Effects of Stacking Sequence on the Transverse Cracking in Quasi-Isotropic Interleaved CFRP Laminates

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SUMMARY: Transverse crack behavior in quasi-isotropic interleaved CFRP laminates was observed by an optical microscope and a soft X-ray radiography system. Seven symmetric laminates composed of the same combination of ply orientations were tested to clarify the effect of stacking sequence on transverse crack behavior in 90° plies. The thickness of 90° plies and the modulus of adjacent plies were found to be most effective on the transverse cracking. To model the experimental results, damage mechanics analysis was used. The predictions of transverse crack evolution based on both energy and average stress criteria were compared with the experimental results. The validity of the present analysis was confirmed. The advantage of this analysis was its applicability to general laminate configuration, once the critical values were determined.

KEYWORDS: CFRP, Quasi-Isotropic Laminates, Transverse Crack, Stacking Sequence, Damage Mechanics, Energy Release Rate

INTRODUCTION

Carbon fiber reinforced plastics (CFRP) are used in the form of the multidirectional laminates. In the failure process of CFRP laminates, unique microscopic damages, such as transverse cracks and delamination, initiate and grow under loading. Especially, transverse cracks are induced in the early stage of the failure process and cause following serious damages, delamination and fiber breaks. This implies the necessity to clarify the behavior of transverse cracking for application of CFRP laminates to primary structures. Although many experiments have been conducted for general laminates[1-3], most of analytical models of transverse cracking have been limited to only cross-ply laminates[4-7].

Gudmundson and Zang [8] proposed a damage mechanics model for the prediction of the thermoelastic properties of composite laminates containing matrix cracks. The analysis can be applied to general laminate configurations. With the analysis, Ogihara et. al. [9] derived the energy release rate associated with transverse cracking, and proposed a model to predict the transverse crack behavior based on both energy and average stress criteria.

The objective of this study is to investigate the transverse crack behavior in quasi-isotropic interleaved CFRP laminates experimentally. The experimental results are compared with the analytical prediction based on the damage mechanics analysis [9] to evaluate the effectiveness of the analysis.

EXPERIMENTAL PROCEDURE

Material

A material system used was CFRP T800H/3900-2 with interlaminar-toughened resin layers, supplied by Toray Inc. The T800H/3900-2 prepreg system has tough and fine polyamide particles on its surfaces, which results in formation of the interlaminar-toughened resin layers at every ply interface in a laminate. The thickness of the interlaminar-toughened layers is approximately 30 μm. T800H/3900-2 laminates are known to provide both high compressive strength after impact damage and high compressive strength at elevated temperatures for moistured test specimens [10, 11]. It is also known that delamination around open holes is suppressed under static tensile loading [12]. Material properties are shown in Table 1 [12].

The laminate configurations were symmetric and quasi-isotropic composed of the same combination of ply orientations (0°, 45°, -45° and 90°) shown in Table 2. The specimen size was 150 mm long, 25 mm wide and 1.5 mm thick. GFRP tabs were glued on the specimen. Free edges of these specimens were polished to observe microscopic damages.

Damage Observation

Quasi-static tensile tests were conducted at room temperature. The cross-head speed was 0.5 mm/min. During the test, the testing machine was periodically stopped and the polished edge of the specimen were directly observed by an optical microscope. A soft X-ray radiography was also used for internal damage observation. The observed area was 50 mm long at the center of the specimen. The number of transverse cracks in the specimen was counted to obtain the transverse crack density, which was defined as the number of transverse cracks per unit specimen length.

Table 1 Material properties of unidirectional T800H/3900-2 laminate.

Longitudinal Young's Modulus (GPa)	143
Transverse Young's Modulus (GPa)	7.99
In-Plane Shear Modulus (GPa)	3.96
In-Plane Poisson's Ratio	0.345
Out-of-Plane Poisson's Ratio	0.490
Longitudinal Thermal Expansion Coefficient (10^{-6} /°C)	-1.52
Transverse Thermal Expansion Coefficient (10^{-6} /°C)	34.3

Table 2 Laminate configurations.

Laminate with Two 90° Plies at the Center	(a) $[0/\pm45/90]_s$
	(b) $[45/0/-45/90]_s$
	(c) $[\pm45/0/90]_s$
Laminate with One 90° Ply Located Symmetrical to the Center Plane	(d) $[0/90/\pm45]_s$
	(e) $[0/45/90/-45]_s$
	(f) $[45/0/90/-45]_s$
	(g) $[90/45/0/-45]_s$

EXPERIMENTAL RESULTS

The first microscopic damage observed was a transverse crack in 90° ply in all laminate configurations. Figure 1 shows a transverse crack observed in 90° ply of T800H/3900-2 $[0/\pm45/90]_s$ laminate (ε=1.5%, ε is laminate strain). It is seen that the transverse crack run through the thickness of the two 90° plies. In Figure 1, a matrix crack in -45° ply is also observed. Matrix cracks were also observed in -45° plies of both $[45/0/-45/90]_s$ and $[45/0/90/-45]_s$, in 45° plies of $[90/45/0/-45]_s$ and in ±45° plies of $[0/45/90/-45]_s$. Figure 2 shows the internal damage state. It is seen that matrix cracks in off-axis plies grow only a little in the width direction. The number of cracks increased as the laminate strain increased. Free edge delamination at -45/90 interface and in 90° plies onset and grow only in a $[45/0/-45/90]_s$ laminate.

Figure 3 shows the transverse crack density as a function of laminate strain. Laminates with two 90° plies at the center, (a) $[0/\pm45/90]_s$, (b) $[45/0/-45/90]_s$, (c) $[\pm45/0/90]_s$ can be regard as $[(\text{Sub. Lam.})/90]_s$ where (Sub. Lam.) is sublaminates whose mechanical properties are expected to be identical in macroscopic point of view. Therefore, transverse crack onset strain in the laminates are expected to be similar. However, experimental results show that the order of transverse crack onset strain is (a) $[0/\pm45/90]_s$ > (b) $[45/0/-45/90]_s$ > (c) $[\pm45/0/90]_s$. This is attributed to the difference in thermal residual stress in the laminate near free edges. That is, the thermal stress is expected to be more severe in the laminate where 0° and 90° plies which have large thermal coefficient mismatch are placed close to each other, and the transverse crack onset strain is expected to be smaller. After the transverse crack onset, the transverse crack density in (b) $[45/0/-45/90]_s$ and (c) $[\pm45/0/90]_s$ became larger than (a) $[0/\pm45/90]_s$ because the stress recovery between the cracks are larger with increasing stiffness of adjacent plies to the 90° ply.

In the laminate with one 90° ply located symmetrically to the center plane, transverse crack onset strain of (d) $[0/90/\pm45]_s$ and (f) $[45/0/90/-45]_s$ which have 0° plies adjacent to 90° plies became larger than the rest, (e) $[0/45/90/-45]_s$ and (g) $[90/45/0/-45]_s$. This is due to the constraint effect of 0° plies. The transverse crack density of (g) was much smaller than any other laminates. This is because of the lack of one side of adjacent ply which causes lower stress recovery.

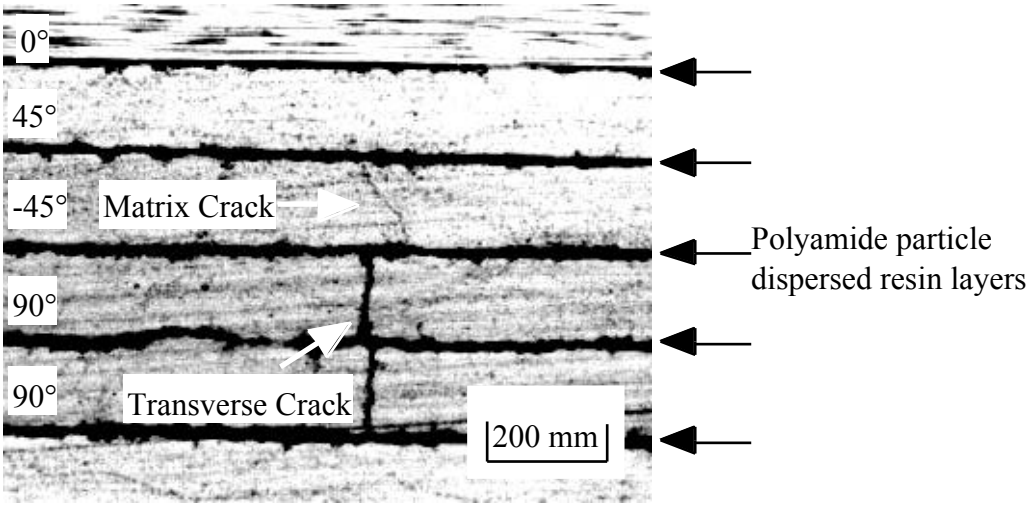

Figure 1 Damage in $[0/\pm45/90]_s$ laminate (edge observation, ε=1.5%, ε: laminate strain).

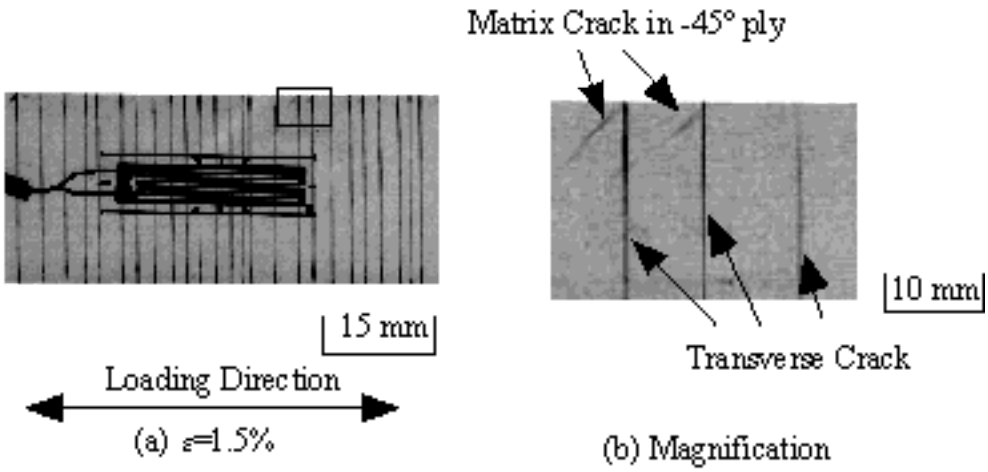

Figure 2 Damage in $[0/\pm45/90]_s$ laminate (X-ray observation).

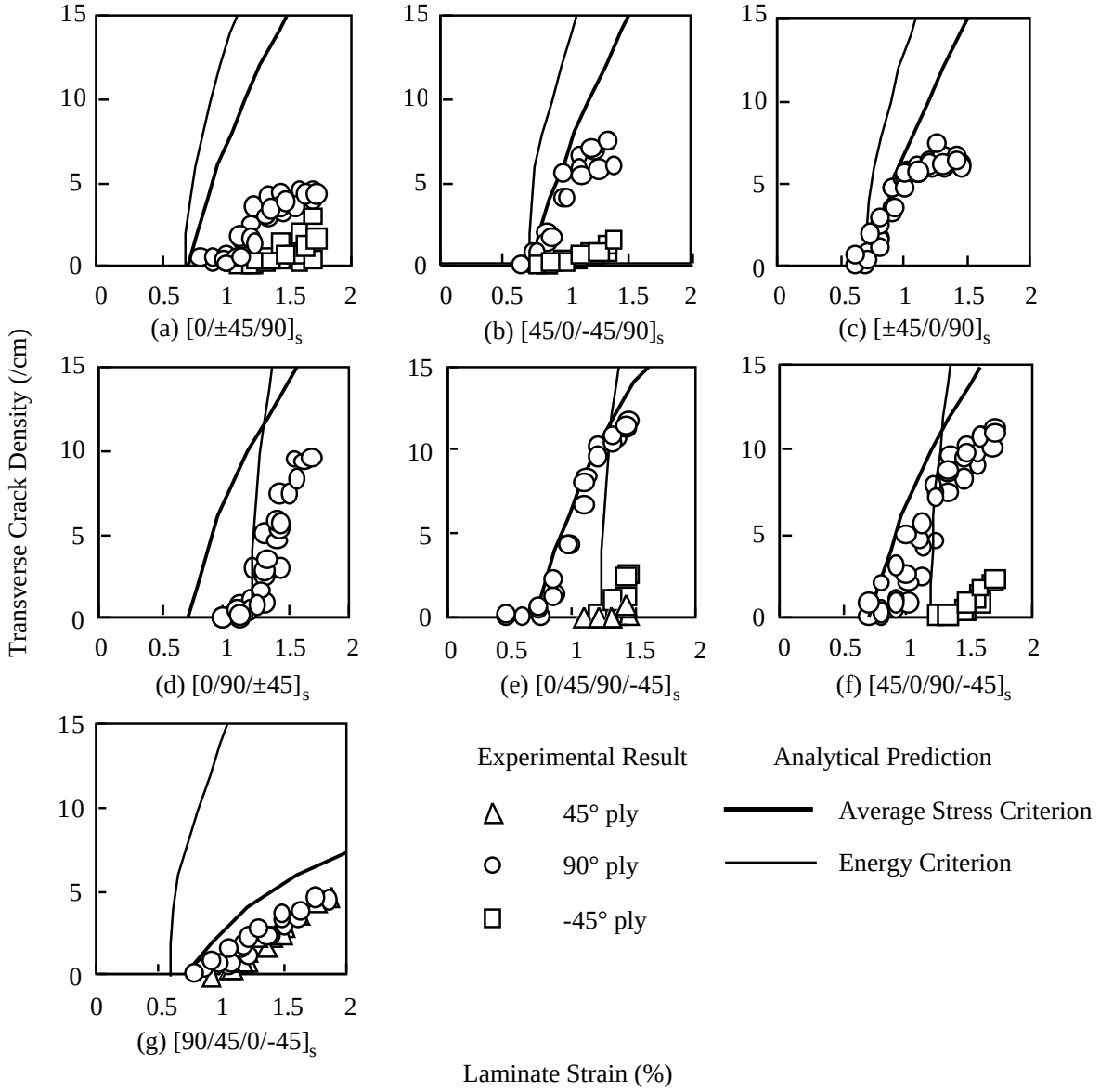

Figure 3 Transverse crack density as a function of laminate strain (experimental results and analytical predictions, σ^k_c = 90 MPa and G_c = 300 J/m^2).

DISCUSSION

We conducted damage mechanics analysis [9] to model the transverse crack behavior. Short review of this analysis is shown here. Gudmundson and Zang [8] developed an analytical model for the prediction of the thermoelastic properties of composite laminates containing transverse cracks. The in-plane compliance matrix of laminates with transverse cracks, $\boldsymbol{S}_{\mathrm{II(c)}}$, can be expressed using an in-plane compliance matrix without transverse cracks, $\boldsymbol{S}_{\mathrm{II}}$, as

$$\boldsymbol{S}_{\mathrm{II(c)}} = \left(\left(\boldsymbol{S}_{\mathrm{II}}\right)^{-1} - \sum_{k=1}^{N} \nu^k \rho^k \left(\boldsymbol{A}^k\right)^T \sum_{i=1}^{N} \beta^{ki} \boldsymbol{A}^i \right)^{-1} \tag{1}$$

where v^k is the volume fraction of ply k, ρ^k is the normalized crack density in ply k, $\boldsymbol{A}^k$ is the matrix defined by the compliance matrix of each ply and a unit normal vector on the crack surface, β^{ki} is the matrix associated with average crack opening displacement in ply k. The (1, 1)

component of the inverse of the in-plane compliance matrix, $1/\mathbf{S}_{II}(\rho^k)_{(1,\ 1)}$ is the laminate Young's modulus $E(\rho^k)$.

Assuming that transverse cracks occur at a constant load and also at the midway between the existing transverse cracks, the energy release rate when the transverse crack density becomes ρ from $\rho/2$, $G(\rho)$ at laminate stress σ is expressed as

$$G\left(\rho^k\right) = \frac{\sum_{i=1}^{N} a^i}{\rho^k}\left\{\sigma - E(0)\left(\alpha_k - \alpha_1(0)\right)\Delta T\right\}^2 \left(\frac{1}{E\left(\rho^k\right)} - \frac{1}{E\left(\rho^k/2\right)}\right) \tag{2}$$

where a^i is the thickness of ply i, $\alpha_1(0)$ and α_k are the thermal expansion coefficients of the undamaged laminate (ρ^k=0) and ply k, respectively, and ΔT is the temperature change from the curing temperature.

In the energy criterion, transverse cracks are assumed to onset when G defined in eq. (2) reaches a critical value, G_c. The relation between the laminate stress and the normalized transverse crack density is expressed as

$$\sigma\left(\rho^k\right) = \sqrt{\frac{G_c \rho^k}{\sum_{i=1}^{N} a^i}\left(\frac{1}{E\left(\rho^k\right)} - \frac{1}{E\left(\rho^k/2\right)}\right)^{-1}} + E(0)\left(\alpha_k - \alpha_1(0)\right)\Delta T \tag{3}$$

In the damage mechanics analysis, the average stress of damaged plies can be derived. In the average stress criterion, it is assumed that the transverse cracks onset when the average stress normal to crack surfaces of ply k reaches a critical value, σ^k_c. Considering the 90° ply, the relation between the laminate stress and the normalized transverse crack density is expressed as,

$$\sigma\left(\rho^k\right) = \frac{\left[\dfrac{\sigma^k_c}{1 - \rho^k \beta^{kk}_{(1,1)}\left(\mathbf{S}_{II}\right)^{-1}_{(1,1)}} + \left[\left\{\alpha_{90} - \alpha_1\left(\rho^k\right)\right\}\left(\mathbf{S}_{II}\right)^{-1}_{(1,1)} + \left\{\alpha_0 - \alpha_2\left(\rho^k\right)\right\}\left(\mathbf{S}_{II}\right)^{-1}_{(1,2)}\right]\Delta T\right]}{\left(\mathbf{S}_{II}{}^k\right)^{-1}_{(1,1)}\mathbf{S}_{II(1,1)} + \left(\mathbf{S}_{II}{}^k\right)^{-1}_{(1,2)}\mathbf{S}_{II(1,2)}} \tag{4}$$

where $\mathbf{S}_{II}{}^k$ is a compliance matrix of ply k, α_2 is a component normal to the loading direction of the in-plane thermal expansion coefficient vector for the laminate, and α_0 and α_{90} are axial and transverse thermal expansion coefficients of a unidirectional composite, respectively.

The predictions based on both energy and average stress criteria are shown in Figure 3. Material properties used are listed in Table 1. Critical values were selected to fit the experimental results. The critical energy release rate and critical average stress are 300J/m^2 and 90 MPa, respectively. Transverse cracks are assumed to onset only when both criteria are satisfied. In other words, the criterion that gives lower transverse crack density at the same laminate strain have to be regarded as a proper prediction. Predictions are in good agreement with the experimental results except for (a), (e) and (f) laminates. In the analysis, average transverse crack opening displacements (COD) are assumed to be equal to that in an infinite homogeneous transversely isotropic medium. But the real COD is different from this assumption, depending on the fiber orientation of adjacent plies and interleaved plies which have different stiffness from 90° plies. This shows that some modifications of the present analysis are necessary.

CONCLUSION

Tensile tests were conducted for seven different kinds of laminates to clarify the effect of stacking sequence on the transverse crack behavior. In the group of laminates with 90° plies at the center, the distance of 0° plies from the neutral plane are closely related with the transverse crack onset strain. Transverse crack density of this group at the final fracture is clearly smaller than $[90/45/0/-45]_s$ laminates.

The damage mechanics analysis was conducted to predict the transverse crack behavior. The predictions were found in good agreement except for some laminate configurations. Some improvement in modeling is necessary for precise prediction.

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