The Layer of Kevlar Angle-interlock Woven Fabric Effect on the Tensile Properties of Composite Materials

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Abstract: This article is based on the structure of three-dimensional angle-interlock longitudinal. The 3-layer, 5-layer, 7-layer and 9-layer of angle-interlock 3D fabrics are woven on sample weaving machine respectively with the 1500D Kevlar fiber twist filament produced by United States DuPont. At the same time, Kevlar plain weave fabric is woven, and three, five, seven and nine layers’ fabric are to be compared. In the process of VARTM composite technology, epoxy resin is matrix material, acetone is diluent, triethylene tetramine is curing agent and the five different fabrics are the reinforced materials respectively. Finally, eight different three-dimensional woven fabric composites were prepared. In this paper, the tensile properties of eight kinds of three-dimensional woven fabric composites were tested respectively. Finally, it is concluded that the five-layer angle-interlock woven fabric prepared by Kevlar fiber shows the best tensile property.

1. Introduction

Tensile properties test is very important in the performance test of composite materials. For textile composites, when the tensile stress is applied to both the ends of the composite material, the internal structure of the material does not change significantly in a short time. After a certain period of time, the internal structure of the composite material began to change, which is the stress concentration phenomenon between the resin and the yarn in the fabric. With the increase of material deformation, the stress also increases and when the composite material can no longer bear more load, the composite material breaks.

Many scholars have studied the mechanical properties of woven fabric composites. This paper will mainly explore and analyze the relationship between the layer of Kevlar angle-interlock woven fabric and the tensile properties of composite materials.

2. Experiment

2.1 Design and weaving of angle-interlock woven fabric

The main components that affect the mechanical properties of the materials are fabric preforms in the three-dimensional fabric composites. Therefore, when the author prepare to make the three-dimensional angle-interlock woven fabric, the fabric structure of the process parameters need to be designed.

Sequentially designed the 3-layer, 5-layer, 7-layer and 9-layer of angle-interlock woven fabric, and the structural parameters are determined as follows:
n=3, Rj=n+1=4, Rw=Rj×n=n(n+1)=12, Sj=n=3, Fm=2n-1=5;
n=5, Rj=n+1=6, Rw=Rj×n=n(n+1)=30, Sj=n=5, Fm=2n-1=9;
n=7, Rj=n+1=8, Rw=Rj×n=n(n+1)=56, Sj=n=7, Fm=2n-1=13;
n=9, Rj=n+1=10, Rw=Rj×n=n(n+1)=90, Sj=n=9, Fm=2n-1=17.

Where:
n - fabric layer number;
Rj - the number of circulating warp yarns;
Rw - the number of woven loops;
Sj - meridian;
Fm - organization maximum float length.

Draw the looming draft of 3-layer, 5-layer, 7-layer and 9-layer of angle-interlock woven fabric, and them are shown in Figure 1:

(a) 3-layer (b) 5-layer (c) 7-layer (d) 9-layer

Figure 1. The looming draft of angle-interlock woven fabric

In accordance with the weaving process flow chart, weaving three-dimensional angle-interlock woven fabric is shown in Figure 2:
It is difficult to deal with the silk-hooking phenomenon caused by continuous friction developing between Kevlar fiber filament, mail eyes and dents and so on for Kevlar fiber filament. Through several experiments and observations, it was found that in the weaving process of the Kevlar fabric, the position of the silk-hooking phenomenon was mostly in the flank of the fabric, and the warp on both sides of the fabric was obviously skewed compared with the middle part. The silk-hooking phenomenon in weaving process of Kevlar fiber is shown in Figure 3:

Through improving the loom and using lubrication reagents to assist and other measures can effectively avoid the Kevlar fiber’s silk-hooking phenomenon. It can be found that there are obvious oblique fringes on the surface of the three-dimensional angle-interlock woven fabric, which will be beneficial to the flow of the resin during the composite molding process. Three-dimensional angle-interlock fabric has a good elastic deformation in the direction of the warp. The fabric is smooth and soft, which is shown in Figure 4:
As the reed number used in the weaving process of the woven fabric is the same, which is the No. 55 reed, and the beating speed is similar. Therefore, after the weaving process is finished, the warp and weft of the five different woven fabrics woven in this section are tested very close. After the manufacture of plain weave fabric, the specifications of the five pre-woven fabric preforms were measured. Kevlar fabric specifications are shown in Table 1:

| Fabric structure          | Total number of roots | Width (cm) | Dense (root / 10cm) | Weft density (root / 10cm) |
|---------------------------|-----------------------|------------|---------------------|---------------------------|
| 3-layer angle-interlock fabric | 84                    | 15         | 55                  | 103                       |
| 5-layer angle-interlock fabric | 86                    | 15         | 56                  | 104                       |
| 7-layer angle-interlock fabric | 88                    | 15         | 56                  | 104                       |
| 9-layer angle-interlock fabric | 90                    | 15         | 57                  | 105                       |
| plain weave fabric        | 85                    | 15         | 56                  | 100                       |

2.2 Preparation of three-dimensional woven fabric composite sheet

The composite process used in this experiment is vacuum assisted resin transfer molding (VARTM) process, which is characterized by low molding pressure, energy saving, simple design, low cost, high molding efficiency and good repeatability\cite{1-3}. 3-layer, 5-layer, 7-layer, 9-layer angle-interlock fabric and plain weave fabric were compounded with E-51 epoxy resin, triethylene tetramine and acetone by VARTM process.

VARTM molding process experienced six stages, respectively as preparation, laying, sealing, perfusion, curing and post-processing\cite{4-6}. They are shown as follows:

(1) Preparation. Design and processing molds, mold surface cleaning and coating release agent are done in this stage.

(2) Laying. The fiber reinforced body, stripping cloth, diversion network, resin diversion tube, vacuum tube in turn tiled in the mold inside.

(3) Sealing. The sealing effect directly affects the quality of the composite, so this step is of the utmost importance. The article placed in step 2 was sealed in a vacuum film with a sealed black tape. Hold the resin guide with a conduit clamp, open the vacuum pump to pump all air inside the unit, and check the seal for leaks based on the vacuum pump pressure gauge pointer until the unit is completely sealed.

(4) Perfusion. When the device is fully sealed, the resin is introduced into the sealed mold cavity through the draft tube under negative pressure until the fiber reinforcement is completely impregnated. After the fabric is completely impregnated, the resin guide tube is sandwiched by the catheter fixture. At this point, continue to supply vacuum can make the bubbles in the resin come out, and the resin bubble is discharged, with a catheter clamp clamping vacuum tube. Close the vacuum pump to form a static seal device.

(5) Curing. In a vacuum apparatus, the resin undergoes a curing crosslinking reaction at room temperature or under heating and is completely cured after twelve hours.

(6) Post-processing. The cured composite materials are demolded and trimmed.

With reference to the corresponding national standard in the book "Fiber Reinforced Plastics (FRP) Standard Compilation"\cite{7}, the standard dimensions of the three-dimensional woven fabric composite specimens required for the tensile properties of fiber reinforced materials are shown in Table 2:
Table 2. Standard dimensions for tensile specimens

| Stretch the sample size | Total length (mm) | Gauge distance (mm) | Distance between clamps (mm) | Parallel width (mm) | End width (mm) |
|-------------------------|-------------------|---------------------|-------------------------------|---------------------|----------------|
| 180                     | 50±0.5            | 115±5               | 10±0.2                        | 20±0.5              |

The tools to be used in the process for the three-dimensional woven fabric composite materials samples are: specifications for a 20cm ruler, a marker pen, a band saw, a number of saw blades and sandpapers. The specific operation process is:

1. With reference to the relevant national standard of mechanical performance test, use the ruler and marker pen to draw the needed size of the sample in the fabric composite board;
2. With a desktop PROXXON mini magic micro-band saw, carefully and slowly cut the outline of the plate;
3. According to the size of the national standard requirements, use the sandpaper to polish and smooth the edge of fabric composite sample plate, and the errors should be controlled within the allowable range of national standard.

2.3 Tensile Properties Test and Result Analysis of 3D Woven Fabric Composites

The 8 different groups of three-dimensional fabric composite materials were processed one by one: the number of composite materials of Kevlar angle-interlock fabric was A, and the number of composite materials of Kevlar plain weave fabric was B. Among them, different layers of fabric were with different figures: Kevlar 3-layer angle-interlock fabric composite materials number is A1, Kevlar 5-layer angle-interlock fabric composite materials number is A2, Kevlar 7-layer angle-interlock fabric composite materials number is A3, Kevlar 9-layer angle-interlock fabric composite materials number is A4; Kevlar 3-layer plain fabric composite material number is B1, Kevlar 5-layer plain fabric composite materials number is B2, Kevlar 7-layer plain fabric composite materials number is B3, Kevlar 9-layer plain fabric composite materials number B4.

Tensile performance test equipment used for the 30KN specifications of the Instron and digital vernier caliper. According to the national standard of the People's Republic of China GB / T 1447-2005 "fiber reinforced plastic tensile test method", the fabric composite tensile test conditions is: in the laboratory, the temperature is (23 ± 2) °C, the relative humidity is (50 ± 10)% , the draw spacing is 50mm, and the loading speed is 10mm / min. They are shown in Figure 5:

![Tensile performance test](image)

(a) composite materials of Kevlar angle-interlock fabric  (b) composite materials of Kevlar plain weave fabric

**Figure 5.** Tensile performance test

After the end of the test, observe the sample, and the tensile damage after the three-dimensional fabric composite sheet samples are shown in Figure 6:
It is found that the specimens of the plain weave composite sheet are distributed along the direction of the yarn perpendicular to the force direction after the tensile fracture occurs, and the fiber yarn drew out after the drawing is obviously observed in the fracture. While, more resin fragments adhere to the fiber, which shows the location of the fracture resin content is relatively low, and thus more prone to fracture. Fabric delamination happens obviously in both of 7-layer and 9-layer angle-interlock fabric, which is explained that resin infiltration which is used for enhancing the strength and tightness of composite materials is incomplete in VARTM processing.

3. Result and Discussion

After tensile test, the test data of each group of composite materials samples were processed by Instron, and the maximum load average of each group was obtained, and the tensile strength was calculated according to the formula. The specific results of this test are shown in Table 3:

| Sample number | Maximum load (N) | Sample width (mm) | Sample thickness (mm) | Tensile strength (MPa) |
|---------------|------------------|-------------------|-----------------------|------------------------|
| A1            | 3117             | 10                | 0.76                  | 410.13                 |
| A2            | 5182             | 10                | 1.02                  | 508.04                 |
| A3            | 6983             | 10                | 1.65                  | 423.21                 |
| A4            | 7954             | 10                | 2.03                  | 391.82                 |
| B1            | 4192             | 10                | 1.11                  | 377.66                 |
| B2            | 6527             | 10                | 1.59                  | 410.50                 |
| B3            | 8570             | 10                | 2.24                  | 382.59                 |
| B4            | 9986             | 10                | 2.99                  | 333.98                 |

The data above, according to GB / T1447-2005 "fiber reinforced plastic tensile properties of the sample method" calculation formula to calculate the tensile strength of the sample, they are calculated as follows:

$$\sigma_t = \frac{F}{b \cdot d}$$  

Where:

* $\sigma_t$ - Tensile strength in MPa (MPa);
* $F$ - maximum load in units of Newton (N);
According to the results presented in Table 5, it can be seen that the tensile strength data of the composite materials of the 5-layer angle-interlock fabric composites are the best in the eight different fabric composite sheet samples, which is 508.04 MPa. The tensile strength data of the plain weave fabric composites are the worst, which is 333.98 MPa.

From Figure 7 it can be more intuitive to find that when the number of layers is the same, the tensile strength of Kevlar angle-interlock fabric composites is better than that of Kevlar plain weave composites; when the fabric structure is the same and the number of layers is different, it can be found that the optimal tensile strength is 5-layer fabric composites, whether in Kevlar angle-interlock fabric composites or in Kevlar plain weave composites. Therefore, it can be deduced that the tensile properties of the composites prepared by Kevlar fiber 5-layer angle-interlock woven fabric are the best among the eight kinds of fabric composite materials.

![Figure 7. The relationship between structure of reinforcement fibres and tensile strength](image)

It can be seen from Figure 7 that the tensile properties of composite materials with different layers are shown to be 5-layer > 7-layer > 3-layer > 9-layer, and the data of the Kevlar 9-layer plain weave composite materials significant decline. The reason for this is likely to be related to the composite structure, thickness and composite process. The results are as follows:

As the plain weave fabric is more closely organized than the angle-interlock fabric, and the 9-layer fabric is more thick, which will make the resin infiltration through the vacuum-assisted resin transfer molding process incomplete. These will result in layers of superimposed 9-layer plain weave composite materials, although the thickness has been close to 3mm and 5-layer angle-interlock composite materials 2 to 3 times, but by stretching the fracture specimen can be observed. In the case of plain weave samples, the phenomenon of fiber extraction at the fracture is more serious, which also shows that the fabric is not too close to the plain weave because of the fine texture of the fabric, which will also obtain the test data when the test is not good.

Due to the tensile test process, whether it is plain or angle-interlock, seven and nine layers of
composite samples in the tensile part of the emergence of a slip phenomenon, the sample did not break in the middle, which to some extent affected the test results.

It can be seen that the composite molding effect of the fabric has a great influence on the tensile properties of the composite sheet compared with the thickness of the fabric. In terms of the tensile properties, the composite process and the experimental effect of Kevlar fiber five-layer angle-interlock woven fabric are the best.

4. Conclusion
In this paper, we mainly study on the weaving technology and compound forming technology of 3D angle-interlock woven fabric with different layers, and test the tensile properties of the composites. Through preliminary research, we can draw a conclusion that the composite materials of Kevlar five-layer angle-interlock woven fabric has the better tensile property. We can also find that improving the loom, using lubrication reagents and taking some other measures can effectively avoid the Kevlar fiber silk-hooking phenomenon.

It is feasible to explore the performance of composite materials by changing multifarious structures of composite materials including both of materials and structures fabric, which is meaningful for further studies on mechanical properties of 3D fabric and provides theories for further improvements on its structures.

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