탄소 섬유강화 복합재료의 중력 낙하 충격으로 인한 손상 평가

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Drop-weight impact damage evaluation for carbon fiber/epoxy composite laminates

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Key Words: carbon fiber/epoxy composite laminates, impact damage resistance, impact damage evaluation, interlaminar reinforcement, scanning acoustic microscopy, cross-sectional fractography.

Abstract

Drop weight impact tests were performed to investigate the impact behavior of carbon fiber/epoxy composite laminates reinforced by short fibers and other interleaving materials. Characterization techniques, such as cross-sectional fractography and scanning acoustic microscopy, were employed quantitatively to assess the internal damage of some composite laminates. Scanning electron microscopy was used to observe impact damage and fracture modes on specimen fracture surfaces. The results show that composite laminates experience various types of fracture; delamination, intra-ply cracking, matrix cracking and fiber breakage depending on the interlayer materials. Among the composite laminates tested in this study, the composites reinforced by Zylon fibers showed very good impact damage resistance with medium level of damage, while the composites interleaved by poly(ethylene-co-acrylic acid) (PEEA) film is expected to deteriorate the bulk strength due to the reduction of fiber volume fraction, even though the damaged area is significantly reduced.

1. Introduction

Although continuous fiber reinforced composite laminates have advantages such as high specific strength, stiffness and chemical resistance, they are susceptible to damage caused by various loadings. These loadings include static loading and low energy impact loading during manufacturing and in service. Among these factors, low energy impact loading (e.g., runway debris thrown by aircraft wheels) can form extensive barely visible or visible sub-surface damage. The presence of this damage can result in a considerable reduction in composite bulk strength and stiffness [1,2]. The damage induced by low energy impact is often a complex mixture consisting of interlaminar fracture (delamination), intralaminar fracture (transverse matrix cracking and debonding between fiber and matrix) and fiber fracture [3,4]. With the exception of fiber fracture, these failures strongly depend on the interlaminar toughening mechanisms and fiber/matrix interfacial strength.

In order to enhance the impact performance of composite laminates, extensive research into interleaving methods [5], controlling fiber/matrix interfacial bond strength [6], modifying fiber fabrics (e.g. woven fabric) [7], and using hybrid composite structures [8] has been performed. These techniques are also beneficial for improving the quasi-static interlaminar fracture toughness.

An accurate evaluation of the fracture and damage is an important guide for composite design. To do this, the damage patterns and modes need to be thoroughly identified using appropriate characterization techniques. Characterization techniques can be categorized broadly into two areas: destructive technique and non-destructive technique. Destructive techniques include cross-sectional fractography and de-ply technique, and the non-destructive techniques include scanning acoustic microscopy, x-radiography, x-ray computed tomography and infrared thermography. A summary of these methods has been given by Gao & Kim [9]. According to their investigation,

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a scanning acoustic microscope (SAM) is a powerful tool in constructing 3D images for damages through the whole thickness of the laminate.

This investigation aims to evaluate the internal damage induced by instrumented drop-weight impact tests in carbon fiber/epoxy composite laminates reinforced by various interlayer materials. Characterization methods such as cross-sectional fractography, scanning acoustic microscopy and scanning electron microscopy are employed. This study also aims to investigate the fracture mechanisms associated with the various interlayer materials. These fracture mechanisms will show how effective the interlayers are in improving the impact performance of the laminates.

2. Materials and Experiments

The material used in this study was NCT 301 carbon fiber/epoxy prepreg from Newport Adhesives and Composites. The compression molding technique was employed to produce 10-ply laminates with the stacking sequence of $[0°/90°]_5$. The curing cycle recommended by the manufacturer was as follows: (1) The temperature was increased to 110°C with dwell time of 30 minutes. (2) It was increased again to 140°C with dwell time of 30 minutes. (3) The mould was then allowed to cool down to room temperature. The mould pressure was 400 KPa for the composite manufacture.

The various interlayer materials listed in Table 1 were introduced semi-automatically in every interlaminar region. The laminates were cut to the final size of 100 x 100 mm^2 for impact tests. An instrumented Dynatup 8250 drop-weight impact machine was employed to perform the non-penetrating impact tests. An impactor fitted with a hemispherical nose of 12.7 mm in diameter was impacted onto the center of a test window of 75 mm in diameter. The non-penetrating impact tests were conducted at five different impact energies between 3 and 33 J.

3. Impact Load - Time Behavior

Figure 1 shows a typical impact load - time (P-t) curve of the laminate specimen obtained from instrumented Dynatup 8250 impact machine. The P-t diagrams of plain composites, composites with Kevlar fibers of 15 mm, 0.8 wt % (uniform distribution), with Zylon HM and with PEEA film were only selected and discussed because of the similar patterns for all composites. The incipient load, P_i, the peak load, P_m, the energy to peak, U_m and the post-peak energy, U_p are represented. The P_i indicates where the impact load drops due to the first failure in the ascending portion of the graph.

The incipient load, P_i and the peak load, P_m, taken from the P-t diagrams are plotted as a function of impact energy in Figs 2 (a) and (b). With increasing impact energy, the P_i's are shown more clearly between 1.6 and 2.6 kN, and the P_i values increase almost linearly. The P_i's for the laminates interleaved by PEEA film are the lowest at every impact energy value and those for the other composites were very similar to each other. As shown in Fig. 2(b), the P_m values also increase from about 3 kN to 6.5 kN as the impact energy increases. It is, however, noted that the increasing P_m values for all the laminates approach about 7.5 kN. Wider scatters for the P_m are depicted at high impact energies than at low impact energies.

4. Damage Characterization

4.1. Cross-sectional fractography

The sub-surface damages of the laminates induced by impact loading of 20J were examined to estimate delaminated area via cross-sectional fractography. The damaged specimens were cut into half along the central damage region using a diamond wheel cutting machine, and then, cut again to produce a quarter size. The quarter size specimen was sectioned through the damage zone at 2 mm. The edges of the sectioned specimens were polished down to 1 μm using a diamond paste. The polished surfaces were observed under an optical microscope to estimate delamination sizes at each interface. It is assumed that the fracture formed in the specimen is symmetrical to the center of impact, and hence, true delamination areas are obtained by multiplying a factor of 4 to the estimated value for the quarter size specimens. It can be concluded from the estimation that all the interlayer materials (Kevlar fibers, Zylon fibers and PEEA film) examined by the cross-sectional fractography improve delamination resistance under the impact loading conditions, as shown in Fig.3.

4.2. Scanning acoustic microscopy

A SAM Sonix micro-Scan system was used to characterize the impact damage. An acoustic beam was scanned over the damaged laminate in water using a transducer with a 15 MHz probe. The c-scan mode was selected for ply-by-ply damage assessment. A proper selection of the threshold value of the data gate is critical to obtain a successful view of the damaged regions. The scanning speed was selected as 121.4 mm/s.

The preliminary SAM tests were performed for the plain laminates and the laminates with Kevlar fibers of 15 mm in length and 0.8 wt % (in uniform distribution), and PEEA film. The composite panels were tami-scanned (same as c-scan) for 32 interfaces with vertical increments. Among these 32 scanned images, depths of 9 interfaces corresponding closely to the actual interface position were selected. Then, an image analysis program was employed to estimate the damaged area at each interface. Figure 4 displays the total damaged areas of the three composites mentioned above as a function of impact energy. The plain composites show the most severe internal damage.

4.3. Fractography using SEM.

Most composite laminate specimens impacted at an impact energy of 20J experience separation between the 9th and 10th (the bottom plane of impact) layers, and as a result, the 9th interface of the composite specimens was observable with an SEM.

Figure 5 shows the fracture surface on the 9th interface for the plain composite. Fractures of the epoxy matrix induced by an impact energy of 20 J are formed in irregular patterns including the matrix fragments of 5-20 μm in size.

Figure 6 exhibits the fracture of a fibre bundle in the composite specimen with PEEA film. These fibers seem to have very strong interfacial bond to the matrix. The high interfacial strength between the fiber and matrix leads eventually to the generation of extensive transverse fiber fractures on the back face rather than fiber pull-out, matrix cracking, etc. Figure 7 shows fracture in Zylon fiber. About half of the fiber along the fiber direction has been extensively damaged with peculiar fracture modes showing fibrillation and longitudinal splits together with extensive deformation. Fibrils seem to be strongly adhered to the fiber. This fracture phenomenon is contrasted with the Kevlar fibrillation that creates many fine fibrils coming out of the main fiber.

5. Concluding Remarks

- As the impact energy increases, the P_i's and P_m's of the laminates increase. The P_m's values approach 7 kN, which is indicative of the maximum impact load bearing capacity for the laminate systems used in this investigation.
- The interleaving technique using PEEA film is effective in reducing the damaged area. Short Zylon fibers (HM and AS) are proven to be excellent candidate materials for short fiber interlayers. The high interfacial bond strength of Zylon fibers with the epoxy matrix enhances fiber-bridging effect, and thus, contributes to the remarkable improvement in interlaminar fracture resistance.
- SEM observations show various fracture and damage modes due to the impact loading; fiber breakage, matrix cracking, delamination, intra-ply cracking, translaminar fracture in the thickness direction and the failure and pull-out of the short Kevlar and Zylon fibers. The composites interleaved by PEEA film show strongly adhered fiber bundles attributable to the action of the fused polymer in the interlaminar region.

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Table 1. Interlayer materials used in this study.

materials	type	wt %	gr/m^2
Kevlar[1]	Fiber 15mm	0.8	2.2
Kevlar[1]	Fiber 15mm	0.4	1.1
Kevlar[1]	Fiber 5mm	0.4	1.1
Zylon[2] HM	Fiber 6mm	0.8	2.2
Zylon[2] AS	Fiber 6mm	0.8	2.2
PEEA[3]	Film	19	106
PA web[4]	Web	3.5	15

[1] Kevlar – DuPont 49 fibers (15 mm, as received, and 5 mm, manually chopped).

[2] Zylon HM (high modulus, 280 GPa) and AS (medium modulus, 180Gpa) – Toyobo PBO (poly(p-phenylene-2,6-bensobisoxazole) fibers.

[3] PEEA – Dow Chemical Poly(ethylene-co-acrilic acid) film (0.1 mm in thickness).

[4] PA web – Polyamide web manufactured by Spunfab®, OH, USA).

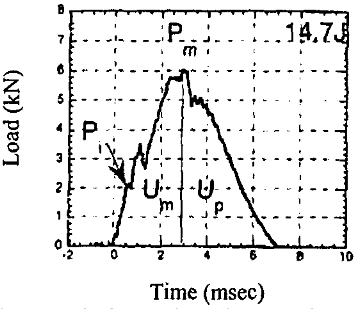
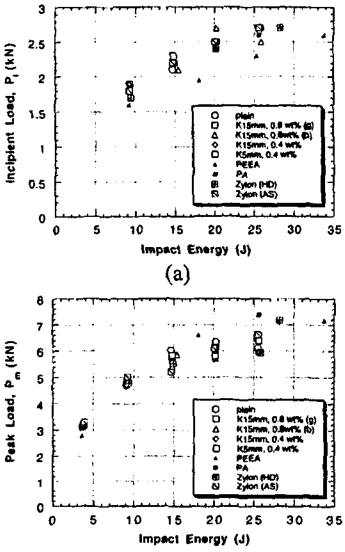


Fig.1. Typical load-time diagram of carbon fiber/epoxy laminate impacted at 14.7J.



(a)

(b)

Fig.2.(a) P_i and (b) P_m vs. impact energy.

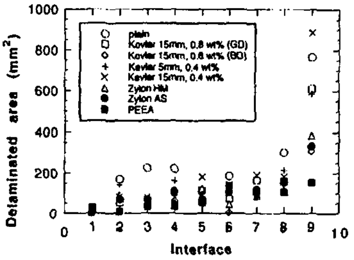


Fig.3.Delaminated area (mm^2) obtained by cross-sectional fractography.

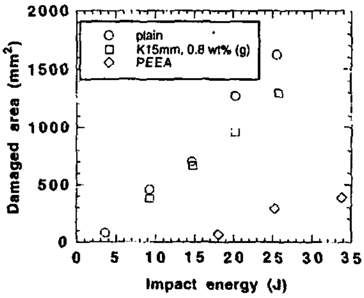


Fig.4. Total damage area vs. impact energy estimated by SAM.

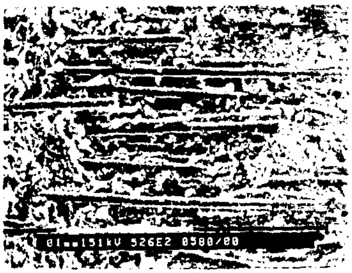


Fig.5. Fracture surface of eighth plane for plain composite.

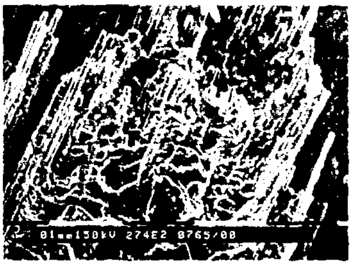


Fig.6. Fiber bundles observed in the composite with PEEA film.

Fig.7. Fracture of Zylon fiber.