Compaction Behavior of 0°/90° Non-crimp Fabrics

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Keywords: Compaction, Layer shift, Noncrimp fabrics (NCFs).

Abstract. Based on the beam theory, a compaction model of 0°/90°non-crimp fabrics was developed to investigate the relationship between the thickness and compression load. A layer of 0°/90°non-crimp fabrics can be treated as two-layer unidirectional fabrics: one layer with 0°and another with 90°. The change of fabric thickness was then modeled as the sum of 0°and 90°unidirectional fabrics. To validate the theoretical model, experiments with 3, 4, 5 and 50 layers were carried out.

Introduction

In liquid composite molding (LCM) processes, multilayer fabrics were placed and compacted in the mold to manufacture high quality parts [1-3]. The preforms were usually compacted in a large degree in order to obtain higher fiber volume fractions. Compaction behaviors of fabrics not only determine the final thickness of products, but also affect the geometrical features of fabrics [4-6]. Studying the compaction behavior of fabrics is therefore very important to determine processing parameter windows and predict mechanical performance.

A lot of studies on the compaction of dry fabrics have been carried out [7-9]. One common phenomenon is that the thickness per layer for multilayer fabrics is less than the thickness of a single layer when the compaction pressure and preform material is given. This observation has been found for woven, knitted, braided and other types of preforms. However, such studies for non-crimp fabrics are few. Due to the benefit of reduced through-thickness crimp in comparison to woven fabrics, NCFs have better mechanical properties and are widely used in marine, aircraft, automobile and construction fields.

To predict the compaction behavior, many researchers developed empirical models by fitting experimental data. Gutowski [10], Simacek and Potluri [11, 12] developed theoretical models for unidirectional fabrics based upon the beam theory. Chen and Chou [13] proposed analytical expressions to describe the relationship between applied compressive forces and reduction in thickness for multilayer plain weave fabrics. However, these models usually contain two or more empirical constants. Only when the empirical constants are given in advance, the relationship between the thickness and pressure can be obtained. Recently, micromechanical models have been proposed as they associate microstructure with the mechanical properties [14]. These models are helpful to provide a comprehensive understanding for evaluating the compaction behavior.

In this paper, the compaction behavior of 0°/90° non-crimp fabrics was studied. Based on the beam theory, the geometric parameters were associated with compressive forces. The elastic deformations of NCFs were deeply analyzed and the effect of number of layers was further researched.

Theoretical Modeling

Non-crimp fabrics can be treated as multilayer assemblies of unidirectional fibers with different orientations. A typical geometric structure of 0°/90°non-crimp fabrics is shown in Fig.1. Ignoring the effect of stitch threads, the geometrical feature is simplified. Only 0° and 90° yarns are contained in the unit cell.
When multilayer NCFs were stacked with same ply angle, 0° layers and 90° layers align in through-thickness direction respectively. Different from the compaction of unidirectional fabrics, the total thickness remains unchanged although there exists layer shift. The reason is that the empty space between 0° (or 90°) yarns cannot be filled by the yarns of an adjacent layer. Layer shift does not lead to nesting. The average thickness per layer for a single layer can be given as

\[ h = b_0 + b_{90} \]

where \( b_0 \) and \( b_{90} \) are the short axes of the cross section of 0° and 90° yarns, respectively.

When the compressive force is applied on the surface of fabrics, the elliptical cross section of 0° and 90° yarns change into complex shapes. The deformed cross-section of the yarn consists of a rectangular part located between two semi-elliptical parts, as shown in Fig. 2. The fibers in middle rectangle are compressed and the fiber volume fraction increases from \( v \) to \( v' \). However, the no compaction occurs in two side parts. The fiber volume fraction in these parts keeps invariant.

The areas of all the parts in cross-section before and after deformation are

\[ S_{\text{ellipse}} = \frac{\pi}{4} ab \]

\[ S_{\text{rectangle}} = 2c b' \]

\[ S_{\text{semi-ellipse}} = \frac{\pi}{8} (a' - 2c)b' \]

Fiber volume continuity requires:

\[ S_{\text{ellipse}}v = S_{\text{rectangle}}v' + 2S_{\text{semi-ellipse}}v \]

As the deformation of cross section in width direction is much smaller than that in length direction, it can be assumed that the long axis contains unchanged before and after compaction.

\[ a = a' \]

The deformation of the fiber cross-section occurs mainly its thickness direction

\[ \frac{b'}{b} = \frac{v}{v'} \]

Substituting Eqs. 2-4 and 6-7 into Eq. 5 gives:

\[ c = \frac{\pi a(b - b')}{8b - 2\pi b'} \]

Then the compressive force, \( F \), can be expressed as
\[ F = 2\sigma \frac{SA}{N_t} \]  

(9)

where \( S \) is the area of samples, \( A \) is the areal density of unidirectional fabrics, \( N_t \) is the line density of yarn and \( \sigma \) is the compressive stress and can be determined as

\[ \sigma = \frac{3\pi E}{\beta^4} \left( 1 - \sqrt[4]{\frac{h}{h'}} \right) \left( \sqrt[4]{\frac{h'\nu_a}{h\nu}} - 1 \right)^4 \]  

(10)

where \( E \) is the axial Young’s modulus, \( \beta \) is a non-dimensional constant defined in [10], and \( \nu_a \) is the maximum fiber volume fraction, which has the theoretical values of \( \pi / 4 \) for square packing and \( \pi / 2\sqrt{3} \) for hexagonal packing.

For a single layer NCF, the relationship between the external compressive force and thickness can be described as

\[ F = \frac{3\pi E S_{0^\circ} A_{0^\circ}}{N_{1,0^\circ} \beta^4} \left[ \frac{\pi a_{0^\circ}(b_{0^\circ} - b'_{0^\circ})}{4b_{0^\circ} - \pi b'_{0^\circ}} \right] \left( \sqrt[4]{\frac{b_{0^\circ}}{b'_{0^\circ}}} - 1 \right) \left( \sqrt[4]{\frac{b_{0^\circ}V_{a,0^\circ}}{b_{0^\circ}V_{0^\circ}}} - 1 \right)^4 \]  

(11)

\[ F = \frac{3\pi E S_{90^\circ} A_{90^\circ}}{N_{1,90^\circ} \beta^4} \left[ \frac{\pi a_{90^\circ}(b_{90^\circ} - b'_{90^\circ})}{4b_{90^\circ} - \pi b'_{90^\circ}} \right] \left( \sqrt[4]{\frac{b_{90^\circ}}{b'_{90^\circ}}} - 1 \right) \left( \sqrt[4]{\frac{b_{90^\circ}V_{a,90^\circ}}{b_{90^\circ}V_{90^\circ}}} - 1 \right)^4 \]  

(12)

As the thicknesses of 0° and 90° yarns cannot be separated from Eqs. 11-12, the parameters can be calculated by numerical analysis method. Substituting Eqs.11-12 into Eq.1, the thickness of NCF after compaction can be obtained.

**Experiment**

**Textile Reinforcement**

The textile composite reinforcement analyzed in this paper is E-glass NCF EDW817 with areal density 178 g/m². Each kind of 0° and 90° yarns contains 2200 fiber filaments with diameter of 16µm. For 0° yarns, the long and short axes of the yarn cross-section are 2.21mm and 0.38mm, respectively. For 90° yarns, the long and short axes of the yarn cross-section are 2.56mm and 0.42mm, respectively. The axial Young’s modulus of glass fiber \( E \) is 72GPa. The non-dimensional constant \( \beta \) is 167.

**Test Procedure**

Compression tests were done on a displacement-controlled testing machine Instron 4467. The test speed was 1 mm/min. Fig. 3 illustrates the measurement technique. The textile reinforcement with a diameter of 80 mm is placed on a bottom plate and covered by a steel plate which has a central circular injection gate with a radius of 5 mm. when the maximum load reaches to 6.4KN, epoxy resin 2008 with the hardener 2008-F was injected into the mold. After cured at room temperature, the specimen was demoulded for measuring the thickness and cross section analysis.
Results and Discussion

The Statistics of Shifting Ratio

Statistics about layer shift of specimens with 3, 4 and 5 layers were carried out respectively. In this paper, the shifting ratio between adjacent layers was defined as \( \xi = \frac{\Delta x \text{ or } \Delta y}{(a + e)/2} \). \( e \) is the width of void space between adjacent yarns. The layer shift was measured by analyzing the cross sections of specimens. The representative images with different layers are shown in Fig. 4. The statistical results are listed in Tables 1-3. It can be seen that the shifting between adjacent layers is random.

Table 1. The shifting ratio of each layer for 3-layer NCFs. The superscripts refer to the directions of layer shift. The subscripts refer to the numbers of adjacent layers.

<table>
<thead>
<tr>
<th>sample</th>
<th>( \xi_{1,2}^x )</th>
<th>( \xi_{1,2}^y )</th>
<th>( \xi_{2,3}^x )</th>
<th>( \xi_{2,3}^y )</th>
<th>( \xi_{2,3}^y )</th>
<th>( \xi_{3,4}^x )</th>
<th>( \xi_{3,4}^y )</th>
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<tr>
<td>1</td>
<td>34.2%</td>
<td>75.7%</td>
<td>55.0%</td>
<td>28.1%</td>
<td>59.3%</td>
<td>43.7%</td>
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<td></td>
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<tr>
<td>2</td>
<td>16.6%</td>
<td>24.2%</td>
<td>20.4%</td>
<td>33.7%</td>
<td>12.1%</td>
<td>22.9%</td>
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<tr>
<td>3</td>
<td>76.9%</td>
<td>84.1%</td>
<td>80.5%</td>
<td>68.7%</td>
<td>49.7%</td>
<td>59.2%</td>
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</table>

Table 2. The shifting ratio of each layer for 4-layer NCFs.

<table>
<thead>
<tr>
<th>sample</th>
<th>( \xi_{1,2}^x )</th>
<th>( \xi_{1,2}^y )</th>
<th>( \xi_{2,3}^x )</th>
<th>( \xi_{2,3}^y )</th>
<th>( \xi_{2,3}^y )</th>
<th>( \xi_{3,4}^x )</th>
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<td>2</td>
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<tr>
<td>3</td>
<td>71.3%</td>
<td>23.1%</td>
<td>36.4%</td>
<td>43.6%</td>
<td>38.4%</td>
<td>28.9%</td>
<td>70.6%</td>
<td>46.0%</td>
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Table 3. The shifting ratio of each layer for 5-layer NCFs.

<table>
<thead>
<tr>
<th>sample</th>
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<th>( \xi_{1,2}^y )</th>
<th>( \xi_{2,3}^x )</th>
<th>( \xi_{2,3}^y )</th>
<th>( \xi_{2,3}^y )</th>
<th>( \xi_{3,4}^x )</th>
<th>( \xi_{3,4}^y )</th>
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<td>44.25%</td>
<td>43.3%</td>
<td>28.9%</td>
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<td>47.2%</td>
<td>17.4%</td>
<td>77.0%</td>
<td>68.4%</td>
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<td>39.3%</td>
<td>64.3%</td>
<td>58.1%</td>
<td>52.9%</td>
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Experimental Verification of Compaction Model

It can be seen that the pressure-thickness data of NCFs with 3, 4, 5 and 50 layers tends to be relatively concentrated from Fig. 5. This indicates that the effect of number of layers is weak on the compaction behavior of NCFs. The reason may be that 90° yarns prevent the nesting of 0° yarns between adjacent layers. In addition, the prediction was compared with the experimental data, and satisfactory agreement was observed.
Conclusions

In this paper, the behavior of the compression response of 0°/90° non-crimp fabrics was studied. A theoretical model was developed based on the beam theory. The model associated fabric thickness with compression load, fabric structure can be used to describe the compressive behavior. Experimental results showed that the shifting between adjacent layers is random. As layer shift cannot lead to nesting, the pressure-thickness curves of multilayers were relatively concentrated.

References

