Fracture Behavior and Mechanism of Advanced CFRP Composite with Various Lay-up Sequences

Bulletin of Osaka Prefecture University
Series A, Vol. 46, No. 2, 1997, pp. 117-124

Fracture Behavior and Mechanism of Advanced CFRP Composite with Various Lay-up Sequences

Yoshiyuki TOMITA*, Atsushi MAEDA** and Kojiro MORIOKA***

(Received November 18, 1997)

Long carbon fibers with 5.5 GPa in average tensile strength-reinforced epoxy plastic laminates have been studied to clarify the fracture behavior and mechanism of the advanced carbon fiber-reinforced plastic (CFRP) composite with various lay-up sequences. Three-point slow bend and instrumented Charpy impact tests were conducted. Two mm-V notch subsize specimens with angles of 0°, 45° and 90° between the fibers of the 0° layers and the longitudinal direction of the specimen ((0°), (45°) and (90°) specimens) were used. The unidirectional laminate (0°/0° ply-(0°) specimen exhibited high slow bend and Charpy impact energies, but the 0°/0° plies had a remarkable anisotropy for its mechanical properties. The mechanical properties of the orthotropic laminates (0°/90° plies-(0°) and (90°)) specimens significantly decreased but those of the 0°/90° ply-(45°) specimen dramatically increased. There was a significant benefit in the mechanical isotropy for the quasi-isotropic laminates (0°/90°/±45° plies). However, slow bend and Charpy impact energies of the 0°/90°/±45° plies -(0°), (45°) and (90°) specimens were 60 and 70 percent, respectively, of those for the 0°/0° ply-(0°) specimen. The results are described and the fracture mechanism of the CFRP composite is discussed based on fractography.

1. Introduction

Carbon fiber-reinforced plastic (CFRP) composites possess attractive mechanical properties such as a high specific stiffness and high strength in addition to a relatively high tolerance to environmental changes[1]. Furthermore, components made of these composites achieve a weight savings on the order of about 20 percent when compared to conventional construction materials made of light metals. Recently, the potential industrial applications for these composites are in the commercial aircraft, transportation, machinery, marine, and public work industries. The advanced carbon fiber/plastic composites should primarily see service as structural materials well into the next century. However, the fracture mechanisms, in particular, in laminate composites that are used for a structural component is thus extremely complicated when compared with that of conventional isotropic metallic materials; fracture processes include matrix cracking, fiber breakage, fiber/matrix interfacial debonding and delamination[2-8]. For such a situation, at our laboratory, a fundamental program has been initiated to understand the fracture behavior and mechanism of the CFRP composite.

In previous papers, the effect of fiber strength on the tensile and bending fracture behaviors and fracture mechanism of a unidirectional long carbon fiber-reinforced epoxy matrix composite has been studied by Tomita and coworkers[9,10]. They have demonstrated that the composite laminates with a smaller angle between the fiber and direction of the specimen length fiber direction independent of the composite type had a high bending fracture energy as well as high strength, but the composites exhibited a remarkable anisotropy in their fracture energy as the angle increased. However, for the composite used for structural components, the isotropy regarding the mechanical properties is an especially necessary requirement. One of the effective approaches for solving this problem has been the development of the mechanical isotropy by changing the lay-up sequences. Therefore, an estimation of the fracture behavior and mechanism of the composite laminates

* Department of Metallurgy and Materials Science, College of Engineering
** Graduate Student, Department of Metallurgy and Materials Science, College of Engineering
*** Technology Research Institute of Osaka Prefecture

with various lay-up sequences is very important for good control of the mechanical properties of the CFRP composite for commercial applications.

In the present work, the long carbon fiber with 5.5GPa in average tensile strength-reinforced epoxy laminates have been studied to clarify the fracture behavior and mechanism of the advanced CFRP composite.

2. Experimental Procedure

The (PAN) carbon fiber and epoxy resin used in this study were supplied by the Toray Corporation of Japan. The typical mechanical and physical properties of the carbon fiber and epoxy resin are given in Table 1. The 3.5 mm thick carbon/epoxy laminates whose schematic illustrations are shown in Fig. 1 were manufactured using a hot-pressing method; unidirectional (designated as 0°/0° plies)(Fig. 1(a)), orthotropic (designated as 0°/90° plies) (Fig.1(b)) and quasi-isotropic (designated as 0°/90°/±45° plies) (Fig. 1(c)) laminates (19 plies) of 0.180 mm prepregs consisted of long carbon fibers (6-7m m in diameter), and the epoxy resins were consolidated under a pressure of 1000 kPa at a temperature of 403 K for 7.2 ks.

Three-point slow bend and Charpy impact tests were performed using the 3.5 mm thick subsize Charpy V-notch specimens. The slow bend test (span length=40 mm) was done using an Instron machine at a crosshead speed of 0.01 mm/s at ambient temperature. Charpy specimens were broken using an instrumented Charpy impact machine calibrated to the 100J capacity at ambient temperature. Two mm V-notch subsize Charpy specimens with different angles (0°, 45° and 90°) between the fibers of the 0° layers and longitudinal direction of the specimen were used (designated as (0°), (45°) and (90°) specimens). A schematic illustration of the specimens is shown in Fig. 2.

Table 1 Mechanical and physical properties of carbon fiber and epoxy resin

Materials	σ_f (MPa)	E (GPa)	E_f (%)	f_N	ρ (g/1000m)	ρ (g/cm^3)
Carbon fiber	5500	294	1.9	12000	800	1.76
Epony resin	54.9	3.72	1.7	-	-	1.25

σ_f=Tensile fracture stress; E=Young's modulus; E_f=Tensile fracture strain; f_N=Number of filaments; ρ=Density

Fractographs were taken of the slow bend specimens using a scanning electron microscope (SEM). The crack initiation and propagation process during the slow bend test and broken fracture surfaces were observed.

3. Results and Discussion

3.1 Mechanical properties

The slow bend and Charpy impact energies of CFRP laminates with various lay-up sequences are shown in Fig. 3. The results are summarized as follows. The 0°/0° ply-(0°) specimen showed a drasti-

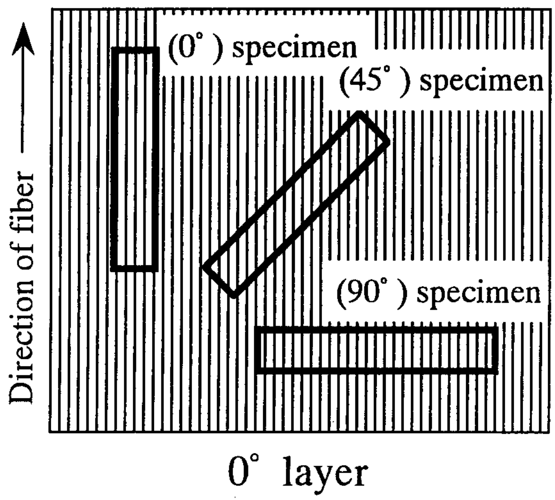

Fig. 2 Schematic illustration of specimen used

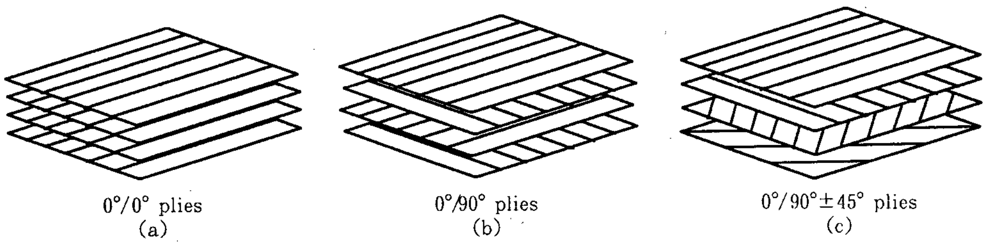

Fig. 1 Schematic illustration of DFRP laminates used

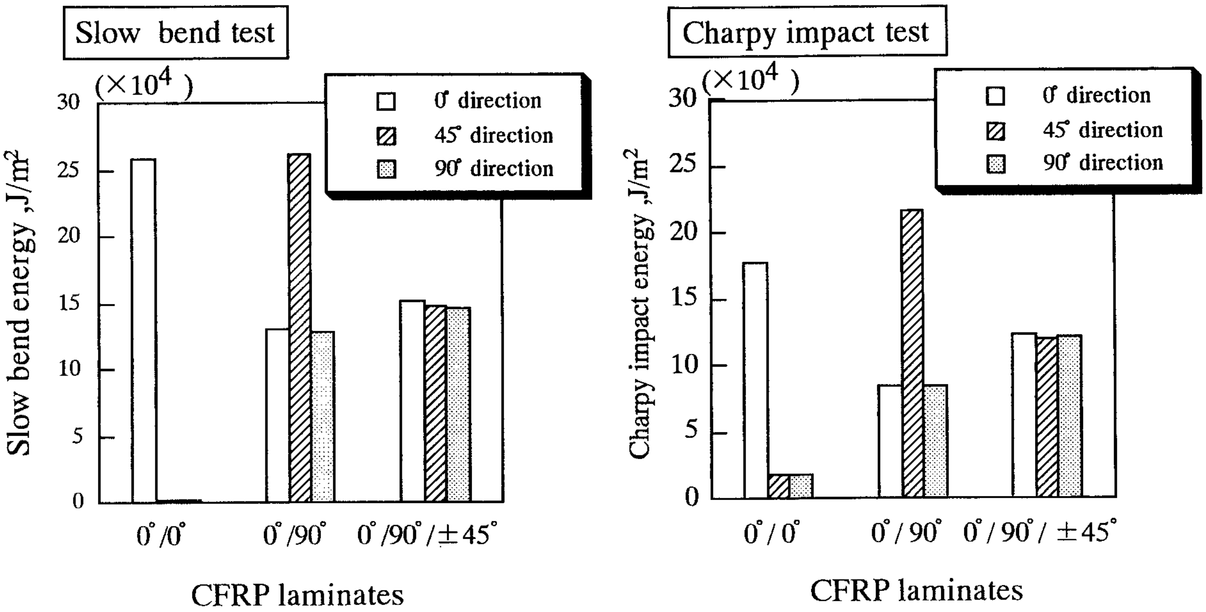

Fig. 3 Slow bend and Charpy impact energies for various CFRP laminates

cally high fracture energy for both the slow bend and Charpy impact tests but the 0°/0° plies-(45°) and (90°) specimens had a significantly low fracture energy. For the 0°/90° plies, the anisotropy in the (0°) or (90°) specimen was improved, but their fracture energies were about 40 percent of those of the 0°/0° ply-(0°) specimen. A remarkable increase in the slow and Charpy impact energies was, however, found for the 0°/90° ply-(45°) specimen. There was a marked benefit in the mechanical isotropy for the 0°/90°/±45° plies though the slow bend and Charpy impact energies of the 0°/90°/±45° plies-(0°), (45°) and (90°) specimens were, respectively, about 60 and 70 percent of those for the 0°/0° ply- (0°) specimen.

3. 2 Fracture behavior and mechanism

In order to clarify the fracture behavior and its mechanism of the carbon/epoxy composite laminates, load vs. displacement curves were analyzed and fracture surfaces of the broken slow and Charpy impact specimens were observed. The crack initiation and propagation processes during the slow bend test were also examined. The results obtained are summarized below. Except for the 0°/0°plies-(45°) and (90°) laminates, the main crack initiated on the compressive side of the laminates propagated toward the notch side. For the 0°/0° ply-(0°) specimen, cracks were formed by fiber breaks due to shear stress on the compressive side (arrow in Fig. 4(a)). The main crack then grew through a brittle fracture of both the fibers and epoxy matrix toward the notch side (arrow in Fig. 4(c)) until linking up with the pull-out of the fibers produced by the tensile stress under the notch (Fig. 4(d)). Thus, the high and long plateau observed in the load vs. displacement curves of the 0°/0° ply-(0°) specimen is due to fracture of both the fibers and matrix independent of the slow bend and Charpy impact tests (Fig. 5). Therefore, a drastically high fracture energy found can be attributed to the high resistance to fracture of the fibers. However, the fracture energy of the 0°/0° plies-(45°) and (90°) specimens showed a significantly low fracture energy because fracture occurred in the fiber/matrix interfaces by the shear or transverse stress which is produced at the interfaces[10]. For the 0°/90° plies-(0°) and (90°) specimens, cracks initiated by fiber breaks are due to shear stress at the cross point of the fiber in the 0° and 90° directions (arrow in Fig. 6 (a)). The cracks, once initiated at the maximum load, catastrophically moved (Fig. 5). This is due to the fact that the crack mainly propagated along the fibers at the 90° direction / matrix interfaces (arrow in Fig. 6(c)) and consequently, a 90° direction dominated fracture occurred (Fig. 6(d)). For the 0°/90° ply-(45°) specimen, the load increased very slowly until it moderately decreased after the maximum load (Fig. 5). The fracture behavior can be described as follows: (1) cracks initiate by fiber breaks at the cross point of the 45° direction (arrow in Fig. 7(a)); (2) the cracks propagate through a

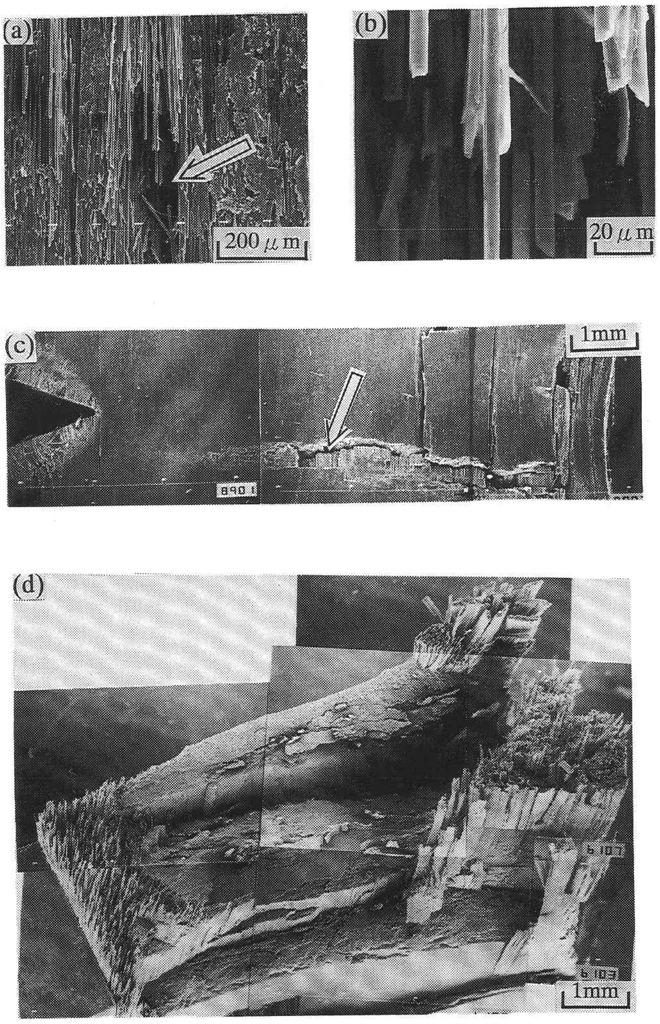

Fig. 4 SEM fractographs from 0°/0° ply-(0°) slow bend specimen. (a) and (b) crack initiation; (b) enlargement of crack in (a). (c)crack propagation process. (d) fracture surface. Arrows indicate cracks.

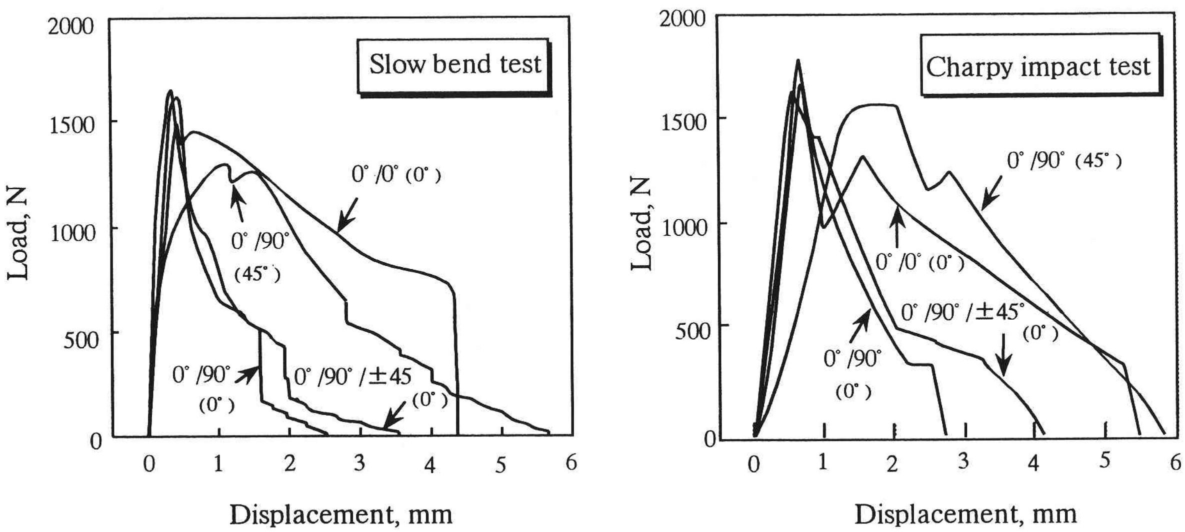

Fig. 5 Load versus displacement curves for various CFRP laminates during slow bend and Charpy impact tests.

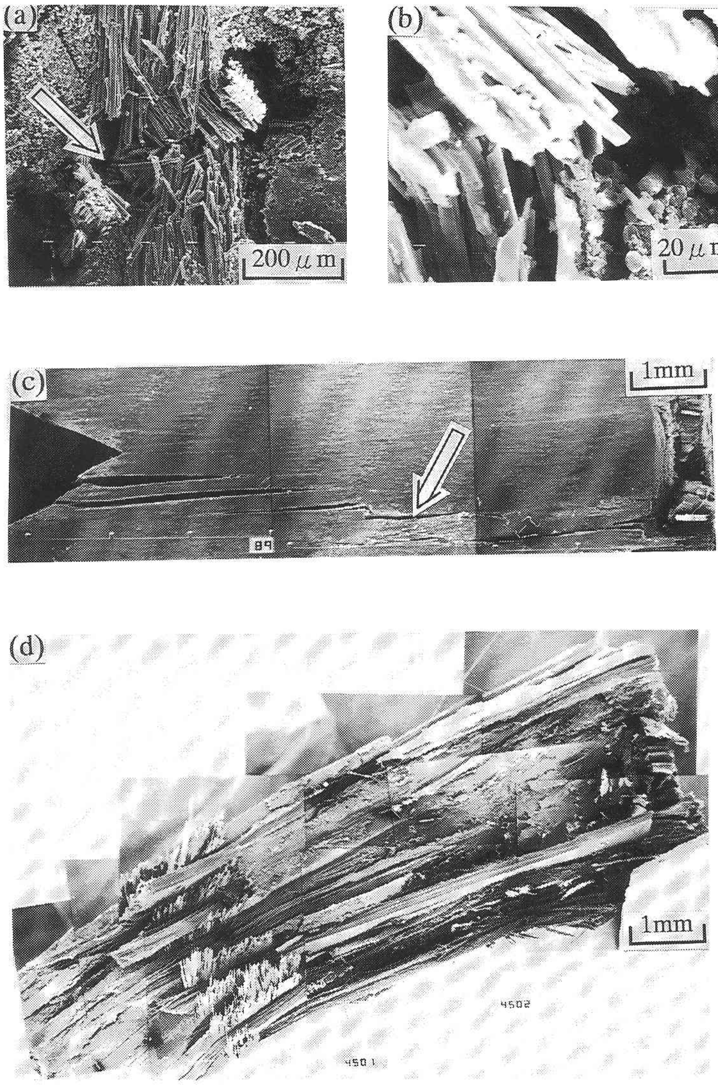

Fig. 6 SEM fractographs from 0°/ 90° ply-(0°) slow bend dpecimen. (a) and (b)d crack initiation; (b) enlargement of crack in(a).(c)crack propagation process. (d)fracture surface. Arrows indicate cracks.

zigzag path along the fibers at the 45° direction/matrix interfaces during deformation, which produced a significantly high crack propagation energy (Fig. 7 (c));(3) consequently, a fiber pull-out dominated fracture occurred[Fig. 7 (d)]. Load versus displacement curves of the 0°/90°/±45° ply-(0°) specimens showed a similar pattern to those of the 0°/90° ply-(0°) (Fig. 5). The fracture occurred due to the fact that cracks initiated by fiber breaks because of shear stress (arrow in Fig. 8 (a)) and they propagated along the interfaces of the fibers at the 0°, 45° or 90° direction/matrix interfaces (arrow in Fig. 8 (c)) until the main crack grew and eventually linked up with the fibers of the 45° direction pulled out by tensile stress under the notch (Fig. 8 (d)). Based on these results, fracture models involving crack initiation and propagation of the laminates studied are schematically illustrated in Figs. 9 to 12.

4. Conclusions

1. The 0°/0° ply-(0°) specimen exhibited a significantly high fracture energy independent of the slow bend and Charpy impact test but the 0°/0° plies-(45°) and (90°) specimens showed a significantly low fracture energy. The former is attributed to the

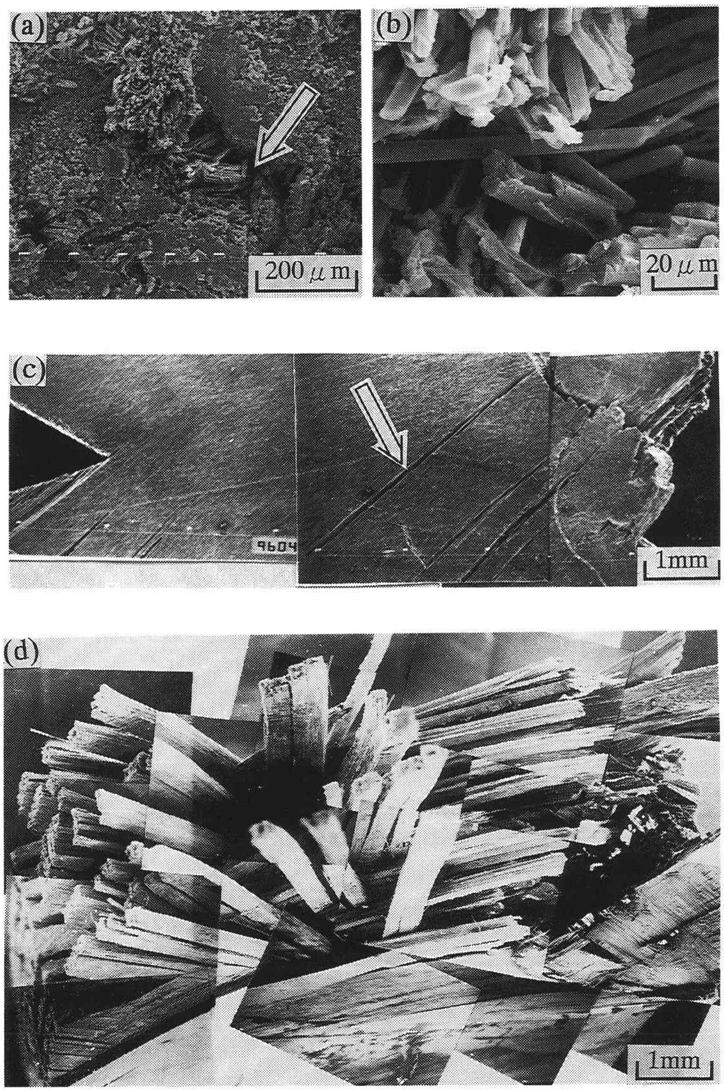

Fig. 7 SEM fractographs from 0°/ 90° ply-(45°) slow bend specimen. (a) and (b) crack initiation; (b) enlargement of crack in(a).(c)crack propagation process. (d)fracture surface. Arrows indicate cracks.

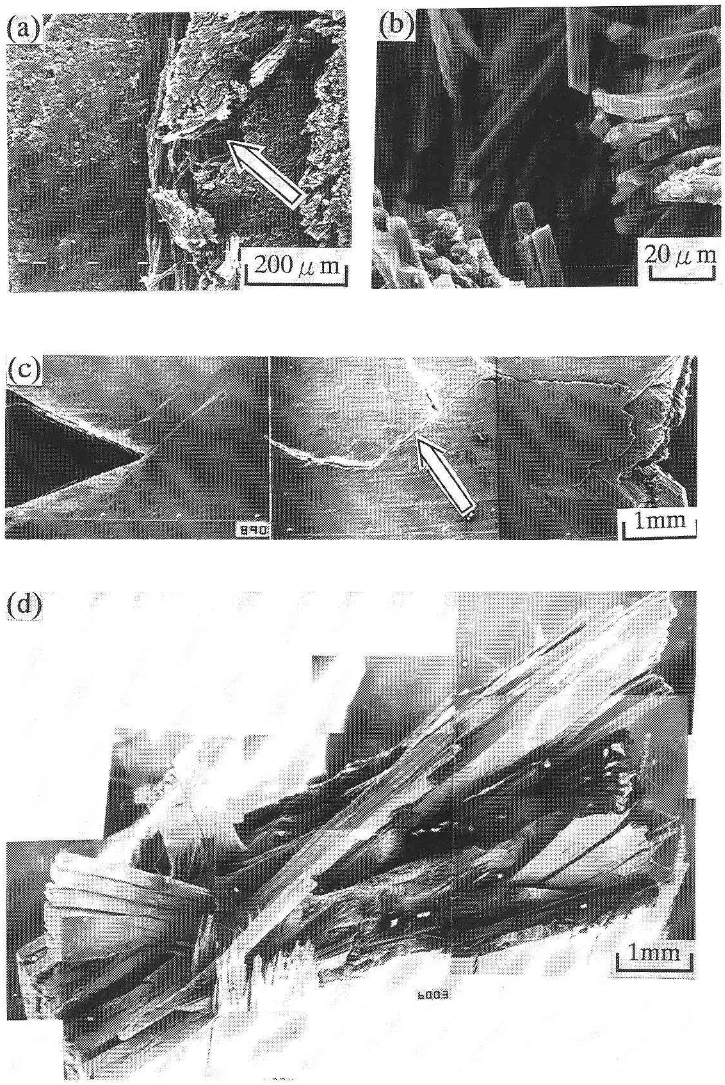

Fig. 8 SEM fractographs from 0°/ 90°/±45 ply-(0°) slow bend dpecimen. (a) and (b) crack initiation; (b) enlargement of crack in(a).(c)crack propagation process. (d)fracture surface. Arrows indicate cracks.

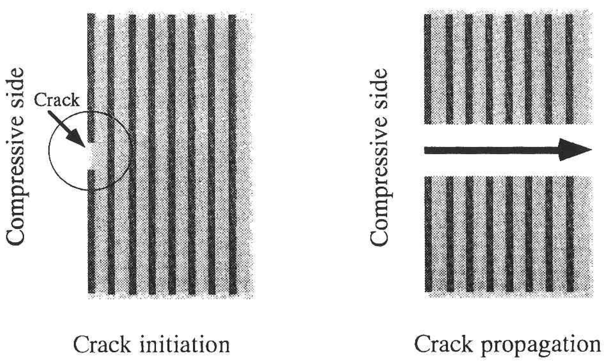

Fig. 9 Schematic illustrations of fracture model for the 0°/0° ply-(0°) specimen

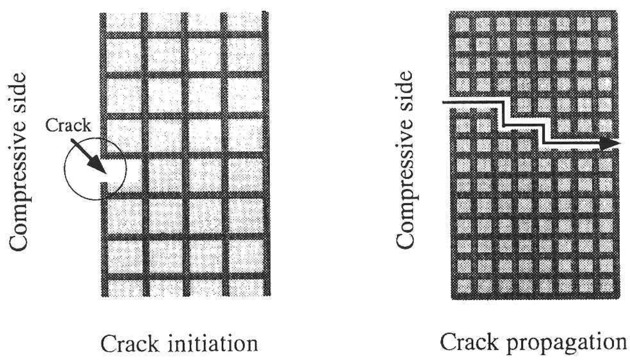

Fig. 10 Schematic illustration of fracture model for the 0°/90° ply-(0°) specimen.

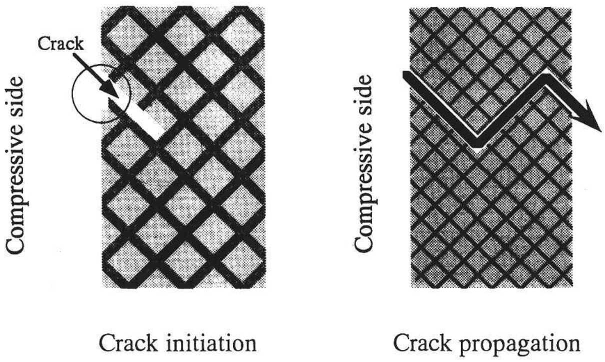

Fig. 11 Schematic illustrations of fracture model for the 0°/ 90° ply-(45°) specimen

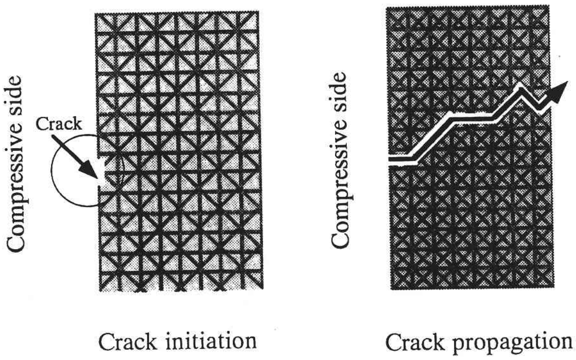

Fig. 12 Schematic illustrations of fracture model for the 0°/ 90°/±45° ply specimen

fact that fracture is controlled by fiber breaks and the latter is due to the fact that fracture is related to the fiber/matrix interfaces.

2. The fracture energies of the 0°/90° ply-(0°) and (90°) specimens were about 40% of those of the 0°/0° ply-(0°) specimen independent of the slow bend and Charpy impact tests. This is due to the fact that cracks initiated by fiber breaks catastrophically propagated along the fibers at the 90° direction/matrix interfaces.

3. For the 0°/90° ply-(45°) specimen, fracture energy dramatically increased the fracture energy because cracks initiated by fiber breaks at the cross point of the 45° the directions propagated through a zig-zag path along the fibers at the 45° direction/matrix interfaces, which produced a high crack propagation energy.

4. For quasi-isotropic laminates (0°/90°/±45° plies), there were marked benefits in the mechanical isotropy, but their slow bend and Charpy impact fracture energies were, respectively, about 60 and 70 percent of those for the 0°/0° ply-(0°) specimen. This is due to the fact that cracks initiated by the fiber breaks propagated along the fibers at the 0°, 45° or 90° direction/matrix interfaces.

References

1) ASM Staff report, *Advanced Mater. Process*, 142 (1992) 16.
2) A. Kelly, *Proc Soc. Lond.*, A319 (1970) 95.
3) P. D. Ewins and R. P. Potter, *Phil. Trans. R. Soc. Lond.*, A294, 507(1980).
4) A. C. Moloney and H. H. Kausch, *J. Mater. Sci.*, 18, 208(1983).
5) J. Spanoudakis and R. J. Young, *J. Mater. Sci.*, 19 (1984) 473.
6) J. Spanoudakis and R. J. Young, *J. Mater. Sci.*, 19, 487(1984).
7) A. C. Moloney, H. H. Kausch, T. Kaiser and H. Bear, *J. Mater. Sci.*, 22 (1987) 381.
8) J. Cook and J. E. Gordon, *Proc. R. Soc. Lond A*, 282 (1964) 508.
9) Y. Tomita and M. Tempaku, *Mater. Charact.*, 38, 91(1997).
10) Y. Tomita, T. Tamaki and K. Morioka, *to be publicated in Mater. Charact.*