STUDY ON THE STRENGTH OF THIN-PLY LAMINATES OF CFRP UNDER INTERLAMINAR SHEAR LOADINGS

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Abstract
Carbon fiber reinforced polymer matrix composites(CFRP) have been widely used in aerospace and aircraft structures because of their excellent mechanical properties and light weight. However the CFRP with standard plies usually have weak interlaminar shear strength, meanwhile, for thin-thickness laminates of a wing skin, it is difficult to balance the ply design with standard plies. It is possible to improve the interlaminar shear strength of CFRP and enlarge the design space by using thinner plies instead of the standard-plies in the laminates. Compared to the laminates with standard layers, thin-ply laminates are expected to exhibit superior damage resistance and result in higher mechanical properties such as tensile, compressive and shear strength. In this paper, interlaminar shear strength of a carbon fiber/epoxy thin-ply laminates under short-beam bending loads was investigated. Unidirectional and quasi-isotropic laminates specimens were prepared using standard prepregs (125g/m^2) and thin-ply prepregs (54g/m^2), respectively. Loading-deflection curves of the laminate specimens were obtained. Significant improvement on interlaminate shear strength was achieved for the thin-ply laminates, which was verified by both experiment and simulation.

1. Introduction

Carbon fiber reinforced polymer matrix composites laminates(CFRP) are attractive structural materials which was widely used in aerospace and aircraft structures because of their high performance. In some structures, e.g. wing skin of airplane, the loading environment is very complicated, so the laminated composites for the wing skin must be able to withstand various loading conditions and require quasi-isotropic laminates for the wing skin structurs. However, limited by thickness and weight, there is not enough space for designing a quasi-isotropic laminate with standard ply. Due to inherent anisotropy, the transverse and interlaminate shear mechanical properties of CFRP are correspondingly poor. The typical damage modes of the laminated composites are transverse microcracking, delamination and fiber-breakage. Besides, a catastrophic failure can occur only with the microcracking and delamination damage without the fiber breakage[1]. The delamination is known to happen because of excessive interlaminar normal and shear stress. Besides, The interlaminar stresses can be concentrated relatively easily near the free edge of the laminated composites, resulting in delamination of the materials.

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In recent years, important progress has been made in the development of composite laminates using thin plies. Thickness of commercially available thin-ply prepreg can be down to about 15 um through the tow spreading technology. With the help of tow spreading technology developed by North Thin Ply Technology (NTPT, Penthalaz, Switzerland), the solar impulse 2 is able to fly day and night without a drop of fuel, the airplane has begun the flight around the world in march 9, 2015. 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 due to increased laminate design space and 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.[2] 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, respectively, in transverse indentation test. Standard ply laminates exhibited delaminations near the back surface of the specimen as well as inside the laminate, whereas delamitation only happened to the inside plies in thin-ply laminates, and the delimitation appeared prior to fiber fractures. Tomohiro Yokozeki et al. [3] 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.[4] studied the experimental characteriztion of mechanical properties and size effect of thin ply composites. The experimental results showed that reducing the ply thickness can lead to dramatic improvements not only in terms of first-ply failure/first-damage stress, but also in terms of 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[5] 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 tomograthy 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[6,7]. Additionally, onset and propagation behaviors of the delaminations were also dependent on ply thickness as well as ply stacking sequence[8-10].

It has been widely recognized that ply thickness has a significant impact on the accumulation of microscopic damage and delamination of the CFRP laminates under different loading conditions. Laminates consisting of thin plies have superior damage and delamination resistance properties which have been confirmed in machanical experiment such as unnotched tension, open-hole compression, and impact. But, there are no similar results on interlaminate shear test so far. So, in this paper, CFRP laminates are fabricated by standard prepregs and thin-ply prepregs respectively, and a comparative study on their mechanical properties is performed. Interlaminar shear test based on ASTM D2344-84 and finite element analysis are implemented to investigate the reason of delamination suppression in thin-ply composite laminates.

2. Experimental procedures

2.1. Materials and specimens

The material system used in this study was a low modulus carbon fiber and toughened epoxy system, T300/901, supplied by Huixing Fiber. The fiber areal weights of the standard ply and thin ply prepregs are 125g/m^2 and 54g/m^2, respectively, and the nominal resin content is 45% for both prepregs. Ply thicknesses of the standard and thin ply prepreg are about 0.125 mm and 0.055mm, respectively.

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To investigate the mechanical behaviors of the thin-ply laminates and standard laminates under interlaminate shear test, the following unidirectional laminates and quasi-isotropic laminates are prepared:

Standard ply laminates: $[0_{20}]$ and $[0/45/90/-45]_{3s.}$
Thin-ply laminates: $[0_{46}]$ and $[0/45/90/-45]_{6s.}$
Fiber volume fraction ν_{pf} of each laminate can be calculated from the fiber areal weight and ply thickness as $\nu_{pf} = w_{af} / (t \cdot \rho_f)$, where w_{af}, t, ρ_f denote the fiber areal weight , ply thickness and the density of the fiber, respectively. So the theoretical value v_f of each laminate is 55%.

To achieve stablity of fiber volume fraction and uniformity of specimen thickness, the specimens are manufactured through the molding process. The curing process of the T300/901 material system is: keeping the samples under temperature of 80℃ for 30 min, then raising temperature to 113℃ and loading compressive pressure of 2 atm for 20 min and finally raising temperature to 130℃ and keeping the pressure of 2 atm for 2 h at 130℃. The fiber fraction of each laminate can be determined through optical microscopy and image processing techniques in preliminary study. C-scan can be used to check up the quality of each laminate.

2.2. Short-beam shear test

The Fig. 1 shows the configuration of the short-beam shear test based on ASTM D3518 and D2344-84. The specimen width *b* is twice of its thickness *h*, the specimen length *L* and span length *l* are six times and four times of its thickness *h*, respectively. Environmental temperature for the test is standard laboratory atmosphere (23 ± 3 ℃). The aim of this test is to achieve interlaminate shear strength of the composite laminates and the strength can be calculated using Eq (1) as follows:

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

where:
F^{iss} = interlaminate shear strength, MPa,
P_m = maximum load observed during the test, N,
b = width of the specimen, mm,
h = thickness of the specimen, mm.

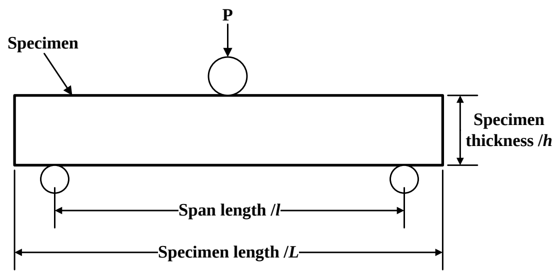

Fig. 1. Specimen for short-beam shear test.

3. Experimental results

3.1. C-scan and optical micrograph

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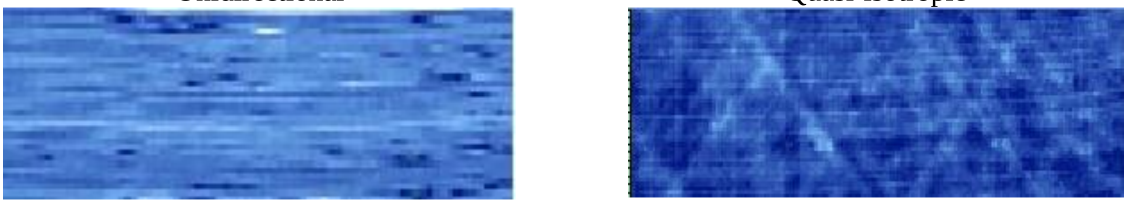
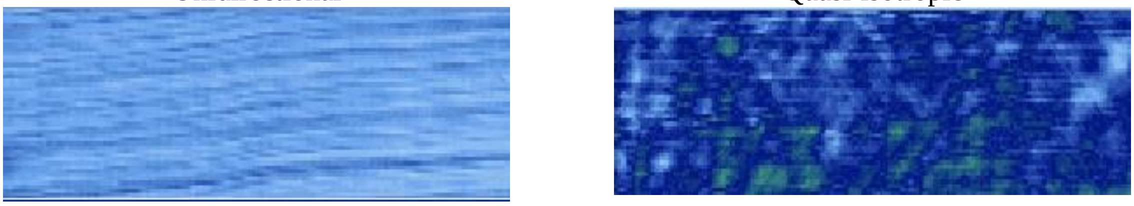
Before the test, C-scan is used to check the internal defects and damage of laminates. In C-scan, the image appears red where there are defects. As shown in Fig.2, both thin-ply and standard ply laminates have no obvious defects or damage. So the molding process can ensure the quality of products.

Unidirectional Quasi-isotropic



(a) standard ply laminates

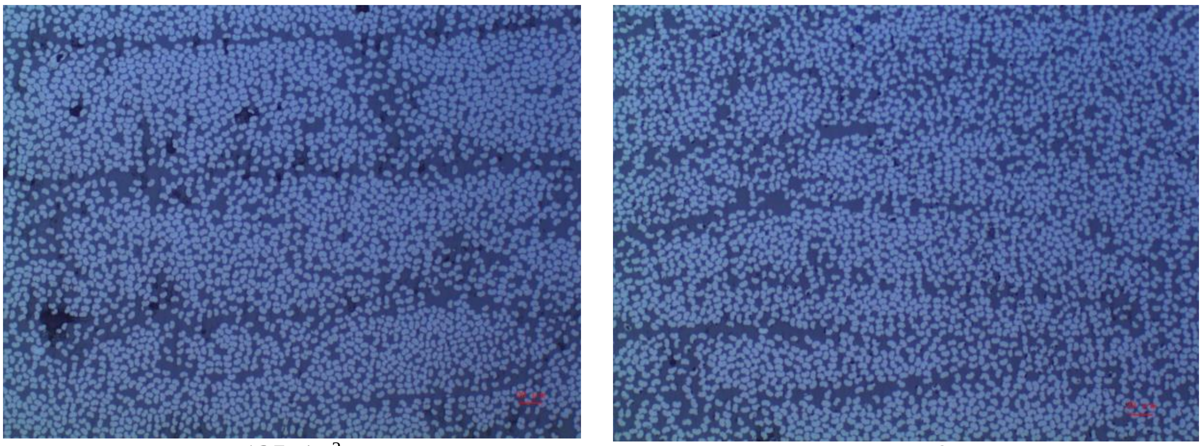
Unidirectional Quasi-isotropic



(b) thin-ply laminates

Fig. 2. C-can images of the laminates

Then, optical micrographs are used to check the microstructrure of the laminates and calculate fiber volume fractions. Optical micrographs of the thin-ply and standard-ply unidirectional specimens are analyzed and presented in Fig. 3. The microstructure of the thin-ply laminate is found to be relatively uniform and the interfaces between the plies are more homogeneous. The microstructure of the standard ply laminate is found to be relatively inhomogeneous with regions of obvious higher or lower fiber volume fractions (in the range of 48－58%). The difference can be denoted by visible fiber bundles and rich resin regions in the standard-ply laminate vs. uniform microstructure for the thin-ply laminate. Additionally, the number and size of defects in thin-ply lamiante is less than standard ply laminate.



125g/m^2 54g/m^2

Fig. 3. Optical micrographs of thin-ply and standard-ply unidirectional specimens

3.2. Results of short-beam shear test

Loading-deflection curves of the unidirectional and quasi-isotropic laminate specimens are presented in Fig. 4 and Fig. 5. It can be seen clearly that the thin-ply laminates have much longer nonlinear phase in the unidirectional laminate experiments and have larger damage deflection in both unidirectional and quasi-isotropic laminate tests. That is to say, the thin-ply laminates exhibit

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flexibility while the standard-ply laminates don't have. These features can explain the phenomenon that the thin-ply laminate can restrain damage and delamination.

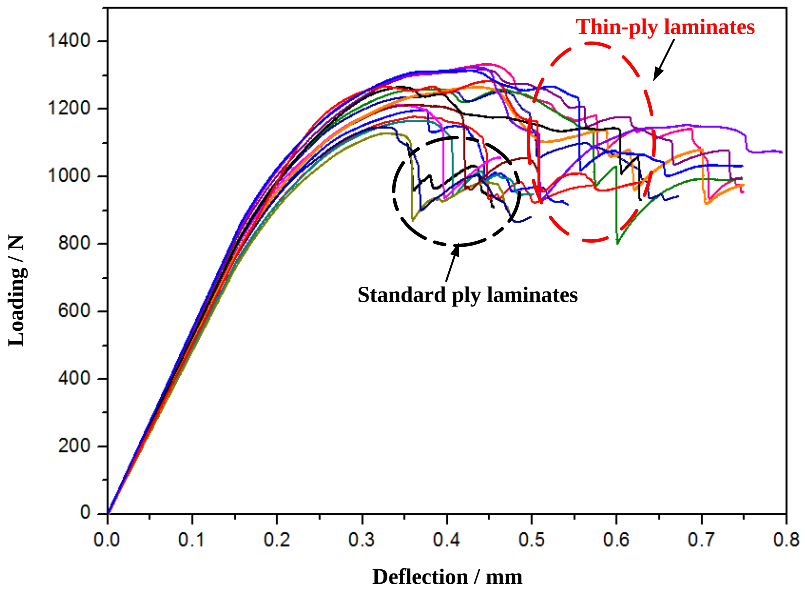

Fig. 4. Loading-deflection curves of the unidirectional laminate specimens.

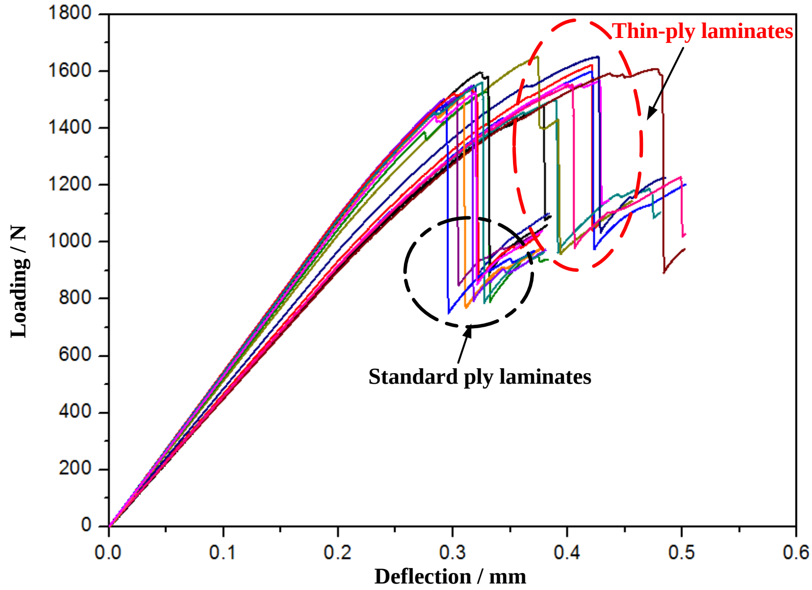

Fig. 5. Loading- deflection curves of the quasi-isotropic laminate specimens.

The measured interlaminate shear strength of the unidirectional laminates with thin-ply and standard-ply is shown in Fig. 6. Compared with the standard-ply laminates, the average interlaminate shear strength of the thin-ply laminates has increased about 6.21 %. Fig. 7 shows the short-beam shear test results of the thin-ply and the standard-ply quasi-isotropic laminates. As shown in Fig. 7, average interlaminate shear strength of the thin-ply laminates is also higher than that of the standard-ply laminates by 13.31%. It should be noted that the specimen thickness is the same for the different laminates in these tests.

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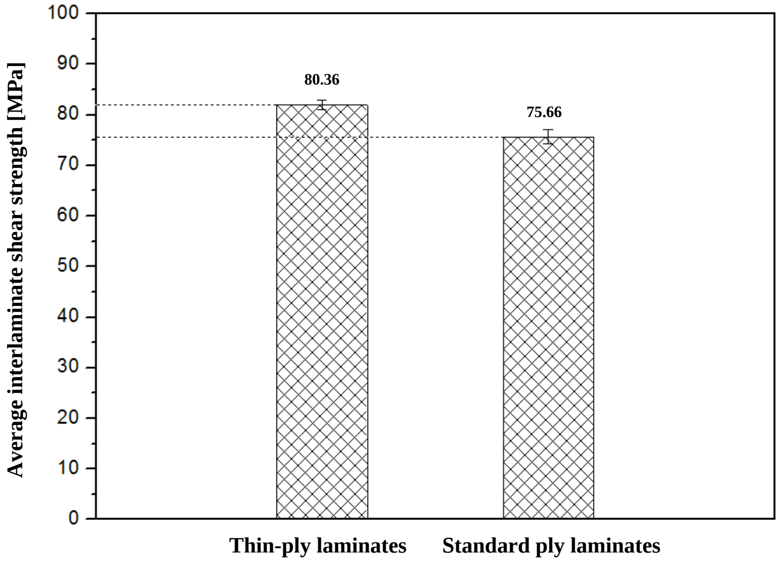

Fig. 6. Average interlaminate shear strength of the thin-ply and standard-ply unidirectional laminates.

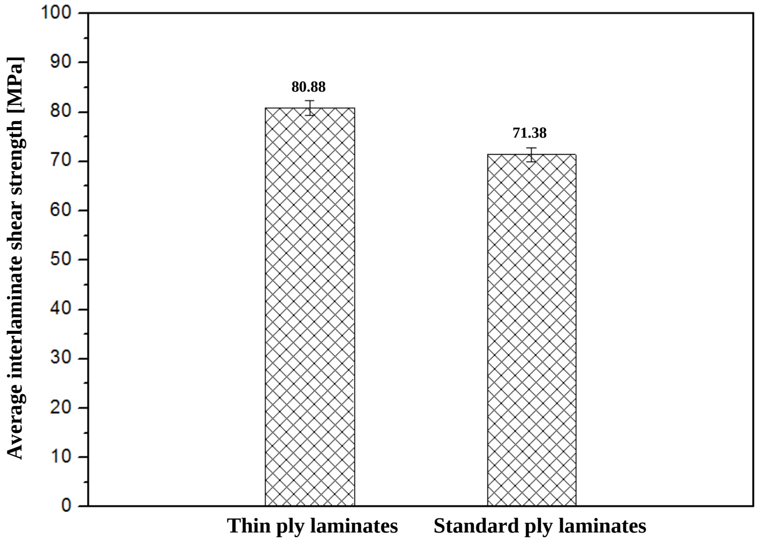

Fig. 7. Average interlaminate shear strength of the thin-ply and standard-ply quasi-isotropic laminates.

Pictures of specimens after testing are presented in Fig. 8. These pictures present all specimens of both unidirectional and quasi-isotropic laminates after short-beam test. From the appearance, all specimens have meet the requirements of the failure modes based on ASTM D3518 and D2344-84. In unidirectional laminates, the thin-ply specimens present more cracks that may be related to the number of interfaces and cracks develepment paths. In quasi-isotropic laminates, the thin-ply specimens exhibit better resistance to deformation and cracking.

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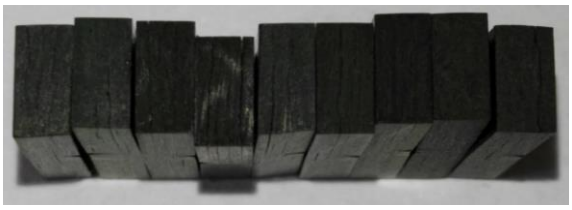
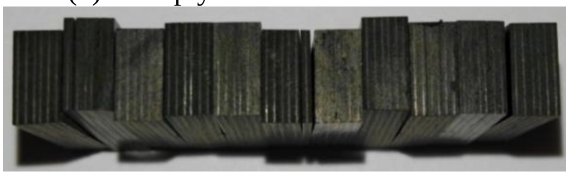
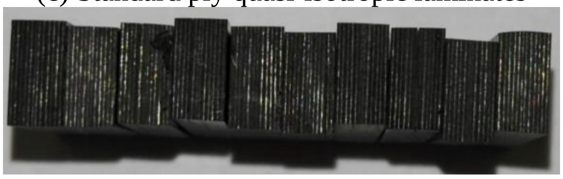


(a) Standard ply unidirectional laminates

(b) Thin-ply unidirectional laminates



(c) Standard ply quasi-isotropic laminates



(d) Thin-ply quasi-isotropic laminates

Fig. 8 Specimen pictures after testing

According to the behaviors of the thin-ply laminate in short beam shear tests, these significant differences in microstructure can explain the relatively poor properties of the standard-ply specimen, as the rich resin regions are inherently more prone to produce defects, leading to the early development of interlaminate shear instability of the laminate. So relatively uniform microstructure that is less defect number and size, for the thin-ply laminate makes initial stress of crack appearance higher under short-beam loading. Besides, the crack evolvepment in the thin-ply laminate have more paths to spread so that its loading-deflection curves exhibit larger damage deflection. In a word, the thin-ply laminate have higher interlaminate shear performance and can restrain the damage and delamilation.

4. Numerical investigations

4.1. Finite element model

To analyze the interlaminate shear stress distribution of all specimens in short-beam shear test, the finite element analysis is performed using the ANSYS software. The numerical models have the same geometry and supporting conditions with the experimental specimens as shown in Fig.9. 8-noded layered solid elements were used for modeling, and geometry nonlinear effect is considered. Finite element model of the standard ply laminate has 20 layeres and 6000 elements, and the thin-ply laminate has 46 layeres and 13800 elements. Material properties of the T300/901 obtained by experments, which is assumed to be transversely isotropic, are shown in Table 1. E_L and E_T are the longitudinal and transversely tension modulus. G_{LT} and G_{TT} are the in-plane and out of plane shear modulus. V_{LT} is the poisson ratio. It is considered that these modulus parameters are the same in thin-ply and standard ply laminate.

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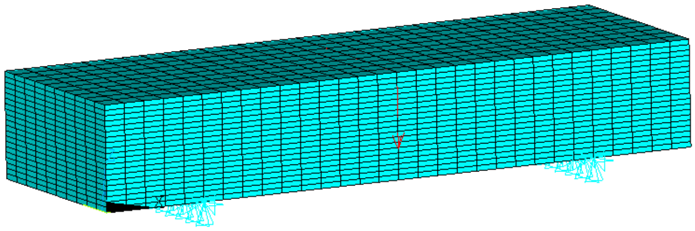

Fig. 9. Finite element modeling

Table 1. Mechinal properties of the T300/901 unidirectional laminates

E_L(GPa)	E_T(GPa)	G_{LT}(GPa)	G_{TT}(GPa)	V_{LT}(GPa)
149.8	10.6	7.71	3.24	0.32

4.2. Finite element analysis

As shown in Fig. 10 and Fig. 11, in order to obtain the interlaminate stress distribution of the specimens more clearly, we divided the specimen into four parts in postprocess. Figures show that two different laminates have different high stress distribution area. Shear stress distribution in the thin-ply laminate is more homogeneous which can relieve the stress concentration.

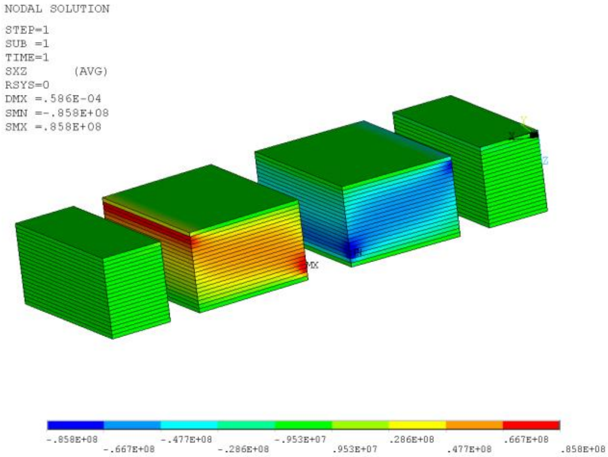

Fig.10. Interlaminate shear stress in standard-ply unidirectional laminate by simulation of short-beam shear test

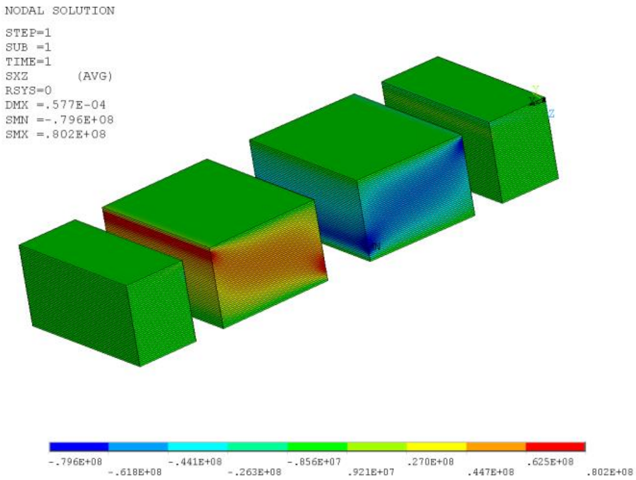

Fig.11. Interlaminate shear stress in thin-ply unidirectional laminate by simulation of short-beam shear test

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5. Conclusions

According to the present results, it is clear that both unidirectional and quasi-isotropic thin-ply laminates have higher interlaminate shear strength than that of the standard-ply laminates. The interlaminate strength of the unidirectional and quasi-isotropic thin-ply laminate has increased by 6.21% and 13.31%, respectively.

From the optical micrographs of the thin-ply and the standard-ply laminate, microstructure of the thin-ply laminate is more uniform and has less rich resin regions. So the probability of appearing large size defects is reduced and the paths of cracking are increased, resulting in the increase of the interlaminate shear strength and nonlinear phase of loading-deflection in the thin-ply laminates.

The FEM shows that the interlaminate shear stress distribution in the thin-ply laminate is more homogeneous and stress concentration is less than that in the standard-ply laminate. The maxium interlaminate shear stress values in simulation of the thin-ply and the standard-ply laminates are agree well with the experiment results.

The phenomenon of restraining damage and delamination in thin-ply laminate is believed to owe to more uniform microstructure and homogeneous interlaminate shear stress distribution.

Acknowledgments

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