Advanced Composite Materials
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tacm20

Damage initiation and growth in composite laminates during open hole compression tests

Hiroshi Suemasu [a], Yosuke Naito [a], Katsuhisa Gozu [a] & Yuichiro Aoki [a]

[a] Department of Engineering and Applied Sciences, Sophia University, Tokyo, Japan

Version of record first published: 20 Sep 2012.

To cite this article: Hiroshi Suemasu , Yosuke Naito , Katsuhisa Gozu & Yuichiro Aoki (2012): Damage initiation and growth in composite laminates during open hole compression tests, Advanced Composite Materials, 21:3, 209-220

To link to this article: http://dx.doi.org/10.1080/09243046.2012.723330

Advanced Composite Materials
Vol. 21, No. 3, June 2012, 209–220

Taylor & Francis
Taylor & Francis Group

Damage initiation and growth in composite laminates during open hole compression tests

Hiroshi Suemasu*, Yosuke Naito, Katsuhisa Gozu and Yuichiro Aoki

Department of Engineering and Applied Sciences, Sophia University, Tokyo, Japan

(*Received 12 September 2011; accepted 13 June 2012*)

The damage initiation and growth near the edges of a circular open hole of laminated composite plates under compressive load were experimentally studied to understand the physical meaning of the open hole compression strength. Damage growth sequence was investigated mainly through optical micrographs of various sections of damaged specimens. When comparatively tough interface laminates were tested, various damages occurred following initial kink band damage in the 0° layers, such as zigzag damage composed of kink bands and transverse cracks in ±45° layers, matrix cracks in 0° layers, and delaminations above and below the 0° layers. High-speed video images showed that unstable growth of the delaminations near the surface was observed prior to the final failure, accompanying buckling of the delaminated layer. The possible sequences of the damage growth were discussed through consideration of the above damage data.

Keywords: composite laminate; open hole; compression; damage; micro-buckling

1. Introduction

Composite laminates are used particularly for aerospace structures due to their high specific strength and stiffness. However, its insufficient toughness and complex damage accumulation prior to failure make weight saving of the composite structures and their application to primary structures difficult. It is required to evaluate the overall performance of the composite laminates by appropriate methods considering the damage tolerant properties. The open hole compression (OHC) test as well as the compression after impact (CAI) test provide us useful design data of the compression strength for aeronautical structures considering damage tolerant performance [1]. OHC test is attractive since it is more economical, less scattered, and easier to perform compared to CAI test whose data have been widely used as a design data considering damage tolerant performance for aeronautical primary structures. Correlation between the CAI and OHC strength has been mentioned by many researchers, while some difference has been also reported [2]. The mechanical meaning of OHC strength is required to be understood so as to properly utilize the OHC strength as design data.

The OHC strength of a composite laminates with high interlaminar toughness is a compressive strength with stress concentration as well as a compressive strength with damage, because some load increase is required after damage initiation for the laminate to totally break. The stress distribution around the circular hole is complex due to the inhomogeneous

*Corresponding author. Email: suemasu@sophia.ac.jp
The present work was conducted under the collaborative research between Sophia University and Japan Aerospace Exploration Agency.

ISSN 0924-3046 print/ISSN 1568-5519 online

http://dx.doi.org/10.1080/09243046.2012.723330
http://www.tandfonline.com

nature of laminates consisting of different direction layers as well as the stress concentration. The relatively weak compressive strength of the fiber reinforced plastics in the fiber direction, resulted from micro-buckling of the fiber embedded in the compliant matrix, depends on not only the constraint of neighboring layers but also nonuniform stress distribution at the notch edge. The singularity of the interlaminar stress makes the failure behavior difficult to predict, in spite that the power of the singularity is much smaller than one half. The singular interlaminar stress at the surface of the hole may not directly cause the initiation of the interlaminar delaminations owing to the stress relaxation mechanism of the interface. The thermal residual stress may have some effect. The laminates of high interlaminar toughness fail after some damage accumulation, while those of weak interlaminar toughness fail at the instant of damage initiation. As various factors influence the failure process, it is difficult to evaluate damage initiation, farther damage accumulation, and the strength of the laminates from the basic data such as compression strength, interlaminar toughness, stress distribution, etc.

Many investigation works [3–22] on damage initiation and accumulation as well as failure problem in a composite laminate having a circular hole under compressive load have been carried out because of scientific interest in the compressive failure mechanism as well as the practical importance of the problem. Ishikawa et al. [3] have studied the OHC strength and proposed an OHC test method, which is easy to conduct. Suemasu et al. [4] mechanically and numerically showed the possibility of the slow stable growth of the compression failure of 0° layer after short unstable propagation. Lessard [5] mentioned the dependence of fiber buckling stress on the distribution of the loading stress. Guynn et al. [6,7] parametrically studied notch sensitivity of the failure. Waas and his coauthors [8–10] showed various damage morphology appearing near the hole edges and discussed the damage and failure mechanism. Soutis and his coauthors [11–13] studied the compressive failure from a view point of a balance of energy. Iarve [14,15] analytically obtained asymptotic solution of interlaminar traction. Lankford [16] studied the effect of hydrostatic stress. Wisnom et al. [17] experimentally studied scaling effects of the notched laminate. Ireman and Eriksson [18] studied the failure problem under various loading conditions. Numerical simulation of the damage accumulation and failure analysis has been conducted by many researchers, for example [19–23]. However, there still remain many uncertainties about the failure mechanism to be solved.

An experimental work was conducted to observe the damage initiation and accumulation process during the OHC test of quasi-isotropic laminates to study the mechanism to control the OHC strength and to understand the mechanical meaning of OHC strength.

2. Specimen and experimental fixture

The material system tested was CFRP (T800/#8633, Toray) quasi-isotropic laminates ($[45°/0°/-45°/90°]_{2s}$). The mechanical properties of this material system are listed in Table 1 [24]. This laminate is aeronautical grade and has comparatively high interlaminar toughness. Specimens shown in Figure 1(a) are cut out from the laminated plates prepared according to the supplier's instruction by using hot-press machine (mini TEST PRESS-10, Toyo Seiki Seisaku-sho, Ltd.) in the laboratory. The surface of the hole was carefully machined and polished to make the effect of the surface defects as little as possible (Figure 1(b)). The specimens were set in the fixture for OHC tests (NAL III method) proposed by Ishikawa et al. [3] shown in Figure 2(a).The test was conducted in a screw-driven test machine. The both sides of the window portion of the anti-buckling parts of the fixture were machined to make the observation by microscope possible during the test (Figure 2(b)). The anti-buckling parts were fixed to the stiff base unit of the fixture with four bolts by a finger tight condition so that both the out-of-plain displacement and the friction did not considerably affect the test results. The both ends of the specimen were set

Table 1. Material properties of T800H/#3633 system [24].

Elastic constant		
Unidirectional composite	E_L	156 GPa
	E_T	8.9 GPa
	ν_{LT}	0.34
	Tensile strength	2700 MPa (1.7%)
	Compressive strength[a]	1420 MPa (0.91%)
Interlaminar fracture toughness	G_{Ic}	200 J/m^2
	G_{IIc}	1650 J/m^2
Quasi-isotropic	E_L	57.5 GPa
	Tensile strength	875 MPa (1.51%)
	Compressive strength	818 MPa (1.42%)
	OHC strength	304 MPa (0.53%)
	CAI strength	147 MPa (0.26%)

[a]The compressive strength is referred to datum of Ref. [25], because the datum is not shown in Ref. [24]

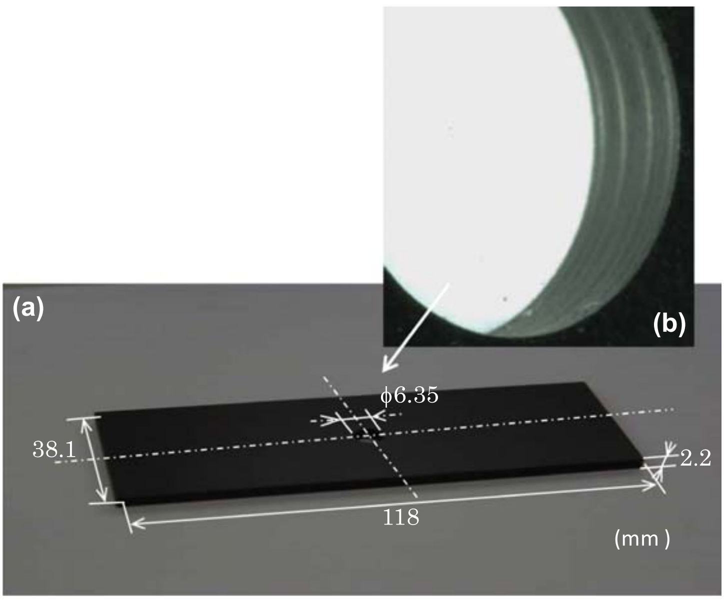

Figure 1. Specimen for OHC test: (a) the dimensions of the specimen and (b) the hole surface.

between two steel blocks with two bolts and also by a finger tight condition. Top of the fixture was pushed by a low cross-head speed (0.2 mm/min) in order not to miss the initial damage.

3. Results and discussion

3.1. Loading history and damages

In Figure 3, load–displacement history is obtained. Insufficient surface contact at the initial stage of the loading resulted in a gradual load increase until the linear state was attained. Slight reduction of stiffness may be observed at about 19 kN due to compression damage in a 0° layers at the hole edge and some stiffness reduction can be seen above 22 kN owing to the

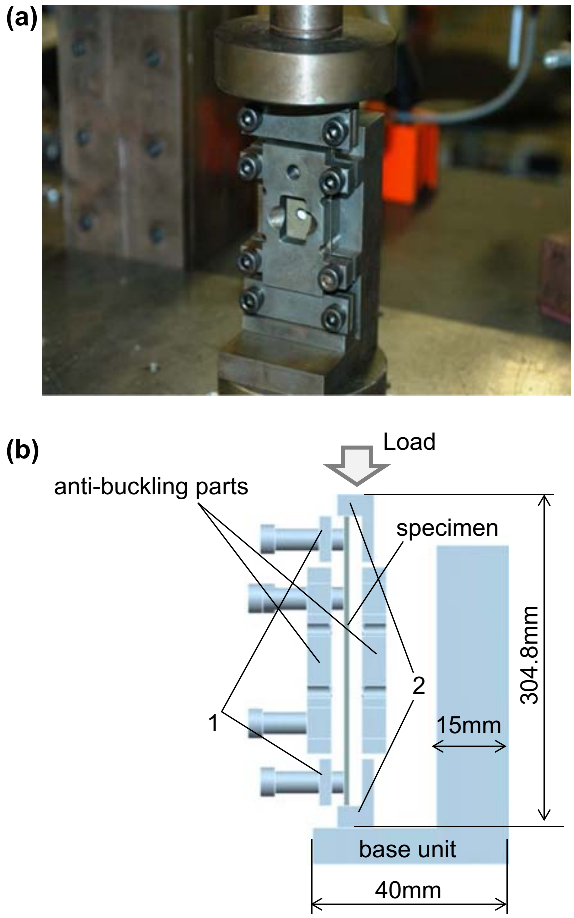

Figure 2. OHC test fixture [5].

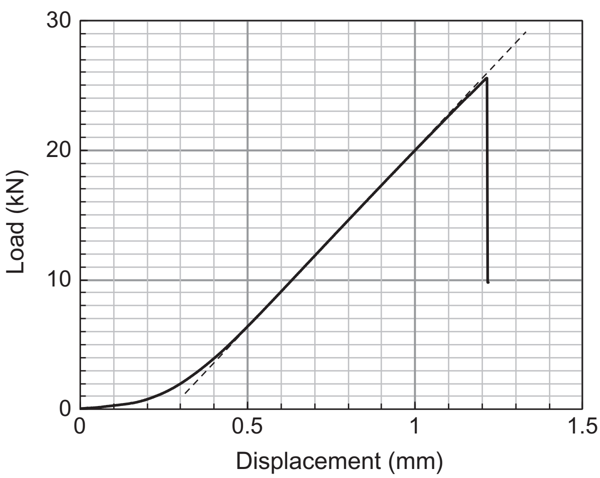

Figure 3. A relationship between the applied load and cross-head displacement.

further gradual reduction of the stiffness probably caused by the stable damage growth. The specimen finally failed at 25.5 kN.

The OHC strength of this specimen was about 304 MPa. It was very close to the value given in the JAXA database [24]. The fine treatment of the hole surface having some effect on the initial damage did not cause noticeable difference on the final strength of OHC specimen. It is because, the final failure occurred under the existence of stably accumulated damage whose size and significance depended not on the initial surface condition but on the load level for the laminates having sufficiently high interlaminar toughness. Considering the stress concentration (10.7 times of nominal stress) obtained by a three-dimensional finite element analysis, the maximum compressive stress in the 0° layer at the occurrence of the initial damage was about 2420 MPa. The strain at the transverse hole edge at this load was about 1.55%. This value was much higher than the failure strain of the unidirectional composite (0.9%) and a little higher than the failure strain of quasi-isotropic laminate (1.4%). (The strains were simply derived by dividing the strength by the Young's modulus.) The 0° layers in the quasi-isotropic laminate are between ±45° layers and their deformation normal to the load is constrained by the neighboring ±45° layers. For the quasi-isotropic open hole specimen, the compressive stress in the fiber direction is high only in the neighborhood of the transverse hole edge. So, the fibers in the neighborhood of the transverse hole edge are supported by not only the ±45° layers but also the neighboring 0° unidirectional composite material compressed by lower stress. The fibers near the hole were a little difficult to deflect and it was the reason that the initial damage load in the 0° layer being caused by a fiber microbuckling occurred at a higher stress than uniform compression condition. It is an important issue to identify the reasons of the dependence of the fiber buckling stress on the stacking sequence and nonuniform stress.

3.2. Damage observed during the experiment

Figure 4 shows video images taken through an optical microscope during compression test. Local compressive failure was first observed in a 0° layer at 18 kN for this specimen and the compression damage sequentially occurred in all 0° layers with the increase of the load before the final failure. The damaged area spread in the circumferential direction by some amount with the load increase. Delaminations stemmed from the compression damage were found in the photograph at 23 kN. Figure 5 is a sequence of the damage growth around the open hole just before the final failure taken by a high-speed video camera (Nac Image Technology Inc. ST-709). The delamination grew at one side of the hole and showed unstable rapid growth accompanying buckling of the delaminated surface layer. The delaminated portion failed due to bending caused by the buckling. During the unstable growth of the damage, another delamination started growing from the other side of the hole in the other transverse direction also accompanying bending failure. Finally, the specimen violently failed.

3.3. Damage inside the specimen

We suspended the experiment and cut the damaged specimens at several sections and carefully polished the cut surfaces. The polished surfaces were observed by an optical microscope to investigate the damage accumulation sequence in the specimens. Micrographs of cross sections of the damaged specimens are shown in Figure 6 whose tests were stopped at the load of 23 kN(a) and 24.4 kN(b), respectively. The sections located at the transverse edge of the hole where the stress was most concentrated. The strongly kinked portions near the hole surface were probably just aside these photographed portion. The photograph at the load of

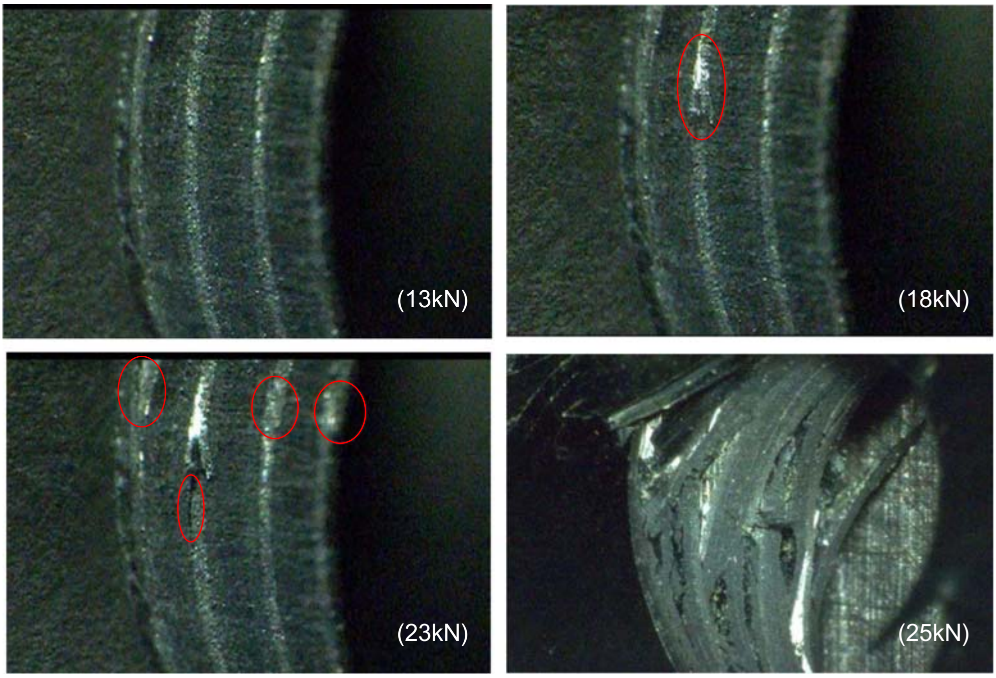

Figure 4. Compressive failures of zero degree layers that occurred in the transverse surface of the hole before failure. Delaminations starting from the damage were seen near upper surface (23 kN).

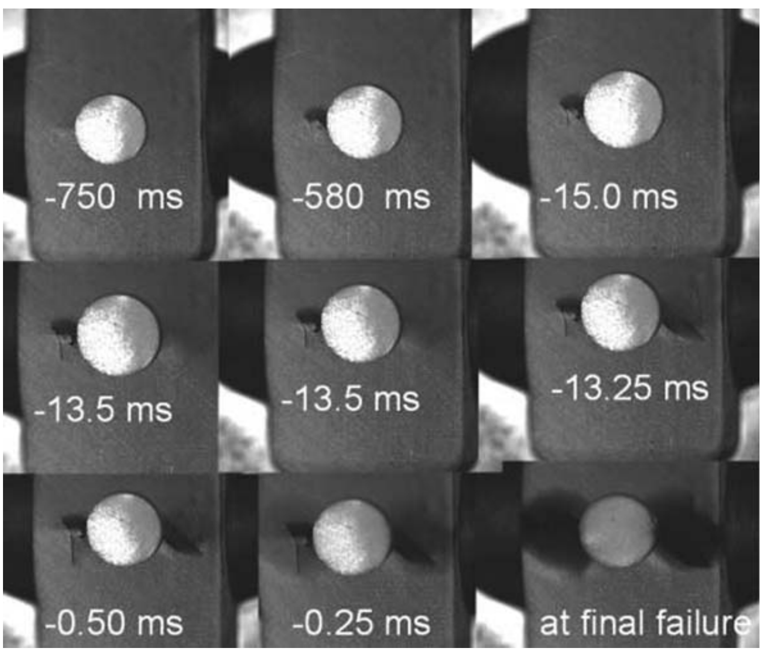

Figure 5. A high-speed video pictures. The times written in the figure mean the time before the final failure.

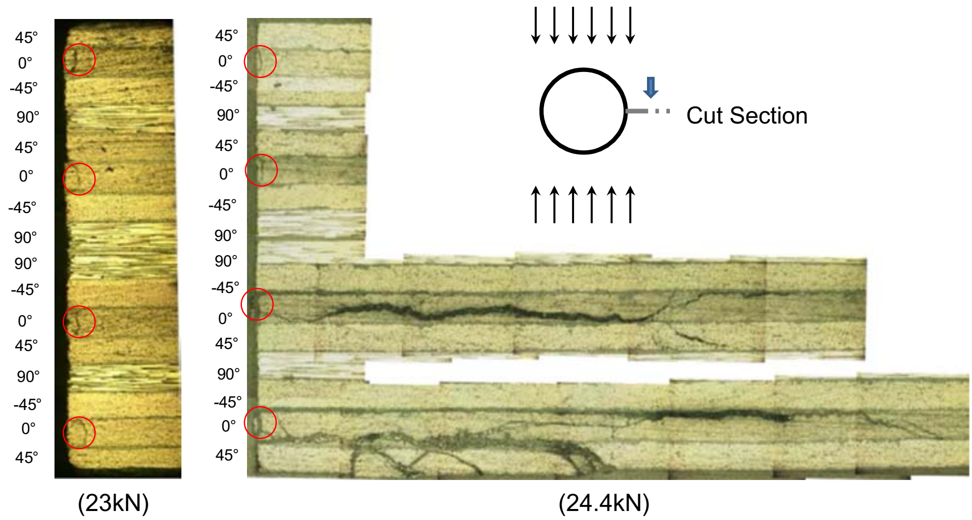

Figure 6. Micrograph of a cross section normal to the load near the hole surface. Matrix cracks are found in a 0° layer near the hole surface which seems to emanate from the damage in 0° compressive failure.

24.4 kN was thought to be the stage just before the failure. The matrix cracks normal to the interface and parallel to the load near the hole surface in the 0° layers were probably originated from the micro-buckling of the 0° layers where the fibers pushed out from the hole surface. Significant delaminations and matrix cracks stemmed from the delaminations horizontally propagated along and in the 0° layers as shown in the Figure 6(b). They were probably originated from the kink band where the fibers kinked in the thickness direction (explained in the following paragraph). The matrix cracks in the bottom layer were the result of the buckling.

A micrograph of an internal horizontal surface in a 0° layer is shown in Figure 7. The specimen was ground down from the surface to the 0° layer and the surface was well polished before photographed. There is a propagated compression failure of the length about 3 mm from the hole surface normal to the load. The magnified photographs at the position (a)–(d) showed that broken fibers near the hole edge inclined in in-plane direction (a), while fibers inclined in thickness direction at the other portions (a)–(d). Because deformation was weakly constrained in the in-plane direction compared to the thickness direction near the hole surface and vice versa the constraint became stronger in the in-plane direction than the out-of-plain direction apart from the hole surface. The micrographs (e) and (f) show the damage at the cross sections parallel to the load near the hole surface and A–A section indicated in the top photograph of Figure 7. Several overlapped kink bands are seen in the photograph. Damaged portion was strongly distorted near the hole surface and less deformed inside the specimen apart from the hole surface. A micrograph of a cross section of the other specimen parallel to the loading direction but a little apart from the hole surface is shown in Figure 8. There are two delaminations emanated from the kink band and growing to the left and the right, respectively, where opening stress should exist.

Figure 9 is a micrograph of a −45° layer. There was zigzag pattern damage, one of which was kink bands and the other matrix cracks. The fibers in the kink band inclined to the thickness direction. The matrix cracks occurred due to shear stress and their surfaces were not very smooth. This zigzag damage probably occurred due to the increased compression

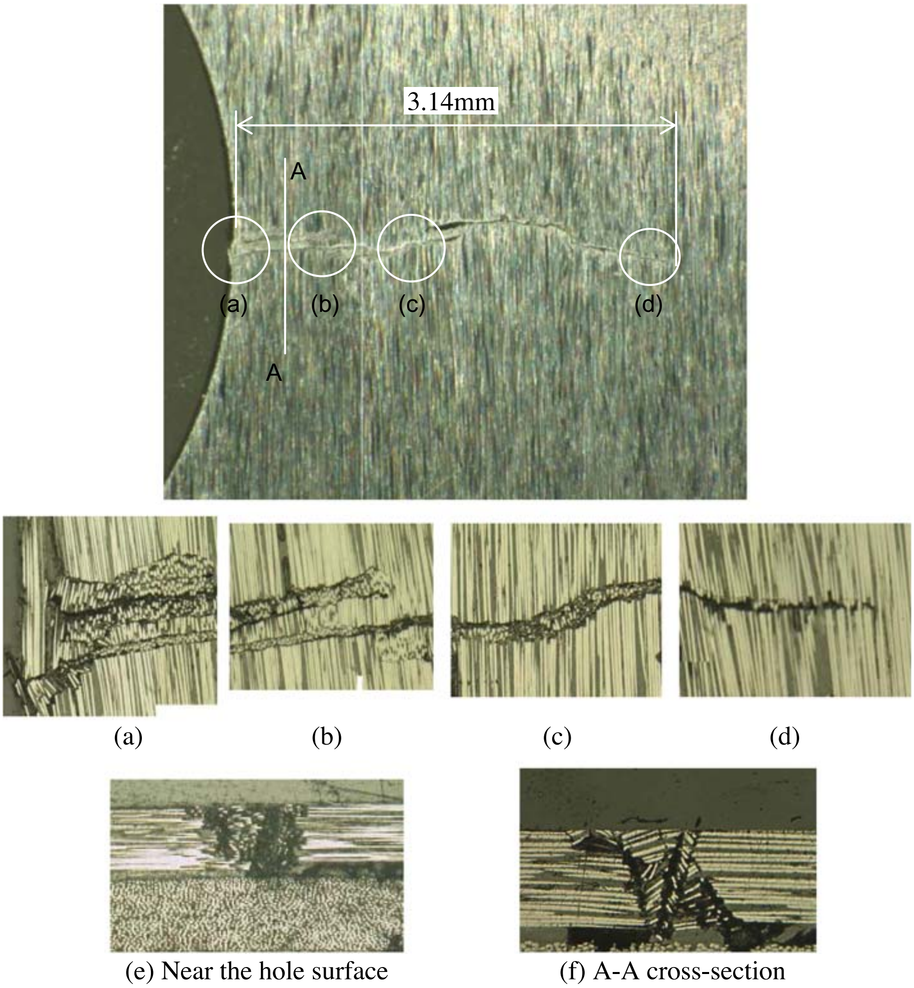

Figure 7. Damage in 0° layer. Kinking failure progressed from the hole surface. The loading direction is horizontal.

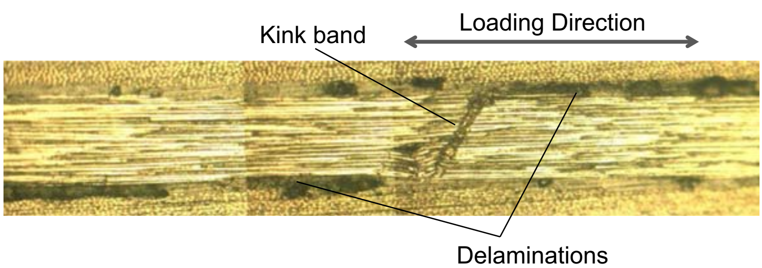

Figure 8. Damage in the cross section parallel to the loading direction.

stress after the failure of 0° layer. This damage must cause strong stiffness reduction of the damaged portion and further stress concentration around the damaged portion.

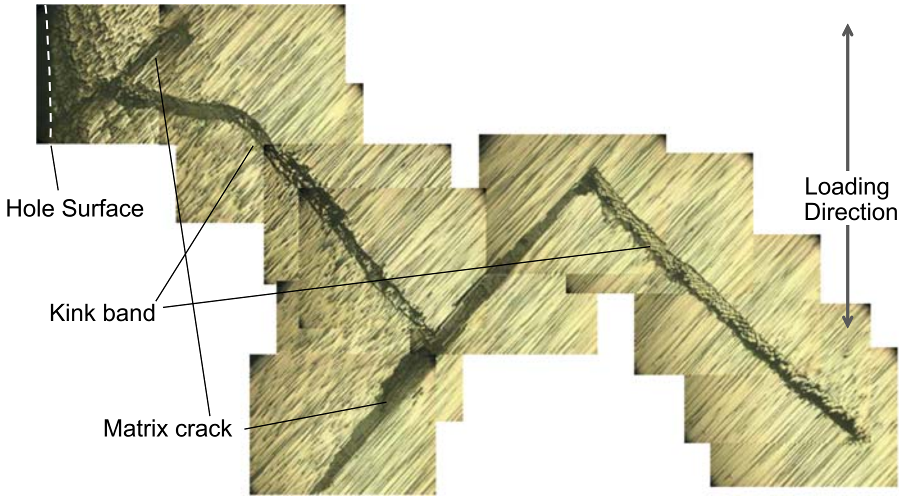

Figure 9. Damage in the −45° layer (third layer from the surface).

The kink band in 0° layer sometimes started from a point inside the specimen a little away from the transverse edge of the hole as shown in Figure 10. This damage may not be observed from the hole surface during the test. Shear stress being zero just at the transverse edge is considerably high near the starting point of this damage and shear deformation of the material before the failure might have some effect on the load of the initial damage. This phenomenon was mentioned by Waas et al. [8].

The damage state of the whole layers was checked for several damaged specimens by polishing the specimens from the top surface to the bottom surface. Figure 11 shows the photographs

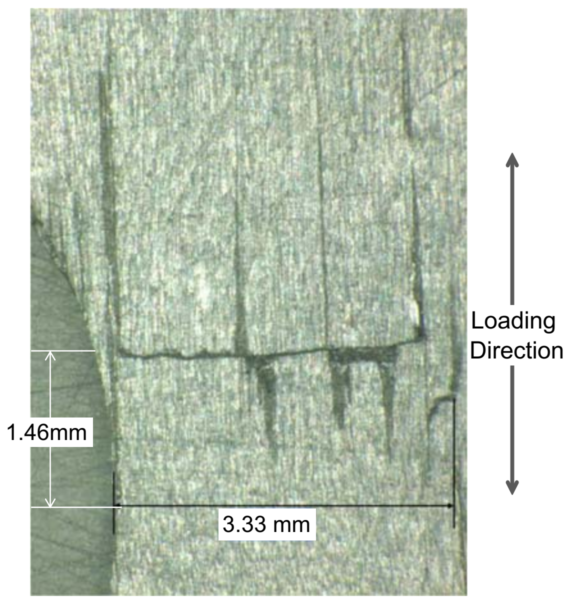

Figure 10. The damage observed in 0° layer away from the transverse edge of the hole (at 23kN, 6th layer).

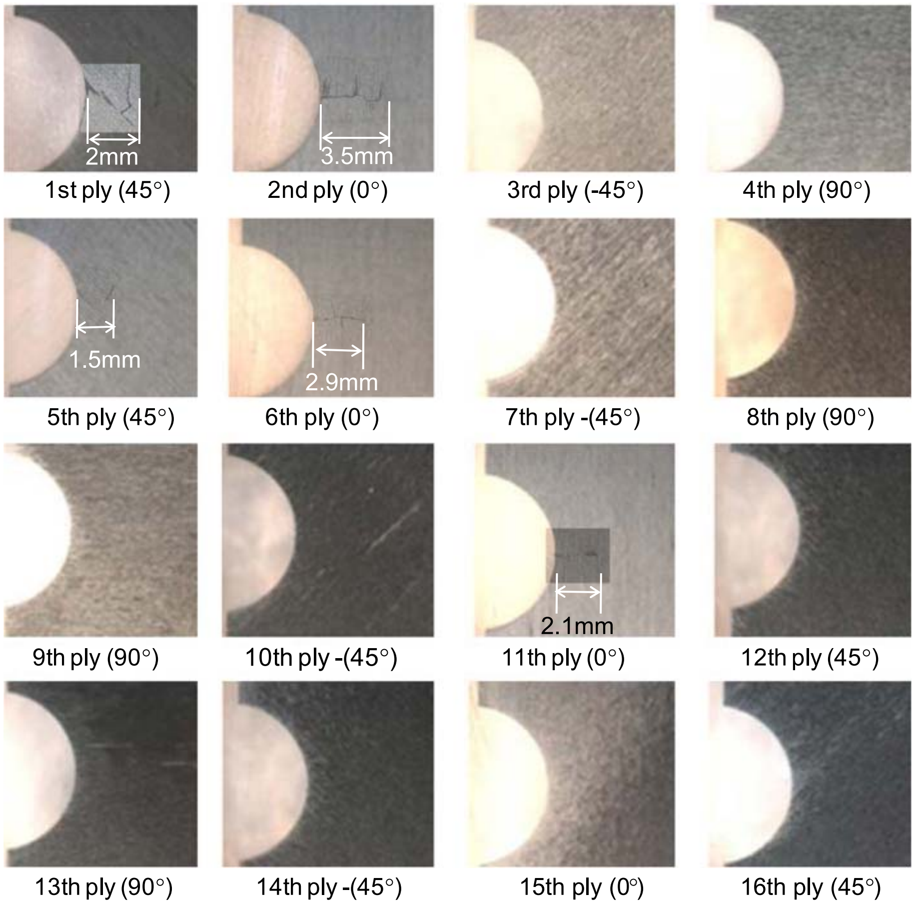

Figure 11. The damage of the whole 16 layers when the test was suspended at 24 kN.

of all the layers whose test was stopped at the load of 24 kN. The kinking damage (similar to the damage shown in Figure 7) was found at the transverse edges of the hole in three 0° layers. The 45° inclined damages (similar to the damage shown in Figure 9) were found at first and the fifth 45° layers above the damaged 0° layers. We found no damage in the other layers.

4. Conclusion

OHC test was conducted on quasi-isotropic composite laminates (T800/#8633) having comparatively tough interface and damage accumulation process was observed by several methods. The compressive damage (kinking band) firstly grew normal to the load in 0° layers which was probably originated by fiber micro-buckling near the transverse edge of the hole surface. Sometimes, the compressive damage was emanated from the position a little apart from the transverse hole edge where the shear stress is considerable. Zigzag pattern damage in ±45° layers consisting of compressive failures in fiber direction and matrix cracks followed the damage of the 0° layer and this damage was thought to play an important role in the failure process by increasing the stress concentration around damage. Delaminations emanated from the kinking bands. The specimens collapsed with unstable delamination growth accompanying buckling of the delaminated surface layer.

Acknowledgments

The authors sincerely express their thanks to Mr Keita Suzuki and Akio Masai for their contributing to the experimental works during their student years.

References

[1] SACMA. SRM 2R-94, Compression after impact properties of oriented fiber-resin composites; 3R-94, Open-hole compression properties of oriented fiber-resin composites. In: Recommended methods test manual for composites; 1994.

[2] Ishikawa T, Aoki Y, Suemasu H. Pursuit of mechanical behavior in compression after impact (CAI) and open hole compression (OHC). Proceedings of the 15th international conference on composite materials (ICCM-15), [CD-ROM] Durban, South Africa; 2005.

[3] Ishikawa T, Shikata N, Hamaguchi Yasumasa, Ben Goichi. Behavior in open hole compression (OHC) tests and proposal of shorter specimen. Proceedings of the 14th International Conference on Composite Materials-ICCM-14, [CD-ROM], Sandiego, CA, USA; 2003.

[4] Suemasu H, Takahashi H, Ishikawa T. On failure mechanism of composite laminates with an open hole subjected to compressive load. Composite Science and Technology. 2006;66:634–41.

[5] Lessard LB, Chang F-K. Damage tolerance of laminated composites containing an open hole and subjected to compressive loadings: Part I – analysis. Journal of Composite Materials. 1991;25:44–64.

[6] Guynn EG, Bradley WL, Ochoa OO. A parametric study of variables that affect fiber microbuckling initiation in composite laminates: Part 1 – analysis. Journal of Composite Materials. 1992;26 (11):1594–616.

[7] Guynn EG, Ochoa OO, Bradley WL. A parametric study of variables that affect fiber microbuckling initiation in composite laminates: Part 2 – experiments. Journal of Composite Materials. 1992;26(11):1594–616.

[8] Waas AM, Babcock CD, query J, Knauss WG. An experimental study of compression failure of fibrous laminated composites in the presence of stress concentration. International Journal Solids and Structures. 1990;26(9/10):1071–98.

[9] Ahn J, Waas AM. Prediction of compressive failure in laminated compression at room and elevated temperature. American Institute of Aeronautics and Astronautics Journal. 2002;44(2):346–58.

[10] Basu S, Waas AM, Ambur DR. Compressive failure of fiber composites under multi-axial loading. Journal of Mechanics and Physics of Solids. 2006;54:611–34.

[11] Soutis C, Fleck NA. Static compression failure of carbon fibre T800/924C composite plate with a single hole. Journal of Composite Materials. 1990;24:536–58.

[12] Soutis C, Fleck NA, Smith PA. Failure prediction technique for compression loaded carbon fiber-epoxy laminate with open holes. Journal of Composite Materials. 1991;25:1476–98.

[13] Berbinau P, Soutis C, Guzl IA. Compressive failure of 0° unidirectional carbon fiber-reinforced plastic (CFRP) laminates by fiber microbuckling. Composite Science and Technology. 1999;59:1451–5.

[14] Lankford J. The compressive failure of polymeric composites under hydrostatic confinement. Composite Part A. 1997;28A:409–18.

[15] Iarve EV, Pagano NJ. Singular full-field stresses in composite laminates with an open hole. International Journal of Solids and Structures. 2001;38:1–28.

[16] Iarve EV. Spline variational three dimensional stress analysis of laminated composite plates with open holes. International Journal of Solids and Structures. 2001;38:1–28.

[17] Wisnom MR, Hallet SR, Soutis C. Scaling effects in notched composites. Journal of Composite Materials. 2010;44(2):195–209.

[18] Ireman T, Eriksson I. Strength of composite laminates containing holes and subjected to complex loading conditions. Journal of Composite Materials. 1997;31(2):1214–48.

[19] Nguyen BN. Three-dimensional modeling of damage in laminated composites containing a central hole. Journal of Composite Materials. 1997;31(17):1672–93.

[20] Afaghi-Khatibi A, Lin Y, Mai Y-W. An effective crack growth model for residual strength evaluation of composite laminates with circular holes. Journal of Composite Materials. 1996;30 (2):142–63.

[21] Lee HH, Hyer MW. Postbuckling failure of composite plates with holes. American Institute of Aeronautics and Astronautics Journal. 1993;31(7):1293–8.

[22] Chang F-K. Damage tolerance of laminated composites containing an open hole and subjected to compressive loadings. Journal of Composite Materials. 1991;25(January):2–43.
[23] Kim SJ, Hwang JS, Kim JH. Progressive failure analysis of pin loaded laminated composite using penalty finite element method. American Institute of Aeronautics and Astronautics Journal. 1988;36(1):75–80.
[24] JAXA-ACDB; Version. 06-1, Advanced composite evaluation technology center, Japan aerospace exploration agency 2011. Available from: http://www.jaxa-acdb.com.
[25] Yokozeki T, Ogasawara T, Ishikawa T. Nonlinear behavior and compressive strength of unidirectional and multidirectional carbon fiber composite laminates. Composites Part A. 2006;37:2069–79.