MECHANICAL BEHAVIORS OF THIN-PLY COMPOSITE LAMINATES UNDER SHORT-BEAM SHEAR AND OPEN-HOLE TENSILE LOADS: PSEUDO-HOMOGENEOUS AND ISOTROPIC BEHAVIORS

Chunfang Huang, Mingchang He, Yonglyu He, Jiayu Xiao, Jianwei Zhang, Su Ju *, Dazhi Jiang *
(Department of Materials Science and Engineering, National University of Defense Technology, Changsha, Hunan, 410073, People's Republic of China)
*Corresponding author, Email: jiangdz@nudt.edu.cn, suju-nudt@nudt.edu.cn

Abstract

In recent years, spread-tow technology provides composites manufacturers a way to fabricate thinner fabrics almost free of fiber twist and crimp which significantly stunting fiber performance. In this paper, interlaminar shear strength of carbon fiber/epoxy thin-ply laminates subjected to short-beam shear loads and tensile behaviors of open-hole carbon fiber/epoxy thin-ply laminates are investigated. Experimental results show that, by tapering the ply thickness, the interlaminar shear strength of the laminates under short-beam shearing is increased and a brittle fracture mode appears in open-hole tensile test of the laminates similar to isotropic materials. By optical micrographs and classical laminate theory analysis, relatively homogeneous microstructure and regular stress distribution make the thin-ply laminates demonstrate pseudo-homogeneous and isotropic behaviors.

Keywords: thin-ply, mechanical behaviors, short-beam shearing, open-hole tension, carbon fiber composite laminate

1. Introduction

Carbon fiber reinforced polymer matrix composites (CFRP) laminates are attractive structural materials which is widely used in aerospace and aircraft structures because of their high performance. However, limited by thickness and weight, there is not enough space for designing a balance laminate with standard thickness ply (0.125 mm) for thin-wall structure such as wing skin. Spread-tow technology provides a possible way to solve this issue. By tapering CFRP prepreg, composite laminates demonstrate a wider range of tailorable properties and superior mechanical properties, namely damage suppression and delamination resistance [1-3]. Comparing to laminates consisting of standard thickness plies, thin-ply CFRP composites have more excellent mechanical properties and broader design space.

In recent years, substantial progress has been made in the field of composite laminates using thin plies [4, 5]. Thickness of commercially available thin-ply prepreg can be down to about 15 μm through the tow spreading technology. The motivation for this trend toward thinner plies is not only to allow the production of thinner and lighter laminates and structures, but also to provide higher strength and damage resistance because of positive size effects.

Thin-ply CFRP composites have recently been reported to exhibit superior damage suppression characteristics compared to laminates consisting of standard thickness plies. Tomohiro Yokozeki et al. [6] studied damage accumulation behaviors of quasi-isotropic laminates ($[45/0\text{-}45/90]_{ns}$) made of thin (0.07 mm) and standard (0.14 mm) plies by transverse indentation test, respectively. Standard ply laminates exhibited delamination near the back surface of the specimen as well as inside the laminate, whereas delamitation only occurred inside plies in the thin-ply laminates, and the delamination appeared prior to fiber fractures. Tomohiro Yokozeki et al. [7] also investigated compressive strength properties as well as the damage resistance properties of the above CFRP such as non-hole compression strength, open-hole compressive strengths and compression strength after impact. The use of thin-ply prepregs resulted in improvement in damage resistance properties against matrix cracking and delamination, which may result in higher compressive strength properties of the composite laminates. R. Amacher et al. [8] studied characterizations of mechanical properties and size effects of thin-ply composites. Experimental results showed that reducing ply thickness can lead to dramatic improvements not only in terms of first-ply failure/first-damage stress, but also fatigue life and ultimate strength. Thin-ply composites present different failure modes with a significantly delayed damage growth and showed quasi-brittle failure instead of extensive delamination and transverse cracking patterns. J.D. Fuller and M.R. Wisnom[9] investigated the pseudo-ductility and damage suppression of thin-ply(0.03 mm) angle laminates($[\pm\theta_5]_s$) with the ply angles varied in range of 15° and 45°. Observation from X-ray computed tomography and microscopy has been shown that the thin ply suppresses delaminations of the laminates. Sangwook Sihn[1] also demonstrated that damage resistance against static, fatigue and impact loading can be improved by using thin-ply prepregs. There are a few other papers also confirming the damage and delamination suppression in thin-ply composite laminates [10, 11]. Additionally, onset and propagation behaviors of the delaminations were also dependent on ply thickness as well as ply stacking sequence [12-14].

In this paper, we try to understand the effects of the thin-ply in the view of pseudo-homogeneous and isotropic behaviors. To do so, unidirectional and quasi-isotropic carbon fiber/epoxy laminate specimens are prepared using prepregs with varying ply thickness such as 0.020 mm, 0.055 mm and 0.125 mm, respectively. Interlaminar shear strength of the carbon fiber/epoxy thin-ply laminates subjected to short-beam shear loads and tensile strength of the open-hole carbon fiber/epoxy thin-ply laminates are investigated.

2. Experimental

Specimens in this study are prepared from T300/EP901 prepregs. The areal weight of fiber in the prepreg and thickness of one single ply of the prepreg, as well as its code name, are shown in Table 1.

Table 1. Properties of T300/EP901 prepregs with different thicknesses

Thickness (mm)	Areal weight of fiber (g/m^2)	Code name
0.020	20	T-20
0.055	54	T-55
0.125	125	T-125

To investigate the mechanical behaviors of the thin-ply laminates and standard laminates under interlaminate shear test and open-hole tensile test, the following unidirectional laminates and quasi-isotropic laminates are prepared (as shown in Table 2).

Table 2. Stacking sequence of UDL and QIL with different ply thicknesses

Ply (mm)	UDL	QIL
T-20	$[0_{120}]$	$[0/45/90/-45]_{15s}$
T-55	$[0_{44}]$	$[0/45/90/-45]_{6s}$
T-125	$[0_{19}]$	$[0/45/90/-45]_{3s}$

Compression molding processing is employed to prepare the laminates for the purpose of obtaining same fiber volume fraction and total thickness. The curing process is set to 80°C-30min-113°C-30min/2MPa-130°C-2h/2MPa.

Short-beam bending is usually used to estimate the interlaminar shear strength of high-modulus fiber-reinforced composite materials. The structural mechanics analysis of the laminates is shown Fig 1. Where the Q_x is the shear force and the M_x is bending moment in the longitudinal axis of the beam.

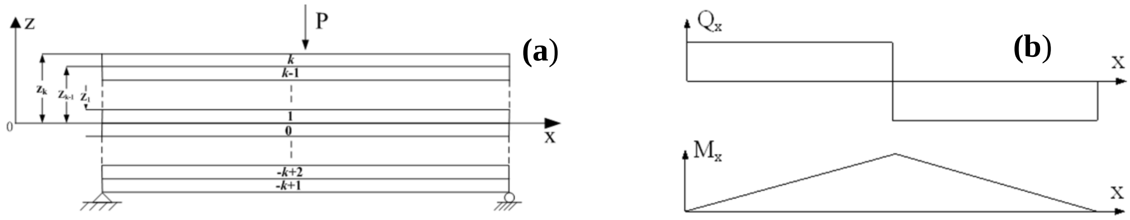


Fig. 1. Structural mechanics analysis of the laminates under three-point bending: (a) configuration of the short-beam bending (b) distributions of shear force and bending moment.

Based on ASTM D3518 and D2344-84, the interlaminate shear strength can be given as follows:

$$F^{sbs} = 0.75 \times \frac{P_m}{b \times h} \tag{1}$$

Where,
F^{sbs} - interlamiante shear strength by short-beam shear test, MPa,
P_m - maximum load during the test, N,
b - specimen width, mm,
h - specimen thickness, mm.

Based on ASTM D5766 -2002, the ultimate open-hole tensile strength can be calculated using follow equation.

$$F_x^{OHTu} = P^{\max} / A \tag{2}$$

Where,
F^{OHTu} - ultimate tensile strength of open-hole laminate, MPa
P^{max} - maximum load prior to failure, N,
A - gross cross-sectional area (disregarding hole), mm^2

3. Results and discussion

3.1. Optical micrograph

Before the test, optical micrographs are used to check the microstructrure of the laminates. Optical micrographs of all specimens are analyzed and presented in Fig. 2. The microstructures of the T-20 and T-55 ply laminates are found to be relatively uniform and interfaces between adjacent plies are more homogeneous. Microstructure of T-125 ply laminate is found to be less homogeneous with obvious rich-resin regions and poor-resin regions. The difference can be denoted by visible fiber bundles and rich resin regions in the T-125 ply laminate vs. uniform microstructure for the T-20 and

T-55 ply laminate. Additionally, the number and size of defects in thin-ply laminate is less and smaller than that in standard ply laminate.

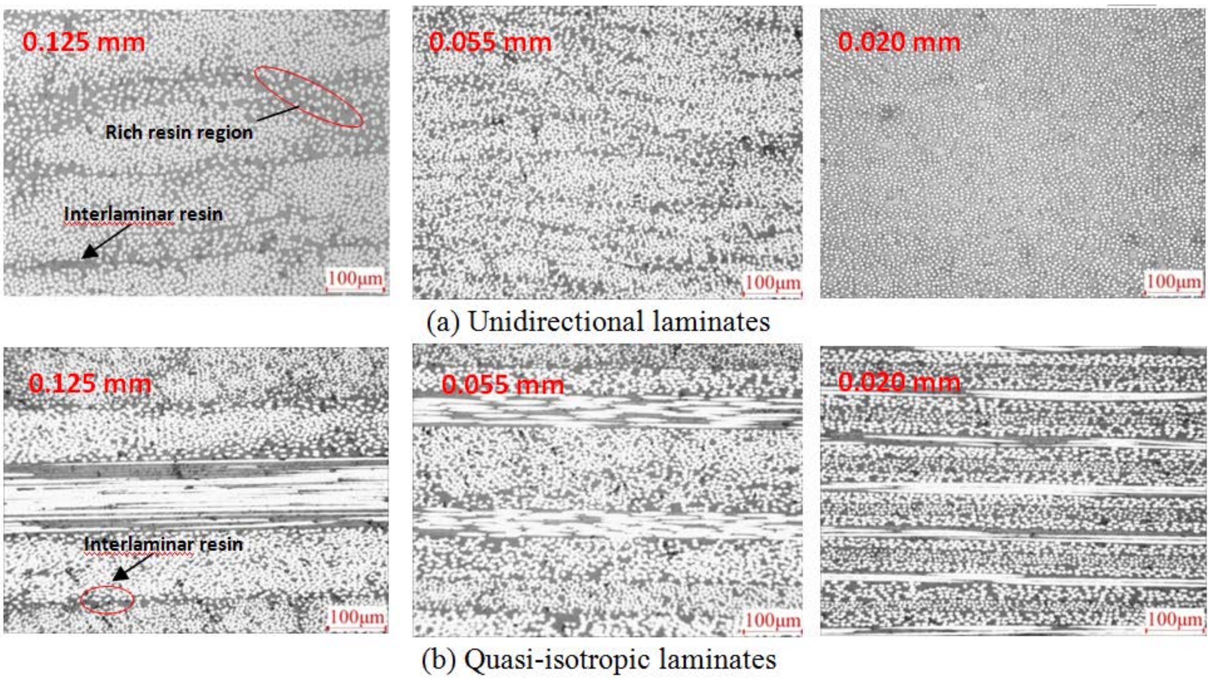


Fig. 2. Optical micrographs of specimens

3.2. Interlaminar shear property

The measured interlaminate shear strength (calculated by Eq 1) of UDLs and QILs with different ply thickness are shown in Fig.3 and Fig.4. Compared with the T-125-ply laminates, the average interlaminate shear strengths of the T-20 and T-55-ply UDL specimens increased by 13.88 % and 6.25 %, respectively, and the average interlaminate shear strengths of the T-20 and T-55-ply QIL specimens increased by 11.85 % and 11.56 %, respectively. In addition, the CV of data becomes smaller for T-20 and T-55-ply laminates.

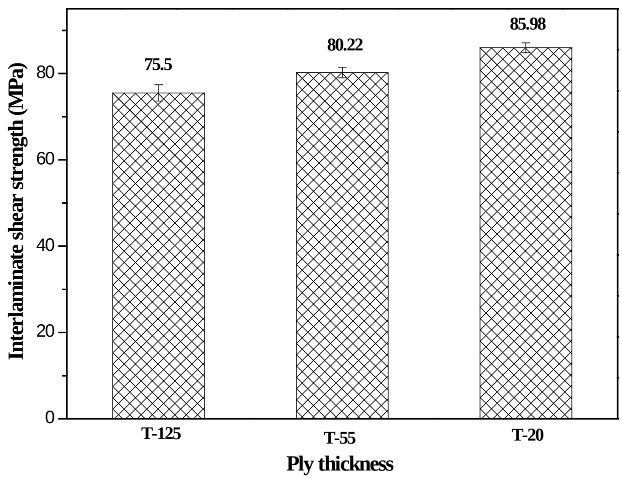


Fig. 3. Average interlaminate shear strength of the unidirectional laminates with different ply thicknesses.

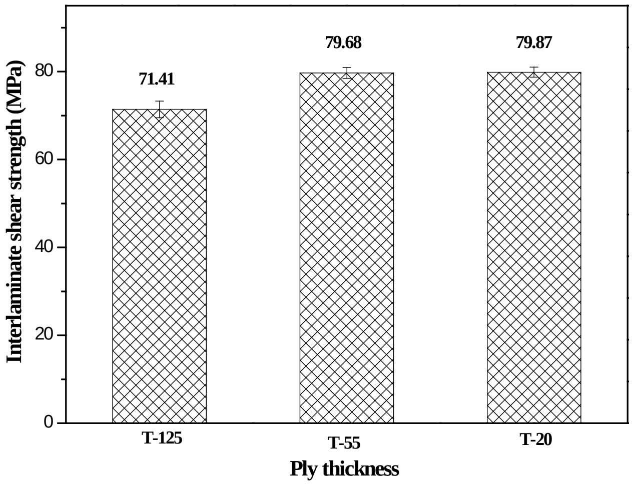
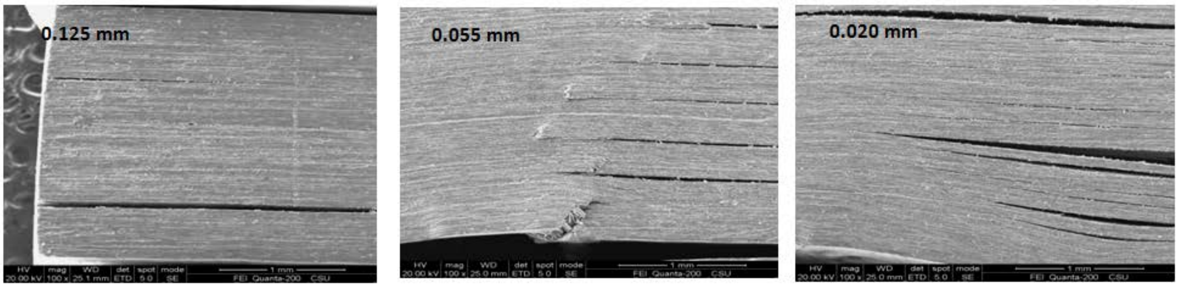
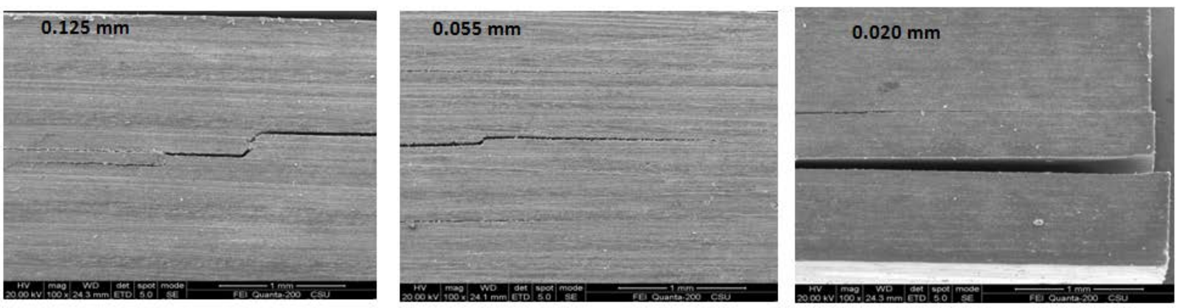


Fig. 4. Average interlaminate shear strength of the quasi-isotropic laminates with different ply thicknesses.

Fig. 5 shows pictures of typical specimens corresponding to different ply thickness after short-beam shear test. The pictures with 100X magnifications are shoot whole thickness of specimen and captured the side cracks on sides of the specimen. Appearance of the cracks in all specimens showed interlaminar shear failure modes and met the requirements of the shear failure modes based on ASTM D3518 and D2344-84. In these specimens, the most striking feature is the change of the morphology of the cracks. In the T-20 and T-55-ply laminates, more interlaminar shear failure cracks can be observed. However, in the T-125-ply laminate specimens, number of the cracks is reduced and a transverse ply cracking appeared.



(a) Unidirectional specimens



(b) Quasi-isotropic specimens

Fig. 5. Failure morphology of the specimen after test

3.3. Stress analysis by Classic Laminate Theory

According to the results presented above, the T-20 and T-55-ply laminates exhibit higher interlamiante shear strength. In order to explore the reasons herein, we checked the interlaminar shear stress of specimens under the short-beam shear loads by Classic Laminate Theory (CLT).

CLT is used to analyze the interlaminar shear stress between the k and k-1 layer in the laminate as shown in equation (3):

$$\tau_{xz}^{k} = -\frac{Q_x}{D}\int_{z_{k-1}}^{h/2} Q_{11}^{(k)} z dz$$
$$D = \frac{B_{11}^2 - A_{11}D_{11}}{A_{11}}, \quad Q_x = \frac{P}{2b} \qquad (3)$$

Where,
k - order number of the layers as shown in Fig. 1,
b - width of the laminate beam, m,
P - load of three-point bending, N,
D - bending stiffness of the laminate,
τ_{xz}^{k} - interlaminar shear stress between the k and k-1 layer,
Q_x - shear force per unit width on cross section of laminate at the x-direction, N/m,
z_{k-1} - Z axis coordinate value of the interface between the k and k-1 layer, m,
h - thickness of the laminate, m,
$Q_{11}^{(k)}$ - axial modulus along the beam axis, Pa,
A_{11}, B_{11} and D_{11} are the in-plane stiffness, coupled stiffness and bending stiffness of the laminate along the beam axis, respectively.

When the laminate is symmetrical, the coupled stiffness B equals zero and the interlaminar shear stress between the k and k-1 layer can be rewritten as equation (4):

$$\tau_{xz}^{k} = \frac{Q_x}{D_{11}}\int_{z_{k-1}}^{h/2} Q_{11}^{(k)} z dz \qquad (4)$$

To investigate the interlaminar shear stress distribution of laminates with different ply thicknesses under short-beam bending, the following quasi-isotropic laminates (the material system used in this analysis is T300/EP901) are studied (as shown in Table 3). Due to the transverse isotropic of unidirectional laminates, the interlaminar shear stress distributions remain invariant with the ply thickness according to CLT. The enhancement of interlaminar shear strength can be regarded as the uniformity of microstructure of T-20 and T-55-ply laminates.

Table 3. Laminates for analysis

Ply thickness (mm)	Quasi-isotropic laminate
0.125000	$[0/45/90/-45]_{1s}$
0.062500	$[0/45/90/-45]_{2s}$
0.031250	$[0/45/90/-45]_{4s}$
0.015625	$[0/45/90/-45]_{8s}$

The interlaminar shear stress on the cross section at middle of the laminate beam is analyzed. According to the equation 4, distribution of the interlaminar shear stress along the cross section thickness can be calculated. Curves of interlaminar shear stress-cross section thickness of laminates with different ply thickness can be obtained. Curve of isotropic materials with the same size and load are also obtained for comparison, calculated by follow equation.

$$\tau_{xz}^{z} = \frac{3P}{4bh}[1-4(\frac{z}{h})^{2}] \tag{5}$$

All laminate short beams in this analysis have 2 mm width and 1 mm thickness, and the three-point bending load is 140 N. As a consequence of symmetry, half of the curve of isotropic materials short beam is shown in pink line in the following figures.

As shown in Fig. 6 and Fig. 7, the curves of interlaminar shear stress on laminate cross-section are obtained. Compared with the shear stress curve of isotropic materials, that curves of thin ply thickness laminates exhibit an approximate distribution to that of the isotropic materials as the decreasing of ply thickness. Especially in Fig. 7, when the ply thickness is closing to 0.015625 mm, the thin-ply laminate has almost the same interlaminar shear tress distribution with isotropic materials and the difference of stacking sequence is slightly influenced the distribution of the interlaminar shear stress. However, in standard ply thickness laminate, the interlaminar shear stress distributions in two stacking sequence laminates are significantly different due to the difference of stiffness between plies. T-125-ply laminate shown in the Fig. 6 should have higher interlaminar shear strength as it has lower interlaminar shear stress maximum under the same loading compared to other ply thickness laminates. But, the opposite results are obtained in the Fig.3 that indicate irregularity of interlaminar shear stress distribution and in-homogeneity of microstructure lead to respectively poor interlaminar shear strength in T-125-ply laminates.

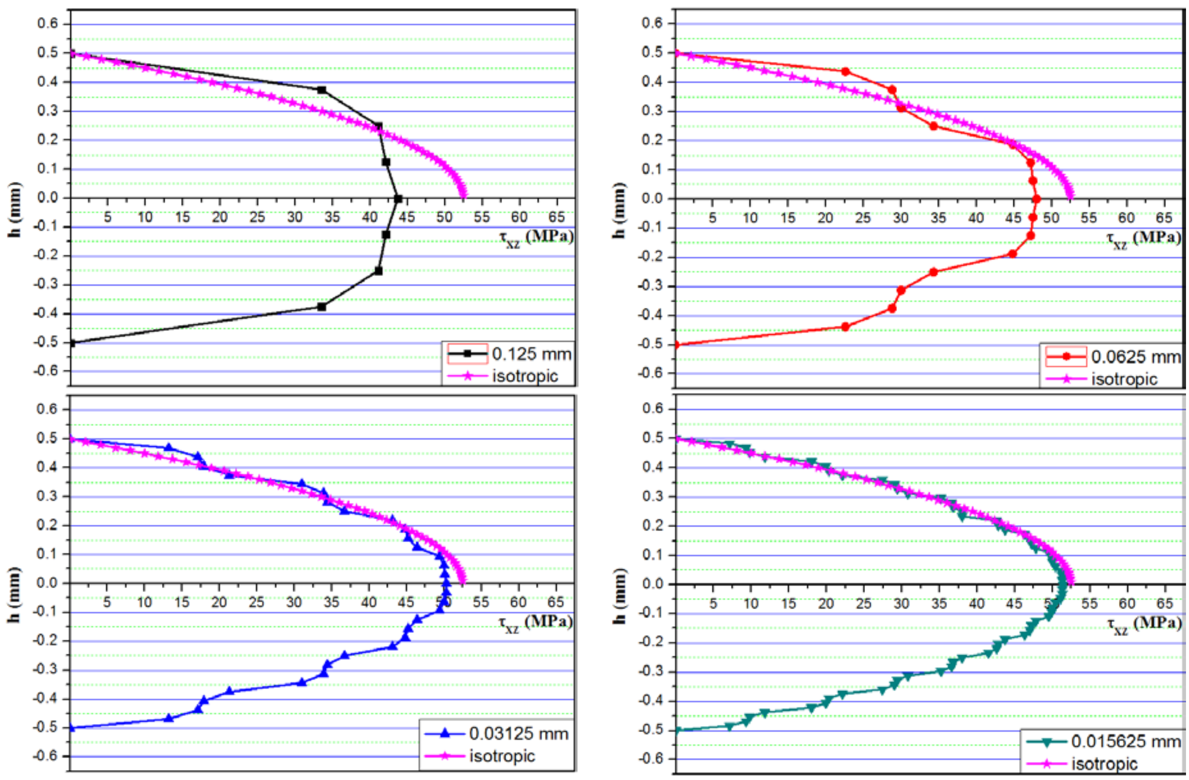
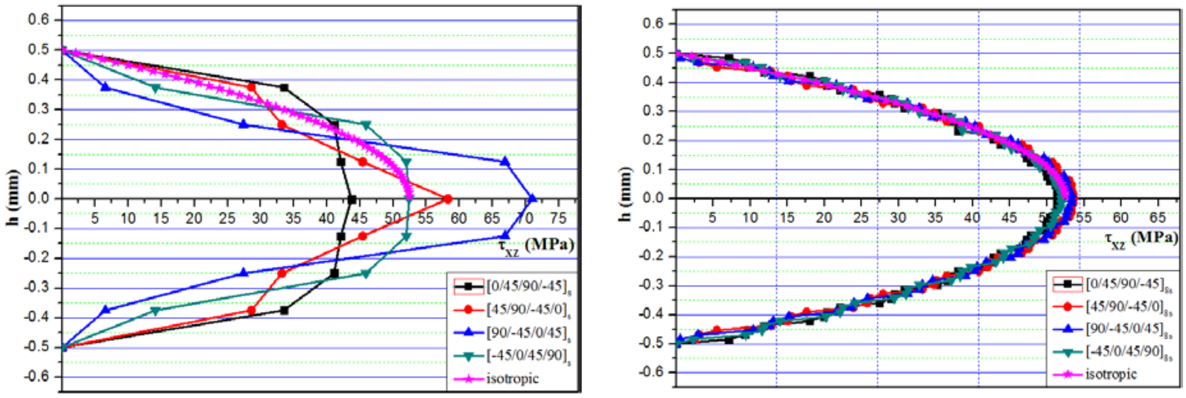


Fig. 6. Distribution of the interlaminar shear stress on cross-section of quasi-isotropic laminates with different ply thickness



(a) ply thickness 0.125mm (b) ply thickness 0.015625mm

Fig. 7. Effects of different stacking sequences on distribution of the interlaminar shear stress on the cross-section of quasi-isotropic laminates with different ply thickness

Based on the optical micrographs and testing data, it can be concluded that the specimens with relatively higher interlaminar shear strength and smaller data CV have more homogeneous microstructures. That is to say, decreasing ply thickness can get more homogeneous microstructures and result in the improvement of the interlaminar properties of the laminate composites. Less interlaminar rich resin regions make the deformation of adjacent two layers be more consistent and the ability to resist interlaminar shear stress can be improved. More homogeneous dispersion of intralaminar fibers with less fiber micro-buckling and fiber clustering can promote to form a good interface between fiber and resin as well as plies. Fewer defects between and inside the plies can relieve the stress concentration and transfer stress better. More excellent interface bonding in the T-20 and T-55-ply laminates let cracks and delaminations transfer cross layer so that more interlaminar cracks present on the side of the specimen. However, in the T-125-ply laminate specimens, cracks and delaminations progress only along a certain interface that make less cracks appear on the side of the specimens. In a word, the microstructure plays an important role in the performance of the thin-ply laminate composite.

According to the CLT analysis results presented above, as sub-laminate scaling and ply thickness decreasing, relatively more flexible stiffness of ply and smaller difference of stiffness between adjacent plies make the T-20 and T-55-ply laminates have more homogeneous interlaminar shear stress distribution similar to that in the isotropic or transverse isotropic materials beams. In other words, inherent anisotropy of laminate composites is weakened as the difference of stiffness between adjacent plies decreased, so that T-20 and T-55-ply laminate beams exhibit similar interlaminar shear stress distribution to that in the isotropic materials beam. Furthermore, smaller coefficients of variation of the interlaminar shear strength of T-20 and T-55-ply laminate specimens are also related to more balanced ply-stacking and similar interlaminar shear stress distributions which is similar to that in the isotropic beams.

3.4. Open-hole tensile property

Based on ASTM D5766 -2002, laminates shall have multidirectional fiber orientations (fibers shall be oriented in a minimum of two directions), and balanced and symmetric stacking sequences, so only quasi-isotropic laminates with different ply thicknesses are investigated in open-hole tensile test. The measured open-hole tensile strength (calculated by Eq 2) of QILs with different ply thickness are shown in Fig. 8. In quasi-static open-hole tensile tests, the T-20 ply specimens demonstrate a 19.84% lower ultimate strength (319.25 MPa) than the T-125 ply specimens (398.26 MPa), and the T-55 ply specimens show a 10.55% lower ultimate strength (356.25 MPa) than the T-125 ply specimens. The T-125 ply specimens show a pull-out failure mode with the failed sections at 45° and -45° angels as well as many delaminations from the side view. Comparison of the failure modes clearly showed a transition from multi-mode failure in T-125 ply laminates to a brittle macroscopic transverse crack initiation at the apex of the hole in the T-20 ply composite laminates, while this brittle failure mode often appears in isotropic materials. This failure mode transition corresponds well to the results given in [1] and [8]. These results could be explained by the absence of early damage growth in thin-ply laminate, which does not redistribute the local stress around the apex of the hole thus leading to premature brittle failure when compared to the standard ply laminates. This is a particular case where damage progression actually improves the ultimate tensile strength of the laminates [8].

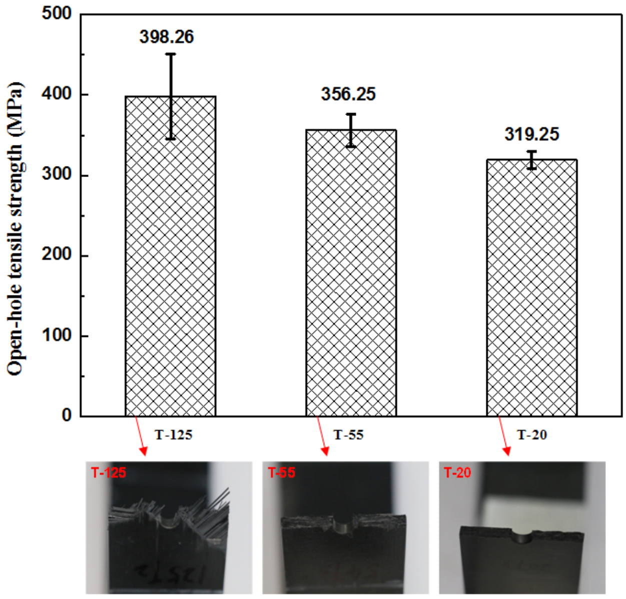


Fig. 8. Average open-hole tensile strength and failure morphology of the quasi-isotropic laminates with different ply thicknesses.

4. Conclusions

According to the present results, it is clear that higher interlaminar shear strength and relatively smaller coefficient of variation of strength of the specimens are obtained in UDLs and QILs with thinner ply. Compared with the T-125-ply laminates, the average interlaminate shear strengths of the T-20 and T-55-ply UDL specimens increased by 13.88 % and 6.25 %, respectively, and the average interlaminate shear strengths of the T-20 and T-55-ply QIL specimens increased by 11.85 % and 11.56 %, respectively. According to the optical micrographs, relatively homogeneous microstructures with less rich resin regions between and within the plies, more uniform fiber dispersion and fewer defects are observed in T-20 and T-55 laminates, that results in higher interlaminate shear strength and smaller coefficient of variation of the data. According to the stress analysis by CLT, tapering ply thickness and sub-laminate scaling make T-20 and T-55-ply laminates demonstrate more balanced stacking and similar interlaminar shear stress distributions to that in isotropic materials as the decreased difference of stiffness between adjacent plies and weakened inherent anisotropy of laminate composites. By tapering the ply thickness, homogeneous-like microstructure, regular interlaminar shear stress distribution and brittle failure mode of the open-hole thin-ply laminate can be regarded as that of a homogeneous and isotropic material, namely pseudo-homogeneous and isotropic behaviors of thin ply laminates

Acknowledgments

We gratefully acknowledge the financial support by National Natural Science Foundation of China (11202231, U1537101).

References

[1] Sangwook Sihn, Ran Y. Kim, Kazumasa Kawabe, Stephen W. Tsai. Experimental studies of thin-ply laminated composites. Composite Science and Technology 2007; 67: 996-1008.
[2] Tomohiro Yokozeki, Akiko Kuroda, Akinori Yoshimura. Damage characterization in thin-ply composite laminates under out-of-plane transverse loads. Composite structures 2010; 93:49-57.
[3] Sasayama H, Kawabe K, Tomoda S, Ohsawa I, Kageyama K, Ogata N. Effect of lamina thickness on first ply failure in multidirectionally laminated composites. Proceedings of the 8th Japan international SAMPE symposium & exhibition (JISSE-8), Tokyo, Japan; November 2003.
[4] Jen-Chung Chen, Chuen-Guang Chao. Numerical simulation and experimental investigation for design of a carbon fiber tow pneumatic spreading system. Carbon 2005; 43:2514-2529.
[5] Hassan M. EL-Dessouky, Carl A. Lawrence. Ultra-lightweight carbon fiber/thermoplastic composite material using spread tow technology. Composites: Part B 2013; 50:91-97.
[6] Tomohiro Yokozeki, Akiko Kuroda, and Akinori Yoshimura. Damage characterization in thin-ply composite laminates under out-of-plane transverse loadings. *Composite structures*, 93:49-57, 2010.
[7] Tomohiro Yokozeki, Yuichiro Aoki, and Toshio Ogasawara. Experimental characterization of strength and damage resistance properties of thin-ply carbon fiber/toughened epoxy laminates. *Composite Structures*, 82: 382-389, 2008.
[8] R. Amacher, J. Cugnoni, and J. Botsis. Thin ply composites: Experimental characterization and modeling of size-effects. *Composite Sience and Technology*, 101: 121-132, 2014.
[9] J.D. Fuller, M.R. Wisnom. Pseudo-ductility and damage suppression in thin ply CFRP angle-ply laminates. *Composites: Part A*, 69: 64–71, 2015.
[10] Sasayama H, Kawabe K, Tomoda S, Ohsawa I, Kageyama K and Ogata N. Effect of lamina thickness on first ply failure in multidirectionally laminated composites. *Proceedings of the 8th Japan international SAMPE symposium & exhibition (JISSE-8), Tokyo, Japan* 2003.
[11] Yamaguchi K, and Hahn HT. The improved ply cracking resistance of thin-ply laminates. *Proceedings of 15th international conference on composite materials (ICCM-15), Durban, South Africa* 2005.
[12] Crossman FW, Warren WJ, Wang ASD, Law Jr GE. Initiation and growth of transverse cracks and edge delamination in composite laminates: Part 2. Experimental correlation. *Journal of Composite Materials*, 14: 88-108, 1980.
[13] Kim RY, Soni SR. Experimental and analytical studies on the onset of delamination in laminated composites. *Journal of Composite Materials,* 18: 70-80, 1984.
[14] Lavoie KA, Soutis C, Morton J. Apparent strength scaling in continuous fiber composite laminates. *Composite Sience and Technology*, 60: 283-299, 2000.