THRESHOLD DAMAGE CRITERIA FOR THIN AND THICK LAMINATES SUBJECTED TO LOW VELOCITY IMPACT LOADS

Ajit D. Kelkar, Christopher Grace and J. Sankar

Center for Composite Materials Research
Department of Mechanical Engineering, North Carolina A&T State University
1601 East Market Street, Greensboro, North Carolina, 27411, USA

SUMMARY: The effects of low velocity impact on laminated composite panels are presented in this study. In the experimental program, 16 ply, 32 ply and 48 ply quasi-isotropic laminated composite panels were subjected to low velocity impact loads. The laminates were held in a special fixture, which was designed to simulate simply supported boundaries. Impact experiments were conducted using a Dynatup low velocity impact testing machine where a drop-weight system was used to strike each panel at 90^0 incidence under controlled conditions of impact velocity. The impactor used was of a constant weight and tip diameter. The impact height and hence the velocity and energy were used as variables in the study. Preliminary impact tests were performed to establish the incipient damage (lower bound) and visible back face damage and spalling (upper bound) energy for each of the 16 ply (thin), 32 ply (moderately thick) and 48 ply (thick) quasi-isotropic graphite/epoxy laminates. Seven energy levels were selected to study the progressive deformation and damage mechanics. It is shown that threshold damage criteria can be established by using a simple FFT smoothening of impact load-time history data.

KEYWORDS: impact, composite structures, nondestructive evaluation, thick composites

INTRODUCTION

Traditionally, uses of graphite fiber-reinforced composites have been confined to secondary structures. However, requirements for reduced structural weight, improved aircraft performance, and efficiency are making the composite materials increasingly competitive for expanded usage in the primary, load carrying structures. Applications are based on knowledge gained through extensive experimental programs. Past experiments have shown that the graphite fiber-reinforced composite laminates have low ultimate strains, no plastic deformation range, and no usable strength in the thickness direction. These limitations become very obvious when laminates are subjected to impact loads.

Resin matrix composites are basically brittle materials, and the damage caused by impact is vastly different from the damage on ductile metal structures. The ductile metals tend to develop indentations which are normally visible. On the other hand, brittle composite materials tend to have both visible and invisible damage. Such damage is usually in the form of delaminations,

matrix cracks and possibly broken fibers. Because of the damage significant strength loss is observed in composite materials Dost et al[1], Chen et al[2], Demuts[3] and Kelkar et al[4]. The potential severity of visible and invisible damage has instigated numerous investigations into the impact behavior of composites.

There are several factors which affect the impact damage mechanics. These factors include effect of material properties Wang et al[5], Kim et al[6], Olesen et al[7], Nettles and Lance [8,9], projectile characteristics, lay-up and stitching, Hull and Shi[10], Wang and Khang[11], Ishai and Shragai[12], environmental conditions Strait et al[13], Pope and Karnhari[14]. Sjoblom[15] showed that for low velocity impacts for which the kinetic energy of the impactor was just above the incipient damage energy, a sudden drop in the measured contact force was observed. The contact force is defined as the contact load divided by the cross sectional area of the laminated composite plate. This resulting threshold load can be measured during a single impact experiment and is easier to obtain than the threshold kinetic energy to initiate delaminations which requires performing a number of impact test and determining the size of the damaged zone in each case. Therefore, the load for damage initiation (incipient damage) is determined from a single experiment and is relatively insensitive to variations in impact velocity. This is verified by Strait et al[16] and Lagace et al[17] showed that incipient damage is seen as a discontinuity in the contact force versus deflection curve, whereas it is sometimes difficult to detect on a force versus time curve. Sjoblom and Hwang[18] obtained similar results. The above method is useful because, as shown by Avva et al[19], a large number of tests needed to be performed by slowly increasing the impact velocity to find the incipient damage point. The literature review indicates that very little work has been reported in analysis of impact load time response using FFT smoothening techniques.

OBJECTIVES

- To study the low velocity impact behavior of thin, moderately thick, and thick composite laminates.
- To predict the threshold damage in thin, moderately thick, and thick composite laminates using the impact load-time history data in conjunction with FFT smoothening technique to reduce some higher frequency material behavior.
- To compare the prediction with the C-scan results.

EXPERIMENTAL PROCEDURE

A series of low velocity impact test were conducted on thin, moderately thick and thick laminates. All of the low velocity impact tests in this research were conducted with the Dynatup Impact Testing Machine, Model 8250, located in the Structures Division, Flight Dynamics Directorate, Wright Laboratory. This low velocity impact test machine has a drop tower equipped with an instrumented impactor (1”, 2.54 cm diameter hemispherical), and a variable crosshead weight arrangement. The selected crosshead/impactor weight was 15.01 lbs. (6.81 kg) and was kept constant for all tests. To achieve variability in energy levels, the drop height was varied from 0.75-inch (0.0191 m) to 16.0 inches (0.4064 m). This was equivalent to a velocity range of 2.0 ft/sec (0.6096 m/sec) to 9.266 ft/sec (2.8242 m/sec) and a corresponding theoretical energy range of 0.938 ft-lb. (1.27 J) to 44.60 ft-lb. (60.47 J). Number of preliminary impact tests were performed on thin, moderately thick and thick laminates. There were two objectives of the preliminary impact tests:

(1) to establish the energy level for the incipient (threshold) damage
(2) to establish the energy level for the visible back face damage (spalling)

The quasi-isotropic graphite/epoxy laminates with thickness ranging from 0.208 cm (0.082 inch) for 16 ply, 0.417 cm (0.164 inch) for 32 ply and 0.635 cm (0.25 inch) for 48 ply were impact tested using a commercially available Dynatup Model GRC 8250 Impact Drop Tester. To test the composite specimens, a support frame was designed to approximate simply supported boundary conditions. The top and bottom plate each had a 12.7-cm (5.0-inch) opening and made of aluminum and steel respectively.

The impact tests were first performed on 16 ply laminates using a constant drop weight of 66.9 N (15.01 lb). The first specimen was tested at a drop height of 13.34-cm (5.25"). The specimen was C-scanned to determine any internal damages. The C-scan results indicated presence of a significant amount of damage, hence for the second specimen the drop height was reduced to 6.35 cm (2.5"). The C-scan results of the second specimen also indicated the presence of the damage. This procedure was continued till C-scan showed almost no damage (incipient damage). It was observed that for 16 ply specimens, the energy level and impact load of 2.53 J (1.87 ft-lb) and 1411 N respectively was required for the damage initiation. This energy level was then recorded as a lower bound energy level or a threshold energy level. To establish the upper bound energy level, or the energy level which causes back face damage (spalling) in the laminate, the drop height was increased incrementally and the specimens were examined for the presence of any back face damages (spalling). It was observed that a drop height of 16.5 cm (6.5”) or the energy level of 10.82 J (7.98 ft-lb) resulted into a significant back faces damage (spalling) in 16 ply laminates.

This procedure was repeated for 32 ply laminates and 48 ply laminates. For 32 ply thick laminate incipient damage occurred at 4.58 J (3.38 ft-lb) and backface spalling occurred at 26.74 J (19.72 ft-lb) and for 48 ply thick laminates these values were 6.43 J (4.74 ft-lb) (incipient) and 60.47 J (44.6 ft-lb) (for back face spalling) respectively. During each impact test a complete impact load-time history was recorded. This impact load-time history can provide a valuable information pertaining to the damage initiation and damage progression in thin, moderately thick and thick composite laminates subjected to low velocity impact loading. In the next section an interpretation of impact load-time history graphs is discussed.

INTERPRETATION OF IMPACT LOAD-TIME HISTORY GRAPHS

The impact load vs. time history graphs can provide very important information about behavior of composite laminates subjected to low velocity impact loading. In 1992, Bogdanovich and Iarve[20] published their analytical studies of impact on composite plates. Bogdanovich presented a dynamic analysis that used spline approximations. His model predicted material behavior that is characteristic of material behavior observed in the present experimental study. Bogdanovich's[21] model predicts high frequency behavior superimposed on a sinusoidal curve.

When determining impact load magnitudes, the raw data from the recorded load time histories is generally used. The load time history can indicate ply level damage when the load history deviates from an expected linear elastic response. In the case of typical low velocity impacts on composite laminates, the load time history from an elastic response, when only considering the fundamental modal response is expected to be approximately a bell shaped curve. To provide a clearer indication of damage, the load time histories were filtered with an FFT

filtering algorithm so that only the fundamental frequency level response would be seen. When the smoothened time history deviates from an approximate bell shaped curve, damage in the laminate is expected.

By their nature, the curves obtained using experimental raw data are usually very difficult to interpret. To aid in the interpretation of these curves a FFT smoothening filtering algorithm was used. These resulting smoothened curves were used in conjunction with the unfiltered curves to study the progressive damage in the composite laminates subjected to low velocity impact loading. The smoothening is accomplished by removing Fourier components with frequencies higher than:

$$1/n\Delta t$$

where n is the number of data points considered, and Δt is the time spacing between two adjacent data points. Therefore, the more points considered at one time, the greater the degree of smoothening. In the subsequent graphs, the number of points considered were 5. This results in frequencies higher than 8000 Hz being removed from the unfiltered data. For example Figures 2 – 4 shows impact load vs. time history unfiltered and filtered data for the 48, 32 and 16 ply thick laminates subjected to various drop height/impact energies. The smoothened data was then used in the present analysis.

An analysis of the impact load-time curves shows that the load at which incipient damage occurs may be derived from filtered load-time history data. Figure 1 shows a raw 48-ply laminate load response at 15.24 cm (6”) drop height. It was observed that this drop height/impact energy was not large enough for incipient damage. Figure 1 show a typical characteristic undamaged material response under impact loading. At this impact energy, there is high frequency material behavior superimposed on a bell shaped curve. It is proposed that any deviation from this characteristic bell shape is indicative of delamination in the laminate (as verified by C-scan examination). The load time history can indicate ply level damage when the load-time history curve deviates from an expected linear elastic response.

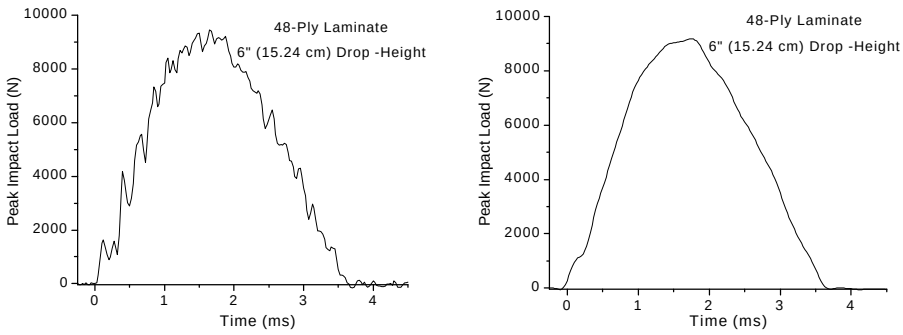

Fig. 1: Example of impact without detectable damage (unfiltered and filtered)

RESULTS

The experimental impact load-time history data clearly indicates that the incipient damage in the 48 Ply (0.25”, 0.635 cm thick) specimen occurs at 26 cm drop height and an impact energy of 17.22 J (12.70 ft-lb). Analysis of Figure 2 shows at the 26 cm drop height there must be a

significant damage as indicated by the severe deviation of the initial linear response of loading.

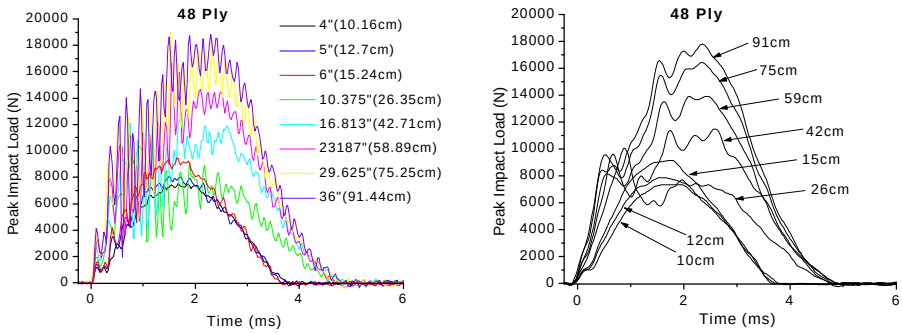

Fig. 2: Impact load-time unfiltered and filtered data for 48 ply thick laminates

As seen in Fig. 2, all impact load-time history curves for drop heights 15 cm (6 in) and above exhibit the same characteristic deviation in their load approximately at the same load range. This indicates that all impacts above the threshold impact energy will exhibit a characteristic drop in their load response. One additional characteristic seen in the load response curves is that for impact energies less than incipient, there is a small deviation near the beginning of the impact load time curve. This maybe representative of matrix damage in the laminate that is more easily seen at lower impact energies. As shown in Figure 2 (load-time curve for 48 ply thick laminate), the deviation in linear response occurred at approximately 10366 N.

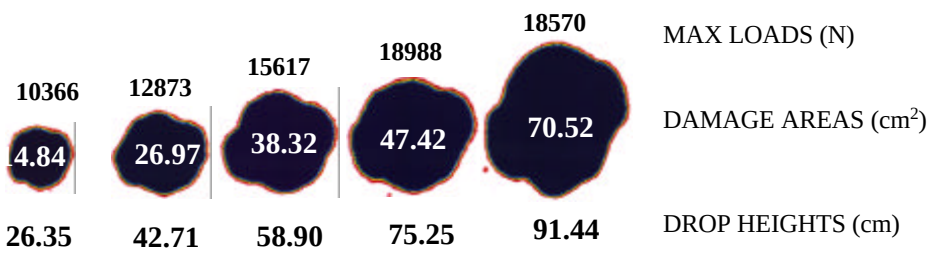

Fig. 3: Progressive impact damage for 48 ply thick laminates

When this specimen was inspected using C-scan it did show an incipient damage, with damage area equal to 14.84 cm^2 (2.3 in^2) as shown in the Fig. 3. Figure 3 also shows the progressive impact damage in 48 ply thick composites.

The same characteristic deviation in the linear response is observed in moderately thick 32 Ply laminates. In 32 Ply laminates (Fig. 4), the incipient damage occurs at approximately 9 cm (3.5 in) drop height and corresponding energy level was 5.71 J (4.21 ft-lb). Furthermore the impact load time curves indicate that for 32 ply moderately thick laminates, the linear response deviates at an incipient load of approximately 3643 N as shown in Fig. 4. Figure 5 shows the progressive impact damage in 32 ply moderately thick composites.

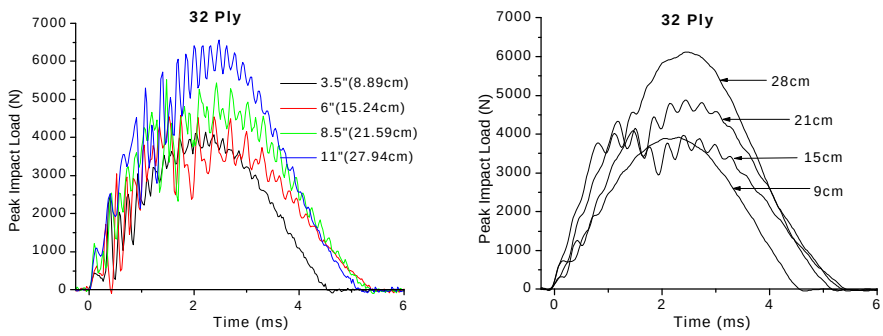

Fig. 4: Impact load-time unfiltered and filtered data for 32 ply thick laminates

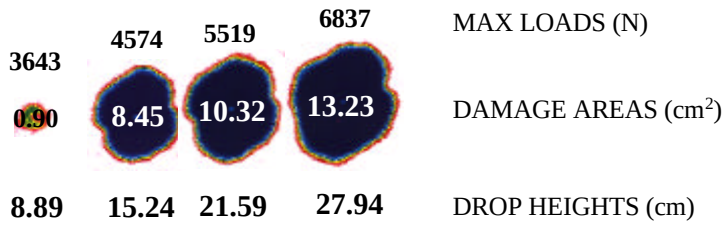

Fig. 5: Progressive impact damage for 32 ply moderately thick laminates

When the impact load time data was analyzed using the FFT smoothening technique, it was observed that there was no obvious load drop at incipient energy levels as shown in Fig. 6. This may be due to the fact that being a thin laminate, there may be a large amount of non-linear plate deformation. This nonlinear plate deformation eventually results into a very small delamination. Therefore there is no obvious load drop reflected in the load response curves. Due to this fact for thin laminates, the incipient damage was detected by using C-scan. The incipient damage load for the 16 ply laminate was approximately 1411 N. The corresponding drop height was 3.81 cm (1.5 in) and impact energy level was 2.34 J (1.73 ft-lb).

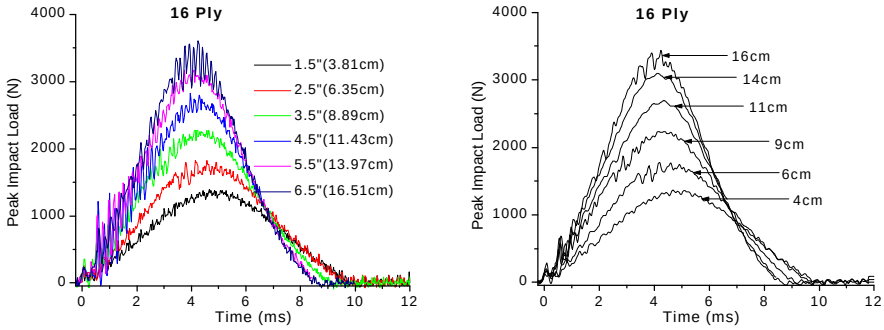

Fig. 6: Impact load-time unfiltered and filtered data for 16 ply thick laminates

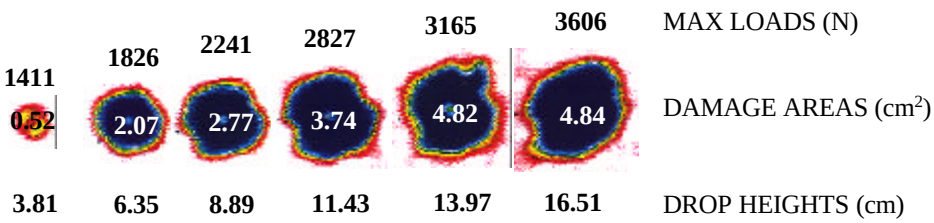

Fig. 7: Progressive impact damage for 16 ply thin laminates

Figure 7 shows the progressive impact damage in 16 ply moderately thick composites. The C-scan results clearly indicate that the impact damage in thick laminates is much more extensive than thin laminates.

CONCLUSIONS

The present progressive damage study of impact on these graphite/epoxy laminated composites resulted in the following conclusions.

- A FFT smoothening technique to remove the higher material frequencies from the impact load time response curves can be effectively used in analyzing low velocity impact behavior of composite materials.
- At the onset of delamination, there is deviation in the impact load time history curve. This deviation is obvious for thick laminates but may not be easy to detect for the thin laminates.
- Thick laminates show multiple deviations in the load response curves, indicating multiple delamination events during impact.
- If calculated on per ply basis, the impact energy levels required to initiate internal damages in the different thickness laminates is almost constant and is approximately equal to 0.136 J (0.1 ft-lb). However study also indicated that thicker laminates require higher amount of energy on per ply basis to cause the back face damages (spalling).
- When comparison of the damages is made with the assumption that laminates are subjected to the same amount of energy levels on a per ply basis, the examination of C-scan data of impacted laminates clearly indicates that the impact damage in thick laminates is much more extensive than thin laminates. .
- The failure mechanisms are different in the thick and thin laminates. In thick laminates, transverse shear seems to be the major failure mechanism. In thin laminate, large deformations resulting in high membrane strains seem to be the major failure mechanism.

ACKNOWLEDGMENTS

Part of this work was performed under Wright laboratory Contract No. F33615-90-C-320708. The authors wish to acknowledge Wright laboratory and the assistance provided by laboratory personnel in manufacturing the specimens and in providing access to the Laboratory's testing facilities.

REFERENCES

1. Dost E. F., Ilcewicz L. B. and Avery W. B., “Effect of Stacking Sequence on Impact Damage Resistance and Residual Strength for Quasi-Isotropic Laminates”, *ASTM STP 1110*, T.K. O’Brien, ed., 1991, 476-500.

2. Chen G. S., Bidingger G. M. and Lou M. C., (1993), “Impact Damage Tolerance of Thin Wall Composite Struts,” *34th AIAA Structures*, Structural Dynamics and Materials Conference, LaJolla, CA, Part 2, 847-858.

3. Demuts E., “Low Velocity Impact in a Graphite/PEEK,” *34th AIAA Struct. Structural Dyn. and Material Conference*, La Jolla, CA, part 2, 1993, 901-908.

4. Kelkar A., “Analysis of Composite Plates Under Quasi-Static Point Loads Simulating Low-Velocity Impact”, *NASA-CR -176485*, August, 1985

5. Wang C. J. and Jang B. Z., (1991a), " Deformation and Fracture Mechanisms of Advanced Polymer Composites Under Impact Loading," *J. Thermoplastic Composite Mat*., 4, 20-45.

6. Kim J. K., Mackay D. B. and Mai Y. W, "Drop Weight Impact Damage Tolerance of CFRP With Rubber Modified Epoxy Matrix," *Composites*, 24(6), 1993, 485-494.

7. Olesen K. A., Falabella R. and Buyny R. A., "Mechanical Behavior of Three Generations of Bismalcimide Composite Prepregs," *37th Int. SAMPE Symp. and Exhibition*, Covina, CA, March 9-12 1992, 37, 705-715.

8. Nettles A. T. and Lance D. G., "A Study of the Damage Tolerance Enhancement of Carbon/Epoxy Laminates By Utilizing an Outer Lamina of Ultra High Molecular Weight Polyethylene," *Int. SAMPE Tech. Conf. 23*, Kiamesha Lake, NY., Oct. 21-24, 1991,62-71.

9. Nettles A. T. and Lance D. G., "On the Enhancement of Impact Damage Tolerance of Composite Laminates," *Composites Engineering* 3(5), 1993, 383-394.

10. Hull D. and Shi Y. B., (1993), "Damage Mechanism Characterization in Composite Damage Tolerance Investigation," *Composite Structures*, 23, 99-120.

11. Wang H. and Khanh T. V., "Low Velocity Impact Damage of Carbon/PEEK Crossply Laminates," *Proc. 8th Int. Conf. of Composite Materials (ICCM/8)*, Honolulu, July 15-19, 1991, 32-E.1-10.

12. Ishai O. and Shragi A., "Effect of Impact Loading on Damage and Residual Compressive Strength of CFRP Laminated Beams," *Composite Structures*, 14, 1990, 130-140.

13. Straight L. H., Karasek m. L. and Amateau M. F., "Effect of Seawater Immersion on the Impact Resistance of Glass Fiber Reinforced Epoxy Composites," *J. Composite Materials*, 26(12), 1992, 1725-1740.

14. Pope G. J. and Karbhari V. M., (1992), "Effects of Freezing on Impact Properties of RTM Composites, and their Applications in Offshore Structures," *Proc. of Int. Conf. on Civil Eng. in the Ocean V*, College Station TX, Nov. 2-5, 828-839.

15. Sjoblom P., "Simple Design Approach Against Low Velocity Impact Damage," *Proc 32nd SAMPE* Symp, Anahiem, CA, 529-539, 1987.

16. Strait L. H., Karasek M. L. and Amateau M. F., "Effects of Stacking Sequence on the Impact Resistance of Carbon Fiber Reinforced Thermoplastic Toughened Epoxy Laminates," *J. Composite Mat*., 26(12), 1725-1740, 1992b.

17. Lagace P. A. and Wolf E., "Impact Damage Resistance of Several Laminated Material Systems," *34th AIAA Struct, Structural Dyn and Mat Conf.*, La Jolla Ca, Pt.4, 1863-1872, 1993.

18. Sjoblom P., and Hwang B., "Compression-After Impact," *Proc 34th Int SAMPE Symp*, Reno, NV, May 8-11,1989,1411-1421.

19. Avva V.S., Vala J.A., and Jeyaseelan M., “Effect of Impact and Fatigue Loads on the Strength of Graphite/Epoxy Composites,” *ASTM STP 893*, 196-206, 1986.

20. Bogdanovich, A. E. and Iarve, Endel V., “Numerical Analysis of Impact Deformation and Failure in Composite Plates,” *Journal of Composite Materials*, Vol. 26, No. 4, p. 520-545. 1992.

21. Bogdanovich, A. E. and Iarve, Endel V., “Analysis of Damage Zones in Graphite-Epoxy Laminates in Low Velocity Impact,” *Mechanics of Composite Materials*, 27(3), p. 270-276, 1991.