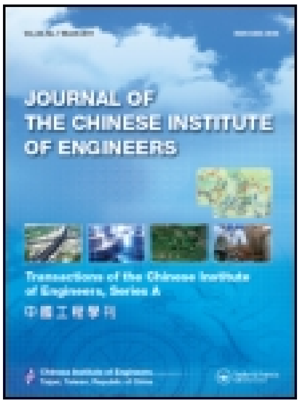

Journal of the Chinese Institute of Engineers
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tcie20

Characterizing tensile strength of notched cross-ply and quasi-isotropic composite laminates

Jia-Lin Tsai [a] & Chung-Wen Chen [b]

[a] Department of Mechanical Engineering , National Chiao Tung University , Hsinchu 300, Taiwan, R.O.C. Phone: 886-3-5731608 Fax: 886-3-5731608 E-mail:

[b] Department of Mechanical Engineering , National Chiao Tung University , Hsinchu 300, Taiwan, R.O.C.

Published online: 04 Mar 2011.

CHARACTERIZING TENSILE STRENGTH OF NOTCHED CROSS-PLY AND QUASI-ISOTROPIC COMPOSITE LAMINATES

Jia-Lin Tsai* and Chung-Wen Chen

ABSTRACT

This study aims to investigate fracture behaviors of notched cross-ply and quasi-isotropic laminates with different stacking configurations. The fracture criterion developed by Vaidya and Sun (1997), based on the postulation that the failure was dominated by the 0 degree ply, was adopted to characterize the failure stresses of the notched laminates. The failure mechanisms of the samples were determined through X-ray examinations. It was found that for $[0/90]_{2s}$, $[90/0]_{2s}$, $[0/\pm45/90]_{2s}$, and $[90/\pm45/0]_{2s}$ laminates, the strengths were quite close to the model predictions. This occurred because there were no severe damage zones observed near the crack tip; therefore, the failure stresses of the notched laminates were dominated by the stress states of 0 degree ply, which can be properly characterized using the fracture mechanics in conjunction with the laminated plate theory. However, for $[0_2/90_2]_s$ and $[90_2/0_2]_s$ laminates, there were severe damage zones observed near the crack tip such that the predicted failures stresses were lower than the experimental data. In contrast, for the $[90_2/\pm45_2/0_2]_s$ and $[0_2/\pm45_2/90_2]_s$, because of the edge delamination taking place within the plies, the failure stresses were considerably lower than the predictions.

Key Words: composite laminates, fracture mechanics, notched samples, tensile strength.

I. INTRODUCTION

Fiber reinforced composites with the characteristics of high strength and stiffness, together with light weight, have been employed extensively in industry. One extraordinary advantage to using the composites is that the mechanical properties can be tailored appropriately through modifying the lay-up sequences. Among the varieties of lay-up configurations, the quasi-isotropic and cross-ply laminates, because they possess balanced in-plane properties, are commonly utilized. From the fracture mechanics concept, the strength of the materials is dominated by the extent of cracks or flaws, so are fiber composites (Daniel and Ishai, 2006). Thus, understanding the strength of the notched composites is becoming an essential task for advanced implementations of materials with safety.

Based on the assertion that the fracture of a notched laminate is controlled by the stress intensity factor of the load carrying ply, Vaidya and Sun (1997) proposed a fracture criterion for notched composite laminates. Because of the complexity of fracture processes and failure mechanisms, some experimental results deviated from the model predictions. Vaidya *et al*. (1998) investigated the effect of the ply thickness on the fracture of the notched laminates, pointing out that the strength and the corresponding failure mode of the laminates were significantly affected by the ply thickness. In order to understand the stress states near the crack tip, Lee *et al*. (2006) performed finite element analysis on the notched laminates. A new parameter, accounting for the local damage effect, was introduced in the fracture criterion model of Vaidya and Sun (1997). Hallett and Wisnom (2006) adopted double-edge-notched specimens with different lay-ups and dimensions in the determination of tensile tests. It was suggested that the failure stress and failure modes of laminates varied

*Corresponding author. (Tel: 886-3-5731608, Fax: 886-3-5720634, E-mail: jialin@mail.nctu.edu.tw)

The authors are with the Department of Mechanical Engineering, National Chiao Tung University, Hsinchu 300, Taiwan, R.O.C.

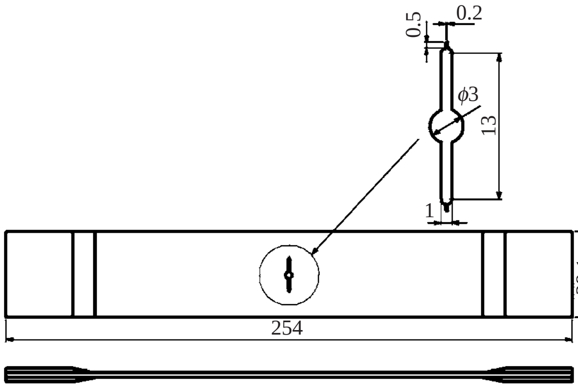

Fig. 1 Dimensions of the notched specimens

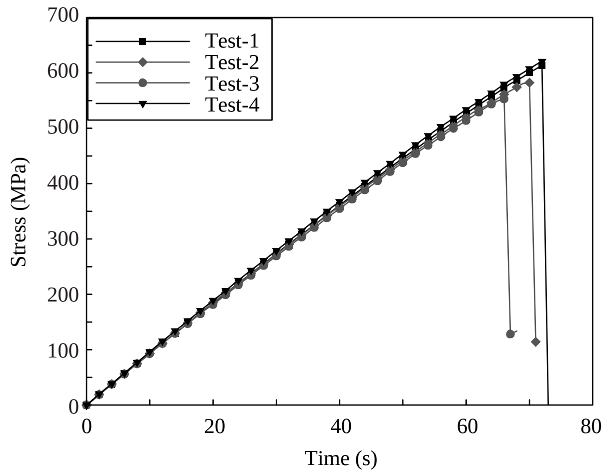

Fig. 2 The stress history of $[90/\pm45/0]_{2S}$ graphite/epoxy notched composites

both with lay-up sequences as well as the specimen size.

In view of the forgoing, it was revealed that the failures, because of notches in the composite laminates, are really complicated. More experimental investigations are required to understand the correlation between composite, strengths and the sensitivity of notches associated with different failure modes. In this study, the cross-ply and quasi-isotropic notched laminates with different lay-up sequences and ply thickness, which are commonly utilized in industry, were taken into account. The objective is to build up a solid relationship between the tensile strength of the notched samples associated with the failure mechanism examined using X-ray detection. In addition, the failure criterion developed by Vaidya and Sun (1997) was employed for failure validation. The applicability of the criterion on the notched laminates corresponding to different stacking configurations was also discussed.

II. SAMPLE PREPARATION AND EXPERIMENTAL PROCEDURE

In this study, two different graphite/epoxy composite laminates, i.e., cross-ply and quasi-isotropic, were employed for the tensile tests. For the cross-ply configuration, four different stacking sequences, $[0/90]_{2S}$, $[90/0]_{2S}$, $[0_2/90_2]_S$, and $[90_2/0_2]_S$, were considered. Similarly, in the quasi-isotropic laminates, there are four different lay-up sequences, i.e., $[0/\pm45/90]_{2S}$, $[90/\pm45/0]_{2S}$, $[0_2/\pm45_2/90_2]_S$ and $[90_2/\pm45_2/0_2]_s$. In addition to the above lay-up configuration, the laminates with fiber orientation close to the loading direction were considered, i.e., $[-5/85]_{2S}$, $[85/-5]_{2S}$,$[-5/40/-50/85]_{2S}$ and $[85/40/-50/-5]_{2S}$. It is noted that in the description of the above laminates, the coordinate system is set coincided to the loading direction.

The unidirectional graphite/epoxy prepreg (CFA-05624E19) samples, provided by AD Group Taiwan, were cut to the proper dimensions and then laid up manually in accordance with the designed stacking sequence. Hot press curing was conducted on the laminates with the recommended curing process. Subsequently, composite coupon specimens 254 mm long and 38.1 mm wide were cut from the composite panels using a diamond saw. In order to generate a central crack, a 3 mm starting hole was drilled at the centers of the specimens using a diamond driller to prevent the delamination caused by the water jet. The line crack was then introduced by a water jet that was further extended by a jeweler's saw blade for creating sharp crack tips. Glass/epoxy end tabs, 40 mm in length, were bound on both ends of the specimens, resulting in a 174 mm gage length. The detailed specimen dimensions are illustrated in Fig. 1.

Tensile tests were conducted on a hydraulic MTS 810 testing machine with stroke control at a strain rate of 0.0001/s. During the tests, the load and displacement histories were recorded using the LabView data acquisition system with a computer. For each lay-up configuration, at least four specimens were tested. Fig. 2 depicts the typical stress curves for $[90/\pm45/0]_{2S}$ graphite/epoxy samples. It can be seen that sudden failure occurs on the samples; thus, the peak values on the stress curves were regarded as the failure stresses of the specimens. Table 1 illustrates the failure stresses of the notched laminates with various stacking configurations.

In order to determine the failure mechanism, the specimens tested at different loading levels prior to failure were examined using X-ray inspection. Before the examinations, the developer ($C_2H_2Br_4$, 1,1,2,2-Tetrabromoethane) was gradually applied on the cracked area of the specimens until it was completely infused into the plies.

Table 1 Failure stress of notched laminates with different stacking configurations

Stacking configuration	Failure stress (MPa)
$[0/90]_{2S}$	833 ± 3.7%
$[0_2/90_2]_S$	1070 ± 5.7%
$[90/0]_{2S}$	828 ± 7.7%
$[90_2/0_2]_S$	1166 ± 1.7%
$[-5/85]_{2S}$	716 ± 2.1%
$[85/-5]_{2S}$	768 ± 2.2%
$[0/\pm45/90]_{2S}$	606 ± 6.8%
$[0_2/\pm45_2/90_2]_S$	431 ± 7.2%
$[90/\pm45/0]_{2S}$	593 ± 5.6%
$[90_2/\pm45_2/0_2]_S$	487 ± 1.9%
$[-5/40/-50/85]_{2S}$	626 ± 3.1%
$[85/40/-50/-5]_{2S}$	648 ± 2.9%

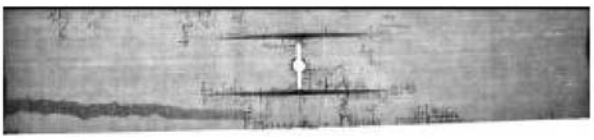

Fig. 3 X-ray examination of $[0/90]_{2S}$ laminate at 90% of failure load

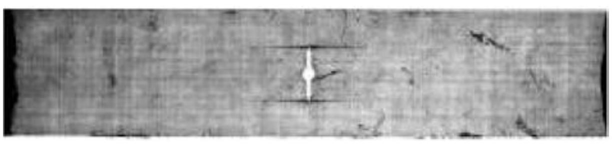

Fig. 4 X-ray examination of $[90/0]_{2S}$ laminate at 90% of failure load

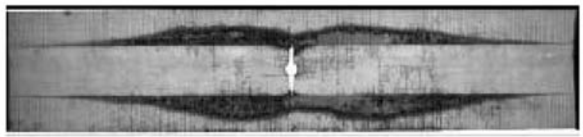

Fig. 5 X-ray examination of $[0_2/90_2]_S$ laminate at 90% of failure load

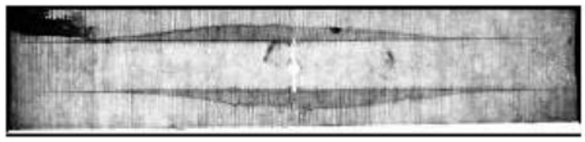

Fig. 6 X-ray examination of $[90_2/0_2]_S$ laminate at 90% of failure load

Fig. 7 X-ray examination of$[0/’45/90]_{2S}$ laminate at 90% of failure load

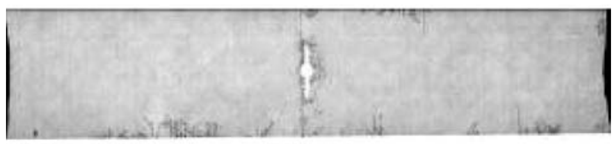

Fig. 8 X-ray examination of $[90/\pm45/0]_{2S}$ laminate at 90% of failure load

III. FAILURE MECHANISM

1. Failure Mechanism of Cross-Ply Laminates

The X-ray detections on the cross-ply laminates at around 90% of failure load were conducted, and the results are illustrated in Figs. 3-6. For the $[0/90]_{2S}$ and $[90/0]_{2S}$ laminates, only a small failure zone in conjunction with matrix cracking along the fiber direction was observed, which indicated most of the fracture energy is still accumulated near the crack tip without any dissipation. In addition, there was no significant distinction in the failure mechanism for these two laminates although their outer ply was different. In contrast, for the $[0_2/90_2]_S$ and $[90_2/0_2]_S$ laminates, a severe damage zone (delamination together with matrix crack) was found on the specimens, and because of the extensive matrix cracking, the fracture energy around the crack tip was dissipated dramatically and the stress state in the 0 degree ply could not be correctly calculated through the laminated plate theory. For the $[0_2/90_2]_S$ and $[90_2/0_2]_S$ laminates, the effective ply thickness was doubled; therefore, the constraining effect from the neighboring ply was relatively weakened as compared to $[0/90]_{2S}$ and $[90/0]_{2S}$ laminates. The weak constraining characteristics may cause the matrix cracking as well as the delamination to take place in the 90 degree ply. In addition for the $[-5/85]_{2S}$, $[85/-5]_{2S}$ laminates, since severe delamination damage near the crack tip was found, the fiber breakage may not regarded as the main failure mechanism of the laminates.

2. Failure Mechanism of Quasi-Isotropic Laminate

The X-ray examinations on the $[0/\pm45/90]_{2S}$, $[90/\pm45/0]_{2S}$, $[0_2/\pm45_2/90_2]_S$, and $[90_2/\pm45_2/0_2]_S$ laminates are shown, respectively in Figs. 7-10. For $[0/\pm45/90]_{2S}$ and $[90/\pm45/0]_{2S}$ laminates, no obvious damage zones were found on the samples. Moreover, the facture mechanisms were not sensitive to the fiber orientation of the outer layer. Similarly, for the $[0_2/\pm45_2/90_2]_S$ and $[90_2/\pm45_2/0_2]_S$ laminates at the 90 or 95% of the failure load, there were no noticeable failure patterns observed on the samples. However, when the load was increased up to 98%, a large area

Fig. 9 X-ray examination of $[0_2/\pm45_2/90_2]_S$ laminate at 95% of failure load

Fig. 10 X-ray examination of $[90_2/\pm45_2/0_2]_S$ laminate at 95% of failure load

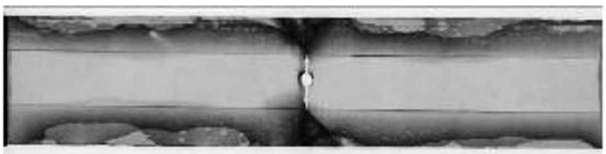

Fig. 11 X-ray examination of $[90_2/\pm45_2/0_2]_S$ laminate at 98% of failure load

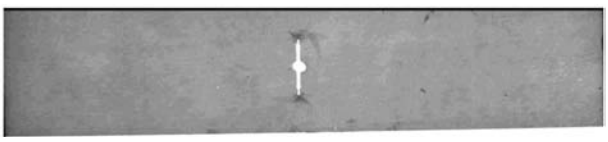

Fig. 12 X-ray examination of $[-5/40/-50/85]_{2S}$ laminate at 95% of failure load

of edge delamination was found on the samples. Fig. 11 demonstrates the edge delamination of the $[90_2/\pm45_2/0_2]_S$ laminates. In general, the edge delamination can dramatically diminish the strength of laminates. For the $[-5/40/-50/85]_{2S}$ and $[85/40/-50/-5]_{2S}$ laminates as shown in Fig. 12, no clear delamination was observed around the crack tip and the fracture was controlled by the breakage of the fibers.

IV. RESULTS AND DISCUSSION

1. Fracture Theory

Vaidya and Sun (1997) proposed a failure criterion for the notched composite laminate, indicating the fracture of the laminate was dominated by the load carrying ply (0 degree ply). As a result, the stress intensity factor of the 0 degree ply can be expressed as

$$K_Q^o = Y\sigma_f^o\sqrt{\pi a}\ , \tag{1}$$

where $\sigma^0{}_f$ denotes the remote laminar stress of 0 degree ply, and Y is equal to $1 + 0.1282(2a/W) - 0.2881(2a/W)^2 + 1.5254(2a/W)^3$ where "a" and "W" stand

Table 2 Mechanical properties of graphite/epoxy composite

E_1 (GPa)	E_2 (GPa)	v_{12}	G_{12} (GPa)
138	8.5	0.44	7.3

for the half crack length and the specimen width, respectively. In principle, the K_Q^o can be regarded as a material constant being adopted as a parameter for characterizing the fracture of the laminate. However, the challenging issue is how to calculate the K_Q^o value and relate it to the remote applied stress σ_f. Based on the laminated plate theory, Vaidya and Sun (1997) established a simple relation for the two quantities as

$$\sigma_f = \frac{\sigma_f^o}{\eta}\ . \tag{2}$$

According to the material properties of the graphite/epoxy laminate given in Table 2, the values of η can be easily calculated from the laminated plate theory. These values are equal to 1.85 and 2.48 for cross-ply and quasi-isotropic laminates, respectively. Thus, the K_Q^o can be expressed in terms of the applied stress σ_f as

$$K_Q^o = Y\eta\sigma_f\sqrt{\pi a}\ . \tag{3}$$

It should be cautioned that the above failure assessment is applicable only for the notched laminates where the failure is dominated by the fiber breakage, and the stress state of the load bearing ply near the crack tip is not influenced dramatically by the damage of neighboring plies.

With regard to the failure mechanisms discussed in the previous section, it was suggested that the fracture of $[0/90]_{2S}$, $[90/0]_{2S}$, $[0/\pm45/90]_{2S}$, and $[90/\pm45/0]_{2S}$ are quite satisfied with the requirement of the fracture theory. Thus, their failure could be characterized by the stress intensity factor of the load carrying layer. Combining Eq. (3) with the experimental data leads to the values of K_Q^o in the 0 degree ply associated with the laminates as listed in Table 3. As expected, the values are quite close to each other, indicating that if no severe damage near the crack was induced during the loading process, then the stress intensity factor in the 0 degree ply could be a proper parameter in modeling the failure of cracked laminates.

2. Cross-Ply Laminates

The averaged value of K_Q^o listed in Table 3 was utilized as a failure criterion to model the tensile strength of notched cross-ply laminates. Based on Eq. (3), the predicted strength for the cross-ply laminates is 809MPa. Fig. 13 illustrates the comparison

Table 3 Stress intensity factor of the load carrying ply in the notched laminates with small damage zone near the crack tip

Stacking configuration	K_Q^o (MPa$\sqrt{m}$)
$[0/90]_{2S}$	248 ± 3.6%
$[90/0]_{2S}$	246 ± 7.7%
$[0/\pm45/90]_{2S}$	242 ± 6.6%
$[90/\pm45/0]_{2S}$	237 ± 5.1%

of the experimental data with the model predictions. It can be seen that for $[0/90]_{2S}$ and $[90/0]_{2S}$ laminates, the predictions were very close to the data. On the other hand, for the $[0_2/90_2]_S$ and $[90_2/0_2]_S$ laminates, the model predictions were relatively lower than the experimental data. This discrepancy is due to the damage of surrounding plies releasing the accumulated stress required for causing fracture in the 0 degree ply. As a result, the stress states near the crack tip of the 0 degree ply may not be accurately calculated through the laminated plate theory. Moreover, in order to facilitate the crack extension in the 0 degree ply, more applied loading is required, and thus, the tensile strength of the notched laminates could be increased accordingly.

In addition to the cross-ply laminates with loading direction coincidental to the 0 degree ply, the cross-ply samples were also subjected to the loading close to the 0 degree ply. Here, 5 degree off-axis loading (referenced to 0 degree ply) was considered in the cross-ply laminates and the experimental results are presented in Table 1. It is noted that for the $[-5/85]_{2S}$ and $[85/-5]_{2S}$ laminates, since the stress states near the crack tip are affected dramatically by delamination failure, the stress intensity factor calculated based on the fracture mechanics may not be accurate and thus is not suitable for failure predictions.

3. Quasi-Isotropic Laminates

When the average value of K_Q^o was employed for the quasi-isotropic notched laminates, the corresponding failure stress was calculated as 605MPa. As compared to the experimental data as shown in Fig. 14, it is reveled that the failure criterion based on the stress intensity factor of the 0 degree ply is capable of describing the failure stresses of $[0/\pm45/90]_{2S}$ and $[90/\pm45/0]_{2S}$ laminates accurately. In addition, the arrangement of the 0 ply in the laminates seems to have no effect on the strength of the notched laminates. Nevertheless, for the $[0_2/\pm45_2/90_2]_S$ and $[90_2/\pm45_2/0_2]_S$ laminates, because the failure mechanism was edge delamination rather than the fiber breakage near the crack tip, the experimental data was lower than the predictions. It is interesting to mention that the

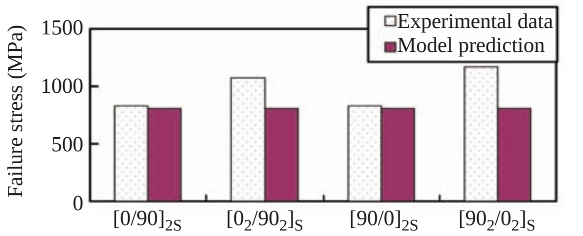

Fig. 13 Comparison of the model prediction with the experimental data for cross-ply laminates

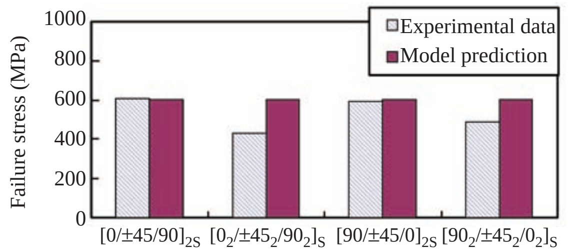

Fig. 14 Comparison of the model prediction with the experimental data for quasi-isotropic laminates

current observations are different from those obtained from the $[0_2/90_2/45_2/-45_2]_S$ laminate presented in the literature (Vaidya *et al.*, 1997) where no severe delamination on the samples was reported. For this family of laminates, perhaps, their failure mechanism relies on the lay-up sequence.

In view of the previous discussions, it is suggested that different fracture mechanisms such as matrix cracking, fiber breakage and edge delamination were observed in the laminates and only the notched strengths in terms of the fiber breakage with small damage zone can be described properly using the current fracture model. In fact, from the experimental results, it is found that the lay-up configurations allowing a larger damage zone exhibit superior strength than other cases, since the local matrix cracking near the crack tip can effectively dissipate the fracture energy and relieve the stress intensity factor of the loading carrying ply. Thus, one should be cautious because the constrained lay-up configurations in which the proposed model can work well may not be a good design for composite laminates. In addition, if the edge delamination occurs, the fracture is no longer dominated by the crack tip property, but the delamination and the corresponding strength could be reduced accordingly.

In addition, for the $[-5/40/-50/85]_{2S}$ and $[85/40/-50/-5]_{2S}$ laminates, since experimental observations indicated that the fiber breakage of 5 degree ply is the main failure mechanism, the fracture criterion based on the K_Q^o concept was extended to the calculation of the new fracture criterion K_Q^5 for the load carrying

Table 4 Stress intensity factor of the 5 degree ply in the notched laminates

Stacking configuration	K_Q^5 (MPa$\sqrt{m}$)
$[-5/40/-50/85]_{2S}$	250 ± 1.6%
$[85/40/-50/-5]_{2S}$	259 ± 3.1%

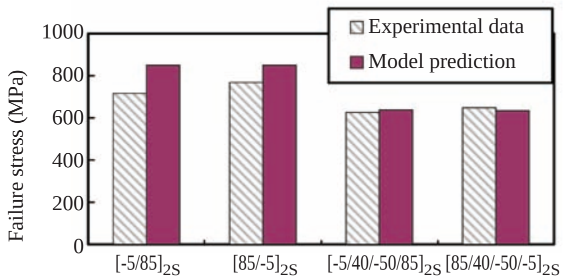

Fig. 15 Comparison of the model predictions with the experimental data

ply as listed in Table 4. It can be found that the value of K_Q^5 is a little higher than K_Q^o. This could be because the pre-crack is not perpendicular to the fiber direction and it would be a little more difficult to rupture the fiber and extend the crack. The model predictions based on the K_Q^5 were compared with the experimental data in Fig. 15. It can be seen that for the $[-5/85]_{2S}$ and $[85/-5]_{2S}$ laminates, because the failure is dominated by the delamination, apparently the experimental data is lower than the model predictions. On the other hand, for the $[-5/40/-50/85]_{2S}$ and $[85/40/-50/-5]_{2S}$ laminates, the fiber breakage is the dominant failure mode, so the stress intensity concept, in conjunction with the laminated plate theory, can be used to predict the fracture of the notched laminates well.

V. CONCLUSIONS

The tensile strength of notched cross-ply and quasi-isotropic laminates were investigated in this study. For laminates with well-dispersed ply such as $[0/90]_{2S}$,$[90/0]_{2S}$, $[0/\pm45/90]_{2S}$, and $[90/\pm45/0]_{2S}$, the damage zone is confined within a small range, and the fracture is dominated by the breakage of the load carrying ply. As a result, the strength of the laminates can be predicted with accuracy using the stress intensity factor of the load carrying ply. However, when the number of plies blocked together increases, the failure mechanism is different from the fiber rupture. For the $[0_2/90_2]_S$ and $[90_2/0_2]_S$ laminates, matrix cracking and the fiber splitting near the crack tip were observed prior to the failure, resulting in the bluntness of the crack tip and the relief of the fracture energy gathered in the load carrying ply as well. Therefore, the strength of the notched $[0_2/90_2]_S$ and $[90_2/0_2]_S$ laminates is higher than those of $[0/90]_{2S}$ and $[90/0]_{2S}$ laminates. With regard to the $[0_2/\pm45_2/90_2]_S$ and $[90_2/\pm45_2/0_2]_S$ laminates, because of the edge delamination, the corresponding strengths are lower as compared to the other lay-up configurations.

ACKNOWLEDGEMENT

This research was supported by the National Science Council, Taiwan, under the contract No. NSC 96-2628-E-009-009 to National Chiao Tung University.

NOMENCLATURE

a	half crack length
K_Q^o	stress intensity factor of 0 degree ply
K_Q^5	stress intensity factor of 5 degree ply
W	specimen width
Y	parameter determined by the ratio, a/W
η	parameter calculated from the laminated plate theory
σ_f	remote applied stress
σ_f^o	remote laminar stress of 0 degree ply

REFERENCES

Bokwen, L., and Bhavani, V. S., 2006, "Lay-up Independent Fracture Criterion for Notched Laminated Composites," *Composites Science and Technology*, Vol. 66, No. 14, pp. 2491-2499.

Daniel, I. M., and Ishai, O., 2005, *Engineering Mechanics of Composite Materials*, 2nd ed., Oxford University Press, NY, USA.

Green, B. G., Wisnom, M. R., and Hallett, S. R., 2006, "An Experimental Investigation into the Tensile Strength Scaling of Notched Composites," *Composites Part A: Applied Science and Manufacturing*, Vol. 38, No. 3, pp. 867-878.

Hallett, S. R., and Wisnom, M. R., 2006, "Experimental Investigation of Progressive Damage and the Effect of Layup in Notched Tensile Tests," *Journal of Composite Materials*, Vol. 40, No. 2, pp. 119-141.

Vaidya, R. S., and Sun, C. T., 1997, "Fracture Criterion for Notched Thin Composite Laminates," *American Institute of Aeronautics and Astronautics (AIAA) Journal*, Vol. 35, No. 2, pp. 311-316.

Vaidya, R. S., Klug, J. C., and Sun, C. T., 1998, "Effect of Ply Thickness on Fracture of Notched Composite Laminates," *American Institute of Aeronautics and Astronautics (AIAA) Journal*, Vol. 36, No. 1, pp. 81-88.

Manuscript Received: Mar. 05, 2008
Revision Received: Aug. 24, 2008
and Accepted: Sep. 24, 2008