# IMPACT-INDUCED DELAMINATIONS IN THERMOSET AND THERMOPLASTIC COMPOSITES

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## INTRODUCTION

Laminated fiber-reinforced composites are engineering materials with many desirable properties including high stiffness and strength. However, the lack of fiber reinforcement in the through-thickness direction makes composite laminates vulnerable to foreign object impact loading. Transverse impact loading can lead to a variety of damages including matrix cracking, delamination and fiber breakage. Delaminations can reduce the strength of a laminate, especially the compressive strength after impact. Impact loading typically causes multiple delaminations that vary in size and shape by depth location. The fracture behavior of impact damages has been a topic of extensive research [1]. Recently significant advances have been made in the area of nondestructive evaluation (NDE) of impact damages in composites. For example, ultrasound is used to map out the details of impact-induced delaminations with ply-by-ply resolution [2].

In this work ultrasonic NDE is used to address three problems in impact-induced delamination. First, quantitative correlation between the energy dissipated in the laminate and the total area of delamination is investigated. The results are compared to mechanical properties of the composite, such as the fracture toughness. Second, the ability of a delamination to block the passage of ultrasound and the associate "shadowing" effects are studied. Finally the impact resistance in terms of the area of delamination per unit of dissipated energy is compared for a thermoset and a thermoplastic composite.

A number of composite systems have been studied in this work, including carbon-epoxy (C/EP), carbon-polyphenylene sulfide (C/PPS), and glass-epoxy (G/EP). Here we use the terms carbon-epoxy and graphite-epoxy interchangeably. Both woven laminates and laminates made of unidirectional prepreg tapes have been investigated. Ultrasonic nondestructive results were compared with destructive tests such as pyrolytic de-ply.
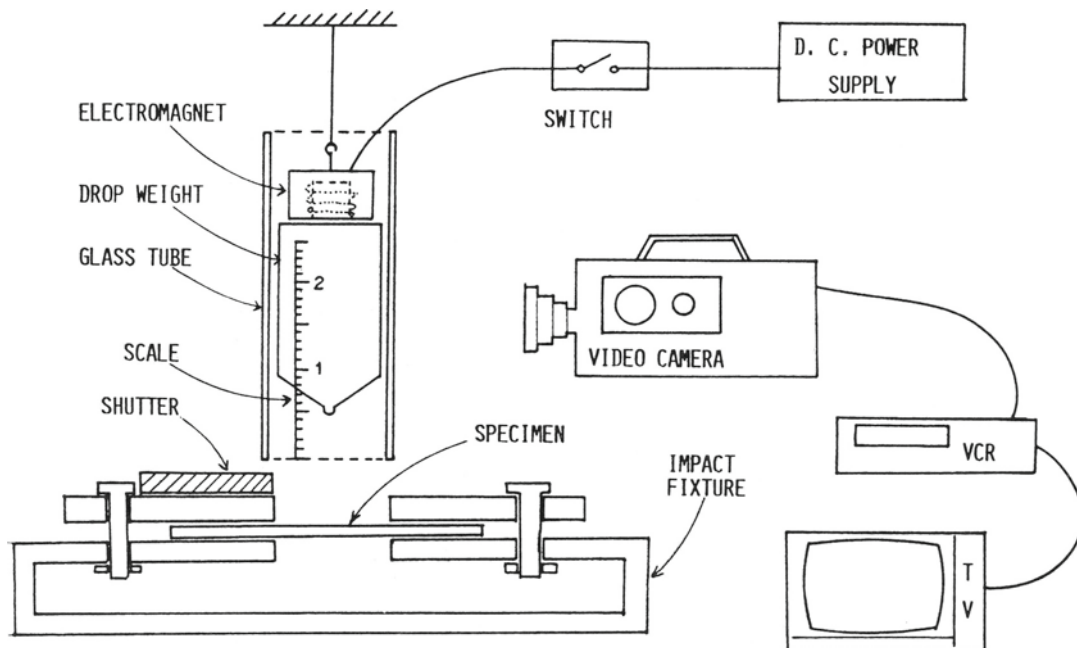
Fig. 1.     Schematic diagram of the experimental setup for impact
            tests of composite laminates.


EXPERIMENTAL TECHNIQUES

The Impact Test Setup

     The experimental setup for carrying out the impact damage tests,
shown in Fig. 1, is similar to those reported in the literature.  It
uses a 9.8 pound 2" diameter drop weight with a 0.5" diameter
hemispherical tup as the impactor.  The steel weight is suspended by an
electromagnet and is released with zero initial velocity by turning off
the current to the electromagnet.  The weight falls in a glass guide
tube.  A scale on a transparent thin plastic sheet is adhered to the
outside of the glass tube.  Tests were also made to insure that
frictional force of the guide tube wall has negligible effects on the
results.  The weight impacts composite coupons clamped in a heavy steel
fixture and bounces back.  A wooden "shutter" is moved over the coupon
to prevent multiple hits.  Two clamping conditions were used in the
experiments: 5" square and 3" diameter circle.

     The falling and rebounding of the impactor behind the transparent
ruler are filmed with a videocamera with a high shutter speed.  The
impact event is then replayed on a television screen connected to a VCR
with a single frame advance feature.  Since the mass of the impactor is
known, the incident and rebound energy and momentum are easily measured
from the height and velocity.  The standard 30 frames per second speed
of the VCR serves as a convenient clock in the velocity measurements.
The energy lost by the impactor is the difference between the incident
energy and the rebound energy.  It was assumed that the energy lost by
the impactor is equal to the energy dissipated in the panel, which in
turn causes delaminations, matrix cracking and, in some cases, fiber
breakages.

## The Ultrasonic Scan System

The ultrasonic scan system consists of a motorized immersion test tank, an ultrasonic pulser/receiver (Panametrics 5052PR), a gated peak detector, an A/D convertor, a digitizing oscilloscope (LeCroy 9400) and a desktop computer. For C-scans a 1/2" diameter 5 MHz transducer with a 4" focal length was used. By adjusting the delay and width of a time window of the gated peak detector, scans can be made on the back surface echo or on backscattered signals from a certain depth in the interior of the panel.

## RESULTS AND DISCUSSION

## Total Delamination Area Estimates

Woven 16-ply glass-epoxy panels with a quasi-isotropic layup were impacted at different energies. Since these panels were transluscent, the delamination damages were visible to the unaided eye. The impacted panel showed a well-defined small circular delamination area on the top (impact) side and a larger circular delamination on the bottom side. To estimate the total delamination area of all plies combined, the delaminations were assumed to be circular and the diameters of the circles were assumed to be increasing linearly from the top to the bottom surface. In this simplifying "trapezoidal model" the total delamination area of a 16-ply panel was obtained by summing up the areas of the 15 circles. It should be pointed out that the delaminations inside the panel are not really circular in shape and the model serves as a quick estimate for the total area of the delaminations.

Ultrasonic pulse echo C-scans were made on the impacted panels by recording the amplitude of the back surface echo with the gated peak detector. The scan results were then displayed in eight levels of gray, as shown in Fig. 2. The scan patterns showed a series of concentric circles. The innermost circular area had approximately the same size as the circular delamination visible from the impact side. The largest circle was about the same size as the circular delamination visible on the bottom side. Using the same "trapezoidal model", the total delamination area can also be estimated from C-scan results. The total delamination area so obtained agreed fairly well with those based on direct visual measurements.

Although the two above estimates based on the trapezoidal model agreed with each other. It was necessary to determine whether they agreed with the actual total area of delamination. To obtain the latter, the delaminations in the coupon were stained with an ether solution of gold chloride and the coupon was then de-plied by partial pyrolization [3]. The gold stained delamination areas on each surface of the unstacked plies, as shown in Fig. 3, were traced and the total area determined. In comparing the area based on the simple trapezoidal model and the actual area, the trapezoid model was found to overestimate the area by about 20%.

## Correlation with Energy Dissipation

Studies of impact damages in composites reported in the literature often correlate the "damage area" based on the outline of the maximum extent of all superimposed delaminations with the incident energy of the impactor [4]. It would be more interesting to compare the energy dissipated in the composite panel with the total area of delaminations caused by the impact. Although delaminations are not the only damages
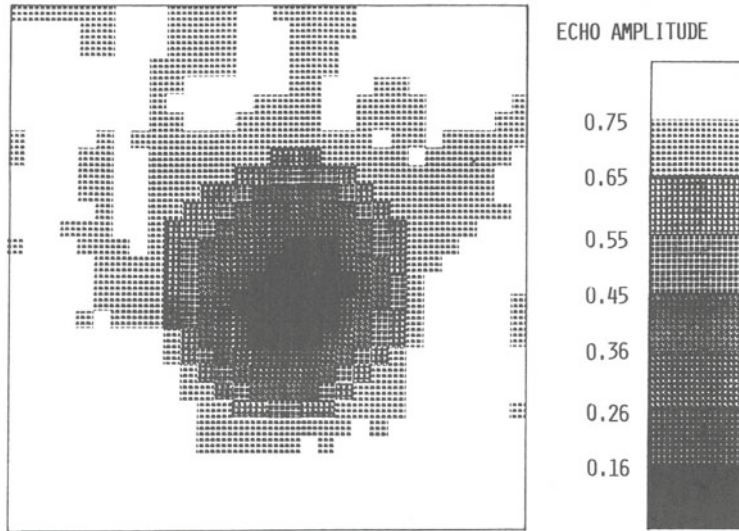
Fig. 2.     Ultrasonic C-scan map of an impacted 16-ply woven glass-
            epoxy panel.  The total scanned area was 1.5" x 1.5".
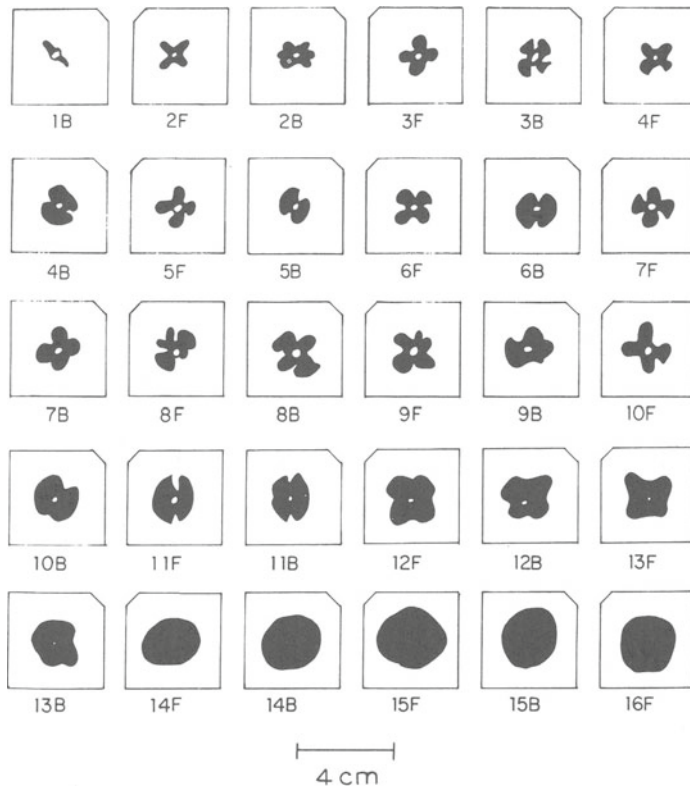


Fig. 3.     Size and shape of impact delaminations in a 16-ply woven
            glass-epoxy laminate as revealed by de-ply.  The gold-
            stained images on the last three or four plies are often
            quite faint and difficult to discern.

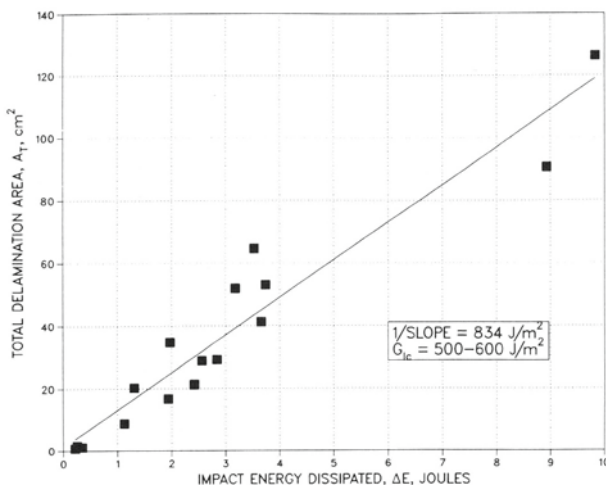TOTAL DELAMINATION AREA VS. ENERGY LOST BY IMPACTOR
FMC GLASS/EPOXY

Fig. 4.    Correlation between total delamination area and dissipated
energy in woven glass-epoxy panels.


caused by an impact, such a correlation would possibly reveal the
fraction of energy consumed by the creation of delaminations.  Figure 4
shows the total delamination area determined by C-scans versus the
energy dissipated.  The inverse slope gives a value of 834 $J/m^2$.
Considering that the C-scan and the trapezoidal model overestimates the
area by about 20%, the inverse slope is approximately 1000 $J/m^2$.  It is
interesting to compare this value with the manufacturer provided mode-I
fracture toughness $G_{Ic}$ of 500-600 $J/m^2$.  This implies that, if one
accepts the notion that $G_{Ic}$ is the energy needed to create a unit area
of delamination, then about 50-60% of the energy lost by the impactor
and dissipated in the panel is consumed by the formation of the
delaminations.  The remaining portions of the dissipated energy are
presumably used up by matrix cracking, fiber breakage, fiber-matrix
debonding and other damages.

     Since there were two different thicknesses in the set of
glass-epoxy panels, the effects of panel thickness on impact damage was
investigated.  In one study [4] the damage area was correlated to the
incident impactor energy normalized by the panel thickness.  In this
work it was found that the damage areas could be drastically different
for the same normalized impact energy. For example, Table 1 shows the
impact data of two woven glass-epoxy panels, one was 0.36 cm thick
(16-ply) and the other 0.58 cm (24-ply).  As can be seen, the damage
area differed by a factor of 3 while the impactor energy normalized by
the panel thickness were about equal.  Table 1 also shows the energy
dissipated in the panel, which correlated very well with the damage
areas.


Table 1.    Effects of panel thickness on impact damages in woven
            glass-epoxy laminates

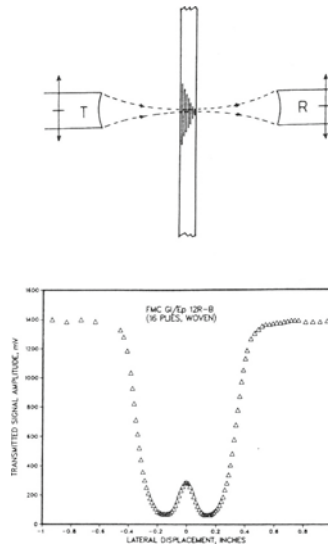| Thickness T (cm) | $E_{in}$ (J) | $E_{in}/T$ (J/cm) | Area (cm$^2$) | $\Delta E$ (J) |
|---|---|---|---|---|
| 0.58 | 16.6 | 28.6 | 91.3 | 8.93 |
| 0.36 | 10.5 | 29.1 | 27.3 | 2.84 |

Fig. 5.    Through-transmission line scan of an impacted glass-epoxy laminate.


## Transmission of Ultrasound Through Delaminations

Delaminations in composite laminates are quite effective in blocking the interrogating ultrasound, however, the degree of opacity depends on the frequency and focusing of the beam and on the contact conditions of the delaminated surfaces.  For example, local stress could hold the surfaces in contact (the "kissing disbond").  Measurements were therefore conducted to investigate the degree of transmission through delaminations.  Figure 5 shows the configuration for making a through-transmission line scan on an impact damaged 16-ply glass-epoxy panel.  The transducers were 1/2" diameter 5 MHz focused probes with a focal length of 4" in water.  Also shown in Fig. 4 is the transmitted signal amplitude versus lateral distance.  As can be seen the signal amplitude decreased rapidly when the beam moved into the damaged zone, however, even at the lowest signal level of 70 mV, there was still a definitely observable transmitted echo.  The maximum and minimum signals in the scan were 1.4 V and 70 mV, differing by a factor of 20.  The small peak at the center of the scan corresponds to the often observed central low damage spot under the impact point.


## COMPARISON OF IMPACT RESISTANCE IN CARBON-EPOXY AND CARBON-PPS PANELS

Because susceptibility of composite laminates to impact delamination has been a weak point of such materials, there has been a continuous effort by the materials manufacture industry to improve the toughness and impact resistance of composites.  Different resin systems have been formulated, some are thermosets and some are thermoplastics.  In this section, results are presented to show the comparison of impact damages in carbon-epoxy and carbon-PPS laminates.  The panels used were 48-ply with $[45/0/-45/90]_{6s}$ layup.  The panels were clamped between two 1" thick steel plates with 3" diameter cutout holes.  The impactor was again the 9.8 pound weight with a 1/2" diameter hemispherical tup.  The total damage area was estimated from ultrasonic C-scans while assuming that the area of the top delamination to be zero in the trapezoidal pattern.  (For nonwoven carbon fiber reinforced laminates, the trapezoidal pattern is essentially a triangle).  Figure 6 shows the experimental results.  As can be seen, the impact resistance of the two systems are quite similar.


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Detailed dependence of impact resistance on mechanical properties such as interlaminar shear strength (ILSS), $G_{Ic}$ and percent elongation to break is not within the scope of this work. However, it is interesting to point out that the percent elongation to break for epoxy and PPS are both in the 4-5% range whereas that of PEEK, a much more impact resistant material, is 25-30%. Moreover, the similarity in damage area in carbon-epoxy and carbon-PPS at the same impact energy has also been observed in other studies.

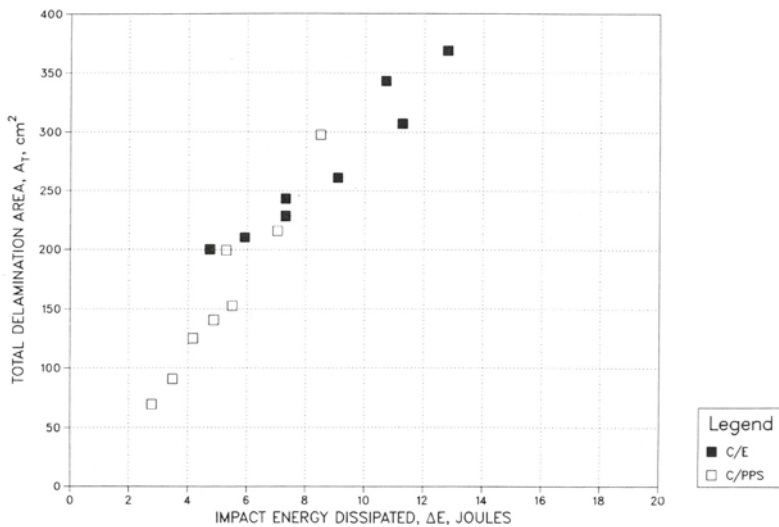## IMPACT OF CARBON/EPOXY AND CARBON/PPS LAMINATES

Fig. 6.    Comparison of impact results in carbon-epoxy and carbon-PPS laminates.

CONCLUSION

Total delamination area due to impact damage was found to correlate approximately linearly with the energy dissipated in the laminate. In woven glass-epoxy laminates, this correlation yielded an empirical value of energy per unit area of delamination. This value was equal to about twice the $G_{Ic}$ value.

Ultrasonic NDE techniques including C-scan and through-transmission line scan revealed considerable detail about the damage zone. The central low damage spot was observed and partial transmission through the delaminations was demonstrated. The latter is quite significant in terms of addressing the "shadowing effect" of detecting damages behind delaminations.

Finally a quantitative comparison was made for impact damages in a thermoset system (carbon-epoxy) and a thermoplastic system (carbon-PPS). Their resistance against impact damage was found to be comparable.

REFERENCES

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4.  M. Kitanaka, H. Kobayashi, T. Norita and Y. Kawatsu, "Damage tolerance of thermoplastic/graphite fiber composites", ICCM '85, pp. 913-929.