influenced a lot by the stitching yarns. When the stitching yarns rupture, the warp tows are unconsolidated. Along the test of 90°, warp tows (0°) are away from each other stepwise just like unparallel tracks, as can be seen from Fig.4(c). Bias tows show obvious displacement. The angle of tows along -45° and 0° becomes smaller. The angle of tows along 45°

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<p>| Table 2—Data of breaking strength and breaking extension of three fabrics along different orientations |</p>
<table>
<thead>
<tr>
<th>Fabric</th>
<th>Orientation</th>
<th>Breaking strength, N</th>
<th>Breaking extension, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triaxial Type I (-45°/90°/+45°)</td>
<td>0°</td>
<td>78.45</td>
<td>35.87</td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>1485.77</td>
<td>101.14</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>2703.56</td>
<td>5.80</td>
</tr>
<tr>
<td>Triaxial Type II (-45°/0°/+45®)</td>
<td>0°</td>
<td>2832.20</td>
<td>8.70</td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>1735.28</td>
<td>105.89</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>70.15</td>
<td>88.99</td>
</tr>
<tr>
<td>Quadraxial Type (-45°/90°/+45°/0°)</td>
<td>0°</td>
<td>2135.62</td>
<td>83.97</td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>2740.05</td>
<td>98.31</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>66.80</td>
<td>92.15</td>
</tr>
</tbody>
</table>
and 0° correspondingly becomes bigger. The final image shows that the stitch yarns are totally broken within the main deformation area.

The picked images of deformation process of Quadraxial Type fabric (-45°/90°/+45°/0°) are shown in Fig. 5. The deformation along 0° is shown in Fig. 5(a). Quadraxial Type fabric presents better balanced performance than other two types of fabric. Some of the tows along the test direction are busted apart. The loops height along 0° exhibits an increase and the stitches fractured till they could not be extended further. Tows along other three directions are all incompact within the main deformation area. Figure 5(b) shows the deformation process along 45° direction. The fabric is kept relatively in order from the exhibition of images. Deformation starts

Fig.3—Photographs of MWK Triaxial Type I fabric at different strain levels (a) along the orientations of 0°; (b) along the orientations of 45°, and (c) along the orientations of 90°
after a large strain level. The stitching yarns break and tows along 0° direction start to draw back firstly. Due to the axial symmetry of two bias layers, tows along both -45° and 45° are efficiently born the load together. Due to the diminishing of the angle between bias and test direction, bias layers are elongated and do not fracture finally. Figure 5(c) shows the deformation of Quadraxial Type fabric at different strain levels along the 90° direction. According to the meso-scale observation, it is apparent that the every single tow of 0° direction on the first layer presents obvious displacement with the promotion of strain levels. The weft 90° tows become aloof one by one. Simultaneously, the tows of 90° which has consistent orientation with the deformation keep unchanged course within per unit lengthways scale and bear large load. Due to the effect of stitching yarns, bias tows along both -45° and +45° bound with the layers of 0° and 90° assist in bearing and dispersing the load.
4 Conclusion

Tensile properties of multi-axial warp-kitted fabric having various structural design are experimentally investigated. It is found that the tensile properties can be well presented when tow layer is used along the relevant testing orientation. But the tensile strength is found to be weak when the corresponding tow layer is deficient. In the test direction of 90° or 0°, the angle between bias tow layers (−45°/45°) and the test orientation would be changed, so that bias tow layers show obvious displacement. With the increase of strain levels, the samples present a remarkable increase in the stitch length (loop height). Stitching yarn exhibits apparent binding effect, especially in Quadraxial Type fabric. Stitching yarn also restricts the displacement of layers and ensures fabric stability in certain degree.

Fig. 5—Photographs of MWK Quadraxial Type fabric at different strain levels (a) along the orientations of 0°; (b) along the orientations of 45° and (c) along the orientations of 90°
Acknowledgement

The authors acknowledge with thanks the financial supports from the Chinese National Science Foundation (NO.11302085), the National Science and Technology Support Program of China (No. 2012BAF13B03) and the Fundamental Research Funds for the Central Universities (No. JUSRP1043).

References
8 Ramakrishna S, Compos Sci Technol, 57(1997)1.