EFFECT OF PLY THICKNESS ON MECHANICAL PROPERTIES IN CFRP ANGLE-PLY LAMINATES

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Abstract

This paper deals with mechanical property and damage evolution in CFRP symmetric angle-ply laminates with different ply thickness. T700SC/2500 carbon/epoxy laminates with stacking sequence of $[(\pm 45)_{12}]_s$, $[(\pm 67.5)_{12}]_s$ *(t-0.05mm prepreg×48plies),* $[(-45)_4/(+45)_4]_s$, $[(-67.5)_4/(+67.5)_4]_s$ *(t-0.15mm prepreg×16plies) are used as specimens. It should be noted that the laminate thickness is almost the same, but the ply thickness are quite different. In 48-ply specimen each thickness of +45 and -45 ply is 0.05mm. Meanwhile, in 16-ply specimen, the ply thickness is 0.6mm if each* $(+45)_4$ *or* $(-45)_4$ *ply is regarded as one blocked ply of +45 or -45 ply. Monotonic tensile tests are performed to understand fundamental mechanical properties of each laminate. Furthermore we estimate damage evolution from mesoscale damage model with loading-unloading tensile test results. 48-ply specimen has been found to exhibit high fracture strain and strength in comparison to 16-ply specimen.*

1 Introduction

Carbon fiber reinforced plastics (CFRP) have been used for aerospace structures because of its high stiffness and strength, and low density. Usually, CFRP is used as laminated materials which are fabricated by laminating many layers of prepregs, it is important for optimum design of composite structures using CFRP to investigate effect of ply thickness on mechanical properties in CFRP laminates. In addition, CFRP is made by laminating the fiber direction in many directions. It is important to understand mechanical response which exhibits nonlinear stress-strain relationships under off-axis loading. In this regard, Ladevese et al [1] predicted mechanical properties in CFRP laminates by mesoscale damage model which they proposed based on continuum damage mechanics. Herakovich et al [2] investigated stress-strain relationships and damage evolution in $[\pm 45]_{3s}$ laminate that exhibits large deformation by mesoscale damage model which considered fiber rotation and variation of cross sectional area.

In this paper, in order to understand effect of ply thickness on mechanical properties and damage evolution in CFRP laminates, we performed monotonic tensile test and loading-unloading tensile test in CFRP angle-ply laminates which have same laminate thickness but different ply thickness. And, we estimate damage evolution from mesoscale damage model proposed by Ladevese et al with loading-unloading tensile test experimental results.

2 Experimetnal Procedure

In this study, T700SC/2500 (Toray Co., Ltd.) laminates have been investigated. We use two types of prepregs, 0.05mm thickness prepreg and 0.15mm thickness prepreg. $[(\pm45)_{12}]_s$, $[(\pm67.5)_{12}]_s$ laminates which used 0.05mm thickness prepreg consist of 48ply. On the other hand, $[(-45)_4/(+45)_4]_s$, $[(-67.5)_4/(+67.5)_4]_s$ laminates which used 0.15mm thickness prepreg consist of 16ply. It should be noted that the laminate thickness is almost the same, but the ply thickness are quite different. In 48-ply specimen each +45 and -45 ply thickness is 0.05mm. On the other hand, in 16-ply specimen, if we regard the blocked $(+45)_4$ or $(-45)_4$ plies as one +45 or -45 ply, the thickness of blocked plies are 0.6mm. The one ply thickness in 48-ply specimen is 12 times thinner than that in 16-ply specimen. Specimen length was 260mm, width was 20mm and thickness was 2.4mm. GFRP tabs were bonded to the ends for the load introduction. Biaxial Strain gauges were bonded at the center of the specimen. Uniaxial high-elongation strain gages were used to only $[(\pm45)_{12}]_s$ laminates. We performed tensile tests and cyclic loading-unloading tests at the crosshead speed 1.0 mm/min for each laminate. In the loading-unloading test, the loading-unloading cycle was repeated five or six times.

3 Experimetnal Results

3.1 Monotonic tensile test We carried out monotonic tensile test in order to evaluate mechanical properties of each laminate. Fig. 1 shows stress-strain behavior in $[(+45)_4/(-45)_4]_s$ and $[(\pm45)_{12}]_s$ laminates. Fig.2 shows stress-strain behavior in $[(+67.5)_4/(-67.5)_4]_s$ and $[(\pm67.5)_{12}]_s$ laminates. Table 1 shows mechanical properties of each laminate in monotonic tensile tests. It is clear that $[(\pm45)_{12}]_s$ laminate exhibited larger failure strain and higher strength than $[(+45)_4/(-45)_4]_s$ laminates. $[(+67.5)_4/(-67.5)_4]_s$ and $[(\pm67.5)_{12}]_s$ laminates showed the similar tendency of $[(+45)_4/(-45)_4]_s$ and $[(\pm45)_{12}]_s$ laminates. Thin ply thickness specimen (48-ply specimen) indicated higher strength and higher fracture strain than those of thick ply thickness specimen (16-ply specimen).

Since strength and fracture strain indicate different tendency, we carried out cyclic loading-unloading test to estimate damage evolution due to ply thickness.

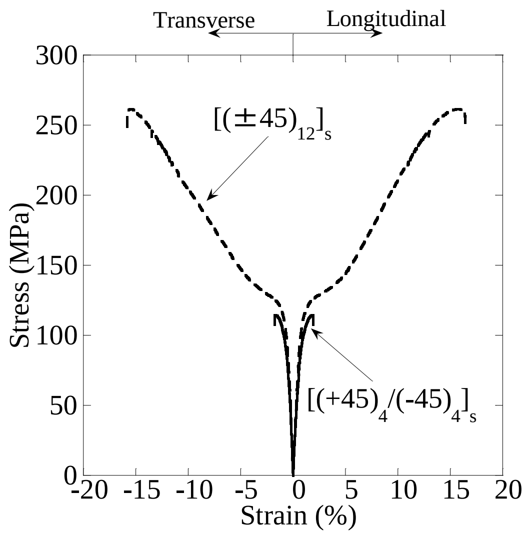

Fig. 1 Stress-strain curves (45°)

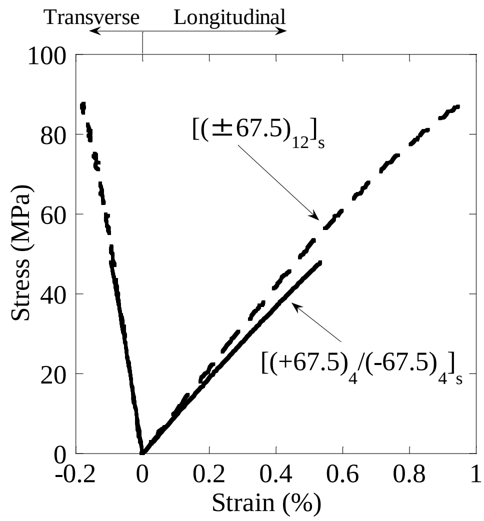

Fig. 2 Stress-strain curves (67.5°)

Table 1 Mechanical properties of each laminate

	$[(\pm45)_{12}]_s$	$[(+45)_4/(-45)_4]_s$	$[(\pm67.5)_{12}]_s$	$[(+67.5)_4/(-67.5)_4]_s$
Young's modulus (GPa)	16.7	14.4	10.6	9.2
Tensile Strength (MPa)	261.5	116.1	87.6	47.9
Fracture strain (%)	16.4	1.91	0.96	0.53
Poisson's ratio	0.78	0.77	0.19	0.17

4. Damage mechanics analysis

We estimate damage evolution of each laminate from mesoscale damage model which based on loading-unloading experimental results with each cycle modulus.

4.1 Mesoscale damage model In this study, we used mesoscale damage model proposed by Ladevese et al [1]. Mesoscale damage model focuses on intermediate scale between micro and macro scale. It does not consider identification of the specific damage at the microscopic level, such as fiber-matrix debonding or matrix cracking. We assume an individual layer of a plane stress state. The strain energy E_D for an individual layer of laminate in a state of plane stress is written:

$$E_D = \frac{1}{2}\left[\frac{\sigma_{11}^2}{E_{11}^o} + \frac{\sigma_{12}^2}{G_{12}^o(1-d_{12})} + \frac{\langle\sigma_{22}\rangle_+^2}{E_{22}^o(1-d_{22})} + \frac{\langle\sigma_{22}\rangle_-^2}{E_{22}^o} - \frac{2\nu_{12}^o}{E_{11}^o}\sigma_{11}\sigma_{22}\right] \tag{1}$$

with

$$\langle a\rangle_- = a \quad if \quad a \le 0; \quad otherwise \langle a\rangle_- = 0 \qquad \langle a\rangle_+ = a \quad if \quad a \ge 0; \quad otherwise \langle a\rangle_+ = 0$$

Subscript 1 describes fiber direction and subscript 2 does transverse direction. The superscript 0 indicates undamaged value. And d_{12} and d_{22} are scalar damage variables, that represent loss of the shear modulus and the transverse Young's modulus, respectively. These two variables are given by loading-unloading test results. Therefore, as the elastic modulus loss of each cycle to the undamaged elastic modulus, damage variable is written as:

$$d = 1 - \frac{E}{E_0} \tag{2}$$

where, d is damage variable, E is elastic modulus at each cycle, E_0 is undamaged elastic modulus. Elastic modulus of each cycle is determined as gradient between intersection point of loading process and unloading process and point which loading process change. We assume no stiffness loss in fiber direction, because fiber break doesn't occur. We can determine thermodynamic forces Y_{12} and Y_{22} in terms of stress components and damage variables. They are defined as:

$$Y_{12} = \left.\frac{\partial E_D}{\partial d_{12}}\right|_\sigma = \frac{1}{2}\frac{\sigma_{12}^2}{G_{12}^o(1-d_{12})^2} \tag{3}$$

$$Y_{22} = \left.\frac{\partial E_D}{\partial d_{22}}\right|_\sigma = \frac{1}{2}\frac{\sigma_{22}^2}{G_{22}^o(1-d_{22})^2} \tag{4}$$

From these variables, we can determine two variable, $\underline{Y}(t)$ and $\underline{Y}'(t)$, which determine damage evolution and correspond to brittle failure under transverse tensile loading as supremum at any time τ during $0 < \tau < t$.

$$\underline{Y}(t) = \sup_{\tau \le t}(\sqrt{Y_{12}(\tau) + bY_{22}(\tau)}) \tag{5}$$

$$\underline{Y'}(t) = \sup_{\tau \le t}(\sqrt{Y_{22}(\tau)}) \tag{6}$$

where b is a material constant coupling between transverse tension and shear effects. These two variables of thermodynamic forces, $\underline{Y}(t)$ and $\underline{Y'}(t)$, that are associated with damage variables.

4.2 Damage evolution in shear direction From the loading-unloading tests on the $[(+45)_4/(-45)_4]_s$ and $[(\pm45)_{12}]_s$ laminates, we can determine σ_{12}-ε_{12} shear behavior and shear damage evolution. Shear and transverse stress are given by classical lamination theory in terms of applied axial stress σ_{xx} as:

$$\sigma_{22} \approx 0 \tag{7}$$

$$\sigma_{12} = 0.5\sigma_{xx} \tag{8}$$

and, shear and transverse strain are given in terms of measured longitudinal and transverse strain, ε_{xx} and ε_{yy} as:

$$\varepsilon_{22} \approx 0 \tag{9}$$

$$\varepsilon_{12} = 0.5(\varepsilon_{xx} - \varepsilon_{yy}) \tag{10}$$

The result of cyclic loading-unloading tensile test of $[(\pm45)_{12}]_s$ laminate is shown in Fig. 3. We consider that shear force dominate in ±45 laminates. Thermodynamic force associated with damage variables are written as:

$$Y_{22} = 0 \tag{11}$$

$$\underline{Y} = \max\big|_{\tau \le t}(Y_{12}) \tag{12}$$

Fig. 4 shows shear damage evolution relationship between shear damage variables d_{12} and thermodynamic force $\underline{Y}$ given by Eq. (12). Damage developed linearly at the early stages on both specimen 48-ply laminates and 16-ply laminates. In 48-ply laminates, d_{12} became almost constant although the stress increases. It is necessary to investigate damage state microscopically at each loading condition. Consideration of fiber rotation change fiber orientation due to tensile loading is also required in damage model.

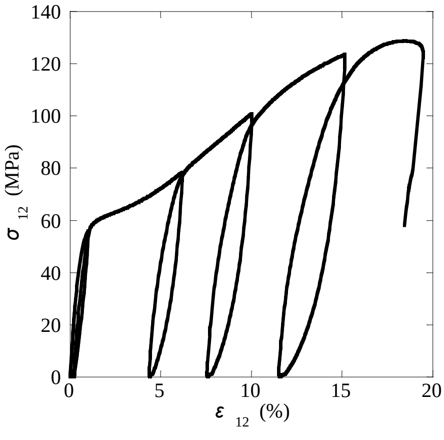

Fig. 3 Shear stress-strain curve of $[(\pm45)_{12}]_s$ laminates

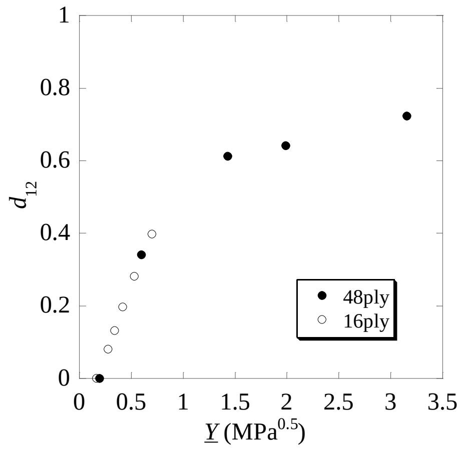

Fig. 4 Shear damage evolution of $[(+45)_4/(-45)_4]_s$ and $[(\pm45)_{12}]_s$ laminates

4.3 Damage evolution in transverse direction Damage development in transverse direction can be determined from cyclic tensile tests of $[(\pm 67.5)_{12}]_s$ and $[(+67.5)_4/(-67.5)_4]_s$ laminates. Stresses of $[\pm\theta]_s$ laminates under tensile loading are determined from classical laminate theory by following equations :

$$\sigma_{11} = B\sigma_{xx} \tag{13}$$

$$\sigma_{22} = (1-B)\sigma_{xx} \tag{14}$$

$$\sigma_{12} = \frac{-1}{2mn}\left[B(1-2m^2)+m^2\right]\sigma_{xx} \tag{15}$$

using $n=sin\theta$ and $m=cos\theta$,

$$B = \left[\frac{m^2(2m^2-1+4m^2n^2\frac{G_{12}}{E_{22}}}{4m^2n^2\frac{G_{12}}{E_{22}}+\left(2m^2-1\right)\left(m^2-n^2\right)}\right] \tag{16}$$

When θ is 67.5°, Eq. (16) gives B=0.218 in the elastic region. It is assumed that B is constant parameter throughout loading history. Then we can determine stress-strain relationships of transverse direction. Fig. 5 shows transverse behavior. From Eq. (5) using experimental results, we can determine transverse damage behavior of transverse damage parameter d_{22} and the variable $\underline{Y}$. Fig. 6 shows transverse damage behavior in $[(\pm 67.5)_{12}]_s$ and $[(+67.5)_4/(-67.5)_4]_s$ laminates. It is clear that thin 48ply specimen is excellent at resistance to damage.

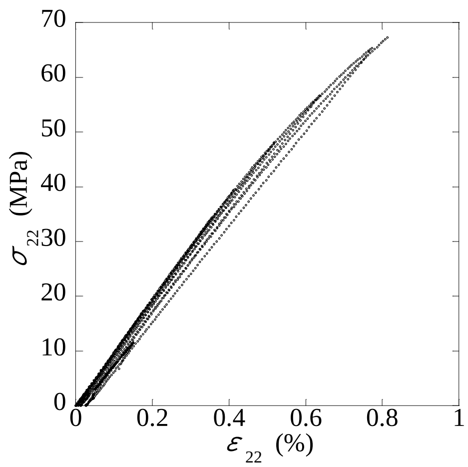

Fig. 5 Transverse stress-strain curve of $[(\pm 67.5)_{12}]_s$ laminates

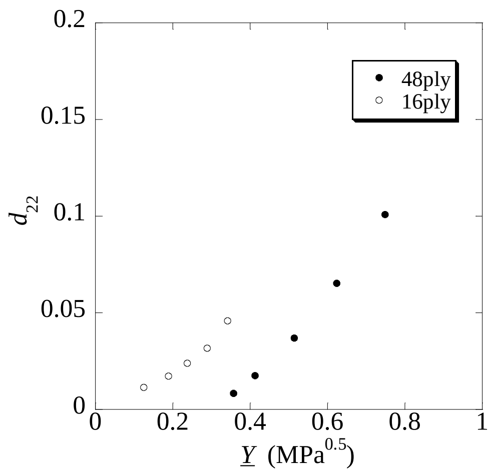

Fig. 6 Transverse damage evolution of $[(+67.5)_4/(-67.5)_4]_s$ and $[(\pm 67.5)_{12}]_s$ laminates

5. Conclusion

We carried out monotonic tensile tests and loading-unloading tests on $[(+45)_4/(-45)_4]_s$ (16-ply), $[(\pm 45)_{12}]_s$ (48-ply), $[(+67.5)_4/(-67.5)_4]_s$ (16-ply), $[(\pm 67.5)_{12}]_s$ (48-ply) laminates, of T700/2500 (Toray Co., Ltd.) laminates. We investigated effect of ply thickness on mechanical property and damage evolution. In ±45° angle-ply laminates, shear damage evolution was measured. In ±67.5° angle-ply laminates, transverse damage evolution was measured. It has been shown that thin ply thickness laminates (48-ply) are superior in terms of resistance to damage, such as damage initiation, in comparison to thick (blocked) ply laminates (16-ply). In ±67.5° angle-ply laminates, it has a small effect of ply thickness in comparison to ±45° angle-ply laminates.

References

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