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Advanced Composite Materials
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tacm20

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Satoshi Kobayashi , Shinji Ogihara & Nobuo Takeda

Version of record first published: 02 Apr 2012.

To cite this article: Satoshi Kobayashi , Shinji Ogihara & Nobuo Takeda (2000): Experimental characterization of the effects of stacking sequence on the transverse crack behavior in quasi-isotropic interleaved CFRP laminates, Advanced Composite Materials, 9:3, 241-251

To link to this article: http://dx.doi.org/10.1163/15685510051033449

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Adv. Composite Mater., Vol. 9, No. 3, pp. 241–251 (2000)
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Experimental characterization of the effects of stacking sequence on the transverse crack behavior in quasi-isotropic interleaved CFRP laminates

SATOSHI KOBAYASHI [1,*], SHINJI OGIHARA [2] and NOBUO TAKEDA [3]

[1] *Takeda Laboratory, Komaba Open Laboratory, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8904, Japan*
[2] *Department of Mechanical Engineering, Science University of Tokyo, 2641 Yamasaki, Noda, Chiba 278-8510, Japan*
[3] *Graduate School of Frontier Sciences, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*

Received 28 January 2000; accepted 28 April 2000

Abstract—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 influential in their effect on transverse cracking behavior. 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.

1. 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, such as delamination and fiber breaks. This implies the necessity to clarify the behavior of transverse cracking for application

*To whom correspondence should be addressed.

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 effect of stacking sequence on 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.

2. EXPERIMENTAL PROCEDURE

2.1. 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

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
Fiber volume fraction (%)	50 ∼ 55

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Table 2.
Laminate configurations

Laminate with two 90° plies at the center (Group A)	(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 (Group B)	(d) $[0/90/\pm45]_s$ (e) $[0/45/90/-45]_s$ (f) $[45/0/90/-45]_s$ (g) $[90/45/0/-45]_s$

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glued on the specimen. Free edges of these specimens were polished to observe microscopic damages.

2.2. 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. lodozinc (ZnI), a dye penetrant opaque to X-rays, was applied along the specimen edge. 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.

3. EXPERIMENTAL RESULTS

The first microscopic damage observed in all laminates was transverse cracks in 90° plies. Matrix cracks in ±45° plies and free edge delamination initiated successively. Quasi-isotropic laminates tested are classified into two groups. In the present study, a laminate group which consists of the laminates with two 90° plies at the center is referred to as group A, and the other laminate group which consists of laminates with one 90° ply located symmetrical to the center plane is referred to as group B. Microscopic damage progress in the laminates in one group is similar.

First, microscopic damage progress in group A laminates are described. Figure 1 shows a transverse crack observed in 90° plies of $[45/0/-45/90]_s$ laminate ($\varepsilon = 1.32\%$, ε is laminate strain). It is seen that the transverse crack runs through the thickness of the two 90° plies. In Fig. 1, a matrix crack in the −45° ply is also observed. Matrix cracks in −45° plies were also observed in $[0/\pm45/90]_s$ laminates; however, matrix cracks were not observed in ±45° plies of $[\pm45/0/90]_s$ or in 45° plies of $[45/0/-45/90]_s$ and $[0/\pm45/90]_s$ laminates until final fracture. Figure 2 shows the internal damage state of $[45/0/-45/90]_s$ laminate ($\varepsilon = 1.32\%$). Because the delamination area becomes black on the image and matrix cracks cannot be detected, dye penetrant was applied along the one side of the specimen

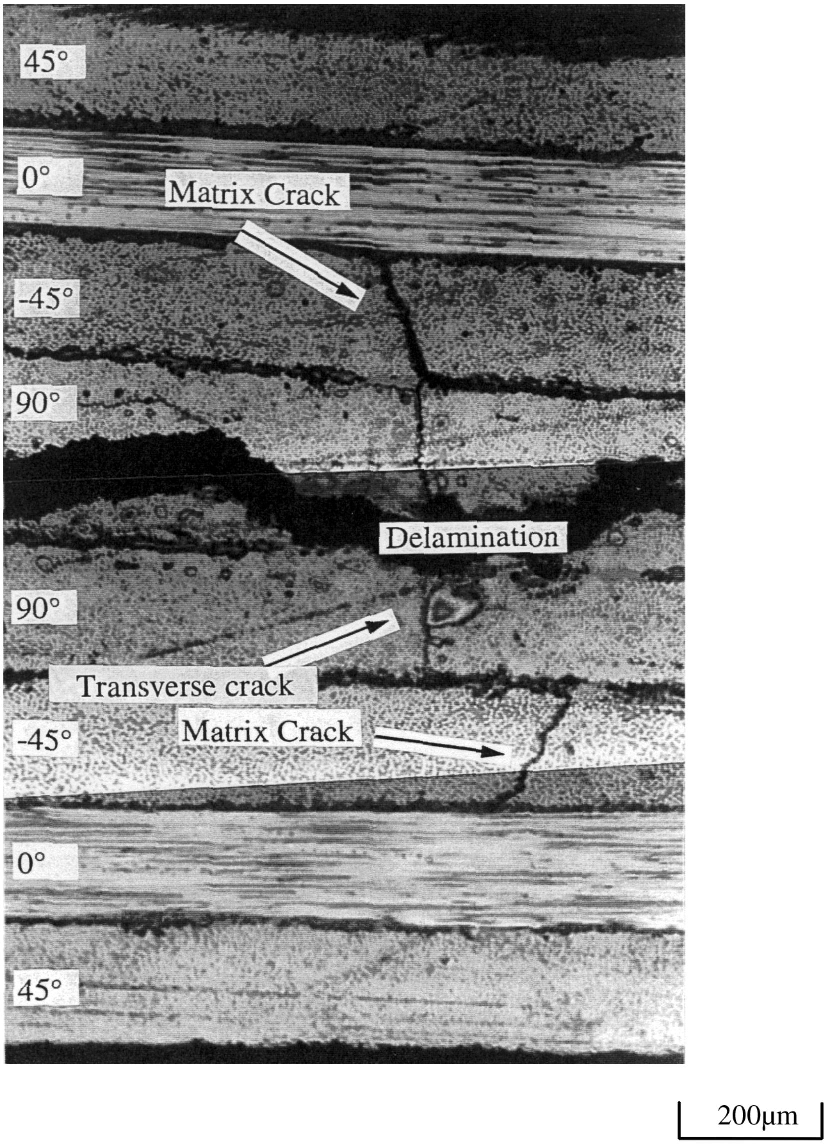

Figure 1. Microscopic damage in $[45/0/-45/90]_s$ laminate ($\varepsilon = 1.32\%$, ε: laminate strain, edge observation).

edge to clarify the behavior of both delamination and matrix cracks near the free edge. It is seen that transverse cracks in 90° plies go through the width direction; however, matrix cracks in −45° plies grew only a little in the width direction. The number of cracks increased as the laminate strain increased. Free edge delamination at the −45/90 interface and in 90° plies initiated in all group A laminates and extensive growth of delamination was observed in $[45/0/-45/90]_s$ laminates.

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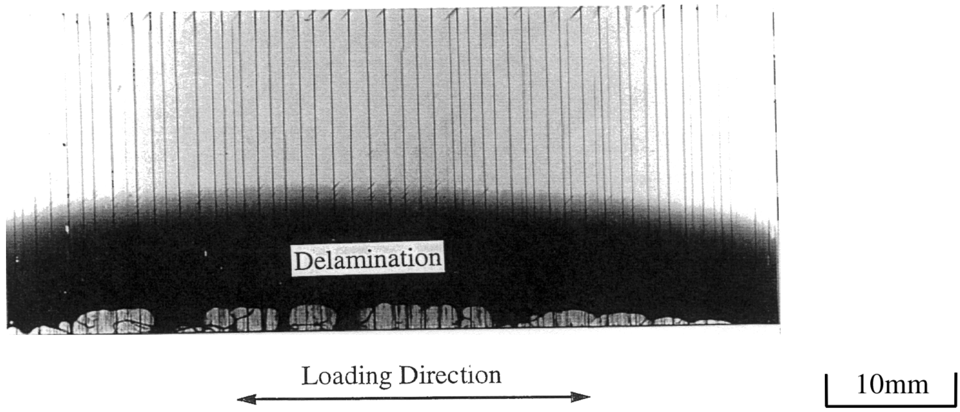

Figure 2. Microscopic damage in $[45/0/-45/90]_s$ laminate ($\varepsilon = 1.32\%$, X-ray observation).

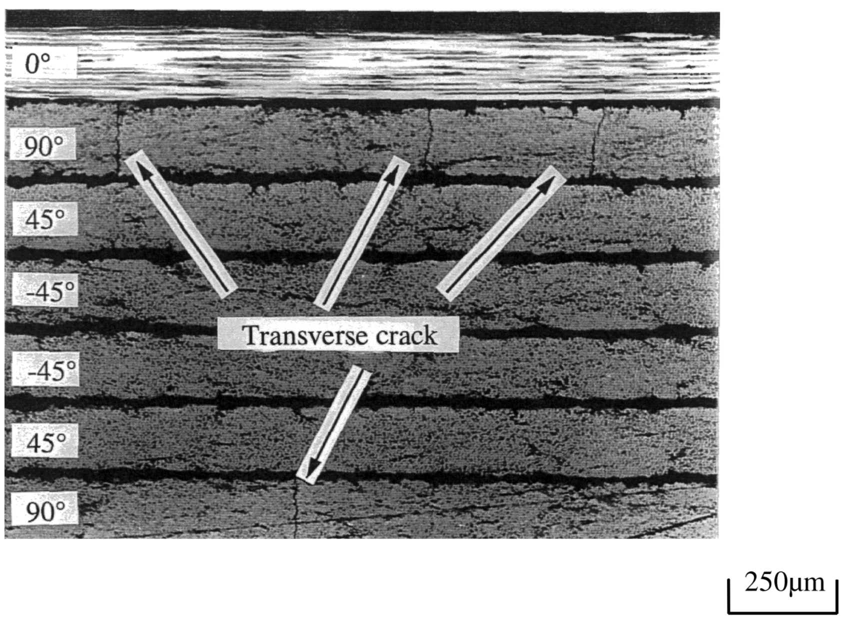

Figure 3. Microscopic damage in $[0/90/\pm 45]_s$ laminate ($\varepsilon = 1.56\%$, edge observation).

Second, microscopic damage progress in group B laminates was observed. Figures 3 and 4 show transverse cracks observed in 90° plies of $[0/90/\pm 45]_s$ ($\varepsilon = 1.56\%$) and $[45/0/90/-45]_s$ ($\varepsilon = 1.59\%$) laminates, respectively. It is seen that the transverse crack runs through the thickness of the one 90° ply. Transverse cracks in 90° plies of $[0/45/90/-45]_s$ and $[45/0/90/-45]_s$ laminates were not perpendicular to the loading direction. This inclination of transverse cracks in 90° plies placed between ±45° plies is attributed to the cross-elasticity effect of ±45° plies which results in generation of out-of-plane shear stress in 90° plies at the free edge [12]. As the load increased, matrix cracks in ±45° plies of $[0/45/90/-45]_s$,

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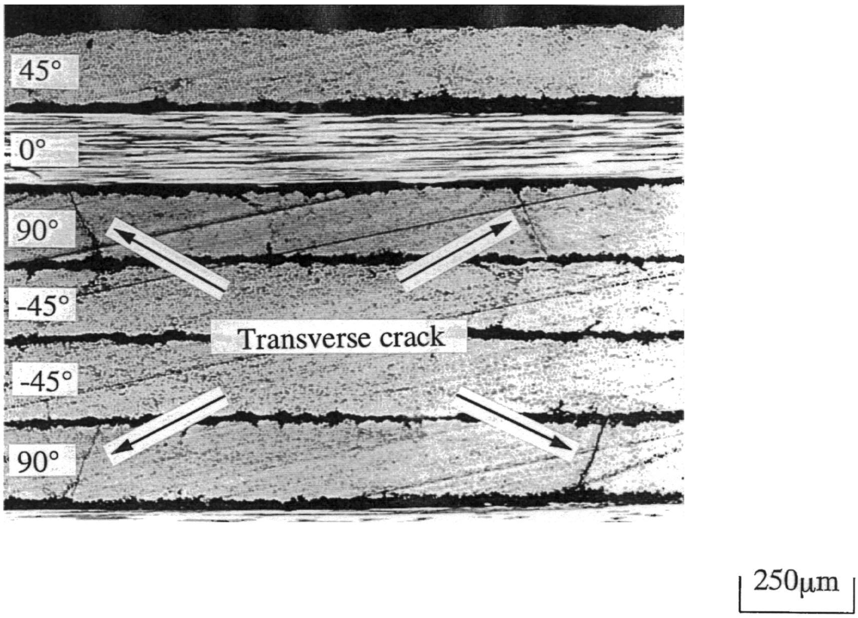

Figure 4. Microscopic damage in $[45/0/90/-45]_s$ laminate ($\varepsilon = 1.59\%$, edge observation).

in $-45°$ plies of $[45/0/90/-45]_s$ and in 45° plies of $[90/45/0/-45]_s$ laminates were also observed around the tip of transverse cracks in 90° plies. Only some small delamination was observed in group B laminates just before the final fracture. Figures 5 and 6 show the internal damage state of $[45/0/90/-45]_s$ ($\varepsilon = 1.57\%$) and $[90/45/0/-45]_s$ laminates ($\varepsilon = 1.51\%$), respectively. Similarly to the group A laminates, transverse cracks in 90° plies go through in the width direction. Matrix crack onset in 45° and/or $-45°$ plies at the free edge and only a little growth in the width direction was observed in $[0/45/90/-45]_s$ and $[45/0/90/-45]_s$ laminates. In $[90/45/0/-45]_s$ laminates, an array of small matrix cracks in 45° plies was observed along the transverse cracks in 90° plies.

Figure 7 shows the transverse crack density in 90° plies as a function of laminate strain. Group A laminates (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.) represents sublaminates whose mechanical properties are expected to be identical from a macroscopic point of view. Therefore, transverse crack onset strain in the laminates is 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 a 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

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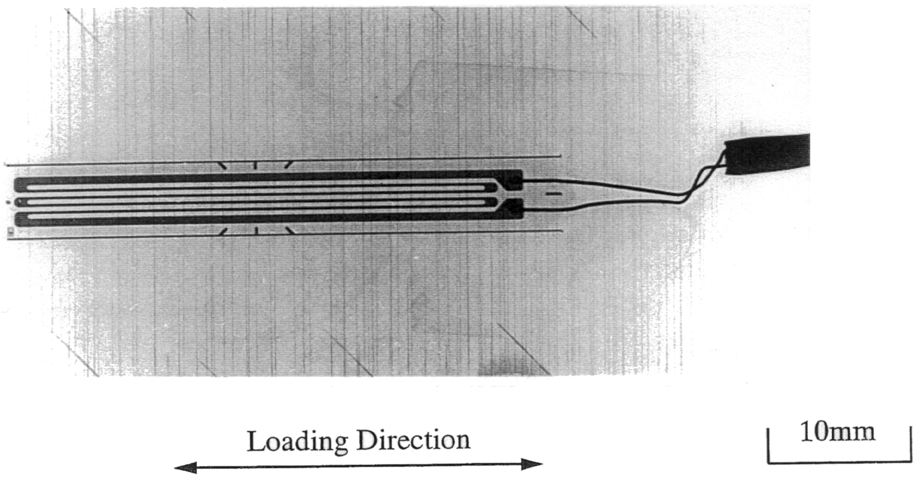

Figure 5. Microscopic damage in $[45/0/90/-45]_s$ laminate ($\varepsilon = 1.57\%$, X-ray observation).

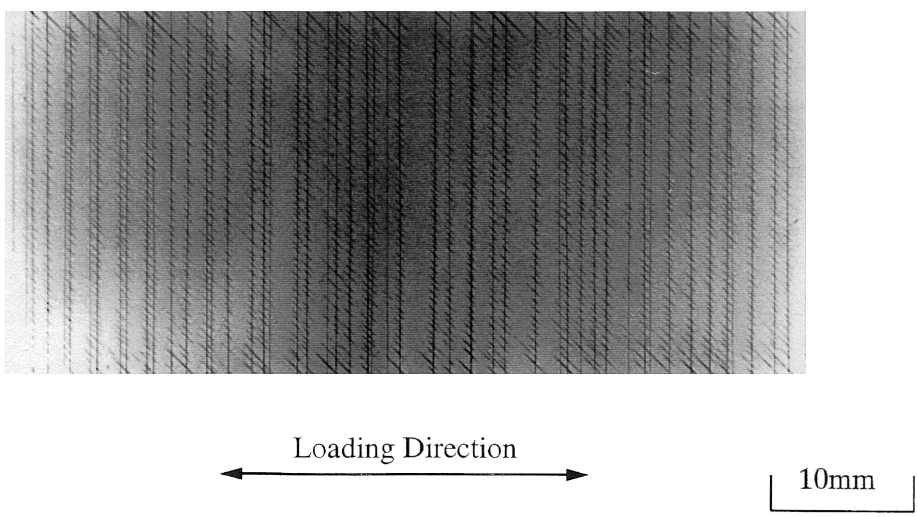

Figure 6. Microscopic damage in $[90/45/0/-45]_s$ laminate ($\varepsilon = 1.51\%$, X-ray observation).

between the cracks becomes larger with increasing stiffness of plies adjacent to the 90° ply.

In the group B laminates, transverse crack onset strain of (d) $[0/90/\pm 45]_s$ 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 that of any other laminates. This is because of the lack of one side of adjacent ply which causes lower stress recovery.

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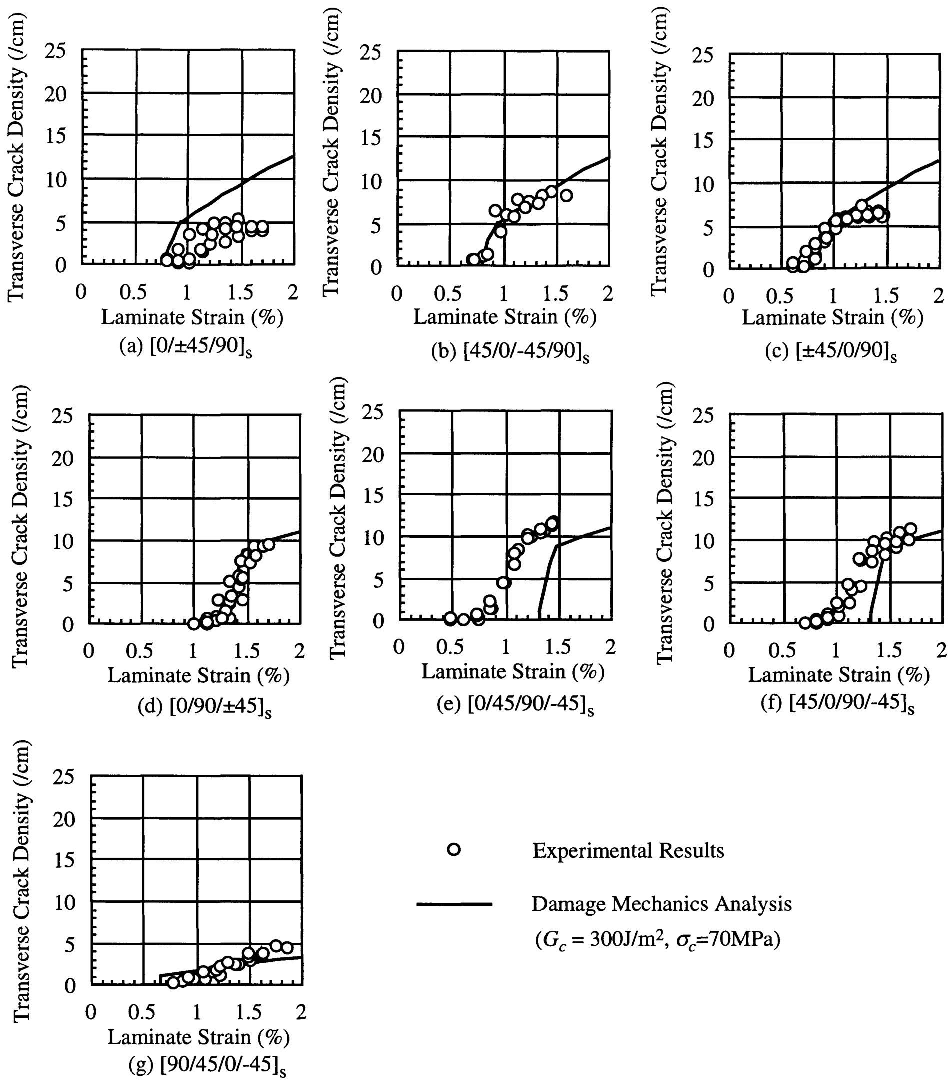

Figure 7. Transverse crack density in 90° plies as a function of laminate strain (experimental results and analytical predictions, $\sigma_c^k = 70$ MPa and $G_c = 300$ J/m^2).

4. DISCUSSION

The authors' group conducted damage mechanics analysis [9] to model the transverse crack behavior. A 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, $\mathbf{S}_{\mathrm{II(c)}}$, can be expressed using an

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in-plane compliance matrix without transverse cracks, $\mathbf{S}_{\text{II}}$, as

$$\mathbf{S}_{\text{II(c)}} = \left(\left(\mathbf{S}_{\text{II}}\right)^{-1} - \sum_{k=1}^{N} v^k \rho^k \left(\mathbf{A}^k\right)^T \sum_{i=1}^{N} \beta^{ki} \mathbf{A}^i \right)^{-1}, \tag{1}$$

where v^k is the volume fraction of ply k, ρ^k is the normalized crack density in ply k, $\mathbf{A}^k$ 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, $1/\mathbf{S}_{\text{II(c)}}(\rho^k)_{(1,1)}$ is the laminate Young's modulus $E(\rho^k)$.

Assuming that transverse cracks occur at a constant load and also 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

$$G(\rho^k) = \frac{\sum_{i=1}^{N} a^i}{\rho^k} (\sigma - \sigma_T)^2 \left(\frac{1}{E(\rho^k)} - \frac{1}{E(\rho^k/2)} \right), \tag{2}$$

where a^i is the thickness of ply i, σ_T is a parameter to consider the effect of thermal residual stress arising from the cure process. Considering the transverse cracking in the 90° ply, σ_T is an axial laminate stress to nullify the thermal residual stress in the 90° ply in the loading direction.

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

$$\sigma(\rho^k) = \sqrt{\frac{G_{\text{c}} \rho^k}{\sum_{i=1}^{N} a^i} \left(\frac{1}{E(\rho^k)} - \frac{1}{E(\rho^k/2)} \right)^{-1}} + \sigma_T. \tag{3}$$

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_{c}^k. Considering the 90° ply, the relation between the laminate stress and the normalized transverse crack density is expressed as

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

where $\mathbf{S}^k_{\text{II}}$ 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.

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 has to be regarded as a proper prediction.

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The predictions based on both energy and average stress criteria are shown in Fig. 7. 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 300 J/m^2 and 70 MPa, respectively. 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 implies that some modifications of the present analysis are necessary.

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5. 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 to the transverse crack onset strain. Transverse crack density of this group at the final fracture is clearly smaller than that of $[90/45/0/-45]_s$ laminates.

Damage mechanics analysis was conducted to predict the transverse crack behavior. The predictions were found to be in good agreement except for some laminate configurations. For more precise prediction, an accurate analysis of COD in interleaved laminates is necessary.

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