Excellence in Science

Application Data Sheet

No. 39

Autograph Precision Universal Testing Machine

Material Testing & Inspection

Evaluation of Open-Hole CFRP

— Static Tensile Testing, Fracture Observation, and Internal Structure Observation —

■ Introduction

Recently, lightweight alternatives to conventional metal materials are being used as structural members where mechanical reliability is required. The main reason for this trend is that lighter products reduce transport weights, which reduces fuel consumption and carbon dioxide emissions during product transport. Fiber reinforced composite materials such as carbon fiber reinforced plastics (CFRP), which consist of a resin strengthened with carbon fibers, are extremely strong and light. Because of this, they are currently a material widely used in aircraft, and are expected to be used increasingly in various types of products, including automobiles, in order to make them lighter. For the development of fiber reinforced composite materials, not just a simple evaluation of their mechanical strength, but also the observation of failure events is important. In addition, from the perspective of quality management, the necessity for evaluation of internal structure of these materials, such as the oriented state of fibers and the presence of cracks, has increased.

In this article, we describe how we use a precision universal testing machine (Autograph AG-250kNXplus) and high-speed video camera (HyperVision HPV-X) (Fig. 1) to evaluate the static fracture behavior of a CFRP based on a test force attenuation graph and images of material failure. We also describe our subsequent examination of the state of the specimens internally using an X-ray CT system (inspeXio SMX-100CT) to investigate the state of fracture inside the specimen. Information on specimens is shown in Table 1. Specimens have a hole machined into their center that is 6 mm in diameter. Fracture is known to propagate easily through composite materials from the initial damage point, and when a crack or hole is present their strength is reduced markedly. Therefore, evaluation of the strength of open-hole specimens is extremely important from the perspective of the safe application of CFRP materials in aircraft, etc.

Table 1: Test Specimen Information

Laminate Structure	Dimensions L (mm) × W (mm) × T (mm), hole diameter (mm)
$[+45/0/-45/+90]_{2s}$	150 × 36 × 2.9, Φ6

Note: The CFRP laminate board used in the actual test was created by laying up prepreg material with fibers oriented in a single direction. The $[+45/0/-45/+90]_{2s}$ shown as the laminate structure in Table 1 refers to the laying up of 16 layers of material with fibers oriented at +45°, 0°, -45°, and +90° in two layer sets.

■ Static Tensile Testing (Ultra High Speed Sampling)

In this test, the change in load that occurs during specimen fracture was used as the signal for the HPV-X high-speed video camera to capture images. Specifically, the AG-Xplus precision universal testing machine was configured to create a signal when the test force on the specimen reaches half the maximum test force (referred to as Maximum test force in Fig. 3), with this signal being sent to the high-speed video camera. Static tensile testing and fracture observation were performed according to the conditions shown in Table 2. A test force-displacement plot for the open-hole quasi-isotropic CFRP(OH-CFRP) is shown in Fig. 2(a). A test force-time plot during the occurrence of material fracture is also shown in Fig. 2(b).

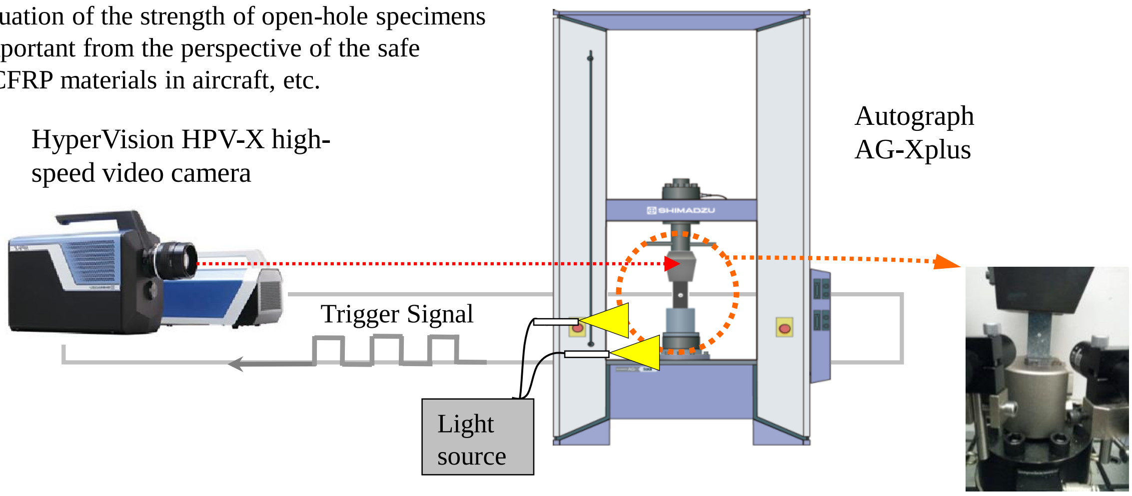

Fig.1: Testing Apparatus

Table 2: Test Conditions

Testing Machine	AG-Xplus
Load Cell Capacity	250 kN
Jig	Upper: 250 kN non-shift wedge type grips (with trapezoidal file teeth on grip faces for composite materials) Lower: 250 kN high-speed trigger-capable grips
Grip Space	100 mm
Loading Speed	1 mm/min
Test Temperature	Room temperature
Software	TRAPEZIUM X (Single)
Fracture Observation	HPV-X high-speed video camera (recording speed 600 kfps)
DIC Analysis	StrainMaster (LaVision GmbH.)

Note: fps stands for frames per second. This refers to the number of frames that can be captured in 1 second.

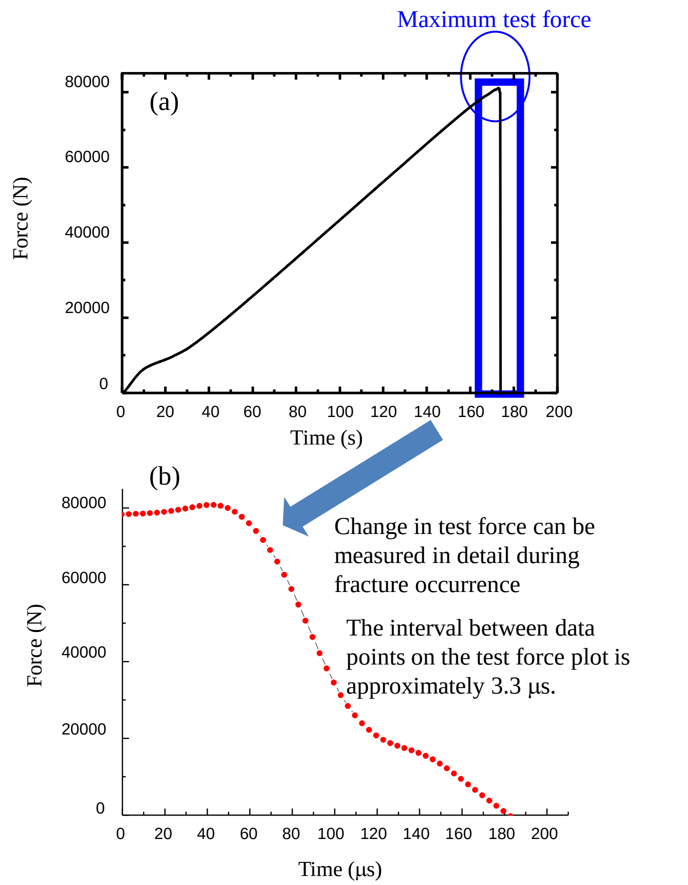

Fig. 2 (a) Test Force-Displacement Curve, and (b) Test Force-Time Curve (in Region of Maximum Test Force)

Fig. 2(a) can be interpreted to show the specimen fractured at the moment it reached the maximum test force, at which point the load on the specimen was suddenly released. This testing system can be used to perform high-speed sampling to measure in detail the change in test force in the region of maximum test force. The time interval between data points on the test force plot in Fig. 2(b) is 3.3 μs.

■ Fracture Observation (High Speed Imaging)

Images (1) through (8) in Fig. 3 capture the behavior of the specimen during fracture around the circular hole. Image (1) shows the moment cracks occur in a surface +45° layer. In this image, the tensile load being applied is deforming the circular hole, where hole diameter in the direction of the load is approximately 1.4 times that perpendicular to the load. In image (2), the cracks that occurred around the circular hole are propagating along the surface +45° layer. In images (3) through (6), a substantial change can be observed in the external appearance of the specimen near the end of the crack propagating to the bottom right from the circular hole. This suggests not only the surface layer, but internal layers are also fracturing. Based on the images of the same area and the state of the internal layers that can be slightly observed from the edges of the circular hole in images (7) and (8), the internal fracture has quickly propagated in the 18 μs period between images (3) and (8).

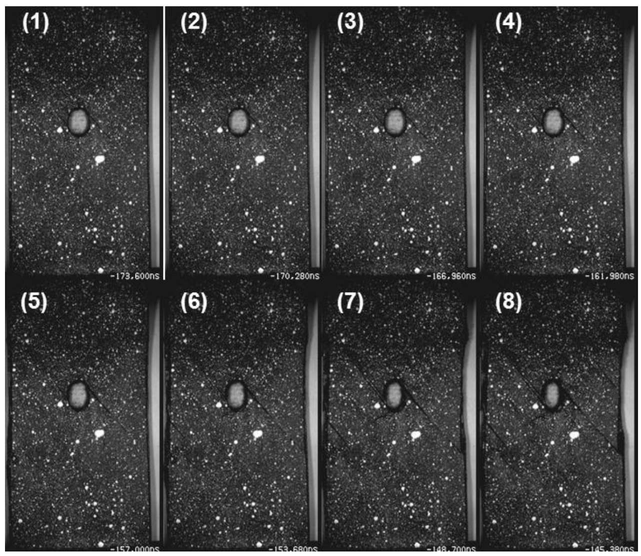

Fig. 3: Observations of OH-CFRP Fracture

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Images (1) through (8) of Fig. 4 show the results of performing Digital image correlation (DIC) analysis on the fracture observation images of Fig. 3. Black signifies areas of the surface layer of the specimen under little strain, and red signifies areas under substantial strain. Looking at images (1) through (4), we can see that strain around the circular hole is focused diagonally toward the top-left (-45°) and toward the bottom-left (+45°) from the circular hole. Images (5) through (8) show the focusing of strain diagonally toward the bottom-right (-45°) and toward the top-right (+45°) from the circular hole in areas where it was not obvious in images (1) through (4). This shows an event is occurring in the surface layer of the specimen that is similar to the process of fracture often seen during tensile testing of ductile metal materials, which is crack propagation in the direction of maximum shearing stress.

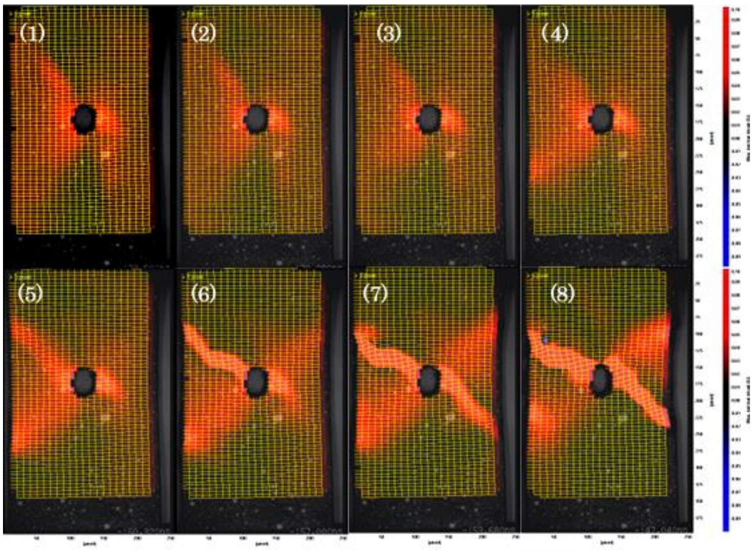

Fig. 4: Observation of OH-CFRP Fracture (DIC Analysis)

■ Internal Structure Observation (CT)

Next, internal observations were performed around the circular hole using a micro focus X-ray CT system to check the state of internal damage to the specimen. The SMX-100CT micro focus X-ray CT system (Fig. 5) is capable of capturing CT images at high magnification. The system rotates a specimen between an X-ray generator and an X-ray detector, uses a computer to calculate fluoroscopic images obtained from all 360° of rotation, then reconstructs a tomographic view of the specimen (Fig. 6). This system was used to perform a CT scan of the fracture area of the OH-CFRP after the static tensile testing and fracture observation performed as described in the previous section, so that the cracks that occurred inside can be observed.

Fig. 5: Shimadzu inspeXio SMX-100CT Micro Focus X-Ray CT System

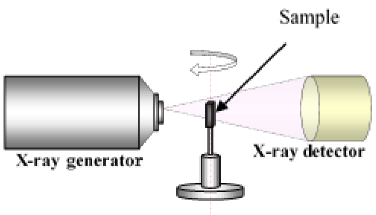

Fig. 6: Illustrated Example of X-Ray CT System Operation

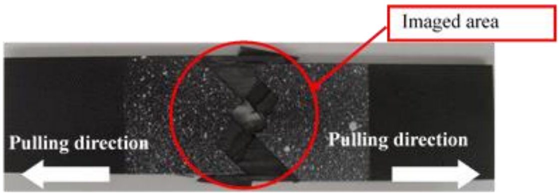

Fig. 7: Specimen After Static Tensile Testing (Specimen Used for CT Scan)

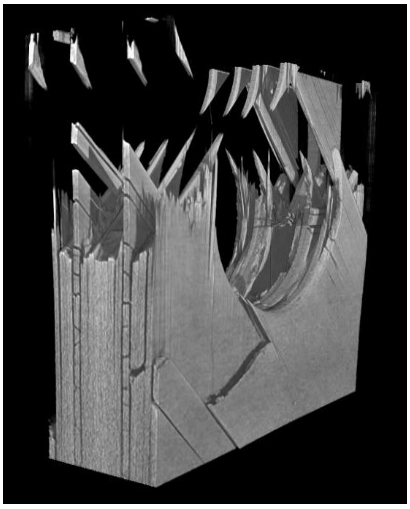

Fig. 8: Fracture Area 3D Image No. 1

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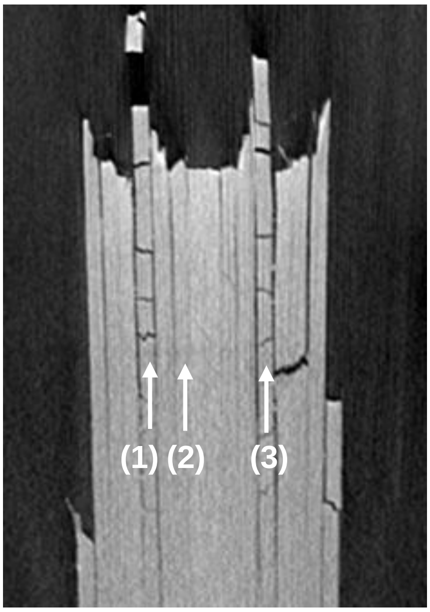

Fig. 9: CT Cross-Sectional Images of the Fracture Area

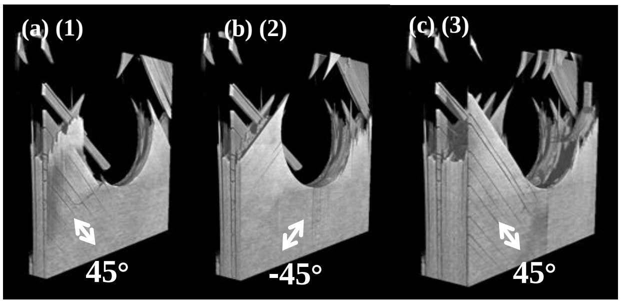

Fig. 10: Fracture Area 3D Image No. 2

Cross-sectional images of the specimen are shown as a 3D image in the 16 layers shown in Fig. 9, we can see that most cracks in the matrix occur in the +45° layer inside the specimen, indicated by the number (1) and (3). (shown in Fig. 10 (a) and Fig. 10 (b), respectively). In this layer, the carbon fibers are all aligned together in a +45° orientation, and the multiple matrix cracks occurring in this layer are probably due to the shearing force caused in this layer by tensile loading, together with deformation of adjacent layers in the direction of the loading. For comparison, a 3D image of the -45° layer inside the specimen (Fig. 9 (2)) is shown in Fig. 10 (b). As is clear from the image, the matrix cracks that occurred in the +45° layer have not occurred in the -45° layer. This difference in fracture state has probably arisen due to different shearing forces and load directions occurring in each layer. Such detailed observation of fracture surfaces associated with multiple matrix cracks was difficult by conventional methods, since to observe fracture surfaces the specimen was processed such as by cutting and embedding in resin, which changed the characteristics of the specimen. However, by using the high-resolution X-ray CT system as described in this article, there is little X-ray absorption difference between air and specimen, and it is possible to observe the state of complex internal damage, even for OH-CFRP in which microscopic damage is normally difficult to observe by X-ray.

■ Acknowledgment

We would like to extend our sincere gratitude to the Japan Aerospace Exploration Agency (JAXA) for their cooperation in the execution of this experiment.

Note: The analytical and measuring instruments described may not be sold in your country or region.

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