Journal of Mechanical Engineering Research Vol. 2 (1), pp. 001-009, February 2010
Available online at http://www.academicjournals.org/jmer

Full Length Research Paper

Fractography of compression failed carbon fiber reinforced plastic composite laminates

M. S. Vinod[1, 4]*, Sunil B. J[1], Vinay Nayaka[1], Raghavendra Shenoy[1,4], M. S. Murali[2] and A. Nafidi[3]

[1]Mechanical Engineering Department, RV College of Engineering, Bangalore – 560 059, India.
[2]Principal, Auden Technology and Management Academy, Bangalore – 560 017, India.
[3]Group of Condensed Matter Physics, University of Ibn Zohr, Agadir 80000, Morocco.
[4]Larsen & Toubro Ltd., Vadodara, Gujarat, India.

Accepted 27 November, 2009

Widespread usage of composites in the advanced technologies, has led to the study of the failure modes by which these composites fail, as identification and hence the interpretation of these characteristic fracture features is necessary to provide valuable information in understanding of the failure behavior of composites. Hence, in this paper, our effort has been in the study of the fractographic features in the carbon fiber reinforced plastic (CFRP) composite laminates under compression loading. Microscopic study with the aid of scanning electron microscope (SEM) has been performed on failed composite fracture surfaces to identify the principal features due to compression loading. This research has led to the knowledge of the nature and origin of fracture, as well as understanding of how the fracture occurs, with an insight into the various characteristic features and its effect of these on the failure modes with the definition of overall crack propagation direction in case of compression loaded CFRP laminates. Also, a model explaining the damage zone leading to kink band formation has been discussed.

Key words: CFRP, compression loading, fractography, SEM, damage zone model, kinking.

INTRODUCTION

Carbon Fibre Reinforced Plastic (CFRP) laminates are extensively used in structure of aircrafts, automobiles, ships, civil infrastructure, chemical processing equipment and sporting goods (Erich, 1985; Daniel and Ishai, 1994; Swanson, 1997; Lee et al., 2002; Hamagami et al., 2003; Marinucci and de Andrade, 2006; Toshiyuki et al., 2008) because of some outstanding physical, thermal and mechanical properties which are realizable with the combination of fiber and matrix resin, particularly light-weight, high stiffness and strength, good fatigue resistance, excellent corrosion resistance and dimensional stability compared with metallic materials (Marinucci and de Andrade, 2006; Lee and Noguchi, 2001).

Although some literatures (Purslow, 1981; Greszczuk, 1981; Johannesson et al., 1984; Purslow, 1986) are available related to the understanding of the damage in composite materials and its effect on the response of composite structures; it has not yet matured to a level, where a satisfactory understanding of the damage characteristics and its relation to failure causes is existing (Purslow, 1986; Garland et al., 2001). In contrast to metals, where fracture process is well known to result from nucleation and subsequent growth of single dominant crack; the fiber reinforced composite laminates is characterized by the initiation and progression of multiple failures of different modes. Consequently, there are many potential failure modes for composite laminates than for metallic materials and hence have to be analyzed in detail for better understanding of its failure.

Despite efforts to process high-quality composite material parts, some untimely failures may occur because of defects introduced during manufacturing (Lemascon, 1994), because of data that were not taken into account during design, or because of misuse of the materials' structure. A skilled postmortem failure analysis provides many pieces of information that will shed light on the process and the design phase, improving the quality of

*Corresponding author. E-mail: vinod.srinivasa@gmail.com.

the structures. According to (Gao and Kim, 1999), fractography technique (destructive technique) is sensitive to damage detection of CFRP when compared to all the major non destructive evaluation (NDE) techniques. Also, the success of damage evaluation depends primarily on the development and choice of appropriate damage characterization techniques and fractography is one of the powerful techniques for elucidation of the fracture behavior of materials (Purslow, 1986; Gao and Kim, 1999) and it further leads to better material design in composite materials. Fractography consists of studying the fracture surfaces of materials and is an essential means through which the story of the structure can be understood and reconstructed. Macroscopic as well as microscopic indications can be revealed through a careful fractographic survey and are indispensable to the technicians and engineers in charge of design and manufacturing who use them to improve their approach (Lemascon, 1992; Lemascon, 1993; USAF, 1992).

Fibers which are parallel to the loading direction increase the strength of the composite structure by orders of magnitude, even to hundred fold of the original value (Lemascon et al., 1996). Also with rapidly increasing use of carbon-fibre composites for primary and secondary structures (Abrate, 1991; Zsigmond and Vas, 2006), the effect of loadings on residual mechanical and structural performance of the composite has become a major issue. Hence, microscopic observation and fractography by means of SEM is used to characterize the damage of CFRP composites under compression loading to evaluate the spatial distributions of the damage and the fracture morphology. The fracture mechanism is discussed with respect to detailed observation of fracture appearance, along with the explanation of the possible damage zone model.

EXPERIMENTAL STUDIES

Materials

Most engineering applications of CFRP composites are based on multidirectional laminates. However, it's felt that if the fractography was to be fully understood, a systematic study should first be made of unidirectional composites. Hence, prepreg sheets of carbon fiber were fabricated and 16 plies of this prepreg sheets were stacked to fabricate Unidirectional (UD) CFRP composite with 2.0 mm in thickness (containing about 65% by volume of carbon fibers). The autoclave molding conditions were 180℃ for 4 h and 200℃ for 2 h of curing.

Mechanical testing

All tests have been carried out on a 100kN INSTRON Universal Testing Machine (Model: 6025) and the machine cross head was programmed to apply the load at constant strain rate of 0.01/s through the entire duration of the test. In order to produce a known mode of failure, standard test specimens as per ASTM standard: D 3410 were loaded in axial compression. All the tests were carried out under ambient conditions. Figure 1 shows the schematic representation of specimen configuration for compression loading with the dimensions being 100 x 10 x 2 mm.

Fractographic characterization in scanning electron microscope

The fractured surface is gold sputtered by evaporation, with Current of 10 mA and Voltage of 1kV for a period of 5 - 8 min. The sputtered thickness is maintained between 600A^o - 800A^o. Fracture surfaces of the specimens were observed by scanning electron microscopy (SEM: JSM-5200, JEOL) to classify the fracture morphology of the reinforcement fiber. The fracture morphology in com-pression tests of unidirectional carbon-fiber-reinforced plastic is mainly divided into two cases, one being macroscopic fracture morphology of the whole specimen and the other the fracture morphology of the reinforcing fibers at the microscopic level.

RESULTS AND DISCUSSIONS

SEM characterization of CFRP

The CFRP samples were tested for its longitudinal and cross sectional morphology, because the mechanical properties of unidirectional carbon/epoxy prepreg laminates (with undamaged, well aligned fibers) against woven carbon/epoxy fabric composites differ in tensile stiffness, strength, in-plane compression, bending and fatigue properties (Cox et al., 1994; Agarwal and Broutman, 1990; Dadkhah et al., 1995). Figure 2a shows the SEM micrographs of the cross sectional uniform distribution of carbon fibers in the epoxy matrix and Figure 2b shows longitudinal distribution of carbon fibers in the epoxy matrix, indicating fairly good manufacturing process for the specimen under test as well as uniform distribution of fibers.

Fractographic morphology of composites failed by axial compression

The predominant macroscopic failure mode has been identified as shear crippling, which looks like a shear failure (Figure 3). Microscopic inspection, however, indicates that shear crippling is frequently the result of kink-band formation (Figure 4). This shear crippling in composites resembles slip lines in metals. SEM examina-tion of the fracture surface revealed stepped structure at different locations as shown in Figure 5a and b. It has been observed that the micro-buckling/kinking (damage zone), which is the formation of reoriented material bands on a plane at some angle to the direction of loading (Abrate, 1991; Zsigmond and Vas, 2006), spreads over several fibers and consist of several crushed and angled breaks, occurs on several planes and the overall fracture surface sometimes consists entirely of series of steps, the height of each step being a multiple of half the buckling wavelength (Lemascon et al., 1996). Local fiber buckling/kinking and fiber fractures leads to an irregular, stepped fracture surface. This is a characteristic feature of compression failure that is failure of the fibers by micro-buckling/fiber kinking (Figure 5c).

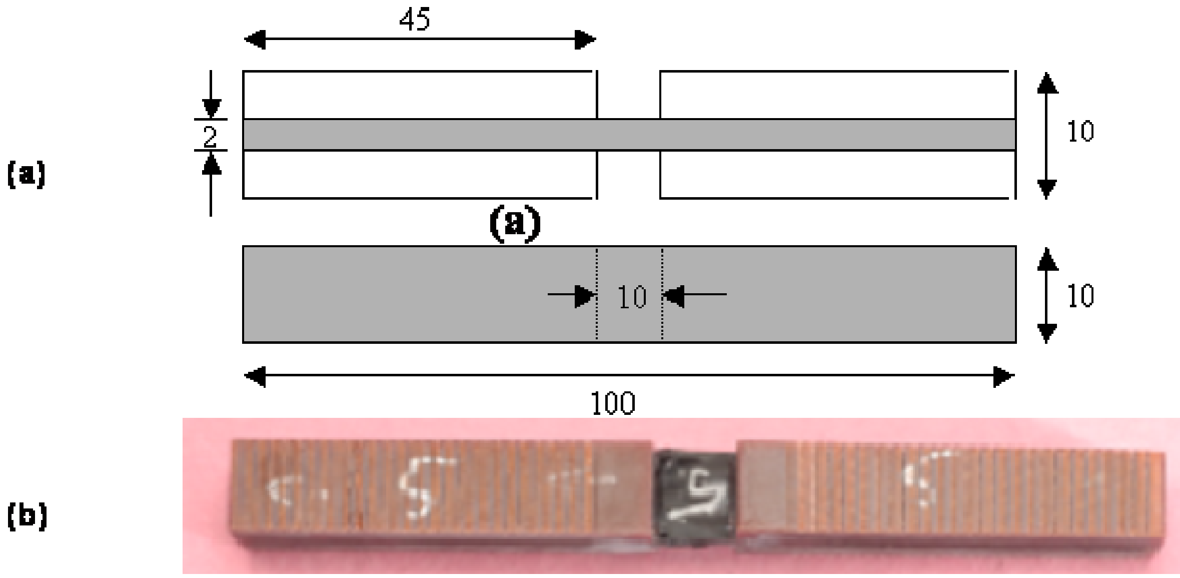

Figure 1. (a) Schematic representation and (b) Actual photograph of the compression specimen.

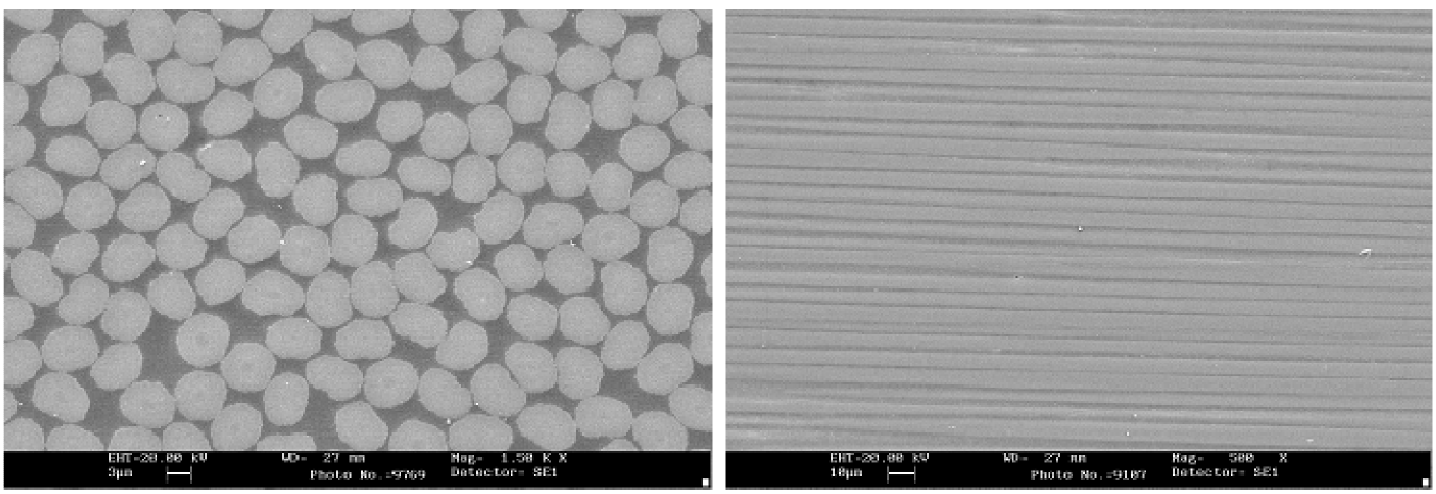

Figure 2. SEM micrograph showing (a) longitudinal and (b) cross sectional uniform distribution of carbon fibers in epoxy matrix.

Figure 3. Fracture surface of compression failed test coupon.

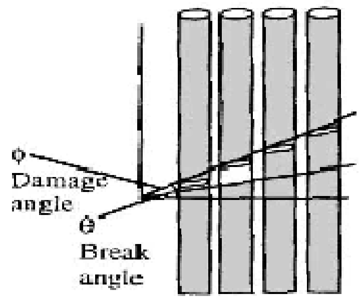

Figure 4. Fracture surface of compression failed test

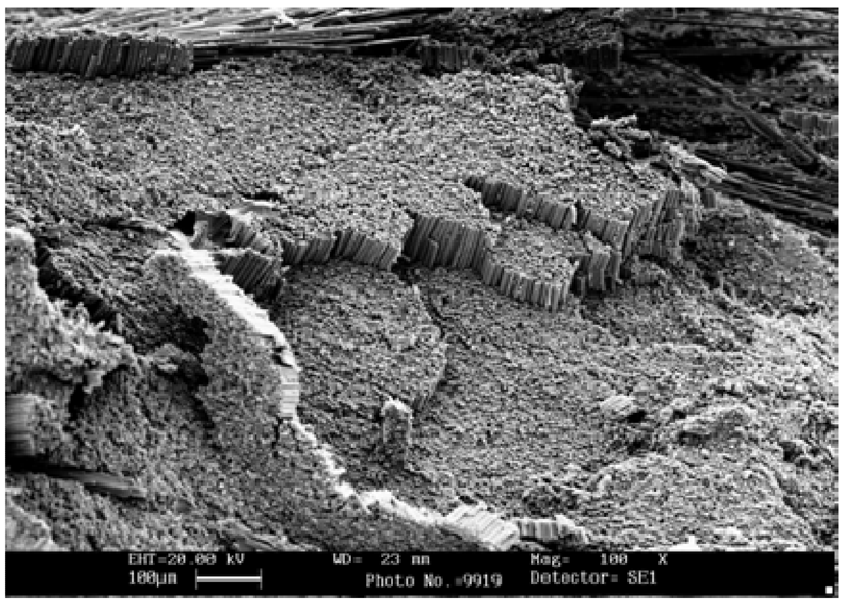

Figure 5a. Stepped fibre fracture.

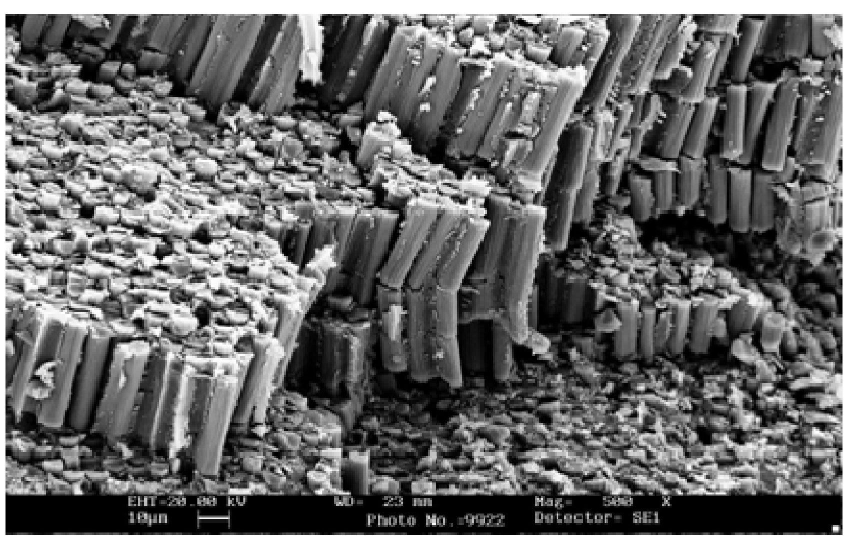

Figure 5b. Fibre fracture by micro buckling and fracture at different heights.

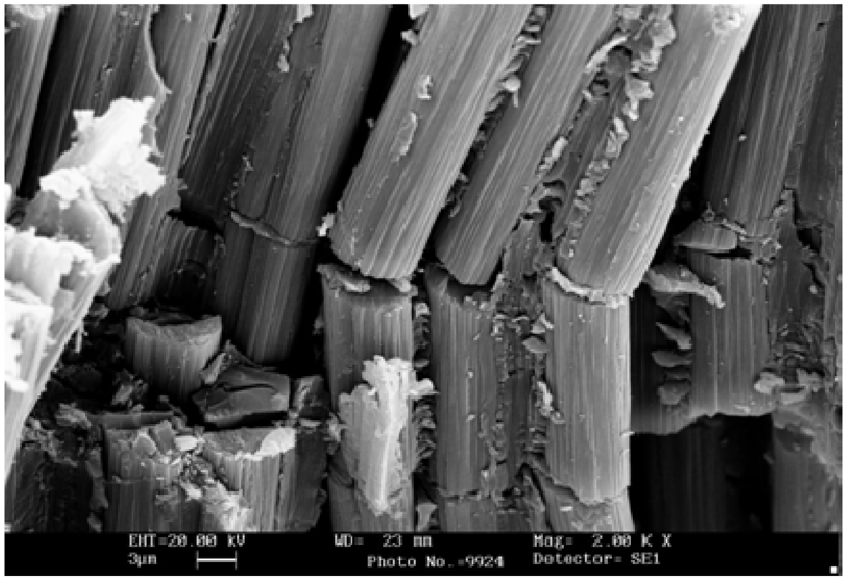

Figure 5c. Microbuckling/Kinking.

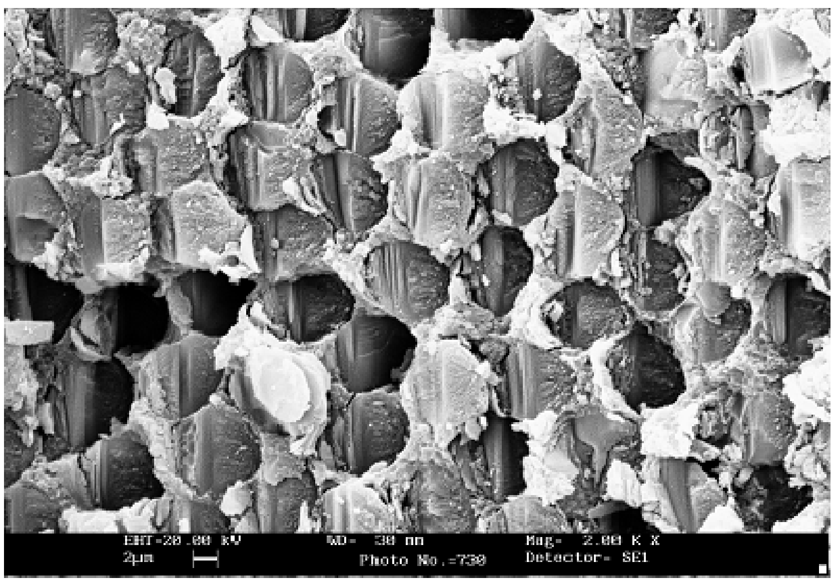

Figure 5d. Chop marks typical of failure under compressive load.

High values of fiber volume ratio, shear or in phase mode micro-buckling has been predicted (Cox et al., 1994), wherein the flexural stresses because of the in-phase buckling leads to the formation of fracture planes (Figure 5c). In Figure 5d, a typical compressive failure feature - Chop marks is observed. At high magnifications in Figure 5e, the fracture surface of the individual fibers showed two distinct areas of smooth compressive and rough tensile areas separated by neutral axis (NA), known as chop marks, where its showing clear evidence of compressive failure from Compression side (C) to the NA and a tension failure from Tension side (T) propagating to the NA. It may also be noted that a strong bond between fiber and matrix is present in (Figure 5e) and also the matrix and fiber debris have been observed, which are characteristic of compression failed samples. Most of the fracture surface features were obliterated due to abrasion of mating fracture surfaces during failure that is post-failure movement of the mating surfaces has caused abrasion over most of the fracture. And in Figure 5f, clearly neutral axis (buckling axis) can be observed and the local crack propagation direction is in the direction perpendicular to it. And the crack propagation is through the thickness. The crack propagates to fracture,

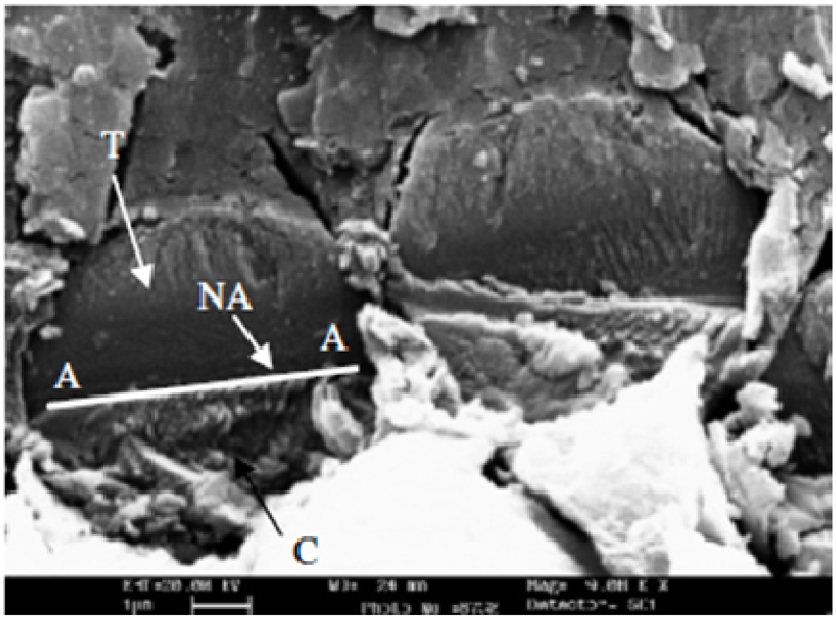

Figure 5e. High magnification fractograph showing chop marks separating tension and compression by neutral axis.

through the individual fibers from the tensile to the compressive side in a direction perpendicular to neutral axis/buckling axis (A-A). Also, the fracture direction and height common to all the fibers in a step indicate localized crack propagation. Thus, the buckling axis (Figure 5f) can be used for determination of the local crack propagation direction and hence identification of the failure origin. Detailed examination of the fractographic features revealed identical local crack propagation direction at most of the preserved regions. Therefore, it was possible to use relative position of the compressive/ tensile facets of the individual fiber in determination/ mapping of the overall crack propagation direction for the sample under study (Figure 6).

Kink bands from damage zones

Kink bands in unidirectional continuous carbon fiber reinforced polymer composites initiate from damage zones formed under axial compressive loads. A damage zone consists of a cluster of locally crushed fibers and broken fibers (Figure 4), that are often fractured at an angle, $\theta > 0°$, normal to the fiber axis (θ is the break angle). Typically, under compressive loads, fiber breaks in damage zones form roughly along a plane at an angle ϕ, normal to the fiber axis (ϕ is the damage angle). These damage zones produce stress concentrations which can lead to instabilities in the nearby fiber and matrix and initiate micro-buckling and kink bands. Also, it has been viewed that the fiber misalignment/fiber waviness has led to the local shear instability and that the applied compressive load accentuated shear stresses already developed around these initial defects, which weakened the surrounding matrix, aiding in fiber micro-buckling. Also these broken fibers transferred the load, producing stress concentrations in neighboring fibers. These stress concentrations are a key mechanism to dictate the growth of damage zones and propagates at an angle, $\left(\frac{\pi}{2}-\phi\right)$, to the loading direction (Narayanan and Schadler, 1999), ultimately leading to local shear instability that causes plastic micro-buckling (Budiansky and Fleck, 1993; Argon, 1972; Budiansky, 1983). ϕ typically ranged between 50 and 70° (Narayanan and Schadler, 1999). Within these damage zones, θ will be oriented at an angle between 30 and 45° (Garland et al., 2001; Amer and Schadler, 1997) to loading direction.

Buckling damage zone

The mechanism of damage zones leading to kink bands is ‘buckling of the region encompassing the damage zone’, much the way a tall thin column might buckle. A schematic illustrating the possible model predicting how a damage zone could lead to kink band formation is shown in Figure 7, as suggested by (Garland et al., 2001). The damage zone grows roughly along an angle ϕ, which will predominantly depend on fiber strength and interface properties. This block of broken fibers and stressed matrix creates a weakened region with reduced load bearing capability. Also, as ϕ increases, this complaint

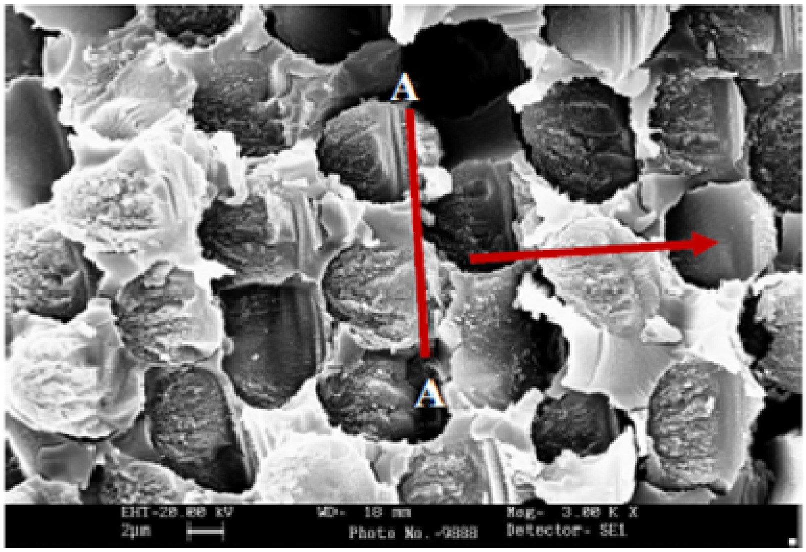

Figure 5f. Local crack propagation direction indicated by an arrow perpendicular to neutral axis AA.

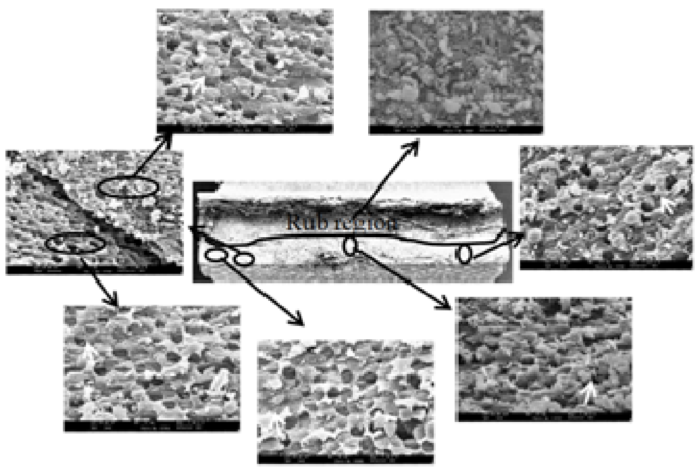

Figure 6. Map of overall crack propagation direction.

region, as indicated in Figure 7, becomes taller and thinner (forming a column) and thus will buckle or distort more easily under compression. The resulting rotation or distortion of this weakened columnar region ϕ would then lead to a kink band. Buckling of this column can result in micro-buckling of neighboring fibers ahead of the damage zone in two ways:

1) The damage zone creates locally high compressive stress concentrations in the intact fibers surrounding it and
2) Buckling of this column can also distort or laterally displace the surrounding fibers.

This causes the fibers to bend, so they generate or further strain the matrix in between. This will cause surrounding fibers to bend to the point where they fracture and kink, triggering kink band formation, as shown in Figure 7. Therefore, the length scales and intensity of the over-compressed region produced by damage zones and distortion ϕ in Figure 7, will determine the critical formation stress and length scales of the resulting kink band.

Other important features are: the kink band angle during this early stage is relatively shallow (10 - 15° from the horizontal); secondly, the fibers within the band rotate slowly until they lie between 15 - 20° from the vertical (Moran et al., 1995). At this point, the rotation becomes unstable, and the fibers rotate rapidly to an orientation of 40 - 45° from the vertical, where they lock up (Landis et al., 2000). As the loading continues more and more fibers

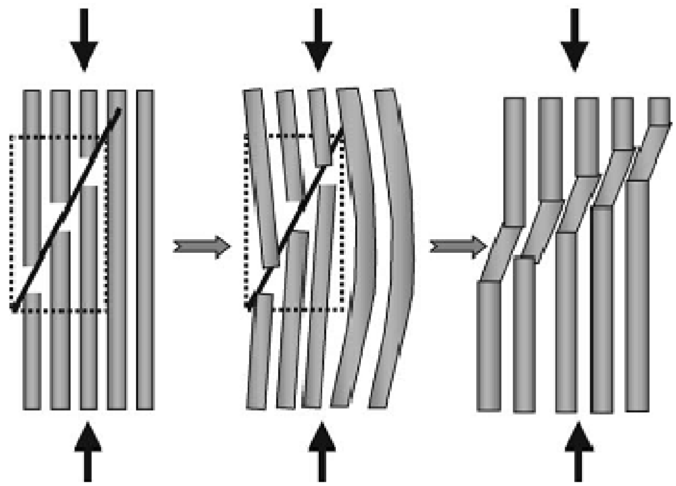

Figure 7. Schematic model of the damage zone leading to kink band formation (Source: Garland et al., 2001 used with permission).

undergo unstable rotation and lock up, and eventually the entire band deforms and shifts to the angle dictated by the fully rotated fibers. Fiber lock-up forces the kink band to spread into the unkinked material by band width broadening. Also, with large values of ϕ develops damage zones because of matrix yielding and interfacial debonding and will also tend to broaden the size of this overstressed region (Garland et al., 2001).

Conclusion

The predominant macroscopic failure mode in the axial compression failed samples has been identified as shear crippling which leads to shear failure on a plane at an angle of 30 - 45° to the direction of loading. Microscopic inspection of the composite, however, indicates that shear crippling is frequently the result of kink-band formation resembling the slip lines in metals. Also, as the axial compression strength of the CFRP is limited by the ability of the matrix to provide stability to the fibers against buckling; so when a compressive load is applied, the composite exhibits micro-buckling phenomena and de-bonding occurs at the interphase. This is illustrated in a model which explains the observed effects of interface and fiber fracture type on compression strength. Also, the early stages of kink band formation involve slow, cooperative fiber bending and rotation and matrix deformation which are confined to a shallow narrow band. These deformations contribute to significant geometric softening of the material in the band. At some point this slow process gives way to rapid fiber bending and rotation and large matrix shearing. This stage is terminated by fiber lock-up. Thereafter, the kink band spreads laterally into the specimen by band width broadening whereby the bends at the edges of the kink band propagate into the unkinked material and finally leads to the fracture of the specimen. Also, the micro-fractographic informed that the micro-buckling occurs on several planes and the overall fracture surface consists of a series of steps and the buckling axes separate compressive failures (C) from tensile failures (T) on the chopped individual fibers.

Relatively simple and basic failure modes in unidirectional laminates are helpful for failure analysis in multidirectional composite structures. It has been confirmed that fractography of each ply in a multidirectional lay-up is close to that in a unidirectional specimen of the same orientation. Therefore, it appears to be important to use the information on failure mechanisms in a positive way to improve mechanical reliability to exploring the influence and behavior of defects, and to provide feedback for the design and manufacturing stages. This research has led to the knowledge of the nature and origin of fracture, as well as understanding of how the fracture occurs, with an insight into the various characteristic features and its effect of these on the failure modes with the definition of overall crack propagation direction. Hence, we have shown the power of fractography in the analysis of failure process (in CFRP). All these characteristics are very valuable in the aerospace structures fabricated by CFRP.

FUTURE WORK

Monte Carlo simulation has been carried out to define the damage zone evolution (Landis et al., 2000; Garland et al., 2001), wherein the angled breaks (flaws) promotes damage zone propagation roughly along an angle, primarily due to the offset of stress concentration. Furthermore, coupling the results of this fractography with Monte Carlo simulation, there will be a huge potential to analyze stochastic damage zone formation and propagation and subsequent kink band formation, given the proper failure criteria such as the statistical distribution for fiber strength, and matrix and interface thresholds.

REFERENCES

Abrate S (1991). Matrix Cracking in Laminated Composites: A Review. Composites Eng. 1: 337-353.
Agarwal BD, Broutman LJ (1990). Analysis and performance of fibre composites. John Wiley and Sons Ltd, New York. pp. 1-15.
Amer MH, Schadler LS (1997). Stress concentration phenomenon in graphite/epoxy composites: tension/compression effects. Composite Sci. Technol. 57: 1129-1137.
Argon AS (1972). Fracture of composites: Treatise on materials science and technology. Academic Press, New York. pp. 79-114.
Budiansky B (1983). Micromechanics. Computers Structures 16: 3-12.
Budiansky B, Fleck NA (1993). Compressive failure of fibre composites. J. Mech. Phys. Solids. 41: 183-211.
Cox BN, Dadkhah MS, Morris WL, Flintoff JG (1994). Failure mechanisms of 3D woven composites in tension compression and bending. Acta Metallurgica et Materialia. 42: 3967-3984.
Dadkhah MS, Morris WL, Cox BN (1995). Compression-Compression Fatigue in 3D Woven Composites. Acta Metallurgica et Materialia. 43: 4235-4245.
Daniel IM, Ishai O (1994). Engineering Mechanics of Composite Materials. Oxford University Press, 2nd Edition.
Erich F (1985), Carbon Fibers and their Composites, United Nations Financing System for Science and Technology for Development.
Gao SL, Kim JK (1999). Scanning acoustic microscopy as a tool for quantitative characterization of damage in CFRPs. Composites Sci. Technol. 59: 345-354.
Garland BD, Beyerlein IJ, Schadlera LS (2001). The development of compression damage zones in fibrous composites. Composites Sci. Technol. 61: 2461-2480.
Greszczuk KB (1981). Fracture of Composite Materials. Proceedings of 2nd USA-USSR Symposium on the Fracture of Composite Materials, Pennsylvania, USA, (Edited by Sih, G. C., and Tamuzs, V. P.,), p. 231.
Hamagami Y, Sekine N, Nakada M, Mityano Y (2003). Time & Temp Dependence on Flexural Strength of Heat-Resistant CFRP Laminates. JSME Intern. J. Series A, 46: 437-440.
Johannesson T, Sjoblom P, Selden R (1984). The detailed structure of delamination fracture surfaces in graphite/epoxy laminates. J. Mater. Sci. 19: 1171-1177.
Landis CM, Beyerlein IJ, McMeeking RM (2000). Micromechanical simulation of the failure of fiber reinforced composites. J. Mech. Phys. Solids. 48: 621-648.
Lee L, Clark SR, Mouritz AP, Bannister MK, Herszberg I (2002). Effect of weaving damage on the tensile properties of three-dimensional woven composites. Composite Structures 57: 405-413.
Lee SH, Noguchi H (2001). Shear Characterization of Hybrid Composites with Non-Woven Carbon Tissue. JSME International J. Series A. 44: 535-541.
Lemascon A (1992). Atlas of Composite Fractography. JNCB, Paris.
Lemascon A (1993). A tool to aid the analysis of structural failure in composite materials, Interesting Technology.
Lemascon A (1994). Failure analysis of structures and composite plastic pieces. 1st Technical Seminar on Failure Analysis of Polymer and Composite Structures, CETIM, Nantes.
Lemascon A, Castaing P, Mallard H (1996). Failure Investigation of Polymer and Composite Material Structures in the Mechanical Engineering Industry. Materials Characterization. 36: 309-319.
Marinucci G, Arnaldo HP de Andrade (2006). Micro-structural Analysis in Asymmetric & Unbalanced Composite Cylinders Damaged by Internal Pressure. Composite Structures. 72: 86-90.
Moran PM, Liu XH, Shih CF (1995). Kink Band Formation and Band Broadening in Fiber Composites under Compressive Loading, Acta Metallurgica Materialia. 43: 2943-2958.
Narayanan S, Schadler LS (1999). Mechanisms of kink band formation in graphite/epoxy composites: a micromechanical experimental study. Composites Science and Technology. 59: 2201-2213.
Purslow D (1981). Some fundamental aspects of composites fractography. Composites. 12: 241-247.
Purslow D (1986). Matrix fractography of fiber reinforced epoxy composites. Composites 17: 289-303.
Swanson S (1997). Introduction to Design and Analysis with Advanced Composite Materials. Prentice Hall.
Toshiyuki S, Yoshiaki K, Yasumasa H, Takenori A (2008). Static and Fatigue Strengths of a G40-800/5260 Carbon Fiber/Bismaleimide Composite Material at Room Temperature and 150°C. J. Composite Mater. 42: 655-679.
USAF Composite Failure Analysis Handbook (1992). CINDAS/USAF CRDA Handbooks Operation. Purdue University, West Lafayette, USA.
Zsigmond B, Vas LM (2006). Examination of the tensile state of Fibers in Braided Fiber Reinforced Composite Tube. Periodica Polytechnica Series Mech. Eng. 50: 63-72.