Evaluating deformability of non-crimp fabric and mechanical performance of non-crimp fabric composites

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1 Introduction

Liquid composite molding, which uses non-crimp fabrics(NCFs), is much cheaper than molding in an autoclave and can produce complex structural parts. NCFs consisting of unidirectional plies arranged in a number of possible orientations, kept together by stitching yarns, shows great potential to replace traditional reinforcements for its combination good stability, outstanding drapability and prominent mechanical performance[1].

Permeable values of fiber preforms used in liquid composite molding (LCM) process is one of the most important parameter, because the permeability allows not only estimation of the processing time, but also evaluation of the success rate of the process[2-4]. During forming of textile reinforcements to three-dimensional geometry, in-plane shear is generally considered to be the primary deformation mechanism. Characterization of this mechanism is used to measure the non-linear response during shear and to determine the limit of deformation[5]. To assess the possible application of these promising NCFs, the mechanical properties of NCF composites are measured, comparing with those of unidirectional(UD) fabric composites, in-plane mechanical properties of NCF composites decrease by less than 15%, but interlaminar properties are improved by the tight stitching.

2 Materials and Experiments

2.1 Materials and composites production

The non-crimp fabrics (Fig.1a and b) were provided by Changzhou Hongfa Zhongheng Advanced Material Technology CO., Ltd. Their parameters are shown in Table 1. The unidirectional fabric(Fig.1c) and bismaleimide resin 6421 were provided by Beijing Institute of Aeronautical Materials. Test directions of the fabric and composites are also indicated in Fig.1. The direction of 0° represents the machine direction of non-crimp fabric during production, while the direction of 0° represents the fiber direction of the unidirectional fabric. Composites for mechanical tests are produced by resin transfer molding(RTM) with the fiber fraction of 58±2% and a thickness of 2mm approximately.

2.2 Experiments

2.2.1 Permeability test of non-crimp fabric performs

To simulate the actual flowing of resin in resin transfer molding, permeability of NCF performs was measured. The permeability value is calculated based on the Darcy’s law. In this experiment, only one-dimensional flowing is taken into consideration, the permeability values can be measured by the
following equation:

\[ t = \frac{n \cdot x^2}{2KP} \] (1)

with the flowing time, \( \eta \) fluid viscosity, \( K \) permeable value, \( P \) infusion pressure, \( x \) the corresponding flowing distance. With fitted \( t-x^2 \) curve, the slope factor will be used to calculate the permeable value \( K \).

Influence of stitching types, fiber volume fractions and flowing directions on permeability of NCF was measured and discussed, compared with the UD fabric. Permeability along the fiber direction, perpendicular fiber direction and along the stitching yarns direction was measured. Curves of permeability versus fiber volume fractions are fitted by modified Kozeny-Carman formula:

\[ K = \frac{r_f^2(1-\nu_f)^3}{4S_\kappa} + b \] (2)

witha related to flowing direction, \( b \) related to the stitching structure, \( S_\kappa \) the Kozeny factor and \( r_f \) the fiber radius[9]. Permeability along the fiber direction, perpendicular fiber direction and along the stitching yarns direction was measured compared with that of the UD fabric.

### 2.2.2 In–plane shear test

Shear deformation of biaxial NCF was studied in picture frame test and bias extension test. The biaxial NCF was mounted in picture frame and extension device, with the stitching yarns parallel to the loading direction or across it, as showed in Fig.2 and Fig.3. It is indicated that shear deformation of NCF could be precisely demonstrated by those two kinds of tests [2].

In picture frame test, the shear angle is decided by the displacement of the testing machine and the shear force is determined by the force applied by the loading machine. The shear angle of the frame \( \gamma \) is related to the displacement of the machine \( x \) by:

\[ \gamma = \frac{\pi}{2} - 2\cos^{-1}\left[\frac{1}{\sqrt{2}} + \frac{x}{2w}\right] \] (3)

where \( w \) is the width of the frame.

The shear force is normalized as

\[ T = \frac{F}{2w\cos^2\frac{\pi}{2}} ; \quad \alpha = \frac{\pi}{2} - \gamma \] (4)

where \( T \) is the shear force per unit width force the frame side, \( w \) is the width of the gripped width of the sample, \( \alpha \) is the frame angle. Three cycles results of the picture frame tests are measured. The 2nd and the 3rd cycles are obviously different with the 1st cycle because of the pre-tension caused by clamping device and the misalignment of the fiber, which makes the fiber near gripping tensed or bent[7-9].

The bias extension test involves clamping a rectangular piece of NCF such that the directions of the fiber tows are oriented at the ±45° to the direction of applied loading. The sample’s length/width ratio \( \lambda \) should greater than 2 so that the sample can be divided into three regions with the fibers in the center regions bear pure shear force, as showed in Fig.3. The shear angle is calculated as

\[ \gamma = \frac{\pi}{2} - 2\cos^{-1}\left(\frac{L_0+x}{\sqrt{2L_0}}\right) ; L_0 = H - W \] (5)

where \( H \) is the length of the sample, \( W \) is the width of the sample, \( x \) is the displacement of the machine[10-13].

### 2.2.3 Mechanical test of composites

To compare with those of UD fabric composites, mechanical properties of NCF reinforced bismaleimide composites are measured. Unidirectional NCF laminates are made of uniaxialNCF(called NCF-U1 for short in this part) and quasi-isotropic laminates are made of uniaxial NCF and biaxial NCF(NCF-B1) respectively. Metallographic and SEM images are used to investigate the internal structure of NCF composites and determine how the defects, such as “channels” or “cracks”, influence mechanical properties[14-17].

Determination of apparent interlaminar shear strength by short-beam method, were used to prepare the specimens and perform tests to measure the tensile, compression, flexural and interlaminar shear properties of the composites respectively.

3 Results and Discussions

3.1 Permeability

To simulate the actual flowing of resin in resin transfer molding, permeability of NCF performs was measured. Permeability is the essential parameter to design the infusion process. Permeability values of unidirectional preforms with different fiber volume fraction are showed in Fig.4. The fitting curve responds to the Koney-Carman equation. The result showed in Fig.4(a) represents the permeable ability of the performs in 0° direction. It is demonstrated that with the same fiber volume fraction the fabric structure has a significant influence on the permeability. It is apparent that the permeability of the uniaxial NCF is lower than the UD fabric, this is because the stitching yarns of the uniaxial NCF has two controversial effects: one effect is that the stitching in a less compaction situation and it has a capillary effect so it can provide additional flowing channels for the liquid. On the other hand, the stitching tension makes the carbon fiber stack more tightly than the UD fabric, the weft yarns of which have little stitching tension. By observing the fabric structure, showed in Fig.5, the distortion of the fiber indicates that the fibers bear a relative strong stitching tension than those in UD fabric, which has a dominated effect on permeability of fabrics, however, fibers in UD fabrics have little in-plane distortion, which manifest that the fibers are in a relaxed “condition” and the gaps between the yarns in UD fabric are larger than those in NCF. Combining these two effects the permeability of the uniaxial NCF is lower than that of the UD fabric in the 0° direction. As to the test in the 90° direction in Fig.4(b), the compaction condition of the fibers also influence the permeability mostly, so the permeability of these two kinds of fabrics in the 90° direction has similar tendency: the liquid flows faster in the UD fabric.

For the orthotropic preforms, permeabilities of the biaxial NCF in 0° and 90° direction, showed in Fig.6(a), are measured in order to identify the effect of stitching yarns on permeability. In the 0° direction, the liquid flowed along the direction of the stitching yarns, the permeability is much higher than that in the perpendicular direction of the stitching yarns. This phenomenon manifests further that the stitching yarns has a positive influence on the permeability of the fabric, which can supply a consecutive “channel” for the flowing liquid. Although the stitching yarns provide extra flowing “channel” for the liquid, the “channel” is disconnected in the flowing direction so that the permeability is much lower in the 0° direction than that in the 90° direction in spite of the same fibers configuration. Results of tests in the 45° direction are showed in Fig.6(b). Fig.6(b) shows that difference between the permeability of the biaxial NCF and the UD fabric becomes small though the UD fabric has more loose yarns stack structure. The consecutive “channel” effect compensates the tight compaction of the fibers caused by stronger stitching tension of the NCF than that of the UD fabric, so it is observed that the measured permeability values of the NCF approximate that of the UD fabric.

The effect of fiber volume fractions on permeability values of different fabrics are also showed in Fig.4 and Fig.6. The effect of fiber volume fraction on permeability of unidirectional performs meet the Koney-Carman equation well. For the biaxial performs the modified Koney-Carman equation is used to fit the permeability K-V curves. It is noted the fiber volume fraction has the similar influence on permeability for all performs. The fitting parameters, such as b in the modified Koney-Carman equation can be used to evaluate the effect of stitching yarns on the permeability: when the stitching yarns enhance the permeability more, the calculated b is higher.

3.2 Shear deformation

3.2.1 Picture frame shear
For the biaxial NCF, the shear deformation behaviors of picture frame tests are measured in the 0° and 90° direction. Three shear cycles are shown in Fig.7 (a). In the test direction of 0°, the first shear cycle for biaxial NCF is obviously different from the second and third cycles, the shear force in the first cycle is much higher than that in other cycles. This is because when the samples are mounted in the frame, it is impossible to make all the yarns parallel to the frame sides, thus the fibers bear tensile loading when sheared in the first cycle, and the stitching tension is not well-distributed. So the first shear cycle cannot reflect the pure shear behaviors, which should be regarded as the “bad tests", however the sample is “conditioned” after the first cycle. As the diagrams of second and third cycles showed in Fig.7, the second and third cycles have little difference, which should be noticed as the pure shear behavior of the NCF. The process of taking away the fibers near the clamps will caused disturbances to fibers in the fabrics, which scatter the shear results, so at least five samples are measured in order to make the C_V is lower than 10%.

The second and third shear cycles of 0° tests show the typical shear compliance curves for NCF. Here shear force should be normalized by the sample length to eliminate the size effect. The shear curve can be divided into two parts: in the small shear angle area, the yarns approach to each other, the shear mechanism can be defined that there are only yarns rotating at the interlace point, so the shear force is very low. Digital images also indicate that there are only fiber orientation varying and no wrinkle occur. For the large shear angle deformation, the shear force becomes noticeably higher than small angle deformation. This is because at the small shear deformation the gaps between yarns give fibers freedom to rotate. After the gaps being occupied, the fibers are compressed which cause high shear force and wrinkle in fabrics. The transition angle, which divided approximately the shear curve into two parts, is called “locking angle”. The limit of forming of the fabrics is often characterized by measurement of the “locking angle”. The results of 0° tests and image analysis shows the “locking angle” is about 17°. At the last part of the curve the shear force is several times higher, which actually represents the tensile resistance of the chain of the stitching yarns.

Fig.7(b) shows results of 90° tests. It is also can be seen that after the “locking angle"(about 17°), the shear force becomes high and wrinkle happens. However the stitching yarns orientation is not along the direction of applied loading, the shear force at large shear deformation is not as high as that of the 0° tests.

3.2.2 Bias extension
Bias extension is another popular approach to characterize resistance of fabric to in-plane shear. According to the experiment results showed in Fig.8, the shear force in 90° direction is obviously lower than that in 0°. In 90° tests, the shear force for NCF is too small (less than 5 N for the whole shear process). This is because in this direction only frictions between fibers and stitching yarns contribute to the shear force. Besides, the specimen edges in the pure shear area are not constrained and fibers can move freely in this area, at relatively high shear angles the sample begins to fail due to slip of fibers. So the only results of 0° tests are illustrated here to characterize the shear behavior of NCF. One can see that the trend of bias extension curve agrees with the results from the picture frame tests well: before achieving the “locking angle”, no wrinkle occurs, the fibers rotate and come close to each other. The “locking angle” can be regarded as the shear range for NCF in forming performs with curved surface. After the “locking angle”, the fibers are compressed, for which the shear force is rapidly increased and wrinkles happen. From the bias extension results, the “locking angle” is about 15°, which shows a good agreement between picture frame test and bias extension test.

3.3 Mechanical properties
Fig.9 shows the mechanical properties of unidirectional composites plates. The tensile,
flexural and compression strength of NCF–U1 composites are decreased by 14.5%, 10.8% and 4.0% than that of UD fabric composites, respectively. However, The ILSS is 4.0% higher than that of UD fabric composites. The decrease of in-plane mechanical strength is caused by fiber free zones near stitching locations. The continuous fiber free zones caused by stitching yarns in NCF-U1 are called “channels” in ply. These “channels” in the fibrous plies cause resin rich regions in the composites, decreasing the fiber volume fractions, which will affect the mechanical performance. According to metallographic observations, the cracks easily occur around the resin rich areas, which may cause stress concentration and early damage. Fig. 10 shows the continuous “channel” in NCF-U1. However, in UD fabric composites there is little “channels” or “gaps” between fibers and the fibers lies relatively straight. Only fiber waviness (showed in Fig.11) caused by a small number of transverse yarns will not affect the mechanical strength severely in 0° direction because the transverse yarns occupy much less volume fraction in UD fabric than that of stitching yarns in NCF. For NCFs, the fabric manufacture process also inevitable cause fiber damage and fiber distortion, which are bad for mechanical properties. According to this structural feature, compared to that of UD fabric composites, the in-plane mechanical performance of uniaxial NCF composites is a little decreased, the decrease is less than 15%, while the interlaminar properties are almost not affected by structural defects.

As for the quasi-isotropic laminates, Fig.12 shows the mechanical properties of these three kinds of composites materials. According to the test results, the NCF-U1 mechanical strength is also about 15% lower than that of UD fabric composites. The reason for strength decline of quasi-isotropic NCF-U1 composites is the same as that for the decline of unidirectional composites. However, when it comes to quasi-isotropic NCF-B1 composites, the mechanical strength of NCF-B1 composites is very close to that of quasi-isotropic UD fabric composites. As showed in Fig. 10 and Fig.13, the images demonstrate the structure feature of these NCF composites. It is easy to be distorted and misaligned for fibers in NCF-U1 because of the loose stitching structure. The proportion of resin rich regions in the composite based on NCF-U1 is obviously higher than other two composites, which evidently decrease the in-plane mechanical strength. Although the tight stitching yarns cause “cracks” in NCF-B1 (showed in Fig.13), fibers are straightened and combined tightly between layers. Metallographic images showed in Fig.13 indicate that there are relatively small amount of resin rich regions and little fiber waviness as UD fabric, with good bonding between layers. According to the tight stitching structure of NCF-B1, fibers have been straightened well, which can take good advantages of the fibers strength. Hence, the mechanical strength is close to that of UD fabric composites and higher than that of composites based on NCF-U1. In quasi-isotropic laminates the quasi-isotropic structure can disperse the resin rich regions to avoid as much decline of mechanical strength as that in unidirectional laminates; because in unidirectional laminates resin rich regions oriented in the same direction in adjacent layers may be connected, which will severely influence the mechanical strength.

4 Conclusions
Characterization of the permeability, deformation behavior and mechanical performance of NCF and NCF reinforced composites leads to the following conclusions:

4.1 Permeability
The permeability of NCFs is close to UD fabric. For unidirectional performs, the stitching yarns have two effects: one is that the fibers assembled by stitching yarns are compacted tightly, which will decrease the liquid flowing in fiber tows; the other one is that the stitching bring in continuous “channels” between fiber tows, which enhance the permeability. Based on these two aspects, the permeability of NCFs is not much lower than that of
UD fabric, which possesses high permeability due to the loose fiber structure. For the biaxial NCF, permeability along the stitching direction is enhanced and higher than permeability in the direction perpendicular to the stitching yarns for the stitching yarns provide extra flowing routes.

4.2 Shear deformation

Shear deformation of biaxial NCFs is characterized by the picture frame shear test and bias extension test. When the biaxial fabric is sheared in the direction of compression of the fibers, the initial shear force is low, due to the shear mode of fiber friction and stitching friction. When the shear angle exceeds about 17°, the shear force increases rapidly because of the onset and intensification of the compression of the fibers. In the direction of tension of the stitching yarns, the shear force mostly results from the stitching tension and is much higher than that in the direction of compression of the stitching yarns. Comparing with the picture frame test, shear behaviors in the direction of tension of the stitching can also be well characterized by bias extension; however, shear force in the direction of compression of the stitching is very low because of much free fiber slip in the shear area before fibers compression occur. This phenomenon will be focused on in future work.

4.3 Mechanical properties

In-plane mechanical properties of uniaxial NCF composites are about 15% lower than those of unidirectional composites based on UD fabric due to the fiber distortions and misalign, while the interlaminar properties are improved by the stitching. As for quasi-isotropic composites, mechanical performance of composites based on biaxial NCF, close to that of UD fabric composites, is better than that of uniaxial NCF composites. This can be attributed to stitching structure of biaxial NCF, which resulting in aligned fibers, less defects and tight bonding between fiber layers.
Table 1 Parameters of preforms

<table>
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<tr>
<th>Perform</th>
<th>Orientation of plies, degree</th>
<th>Plies</th>
<th>Stitching yarns</th>
<th>Mass, g/sqm</th>
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<tbody>
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<td>UD fabric</td>
<td>0</td>
<td>3K Toray T300</td>
<td>---</td>
<td>160</td>
</tr>
<tr>
<td>Uniaxial NCF</td>
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<td>3K Toray T300</td>
<td>30D-PET</td>
<td>166</td>
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<tr>
<td>Biaxial NCF</td>
<td>45; -45</td>
<td>3K Toray T300</td>
<td>30D-PET</td>
<td>332</td>
</tr>
</tbody>
</table>

Fig. 1. Samples of UD fabric and NCF: (a) UD fabric; (b) uniaxial NCF; (c) biaxial NCF.

Fig. 2. Picture frame test (loading on an Instron testing machine).
Fig. 3. Bias extension test, shear angle is uniform in region ①.

Fig. 4. Results of permeability of unidirectional preforms: (a) in direction of 0°; (b) in direction of 90°.

Fig. 5. Light microscope images of unidirectional preforms: (a) UD fabric; (b) uniaxial NCF.
Fig. 6. Result of permeability of orthotropic preforms: (a) permeabilities of biaxial NCF in the direction of 0° and 90°; (b) permeabilities in the direction of 45° of biaxial NCF and UD fabric preforms.

Fig. 7. Shear diagrams of picture frame tests of biaxial NCF (a) in the direction of tension of stitching; (b) in the direction of compression of stitching. Error bars show standard deviations of the tests. Three cycles were registered.

Fig. 8. Bias extension diagrams of biaxial NCF in the direction of tension of stitching.

Fig. 9. Comparison of uniaxial NCF laminates and UD fabric laminates on mechanical properties: (a) In-plane mechanical strength; (b) Interlaminar shear strength.
Fig. 10. (a) Metallographic and (b) SEM images of uniaxial NCF laminates with continuous channels which lead to resin-rich defects.

Fig. 11. Metallographic images of uniaxial UD fabric laminates with fiber waviness.

Fig. 12. Comparison of quasi-isotropic laminates based on different preforms on mechanical properties: (a) In-plane mechanical strength; (b) Interlaminar shear strength.
Fig. 13. (a) Metallographic and (b) SEM images of biaxial NCF laminates with cracks which lead to resin-rich defects.

References


