Effects of Fiber Directions on Strengths of Notched Specimens of C/C Composite

Tensile and fatigue failure behavior of C/C composites with fine woven fiber-cloth laminates was investigated in several configurations of specimens. A 3.2mm thick plate, which has the quality of machine-ability, was used for testing material. During the machining process of specimens, care was taken that the fiber directions of 0°/90° and −45°/45° orientation were set against the loading direction. Tensile and fatigue tests were performed under load control techniques. Notches were made on some specimens, and their fracture behavior was observed. Some different notch shapes were used to investigate the effect of fiber orientation on the fracture behavior of the material. The results showed that the critical fracture stresses on the specimen were affected by fiber orientation and notch shape. In addition, the shear stress conditions affected the fracture behavior.

Key words: C/C composites, Notched direction, Slit, Fiber direction, Tensile strength, Fatigue strength, Shear fracture

Table 1 Mechanical properties.

<table>
<thead>
<tr>
<th>C/C type</th>
<th>Grade</th>
<th>Bulk Density [g/m³]</th>
<th>Flexural strength [MPa]</th>
<th>Compressive strength [MPa]</th>
<th>Tensile strength [MPa]</th>
<th>Ash content [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2DCC/C</td>
<td>CX-31</td>
<td>1.61</td>
<td>90</td>
<td>249</td>
<td>98</td>
<td>0.02</td>
</tr>
</tbody>
</table>

*⊥: perpendicular to laminate  ⊥/∥: parallel to laminate

Received Apr 9, 2012 © 2012 The Society of Materials Science, Japan

Tsuyoshi Tohikubo *, Masaki Fujikawa **, Chobin Makabe ***, Sofyan A. Setyabudi **** and Anggit Murdani *****
is $7\mu m$. Figure 1 shows the appearance of the material.

The specimens which have a basic geometry of 130mm length and 30mm width were made by machining process. The loading axis of the specimen was set at parallel or perpendicular to the fiber bundle orientation, and 45° inclined to the fiber bundle orientation. Hereinafter, these angles $\alpha$ of fiber will be shown by $\alpha = 0°/90°$ and $\alpha = -45°/45°$, respectively. A notched specimen with blunt notch root was also prepared in order to obtain reference data for fatigue mechanisms.

Figure 2 shows the geometry of the specimens. Figure 2 (a) is a smooth specimen; Figure 2 (b) is a slit specimen in which slit direction was 45° inclined to the loading axis; Figure 2 (c) is a slit specimen in which slit direction was perpendicular to the loading axis; and Figure 2 (d) is a specimen with a blunt notch. The specimens were manufactured based on fiber direction and loading direction (In each case, $\alpha$ was set at 0°/90° or -45°/45°). The specimen thickness was 3.2mm, and the ligament width of notched and slit specimens and the width at parallel section of smooth specimen were 20mm. The angle $\beta$ of slit direction against specimen axis will be represented in the figures with $\beta = 90°$ for the case of Fig. 2 (c) and $\beta = 45°$ for the case of Fig. 2 (b).

The tensile tests were performed by the load control method (the method of increasing the load gradually). When the displacement in the test section of the specimen stopped after increasing the load in the testing step, the next load level was applied. The load was increased 1 MPa at every testing step, and the test was continued until the specimen was broken. The displacement was measured between the parallel marked lines with 30mm distances. Fatigue test was performed by using an electro-hydraulic servo type of testing machine. The frequency of 2 Hz and stress ratio of $R = -1$ and $R = 0$ are mainly used for the fatigue test. Also, the frequency of 10 Hz was set for the fatigue test of some specimens. The initiation and growth of the crack and the damage pattern on the specimen were observed directly by a microscope.

3 Experimental results and discussion
3.1 The damage caused by tensile test

Figure 3 shows the stress-strain diagram of the static tensile tests with load control techniques. The results for smooth specimens and slit specimens were compared. The stress values for each specimen were calculated by net stress with parameters of the ligament area. Figure 3 (a) shows the result of $\alpha = 0°/90°$ and Fig. 3 (b) that of $\alpha = -45°/45°$. By comparing these results, it is understood that the ultimate tensile strength $\sigma_B$ of $\alpha = 0°/90°$ was higher for each specimen geometry. Also, it is understood that, in order, the ultimate tensile strength $\sigma_B$ of specimens is first, the 90° slit specimen (specimen with $\beta = 90°$), second, the 45° slit specimen (specimen with $\beta = 45°$), and third, the smooth specimen, in each fiber direction. In these experimental conditions, the strength $\sigma_B$ of the slit specimen was higher than that of the smooth specimen. From the specimen geometry, the tests were performed under plane stress conditions. So, the tendency of strength, in order, of relatively thin specimens in the present study is different from the case of metals.

To discuss the tendency of strength in the present experimental conditions, the features of broken speci-
mens were observed. Figure 4 shows those of the smooth specimen. Figure 4 (a) shows the case of $\alpha = 0^\circ/90^\circ$, and Fig. 4 (b) $\alpha = -45^\circ/45^\circ$. The fracture direction in the case of $\alpha = 0^\circ/90^\circ$ was inclined almost $45^\circ$ through the thickness direction and was almost perpendicular to the axis direction. In plane stress conditions, the direction of maximum shear stress inclines $45^\circ$ in the thickness direction. The phenolic resin, which was used to fix the carbon fiber, was damaged by shear deformation under plane stress conditions in the first stage of fracture. Then, the carbon fibers broke under the influence of shear deformation. On the other hand, in the case of $\alpha = -45^\circ/45^\circ$, the fracture direction was strongly influenced by the fiber directions. Necklike patterns were observed in the broken specimen. Slipping patterns were observed on the flat surface of the specimen. In the stage of the present study, it is evaluated from the features of broken specimens that the damage to the phenolic resin was related to the deformation of the fiber, and caused by the peeling of the fiber and matrix (e the phenolic resin).

Also, from the view in thickness (undersides of Fig. 4 (a) and (b)), the expansion of thickness was observed in both cases of $\alpha = 0^\circ/90^\circ$ and $\alpha = -45^\circ/45^\circ$. From the comparison of the broken features of the smooth specimens (Fig. 4) and slit specimens (Fig. 5 and Fig. 6), when the fibers were oriented in the direction in which the load displacement was constrained, the damage area was localized in a narrower section.

Figure 5 shows the broken features of the $90^\circ$ slit specimens. In the case of $\alpha = 0^\circ/90^\circ$, the deformation of the fiber is limited to a narrow band of ligament, and the macroscopic mode of unstable fracture was mode I, but the fracture direction through the thickness was partially inclined. In the case of $\alpha = -45^\circ/45^\circ$, the thickness also decreased slightly at the outside of the slit part. Also, it was expected that the damage to the phenolic resin was caused by the slip deformation in the direction of the fibers. The crack grew in the $45^\circ$ inclined direction from the bottoms of slits, and the zigzag pattern was formed due to the different crack growth directions of both slit sides.

Figure 6 shows the features of the broken $45^\circ$ slit specimens. In the case of $\alpha = 0^\circ/90^\circ$, fracture mode was combined with modes I, II and III, and cracks expanding from both sides look likely to coalesce at the center section. In the case of $\alpha = -45^\circ/45^\circ$, the fibers were broken along the crack growth direction or fiber direction.

From the observation results of broken specimens and examination of the relationship between tensile strength and fracture behavior, it was discussed whether the tensile strength was determined by the conditions of the deformation constraint. So, since the deformation in tensile tests was related to the directions of slip deformation in phenolic resin and directions of carbon fiber, it was considered that the slip deformation easily developed in the direction of peeling or separation between the phenolic resin and carbon fibers. Because of that, the tensile strength was lower in the case of $\alpha = -45^\circ/45^\circ$. Also, the lower effect of stress concentration on fracture strength appeared in the present material. It is not the same tendency as in the case of metal. Because of that, there is an order to ultimate tensile strength according to specimen geometry. In the case of a metal, the yield strength of a bar specimen with a deeper circumference notch was higher than that of a smooth specimen due to the plastic constraint. In the present experimental cases, during the processes of plastic deformation of phenolic resin and the fracture of carbon fibers, the phenomenon is the same as if the plastic constraint had occurred. Then, that phenomenon and the sizes of damaged areas observed in Figs. 4–6 affected the ultimate tensile strength of slit and smooth specimens.
3.2 The fracture behavior by applied cyclic stress

Unlike the case of a metal, it is important in the fatigue process of the present C/C composites that the carbon fiber broke from the effects of shear stress after damage to the phenolic resin, which bonds a bunch of the carbon fiber. Since the frequency was set to 2 Hz in the present fatigue tests, it will take a longer time to obtain the fatigue limit by applying stress of 10⁷ cycles. Therefore, following the methods of Goto et al.³ and Hatta et al.,⁴ the fatigue limit was evaluated by the simple method. Thus the fatigue tests were performed by Load Increase Test (LIT)³, ⁴ in which applied stress was increased in a decided stress range after a decided number of cycles was applied step by step. To confirm the effectiveness of LIT, fatigue strength for 2 × 10⁶ stress cycles was measured by using plural specimens by the normal method. Then this result was compared with the fatigue strength for 2 × 10⁶ stress cycles, which was obtained by LIT.

Figure 7 shows an example of the fatigue strength or fatigue limit σₜ for 2 × 10⁶ cycles, which was obtained under constant stress amplitude by using plural specimens. Figure 7 is the S-N curve in the case of the 90° slit specimen under stress ratio R = −1. For α = 0°/90°, when the stress amplitude σₐ was 30 MPa, the specimen did not break until 2 × 10⁶ cycles. However, the specimen broke at about 10⁵ cycles when σₐ was 32 MPa. For α = −45°/45°, the specimen did not break until 2 × 10⁶ cycles under σₐ = 24 MPa. However, the specimen broke at about 10⁴ cycles under σₐ = 26.5 MPa. From these examples, it was assumed that there is a clear critical stress amplitude under which the specimen endures the application of 2 × 10⁶ stress cycles. In the case of the broken specimen, the number of cycles to failure was lower than 10⁴ under the present study conditions. Therefore, following the results of Goto et al.³ and Hatta et al.,⁴ the fatigue limit σₜ was determined by LIT using one specimen.

Figure 8 shows the examples for the method of LIT. The load was increased step by step, and the same level of stress amplitude was repeated 2 × 10⁴ cycles in every step. The increased level of stress amplitude was 2 MPa, and the value of fatigue limit σₜ was set at 2 MPa lower than the maximum stress amplitude that was applied when breaking the specimen. Therefore, note should be taken that the exact fatigue limit was not determined in this study. Examples shown in Figs 8 (a) and (b) are the results for the case of 90° slit specimen and 45° slit specimen under R = −1. It is found that the fatigue limits obtained by LIT are little different from the results for that in Fig. 7. Therefore, we decided that the fatigue limit σₜ can be approximated by the results of LIT. Now the stress amplitude was calculated by net stress.

Figure 9 shows the tendency of fatigue limit σₜ obtained by LIT. The values of σₜ are compared for each test specimen in the bar chart. The results under R = 0 and R = −1 are summarized by maximum cyclic stress σₘₐₙ in each test. It is clear that the fatigue limit σₜ in the present tests depended on the fiber orientation. Now, the left-hand sides are the case of α = 0°/90°, the right-hand sides α = −45°/45°. Because the maximum cyclic stress was the parameter used, the fatigue limit for R = 0 was shown to be higher than the level for R = −1.

The variation in fatigue limits for the smooth specimen
and 45° slit specimen showed almost the same tendency, and the fatigue limits for the 90° slit specimen and notched specimen were almost the same, when stress ratio $R$ was 0. However, where $R = -1$, less influence of the specimen geometry on the difference in fatigue limit was observed, and the difference in fiber direction strongly affected the fatigue limit. In both cases of $R = 0$ and $R = -1$, the fatigue limit for the specimen with $\alpha = 0°/90°$ was higher than that with $\alpha = -45°/45°$. There is less effect of specimen geometry on fatigue strength, compared with the results of the tensile test. But the fracture behavior of a fatigue specimen was related to the damage to the phenolic resin and succeeding breaking of carbon fibers.

Figure 10 shows the features of the broken smooth specimen. In the case of $\alpha = 0°/90°$, $R = -1$ as shown in Fig. 10 (a), the crack growth direction was determined by maximum shear stress direction under plane stress conditions. The cross section of the fracture surface, which was formed by crack growth, inclined in an almost 45° direction. It seems that a small amount of deformation accumulated in the tensile direction in the case of $R = 0$, at final stage of fracture. The cracks started to grow from both sides of the specimen edges. In vicinity of the edges, the crack growth direction was almost perpendicular to the loading axis. But, entirely, the crack grew at an almost 45° incline through the thickness direction. From the view of the flat surface of specimen in the case of $R = 0$, it is found that the cracks which initiated from both sides coalesced with each other at the final stage of fracture, because the crack initiation sites on both side were not in the same position relative to the center line. So, in the center section of the specimen, the fracture surface was inclined at both specimen plane face and through the thickness direction.

Figure 10 (b) shows the case of $\alpha = -45°/45°$. Inclined cracks were expected to grow in both the thickness direction and specimen plane face. The same as the case of the tensile test, it is considered that the deformation and damage to the phenolic resin affected the final fracture pattern of the specimen, and the fracture direction was related to the directions of carbon fibers, when constraint on the deformation direction was small.

Figure 11 shows the broken features of the 90° slit specimen. Figure 11 (a) shows the cases of $R = -1$ and $R = 0$ where $\alpha$ is 0°/90°. The inclined crack growth was traced in the thickness direction. By comparing with the smooth specimen, it is not clear that the crack grew in the direction of maximum shear stress. However, a mixed mode fracture of shear mode and tensile mode was observed. It is considered from the features of fracture surfaces that the resistance to shear deformation in the case of $R = 0$ was higher than that in the case of $R = -1$.

Figure 11 (b) shows the case of $\alpha = -45°/45°$. The features of fractured specimens are somewhat different depending on the stress ratio. In the case of $R = -1$, the specimen looked likely to break under plane stress conditions, the cracked surface was inclined in the thickness direction. On the other hand, in the case of $R = 0$, features similar to those in the case of Fig. 5 (b), which were obtained in the tensile broken specimen, were observed, and the crack growth direction changed. As mentioned above,
the rapid growth of the crack occurred just before the break. Therefore, in the case of \( R = 0 \), it is considered that the effects of one-directional deformation accumulated during fatigue process, and that peeling between the phenolic resin and carbon fibers effected the crack initiation and growth. Those were related to the patterns of fracture surface.

It is emphasized that the fatigue limit of the 90° slit specimen was higher than that of the smooth specimen in the case of \( R = 0 \). As that result is reviewed from fracture patterns of the specimens, it is discussed that the strength order in specimen geometry is related to shear deformation. In the case of the 90° slit specimen, the crack growth direction did not coincide with the direction of maximum shear stress in a wide area. Such tendency would indicate that the range of repeated shear deformation was wider in the case of \( R = -1 \).

Figure 12 shows the broken features of 45° slit specimens. The fracture surface morphology in this case is more complex than in the tensile fracture test. In the case of \( R = -1 \) and \( \alpha = 0°/90° \) as shown in Fig. 12 (a), the crack grew almost perpendicular to the specimen axis from the slit bottoms on both sides at the specimen plane face, and the crack grew at an inclined direction through the thickness. In this case, the angles of slits did not affect the fracture orientation, and the crack initiation and growth from a slit bottom were related to the fracture pattern. In the case of \( R = 0 \), cracks initiated at the both sides of the slit, and these cracks connected at the final fracture process. In the case of \( R = -1 \) and \( \alpha = -45°/45° \) as shown in Fig. 12 (b), the crack grew along the slit direction and fiber direction. However, the crack growth was only affected by the fiber direction and was not affected by the direction of the slit in the example of \( R = 0 \). This example shows that the manner in which the specimen broke was related to the damage to the phenolic resin and deformation direction of the fibers rather than the stress concentration at the first stage of crack initiation. Similar results were obtained for the tendency of the fatigue limits for smooth specimens and 45° slit specimens. It is considered from a comparison of Fig. 12 and Fig. 10 that reason for the tendency of fatigue limit is related to the formation mechanism of the fracture surface.

Figure 13 shows the broken features of the blunt notch specimens. In the case of \( R = -1 \), the crack grew in the inclined direction through the thickness in all specimens’ orientation \( \alpha \). In the case of \( R = 0 \), the cracked surface did not appear under the plane applied maximum shear stress. This tendency is similar to that of the 90° slit specimen. The feature just before breaking is shown in the case of \( R = 0 \) and \( \alpha = -45°/45° \). The patterns likely to have one directional deformation are observed in that specimen. It is assumed that the condition of deformation constraint and the effect of stress concentration on shear deformation are different for the blunt notched specimen and slit specimens. In future study, it will be investigated how the stress concentration affects fracture behavior when a thicker specimen is used for testing.

It was difficult to observe the initiation and the growth of the crack in the carbon fibers in detail with high magnification. However, the breaking of a specimen suddenly occurred at the final stage in the process of fatigue fracture, as in the process of the tensile fracture. Also, in the process of fatigue fracture, the cracking in phenolic resin was observed at a relatively early stage. In the case of a slit specimen, the crack grew from near the bottoms of the slits, and the crack grew rapidly with the shear deformation just before breaking. Also, the damages in phenolic resin did not continuously expand, but dispersed in some parts. The damage occurred in such parts with shear deformation and extended in the direction of the carbon fibers. As reported by Murdani et al., it was understood from the present results that final fracture behavior was related to the strength of fibers, too. The fracture mode was mixed mode, and when the shear mode along the fiber direction developed strongly, the level of fatigue strength became lower.
4 Conclusions

The strength of smooth specimens and slit specimens were compared. Fatigue limit was determined using a simplified method. The angles $\alpha$ between the carbon fibers and specimen axis were set at 0°/90° and −45°/45°. The directions of the slit against the load axis were set at 90° (for 90° slit specimens) and 45° (for 45° slit specimens). The main results obtained are as follows:

(1) The effect of the specimen geometry on ultimate tensile strength was clearly apparent, and, in order, the ultimate tensile strength according to specimen geometry was first, 90° slit specimen, second, 45° slit specimen, and third, smooth specimen. The effect of the specimen geometry on fatigue strength was less than that on ultimate tensile strength. However, in those tests, the highest strength was obtained where the fiber direction $\alpha$ was 0°/90°.

(2) The damage to the phenolic resin by shear deformation (or slipping) and the subsequent breaking of carbon fibers were related to the strength of the present material. Therefore, in the case of $\alpha = −45°/45°$, the strength became lower because the fracture easily extended along the fiber direction. In case of $\alpha = 0°/90°$, the fracture surface tended to form in an inclined direction through the thickness.

(3) In this experiment, the fracture strength was influenced by the resistance to slipping deformation which was caused by the carbon fiber orientation and the method of cutting the slit processing, rather than by the stress concentration in the vicinity of the bottom of slit.

References