Residual Bending Strengths of CFRP Laminates after Impact*

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In the present work, static and fatigue residual bending strengths of carbon fiber reinforced plastic (CFRP) laminates having impact damage are evaluated with four- and three-point bending tests. A steel ball was launched from an air gun and impacted upon CFRP laminates to generate impact damage. The delamination growth during fatigue tests and the fracture surface are observed with a scanning acoustic microscope and scanning electron microscope, respectively. The residual strengths determined by the four-point bending test are reduced, particularly when the impacted side is compressed. The degree of reduction is influenced by the propagation of surface cracks near the impact impression. The residual strengths determined by the three-point bending test are almost the same whether the impacted side is the top or the bottom. It is determined that the degree of reduction of strength is governed by the slide of the transverse cracks due to the shear force.

Key Words: Reinforced Plastics, Fatigue, Material Testing, CFRP Laminates, Residual Strength, Impact Damage, Damage Growth, Bending Test

1. Introduction

Fiber reinforced plastics (FRP) are advanced materials, especially carbon fiber reinforced plastic (CFRP) laminates used in aerospace and other applications. These materials have high specific modulus, high specific strength and the possibility of tailoring of material characteristics, compared with traditional materials. However, these advantages are ones of for static properties, and CFRP is relatively easily damaged by impact. CFRP is damaged upon impact of foreign objects⁽¹⁾ at even low impact velocities (impact velocity of less than approximately 100 m/s), for example in the case of a tool dropping on a surface during maintenance, an airplane kicking up stones during take-off or landing, or a bird striking an airplane surface. The impact damage is visible externally as an impact impression and surface cracking.

Transverse cracking and delamination occur in the interior of CFRP.

In requirement of the damage tolerance design of airplanes, residual strength of CFRP laminate after impact has been investigated with tensile, compression, bending and shear tests, as shown in Abate's review⁽²⁾. In particular, it was pointed out that the residual strength for compression was remarkably reduced, compared with other test cases. This is usually called the problem of compression after impact (CAI)⁽³⁾. The reason for the residual strength reduction in CAI is recognized as delamination buckling⁽⁴⁾. Chatterjee et al.⁽⁵⁾ used artificial delamination in FRP laminate to research the effect of the delamination on the residual strength. They discussed the mechanism of the reduction for CAI problems. Detailed mechanisms for other types of problems have not been proposed.

In practical structures, CFRP laminates are generally used as elements of thin-walled structures. These structures are often deformed under bending rather than in-plane stress. Therefore, it is important to investigate residual bending strength of CFRP laminates following foreign-object impact and the mecha-

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nism of its reduction.

In the present work, the static and fatigue residual strengths of CFRP laminates having impact damage are evaluated with four- and three-point bending tests. A steel ball was launched from an air gun and impacted upon CFRP laminates to generate actual impact damage, because we consider that the interaction between actual impact damage and the residual strength is important. The growth of the delamination during fatigue tests and the fracture surface are observed with a scanning acoustic microscope (SAM) and scanning electron microscope (SEM), respectively. Based on these experimental results, mechanisms of damage growth in CFRP laminates are proposed to account for the reduction of the residual bending strengths.

2. Specimens

The specimens were made of stacked carbon/epoxy prepreg (Toray P 3051-15, carbon fiber T 300-3000, epoxy resin #2500). Three different stacking sequences of specimens are used: type A ($[0^\circ/90^\circ_6]_{\text{SYM}}$), type I ($[10^\circ_2/45^\circ_2/90^\circ_2/-45^\circ_2]_{\text{SYM}}$) and type J ($[10^\circ_2/90^\circ_3/45^\circ_3/-45^\circ_4]_{\text{SYM}}$), taking the longitudinal direction of the specimens as 0° . The stacking sequence of type A was selected to facilitate observation of the damage growth. Types I and J are quasi-isotropic and similar to practical laminates. Every specimen had a length of 180 mm, a width of 40 mm and a thickness of 3.75 mm. The residual bending strengths of the type A and type J specimens were estimated by the four-point bending test and those of type A and type I were estimated by the three-point bending test.

3. Experimental Method

3.1 Impact test

3.1.1 Impact test equipment The impact test equipment is shown in Fig. 1. A steel ball of 5 mm diameter was launched from an air gun and impacted upon a specimen to generate initial damage. The velocity of the steel ball was less than 120 m/s to avoid perforating the specimen. The specimen was clamped at both ends to 15 mm from the edge by steel

Fig. 1 Impact test equipment

plates of 10 mm thickness. Although the impact point was the center of the specimens for the four-point bending test, it was longitudinally shifted by 30 mm from the center for the three-point bending test. The patterns of the impact damage in the specimen were the same for the three- and four-point bending tests. For the three-point bending test, the damaged area was subjected to the effects both of bending and shear force. In the present work, the impact energy refers to the kinetic energy of the steel ball just before the collision.

3.1.2 Impact damage The impact damage in the CFRP laminates was observed with a SAM (UH-Pulse 100 and frequency of acoustic lens, 30 MHz; Olympus Optical Co., Ltd.). As examples of the observation results, the delaminations for types A and J are shown in Figs. 2 and 3, respectively. Based on the observations performed with the SAM and the optical microscope, the typical impact damage pattern is drawn in Fig. 4. A circular impact impression with microbreaking of fibers appears on the impacted surface due to the impact of the steel ball. A long

(a) Delaminations

(View of impacted side with SEM. Delaminations are designated from the impacted side in alphabetical order)

(b) Impact impression

(Impacted surface observed with optical microscope)

Fig. 2 Impact damage in type A specimen (Impact energy: 1.7 J)

(a) View of the impacted side with SAM

(b) View of the back side with SAM

Fig. 3 Impact damage in type J specimen
(Impact energy : 2.5 J ; delaminations are designated from the impacted side in alphabetical order)

Fig. 4 Typical impacted damage in $[0^\circ_n/90^\circ_n]_{\text{SYM}}$

crack in the direction of orientation of fiber axis occurs on the back-side surface. Delaminations are generated at the interface due to the mismatch of the stiffnesses of the layers. The delamination is usually

(a) Impacted side : compression

(b) Impacted side : tension

Fig. 5 Four-point bending test equipment

(a) Impacted side : compression

(b) Impacted side : tension

Fig. 6 Three point bending test equipment

called peanut- or rip-shaped with the major axis oriented in the fiber axis orientation of the lower layer for that interface. The transverse cracks without fiber breakage in the layer are connected with the delaminations and incline obliquely toward the impact point.

3.2 Residual bending strength test

The residual bending strengths of the specimens were estimated with a four-point bending test which applies pure bending moment and a three-point bending test which applies shear force and bending moment. Both bending tests were carried out in accordance with ASTM standard D790M⁽⁶⁾ except for the width of the specimen, as shown in Figs. 5 and 6. As the impact damage in the specimen is asymmetrical along the thickness direction, the tests are categorized into four types as follows: the impacted side is subjected to compressive stress during four point-bending (4BC), the impacted side is subjected to tensile stress during four-point bending (4BT), the impacted side is subjected to compressive stress during three-point bending (3BC) and the impacted side

is subjected to tensile stress during three-point bending (3BT).

In the static and the fatigue bending tests of the residual strength after impact, a fatigue test machine (Instron 8501, load capacity: 100 [kN]) was used. The static test was carried out at 1 mm/min cross-head speed of the machine. In the fatigue test, the load variation was a sine wave with 3 Hz frequency and 0.1 load ratio (maximum load/minimum load). In both bending tests, when the specimen was broken into more than two pieces, we evaluated the instant of the fracture.

The maximum nominal stresses for both bending tests were adopted to arrange the experimental results. Assuming that the impacted specimen is homogeneous without damage and governed by the laminated beam theory with infinitesimal deformation, the maximum stresses are given as follows:

for the four-point bending test,

$$\sigma_{\max} = \frac{P(L-L_1)}{4Z}, \quad (1)$$

and for the three-point bending test,

$$\sigma_{\max} = \frac{PL}{4Z}, \quad (2)$$

where Z is the modulus of section as given by

$$Z = \frac{bd^2}{6}$$

and P , b and d denote the load, the width and thickness of the specimen, respectively. L (=120 mm) and L_1 (=60 mm) are the support span of the specimen and the distance between both load points of the four-point bending test.

For some specimens, the fatigue test was sometimes interrupted and the specimen was removed from the bending equipment in order to observe the damage growth with the SAM. After the bending test, the delamination surface was observed to confirm the fracture mode with the SEM (JSM-T200, JOEL Co.,

Ltd.).

4. Experimental Results and Discussion

4.1 Four-point bending test

4.1.1 Residual strength The static residual strengths determined by the four-point bending test for the type A and J specimens are shown in Fig. 7. The static residual strength decreases with increasing impact energy. Because the impact damage area is proportional to the impact energy for the same impactor⁽⁷⁾⁽⁸⁾, it is determined that the impact damage influences the residual strength directly. The residual strength of the type A specimen in the 4BC test is reduced remarkably, compared with the results for the 4BT test. For the type J specimen, the residual strength in the 4BC test is slightly less than that in the 4BT test.

The fatigue residual strengths determined by the four-point bending test are shown in Fig. 8. The residual strength in the 4BC test is much lower than that in the 4BT test for type A specimens. The tendency of the fatigue residual strengths is the same as that in the static test. It is shown that a quasi-isotropic laminate such as the type J specimen is stronger than an anisotropic one such as the type A and J specimens.

4.1.2 Mechanism of damage growth The damage growth in the type A specimen was observed with the optical microscope for the impacted surface and the SAM for the delamination. The growth of the impact impression crack, that is, the surface crack

Fig. 7 Static residual strength for four-point bending test (Specimens: types A and J)

Fig. 8 Fatigue residual strength for four-point bending test (Impact energy: 1.7J for type A and 3.3J for Type J, open symbol: fracture, solid symbol: non-fracture)

from the impact impression, is shown in Fig. 9. The crack appears on a line tangent to the impact impression and propagates with fiber breakage in the impacted surface. The delamination growth of the same specimen is shown in Fig. 10. It is determined that delamination (A) at the interface near the impacted side develops with the impact impression crack, although another delamination which is not shown in Fig. 10 does not vary in magnitude. Based on the results shown in Figs. 9 and 10, the propagation of the impact impression crack with fiber breakage induces delamination growth and final fracture of the specimen. Figure 11 shows a photograph of a cross section near the impact impression in the type A specimen, just after the appearance of the impact

Fig. 9 Growth of impact impression crack in four-point bending test (Specimen: type A, impacted energy: 1.7 J, maximum stress: 0.64 GPa, impacted side: compression)

Fig. 10 Delamination growth (Delamination (A) in Fig. 2 (a) during fatigue four-point bending test observed with SAM, specimen: type A, impact energy: 1.7 J, maximum stress: 0.64 GPa, 65 000 Cycles, impacted side: compression)

impression crack. It is predicted that the microbuckling of the fibers due to the compression stress induced by the bending deformation causes the appearance of the crack.

To confirm the fracture mode of delamination growth, the surface of the delamination growth was observed with the SEM, as shown in Fig. 12. The hackle which appears on the surface shear stress⁽⁹⁾, is not found in Fig. 12. Therefore it is determined that the delamination growth is mode I type.

On the other hand, in the fatigue 4BT test, the large delamination (B) at the interface (B) near the back side is extensively buckled. Because its growth is very slow, the residual strength is little reduced.

4.2 Three-point bending test

4.2.1 Residual strength The static and fatigue residual strengths in the three-point bending tests are shown in Figs. 13 and 14, respectively. The residual strength is greatly reduced with higher impact energy. The static and fatigue residual strengths in the 3BC test have the same values as those in the 3BT, different from the results for the four-point bending tests. The residual strength of the type I (the quasi-isotropic laminate) specimen is little

Fig. 11 Impact impression crack generated by fatigue four-point bending test (Specimen: type A, impact energy: 1.7 J, 50 000 Cycles)

Fig. 12 Surface of grown delamination observed with SEM (Specimen: type A, impact energy: 1.7 J)

reduced, compared with the results obtained for the type A specimen.

4.2.2 Mechanism of damage growth The delamination growth was observed with the SAM. Figure 15 shows the delamination growth in the type A specimen. Figures 15 (a) and (b) are the results

Fig. 13 Static residual strength for three-point bending test (Specimen: types A and I)

Fig. 14 Fatigue residual strength for three-point bending test (Impact energy: 1.7 J for types A and 1.7 J for type I, open symbol: fracture, solid symbol: non-fracture)

(a) Impacted side: compression

(b) Impacted side: tension

Fig. 15 Delamination growth during fatigue three-point bending test (View of the impacted side with SAM. specimen: type A, impacted energy: 1.7 J, maximum stress: 0.51 GPa)

(a) View of the impacted side with SAM

(b) View of the back side with SAM

Fig. 16 Delamination growth during fatigue three-point bending test (Specimen: type I, impact energy: 2.5 J, maximum stress: 0.87 GPa, impacted side: compression)

Fig. 17 Damage growth model in three-point bending test

(a) Delamination (A)

(b) Delamination (B)

Fig. 18 Surface of grown delamination observed with SEM (Specimen: type A, impact energy: 1.7 J)

of 3BC and 3BT tests, respectively. The right side of the delamination to the impact point is developed in Fig. 15(a) and the left side in Fig. 15(b). Figure 16 denotes the delamination growth of the type I specimen in the 3BT test. In the four-point bending test, only some of the delaminations grow.

Next, we consider the mechanism of the damage growth in the three-point bending test to account for these phenomena. Figure 17 shows the damage

growth model for the 3BT test. Because the transverse cracks in the 90° layer incline toward the impact point, the crack slides according to the shear force. Thus in Fig. 17, the left side of the lower delamination where the in-plane force is tensile opens and grows in a combination of modes I and II. On the other hand, the delamination at the side where the in-plane force is compressive grows in mode I. To confirm the validity of the mechanism, the delamination surface after fatigue test was observed with the SEM. The results are shown in Fig. 18. On the surface of the fracture which was predicted to show growth of a combination of modes including mode II, the hackle⁽⁹⁾ was observed. On the surface predicted as mode I, it was not. According to the proposed mechanism, the transverse crack of the opposite side slides during the 3BC test. Therefore, it is understood that the residual strengths for 3BT and 3BC tests are approximately the same, although the growth patterns of the delaminations are different.

5. Conclusion

In the present work, the residual strengths of CFRP laminates after impact were measured by four- and three-point bending tests. The mechanisms of the damage growth which directly influences the residual strength were investigated. It was found that the propagation of the impact impression crack under compressive force induces reduction of the residual strength in the four-point bending test, and the sliding of the transverse cracks caused by the shear force induces it in the three-point bending test. Although the stress field in damaged CFRP laminates is complicated, the damage growth in CFRP laminate can be explained by macroscopic stress resultants.

In practical structures made of CFRP laminates, the bending moments, shear forces and in-plane forces are combined in a complicated manner. According to the present results, the combination of the bending moment and shear force effects helps prediction of the growth pattern of the damage after impact and the residual strength of the CFRP structure.

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