FRACTURE ASPECTS OF QUASI-ISOTROPIC CFRP LAMINATES UNDER UNIAXIAL COMPRESSION

Yuuki Kano[1], Masahiro Arai[2], Eiichi Hara[3], Takashi Ishikawa[4], Keita Goto[5]

[1]Graduate Student, Nagoya University, Fucho-cho Chikusa-ku, Nagoya, Japan
Email: kano.yuuki@g.mbox.nagoya-u.ac.jp
[2]Dept. Aerospace Engineering, Nagoya University, Fucho-cho Chikusa-ku, Nagoya, Japan
Email: arai@nuae.nagoya-u.ac.jp
[3]Japan Aerospace Exploration Agency, 6-13-1 Osawa, Mitaka, Japan
Email: eichi12@chofu.jaxa.jp
[4]National Composite Center, Nagoya University, Fucho-cho Chikusa-ku, Nagoya, Japan
Email: ishikawa@nuae.nagoya-u.ac.jp
[5]National Composite Center, Nagoya University, Fucho-cho Chikusa-ku, Nagoya, Japan
Email: goto@nuae.nagoya-u.ac.jp

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Abstract

Fracture aspects of carbon fiber reinforced plastic (CFRP) are more complicated than those of traditional metal materials. Composite materials exhibit sudden catastrophic fracture under longitudinal compression loading. Therefore, the location and types of failure can be observed from the aspect of the specimens after compression tests. However, the order of fractures, such as transverse crack, fiber breaking and delamination, is not clear. To clarify the fracture processes, we conducted compressive tests with coupon specimens observing failure of quasi-isotropic CFRP laminates by high speed imaging and optical microscopy. Firstly, high speed imaging showed the location of initial fracture and subsequent damages. In addition, the location of initial fracture is effected by the strain distribution in the thickness direction. Secondly, optical microscopy revealed that the initial fracture as a result of micro-buckling in longitudinal fiber bundle was occurred and this damage led to delaminations in the adjacent layers. Finally, from these results, the fracture mechanism of the laminates under uniaxial compression was considered.

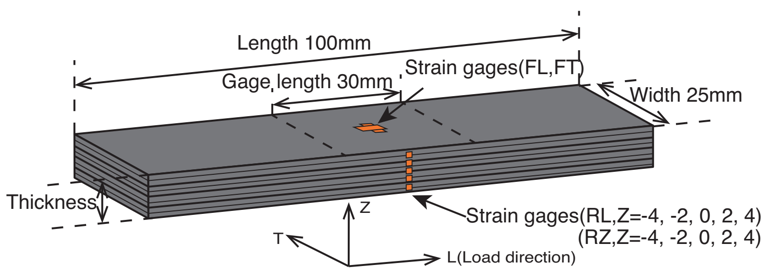

Figure 1. Schematic of the CFRP specimen.

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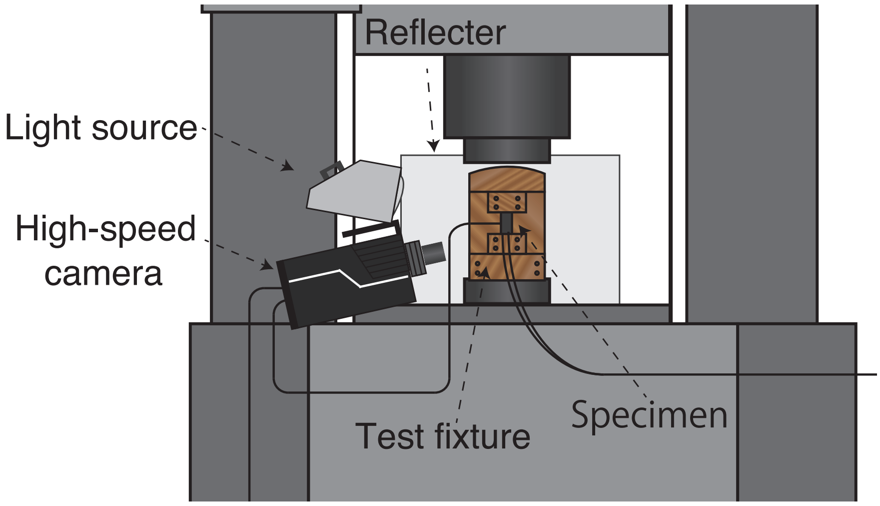

Figure 2. Overview of the compressive test system.

1. Introduction

Carbon fiber reinforced plastics (CFRPs) are increasingly used in major parts of aeronautical and aerospace structures. Material tests and component structural tests of composite structure are required and carried out in aircraft development program. It was reported that premature and catastrophic failure is observed under compressive loading tests. Generally, the compressive failure is called as "brooming failure" from observed failure aspect of the CFRP specimens. In the compressive tests using coupon specimens, buckling and failure at end specimen often occur. In order to avoid these difficulties, various standard tests were proposed [1-4] for the compressive tests of CFRP laminates. ASTM D 3410 shows several failure modes included brooming failure and instruct to report the failure mode about tested specimens. However, it is difficult to estimate the failure starting point and failure process in the catastrophic failure and fracture propagation. In the present study, high speed imaging[5] of compressive failure has been reported to describe and reveal the mechanism of compressive failure. Focusing the discussion on the strain distribution on the side of the CFRP specimen under compressive tests, the failure aspects and fracture propagation were considered in detail.

2. Experimental Procedure

2.1. CFRP Specimens

T800S/3900-2B Carbon-Epoxy prepreg (Toray) was used in the present study. 32ply and 64ply quasi-isotropic laminates$[45/0/\text{-}45/90]_{ns}$(n=4, 8) were made by autoclave. The CFRP was cut into 100mm length and 25mm width as shown in Fig. 1. Fiber orientation of the specimens 0° of the fiber orientation was defined to the fiber direction(L direction), and the 90° was defined to the transverse direction of the fiber (T direction), respectively.

Schematic figure of the compressive tests is shown in Fig. 2. For the experiments, universal material test equipment INSTRON 5985 was used. Using a jig of the compressive testing upper and lower sides of the CFRP specimen was clamped where gage length of the specimen is 30mm. Cross head rate in the compressive test was specified to 1mm/min. For the high speed imaging for the capturing the fracture phenomena, high-speed camera SHIMADZU HPV-X was employed[5]. The time interval for the high speed imaging was 8μsec. The number of flame are 256, and the total time for the capturing is 2050μsec.

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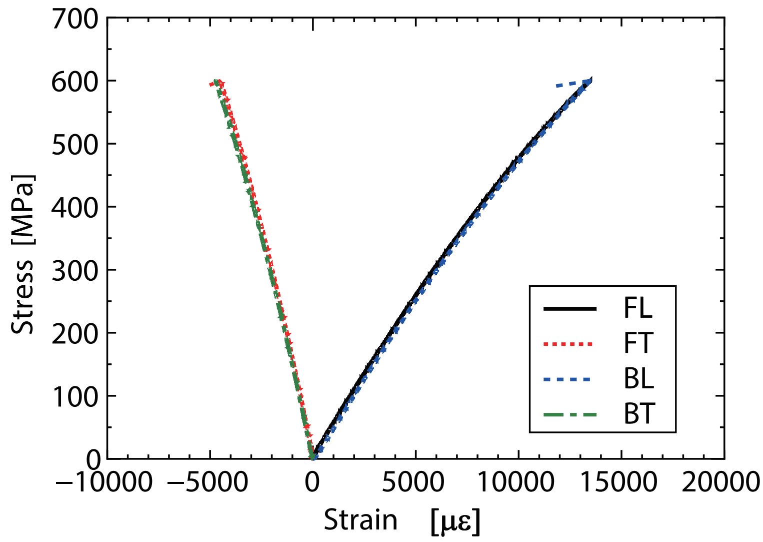

Figure 3. Stress-strain curves of $[45/0/\text{-}45/90]_{8s}$ laminate.

Photron HVC-SL was used for the lightning. In the present study aluminum was used to make the trigger signal when the catastrophic fracture occur in the CFRP specimen. An electric current was flowing to an aluminum ribbon, and that made a trigger signal occur by cutting the aluminum ribbon.

To evaluate the fracture aspects and initial fracture occurring in the CFRP specimens after compressive test, the side-surfaces of the specimens were observed by optical microscope KEYENCE VHX-600.

3. Experimental Results

As shown in Fig 1, strain gages (FL, FT) on the surface and those (BL, BT) on the back-surface of the specimen were employed to monitoring strain histories in the compressive tests of the quasi-isotropic 64ply specimens. The stress-strain relations obtained by these strain gages are shown in Fig. 3. Buckling behavior wasn't observed until the catastrophic fracture occurred in the specimen. When the strain for the longitudinal direction of the specimen reached $5000\mu\varepsilon$, the stress-strain relation became non-linear behavior as shown in the Fig. 3.

High-speed photograph obtained by 32ply quasi-isotropic CFRP are shown in Fig. 4. Initial fracture caused by compression loading in the quasi-isotropic laminate is that of the 0°layer damage on the middle plane in the CFRP laminate as shown in the Fig. 4(a). Starting from the initial damage, delamination propagated to the loading direction (longitudinal direction of the specimen). As shown in Fig. 4(b), the half-side part of the specimen began to bend as the delamination extended, then the total damage extend to the left side of the specimen with fiber breaking and delamination. Finally, it was confirmed that the damage extended from the middle plane to the right-hand-half side of the specimen occurring fiber breaking and delamination.

Pictures of the Quasi-isotropic 64ply CFRP laminate after compressive test are shown in Fig. 5(a). In these pictures, the fracture with Kink band on the right side near the middle plane and the brooming failure based on fiber breaking and delamination can be observed.

A series of high-speed photographs of the specimen when the failure and fracture occur are shown in Fig. 5(b)-(k). It was found that the origin of the fracture subjected to the unidirectional compressive load

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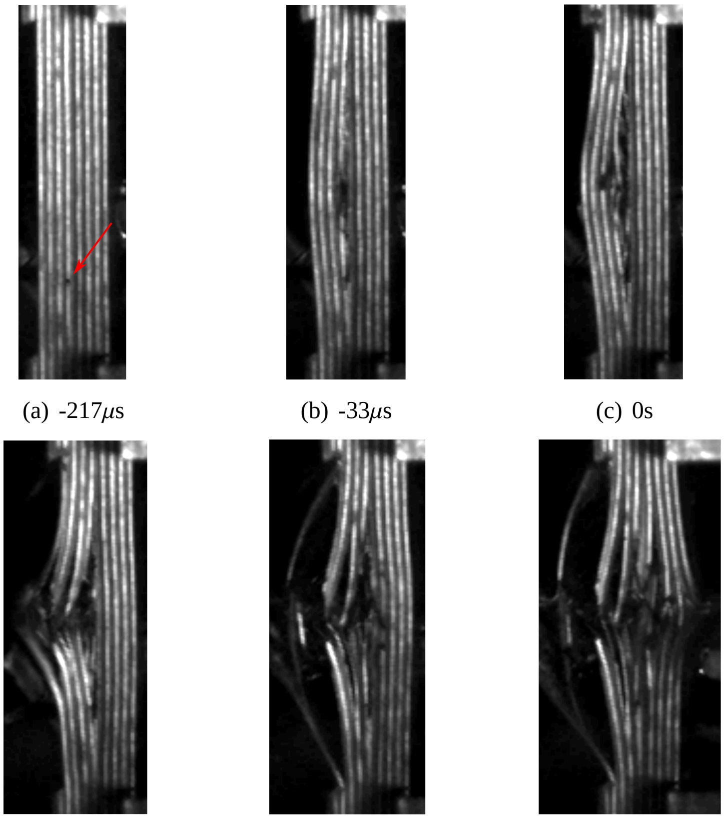

(a) -217μs (b) -33μs (c) 0s

(d) 14μs (e) 46μs (f) 62μs

Figure 4. High-speed imagings of T8-32p-#44.

arises on the 0°layer around the middle plane of the laminate. From this original fracture point, the fiber breaking and delamination occur and propagate sequentially to the outer layer of the laminate.

Observed from the high-speed photographs, when the initial fracture occur on the middle plane of the CFRP laminate, the damage and fracture extend from the 0° layer of middle plane to the outer layer. As shown in Fig.6, strains for longitudinal and transverse direction were measured with five series (2mm pitch) of strain gages which were put on the side surface of the specimen.

Fig.6 shows the strain data of the 64 ply quasi-isotropic CFRP laminate in Fig.5 when the fracture occurs. Note that the compressive strain is express as plus and the tensile strain is expressed as minus in this graph. The location of middle plane of the laminate is specified z=0. From Fig.6(a), the strain for the longitudinal direction indicates maximum value at z=0mm, and the tensile strain for the transverse direction indicates minimum value at z=0mm and maximum value at z=±2mm.

From these results, each layer deform into the transverse direction caused by Poisson's effect. On the other hand, deformation of the middle layer was restricted by adjacent outer layer. Therefore the longitudinal compressive strain indicates maximum value in the 0°layer on the middle plane and the 0°layer includes high strain energy compared with adjacent layers. From these factors, initial fracture occur in the 0° layer around the middle plane as shown in Fig.5(b). Namely, in the discussion of the strength of quasi-isotropic laminates, it was found that the compressive strength of the 0°layer is dominant.

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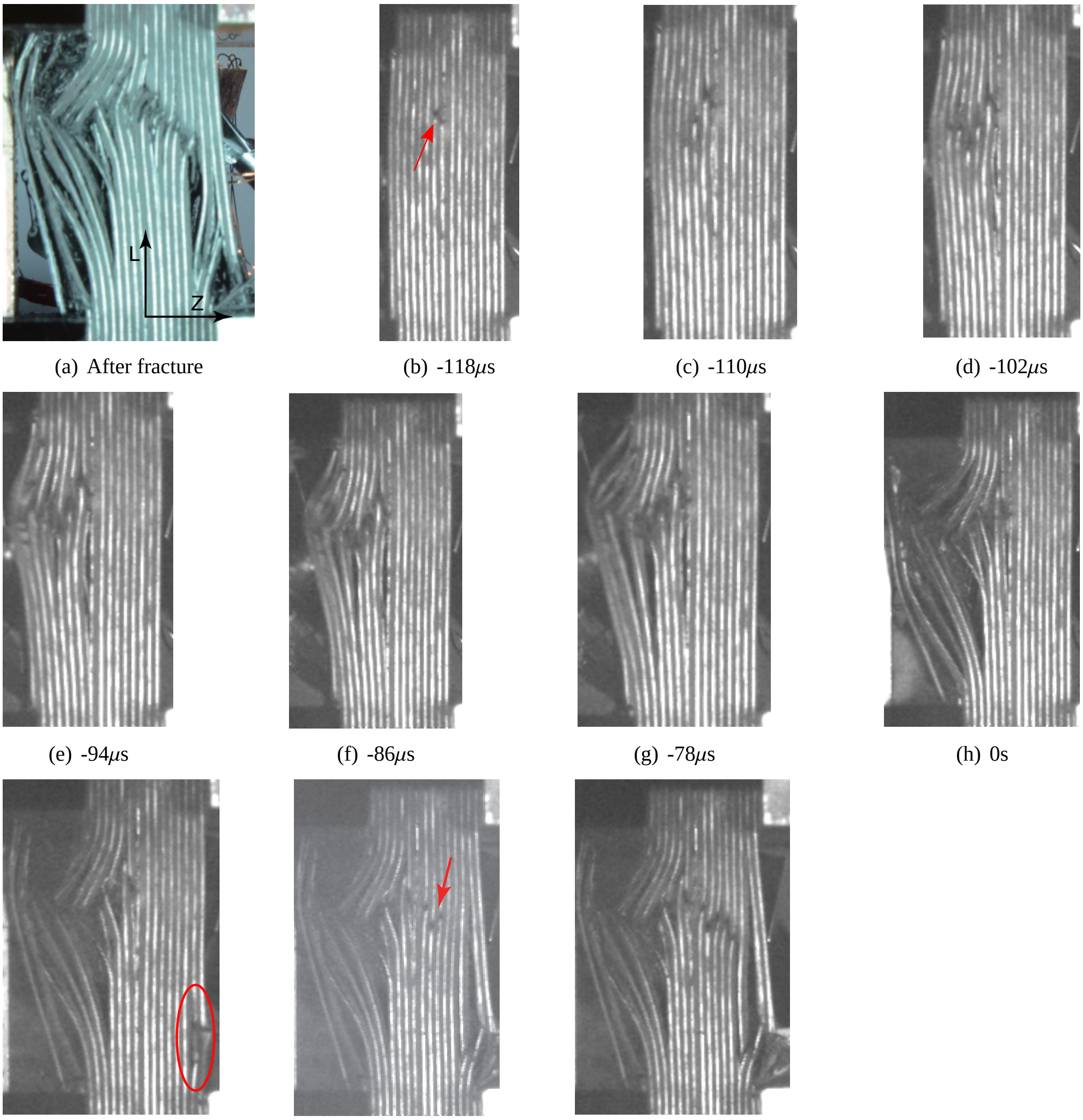
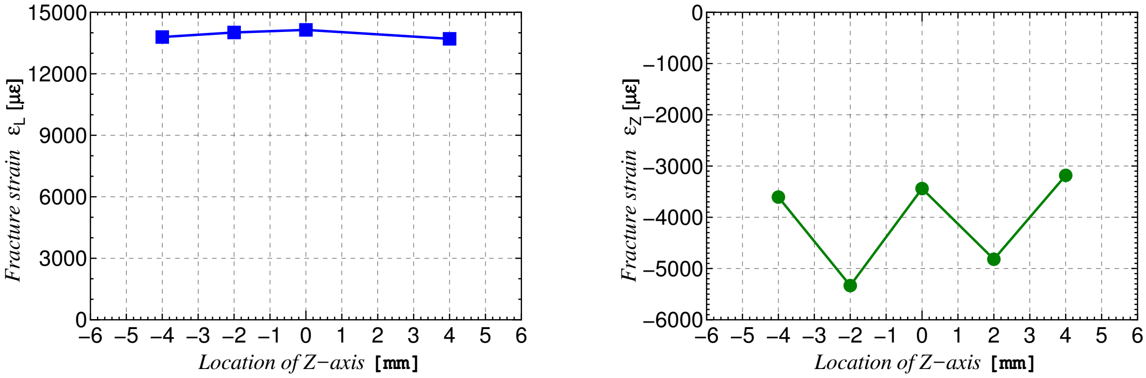


(a) After fracture (b) -118μs (c) -110μs (d) -102μs

(e) -94μs (f) -86μs (g) -78μs (h) 0s

(i) 1449μs (j) 1481μs (k) 1489μs

Figure 5. High-speed imagings of T8-64p-#11.



(a) L direction

(b) Z direction

Figure 6. Fracture strain distribution on the right surface of T8-64p-#11.

4. Conclusion

In the present study, to clarify the fracture processes of CFRP laminates, compressive tests with coupon specimens were conducted observing failure of quasi-isotropic CFRP laminates by high speed imaging and optical microscopy. High speed imaging showed the location of initial fracture and subsequent damages. In addition, the location of initial fracture is effected by the strain distribution in the thickness direction. Optical microscopy revealed that the initial fracture as a result of micro-buckling in longitudinal fiber bundle was occurred and this damage led to delaminations in the adjacent layers.

Therefore, microscopic damage of the 0°layer occur around the middle plane of the laminate, then the initial fracture leads the delamination of 45° and -45° adjacent layers. After that, bending deformation of the laminate occur, and the fiber breaking and delamination extend to the outer layers of the laminate. It was confirmed that the mechanism is the main mechanism of the fracture and damage propagation when the quasi-isotropic CFRP laminate is subjected to the unidirectional compressive loading.

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