PROGRESS REPORT

# FRACTOGRAPHY OF COMPOSITE DELAMINATION
## NAG-1-705

### 1 OCTOBER 1987 - 15 APRIL 1988

## ABSTRACT

Studies have been made of the fractography of mode II delamination
and the impact damage of carbon fiber reinforced polymer composites.

Laminates fractured under mode II loading were potted in a clear
epoxy polymer, sectioned and polished and examined using transmission and
reflection light microscopy. There were only occasional fibers bridging the
mode II cracks. These cracks were not always visible probably because the
crack opening displacement was to small as to be resolved using light
microscopy.

A study was made of the effect of repetitive impacts on a laminates of
AS4/3501-6 and IM6/3501-6. Plots of cumulative impact energy $vs$
cumulative absorbed energy exhibited a sharp change in slope which
corresponded to the damage area reaching the edges of the specimen. The
initial slope was highly reproducible for both composite materials. On the
other hand, the intersection point between the two slopes, where the damage
area reaches the specimen edges, was highly variable between specimens.
This variability is tentatively ascribed to differences in laminate quality.

## RESULTS

The work under this Grant during the reporting period has been on
two topics; (a) mode II delamination and (b) impact damage.

### Mode II Delamination:

The load frame shown in Figure 1 was constructed to load end-
notched carbon fiber laminates to induce a pure mode II crack and then pot
the cracked specimen in a clear epoxy for sectioning and microscopy. As
shown in Figure 2, the specimen is clamped at one end and deflected
downward at the other end by turning a bolt with a short wooden dowel
contacting the specimen. Crack growth at the edge of the specimen was

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observed using a telescope and when the crack reached about half the length of the specimen a mold was built around the free end of the laminate (including the dowel), filled with the potting resin and heat cured.

The test laminate was a unidirectional 16ply, AS4/3501-6 composite 1in. wide and 4in. in length. Excessive bending of the specimen near the clamped end resulted in failure before a delamination could be produced. This problem was solved by supporting the specimen with two laminates 0.5in wide and 2.25in and 3.25in long respectively as shown in Figure 2. Using this configuration, a mid-plane crack could be initiated without any apparent breakage at the clamped end.

Two loading configurations are shown in Figure 2. In one case (Figure 2A), the laminate was precracked using a knife blade, the upper section cut away and the dowel positioned against the protruding lower section. In order to minimize Mode I loading, a wire was wrapped around the specimen as shown in Figure 2A. Judging from visual observations the mode I opening displacements are minimal at the crack front that had propagated one-half the length of the specimen so that mode I loading is minimal near the crack front.

The loading configurations shown in Figure 2B should produce a pure mode II delamination. However, we have not yet induced a crack in this fashion. The fractography results reported here are for cracks produced using the "mixed mode" technique (Figure 2A).

The general appearance of the cut sections is shown in Figure 3. Two major cracks developed in the specimen ; the major mixed-mode crack along the central plane and a pure mode II crack in the upper half of the specimen. For the most part, these cracks progressed through the matrix with relatively little fiber bridging. Occasionally, there was evidence of fibers spanning the crack (Figure 4). The mode II crack was not continuous. As shown in Figure 5, the crack is distinct on the left and right hand sides of the photomicrograph but disappears in the center.
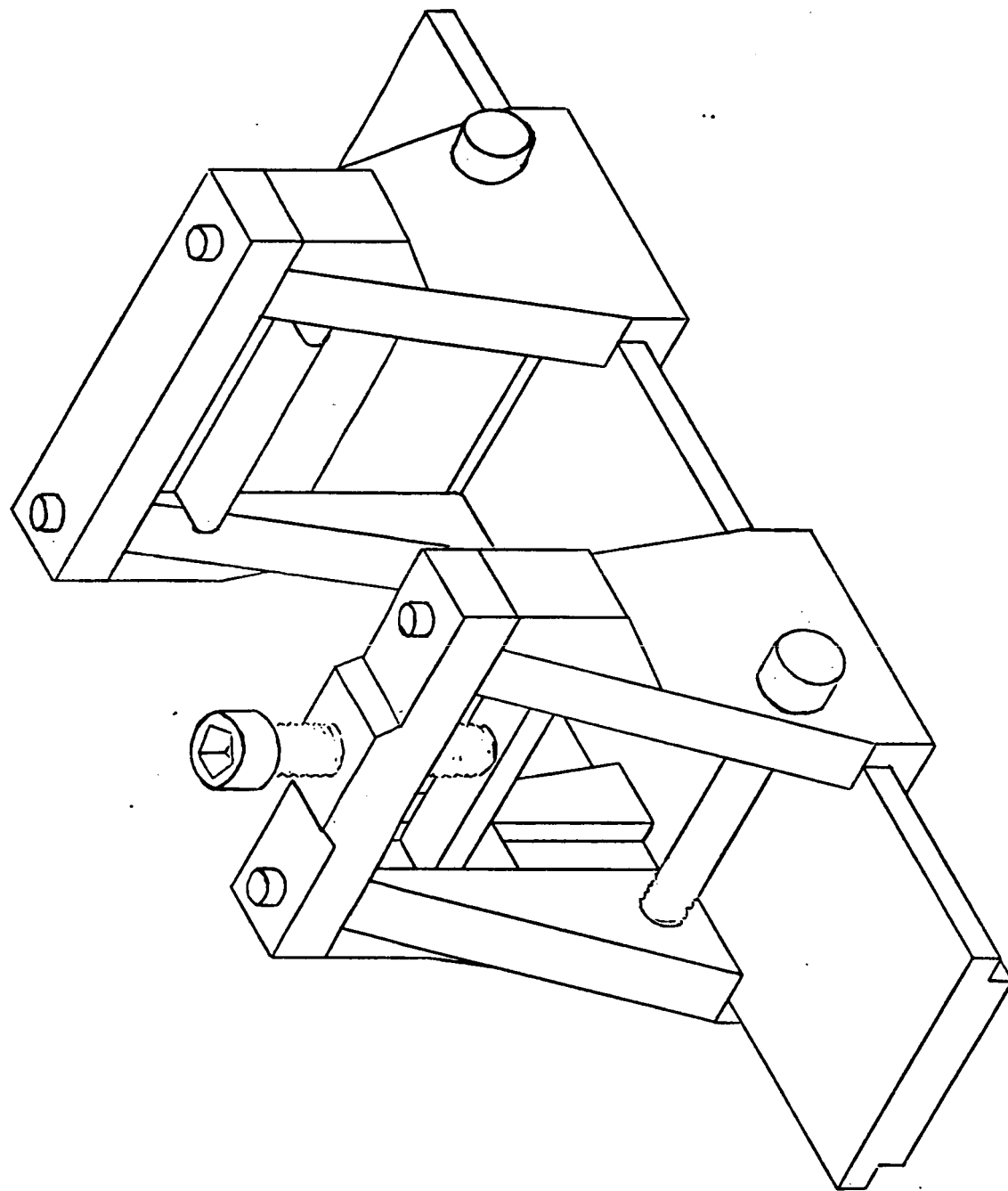
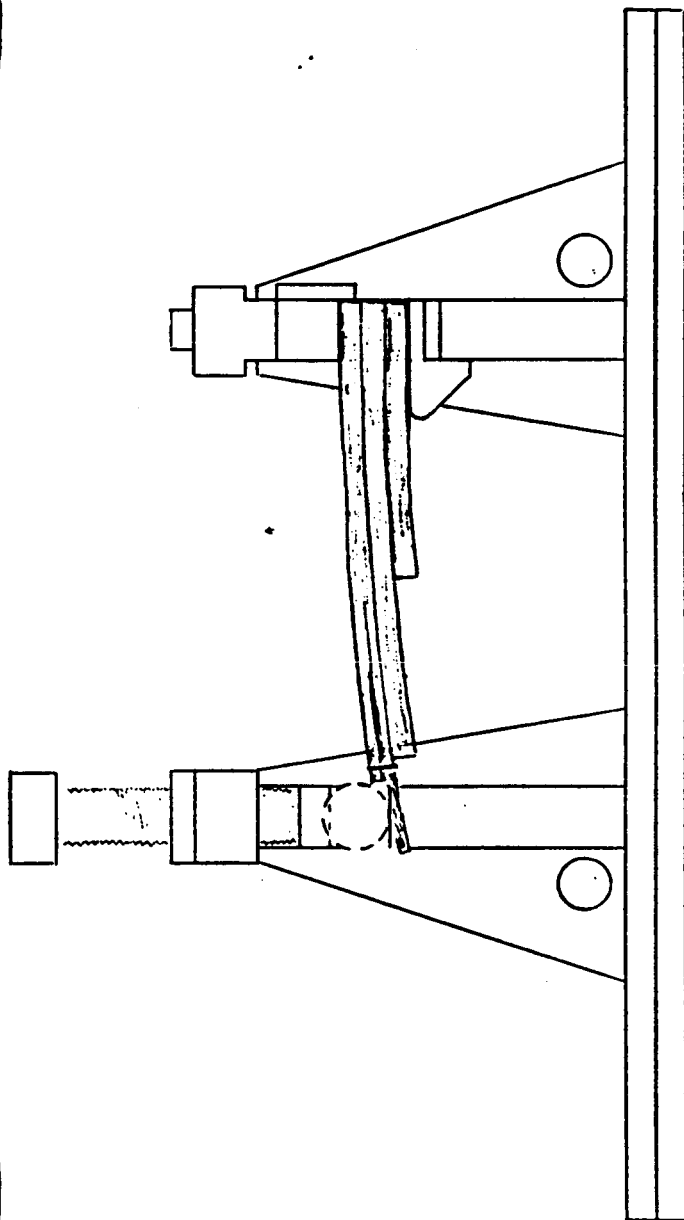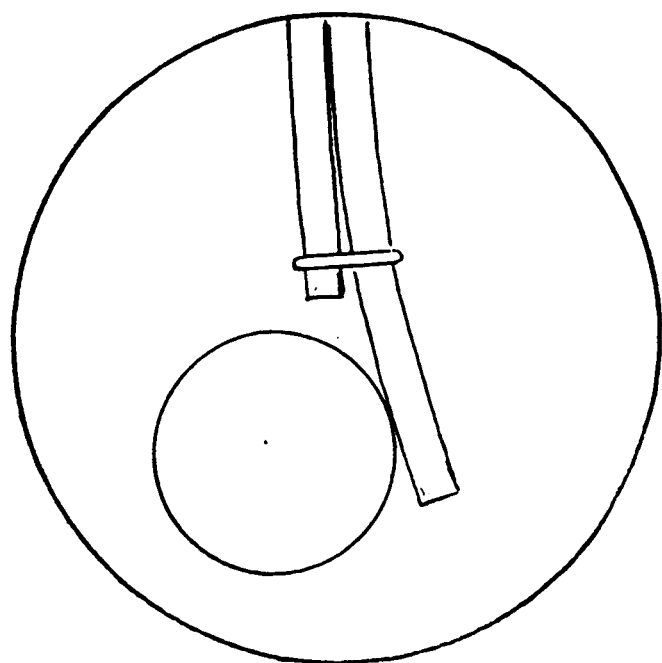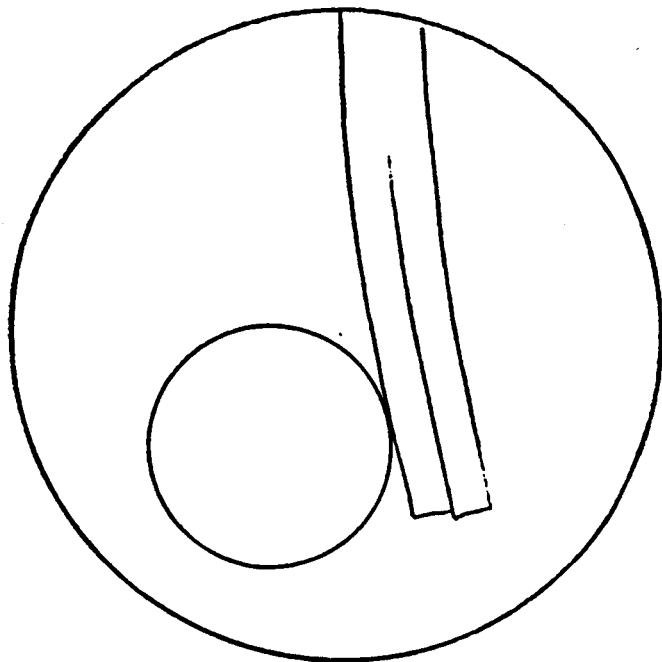Figure 1 - Load frame for mode II delamination

Figure 2 – Cut-away view of (A) specimen in load frame, (B) test configuration for "mixed" mode loading, and (C) for pure mode II loading. The specimen is supported by two smaller laminates

The general appearance of the cut sections is shown in Figure 3. Two major cracks developed in the specimen ; the major mixed-mode crack along the central plane and a pure mode II crack in the upper half of the specimen. For the most part, these cracks progressed through the matrix with relatively little fiber bridging. Occasionally, there was evidence of fibers spanning the crack (Figure 4). The mode II crack was not continuous. As shown in Figure 5, the crack is distinct on the left and right hand sides of the photomicrograph but disappears in the center.
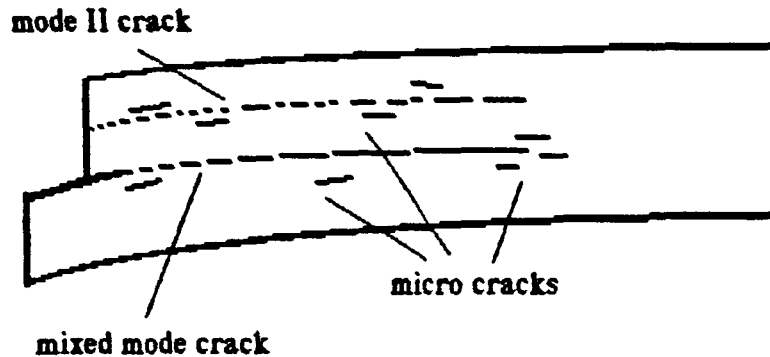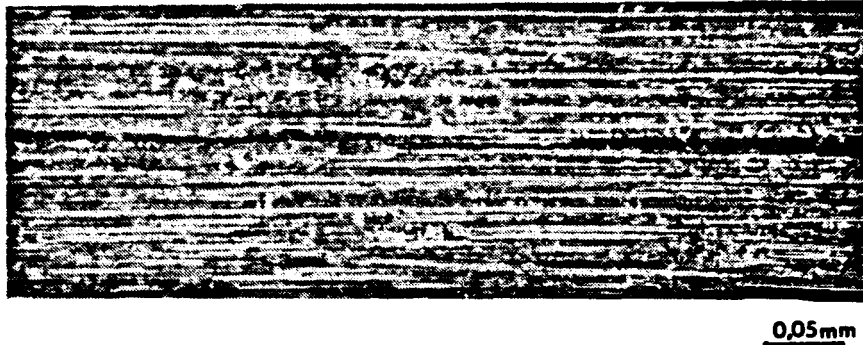


Figure 3 - Schematic of cracking in a mode II specimen



0,05 mm

Figure 4 - Central mode II crack (Figure 3) showing occasional fiber crossover

0,05mm

Figure 5 - Discontinuity in mode II crack


As shown schematically in Figure 3, there were microcracks near the major crack and especially ahead of the crack front. It was sometimes difficult to distinguish microcracks from laminate imperfections but there is the distinct possibility that "satellite" microcracks develop ahead of the mode II cracks but then close-up once the crack front has passed. The formation of these satellite cracks constitute part of the energy of mode II crack propagation.

The stressed laminate revealed extensive fiber breakage throughout the specimen. In Figure 6, photomicrographs are shown of a section cut through an unstressed laminate and a section through the stressed laminate. In the latter, many of the fibers appear to have broken into short segments.

Conclusions and Future Work. The mode II cracks appear to propagate through the matrix with relatively little fiber bridging. This is in distinct contrast to Mode I delamination where there was extensive fiber bridging. The pure mode II crack seemed to be discontinuous in that the crack "disappears" for a short section and then reappears again. Quite possibly the the crack opening becomes too small to be observed at the magnifications used here. This explanation is supported by the fact that in the presence of a small mode I component, the crack was continuous. In principle, a mode II crack should not involve any opening displacement. The fact that it can be seen at all indicates that at the local level there is some mode I component.

Future work will include modifications of the load frame to prevent specimen cracking at the fixed end without having to resort to stiffening members. One possible solution is to use thinner (8ply) laminates so that the bending stress for delamination is less than the stress for transverse

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cracking. The excessive fiber breakage (Figure 6) may have been the result of the high stresses needed to delaminate the stiffened specimen.

Further tests are planned for the AS4/3501-6 laminate to confirm and possible extend the observations reported here. Subsequently, a unidirectional laminate with a higher fracture energy will be tested.

Cross-ply (0/90) laminates will be tested. Based on impact damage fractography, delamination is expected to occur in the resin layer between plys rather than intra-ply. The experiments reported here on mode II delamination and in previous reports on mode I are actually intra-ply failures which are rarely encountered in impact damage.
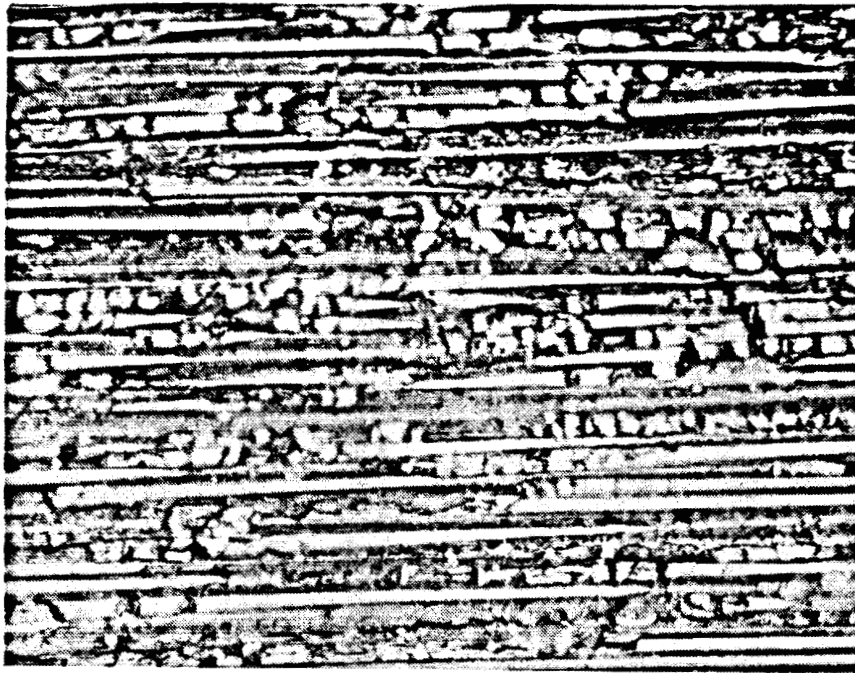
A



B

0.01 mm

Figure 6 - Fiber fracture in tested specimen (A) not observed in untested laminate

## Impact Tests:

An investigation has been undertaken to determine the effect of matrix properties (and other factors) on laminate impact damage. The test method, which was originated at the DFVLR (1) in West Germany, involves

1. Stellbrink, K., "The Repetitive Dropweight Test with Increasing Energy," Wissenschaftlich-technische Tagung :12, Verstarkete Paste '88, Berlin, DDR, 1988 p.21

repetitively impacting a specimen and plotting the cumulative impact energy *vs* the cumulative adsorbed energy. These plots typically exhibit a change in slope which has been attributed (1) to a change in the damage mode, i.e., from predominantly delamination to the onset of fiber fracture.

The test lends itself to materials development since the test laminate is relatively small and one specimen yields damage information over a range of impact loads. In this study the extent and type of damage at various stages of impact history are being determined using acoustic backscattering, x-ray computerized tomography (CAT scanning) and metallographic sectioning for microscopy.

Experimental. The drop weight impact test equipment is shown in Figure 7. A round nose (1cm diameter) impacter is fitted with an accelerometer and an electro-optical detector records the drop and rebound heights. The computer controls calculate the incident and adsorbed energy as well as the force and displacement. The specimen was a 16ply, [0/90] laminate 10cm in length and 5cm wide. The specimens were fabricated from AS4 and IM6-3501-6 prepreg (Hercules Inc.) in the composite fabrication facility in the Mechanical Engineering Department of the University of Utah using conventional vacuum bag/autoclave procedures. The test laminates were clamped to steel blocks so that the impact area of 5cm X 5cm was unsupported.

Results. Typical repetitive impact test (RIT) results are presented in Figure 8 for AS4/3501-6 and IM6/3501-6 specimens. There is a distinct change in slope in all cases. The force-displacement traces are shown in Figure 9 for impacts in the initial slope (stage I) and the secondary slope (stage II). These traces correspond to the 5th, 12th, 15th and 23rd impact (Figure 8A). In stage I ( impact 5 and 12) the impacter response is essentially linear (Figure 9A) but is distinctly nonlinear in the stage II region (Figure 9B).
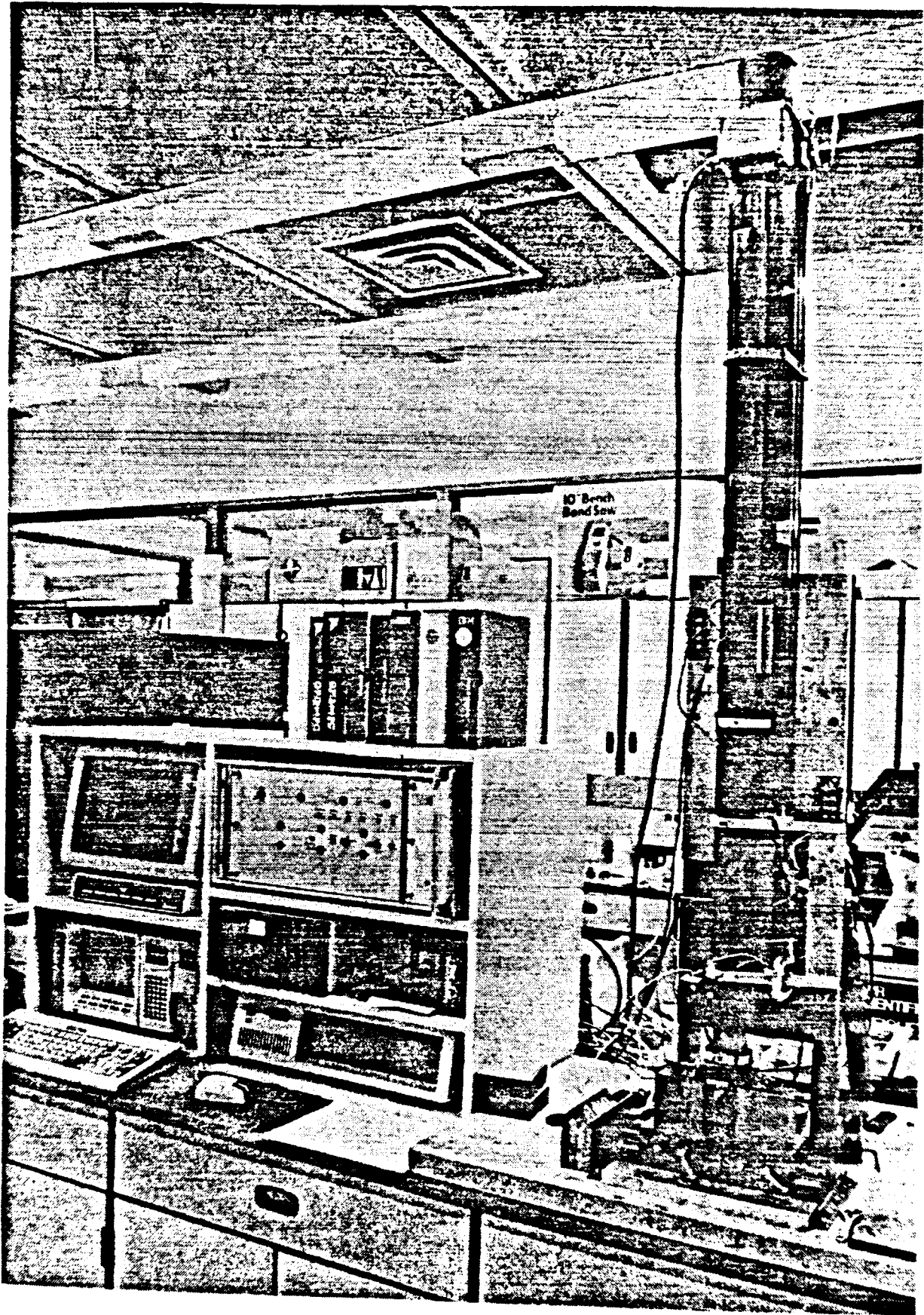
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Figure 7 - Drop-weight impact test equipment including devoted computer hardware (courtesy of Prof. John Nairn)
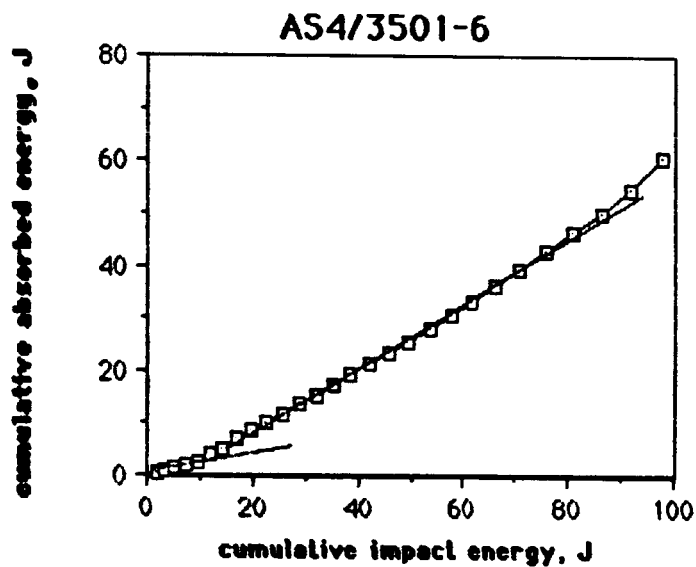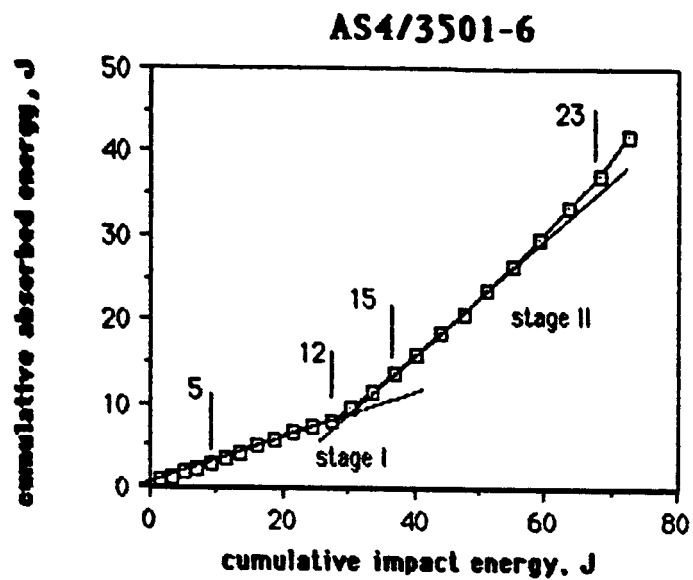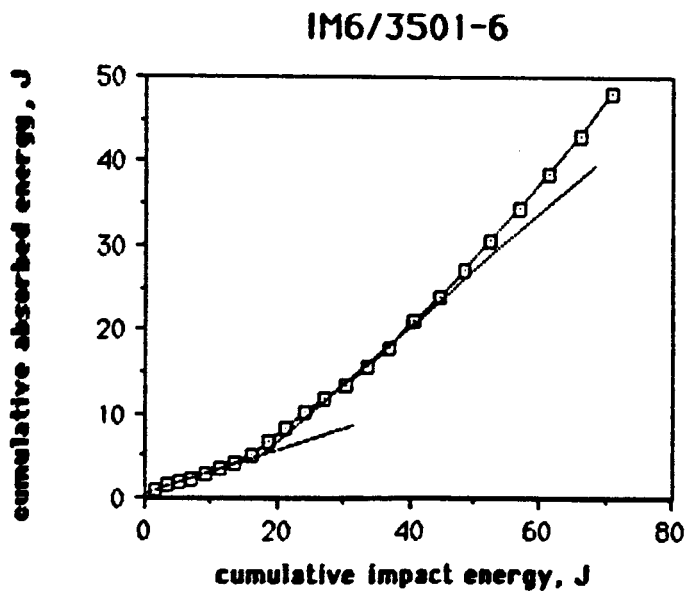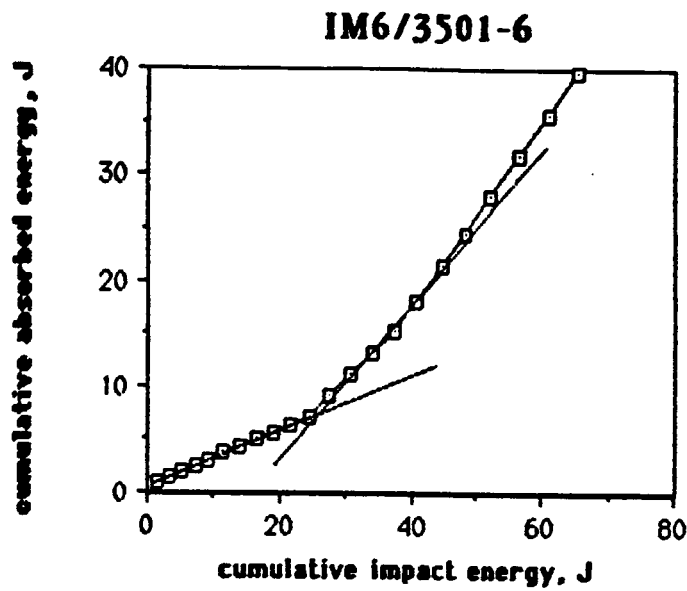
Figure 8 A - Typical RIT data: cumulative impact energy vs cumulative absorbed energy (AS4/3501-6)

## IM6/3501-6



## IM6/3501-6



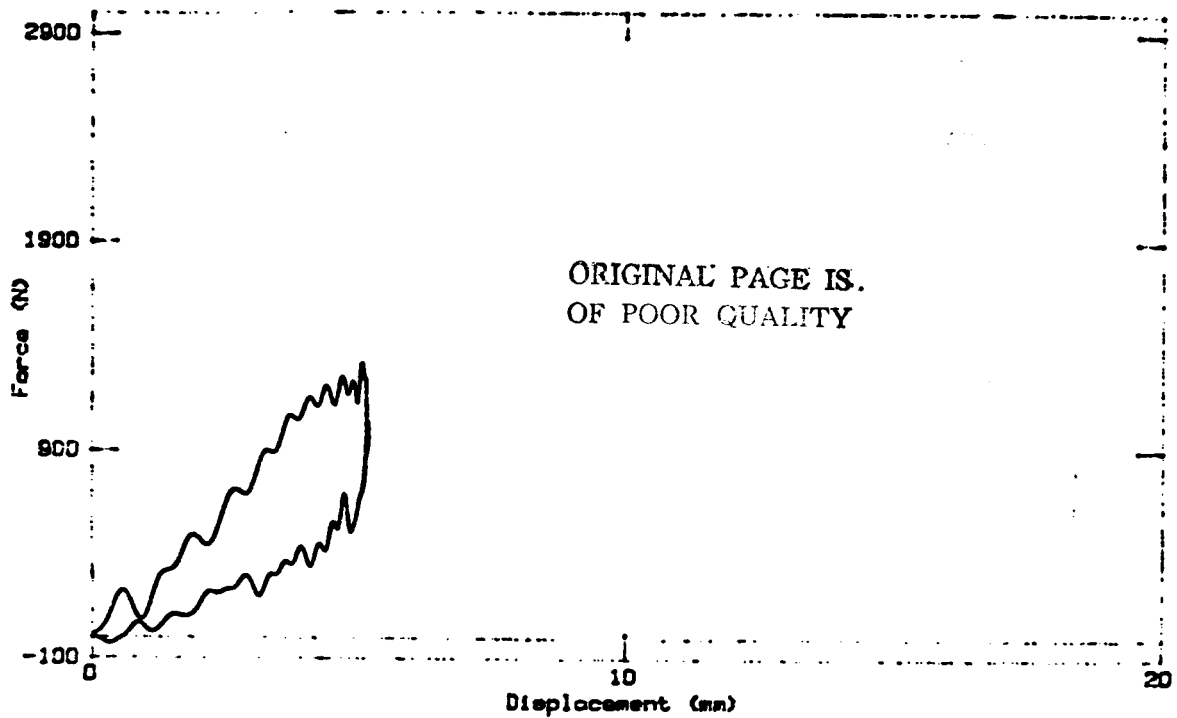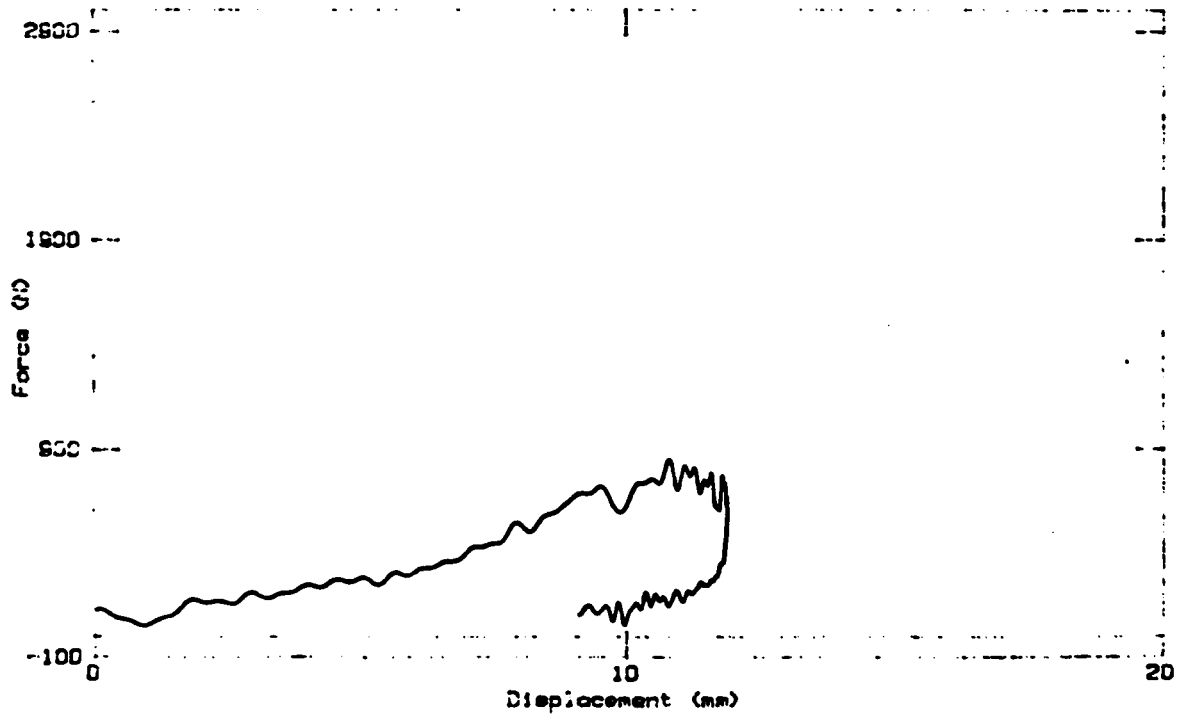Figure 8 B - Typical RIT data: cumulative impact energy vs cumulative absorbed energy (IM6/3501-6)
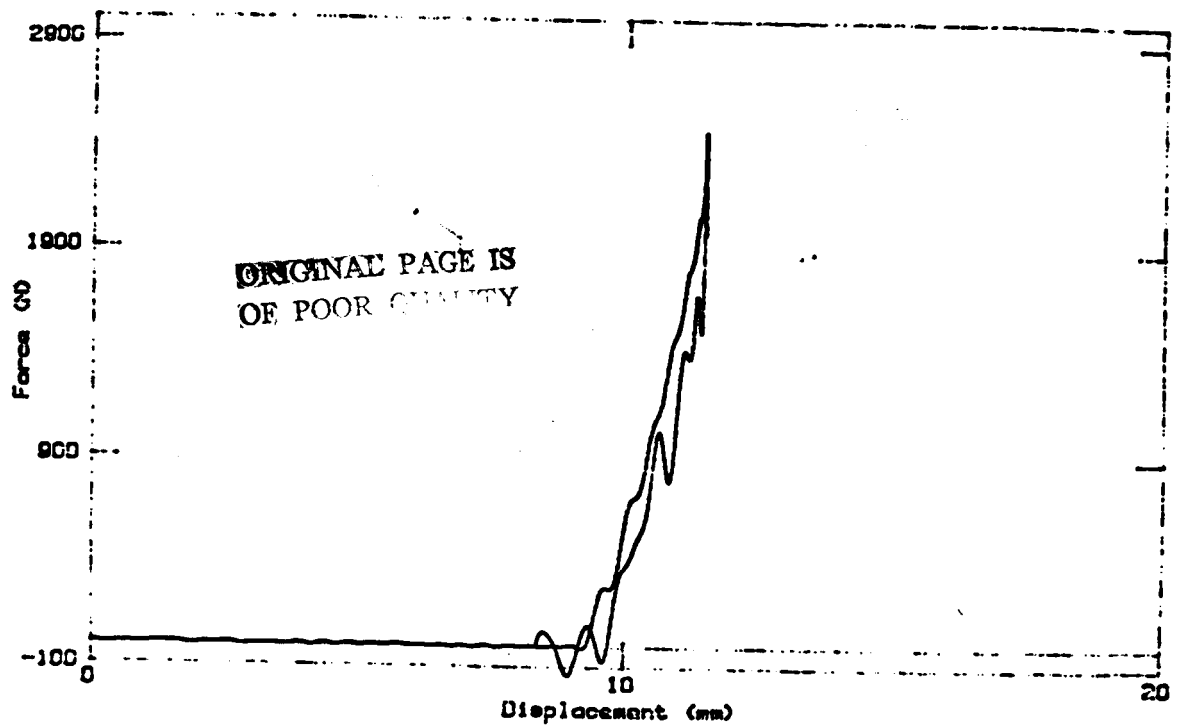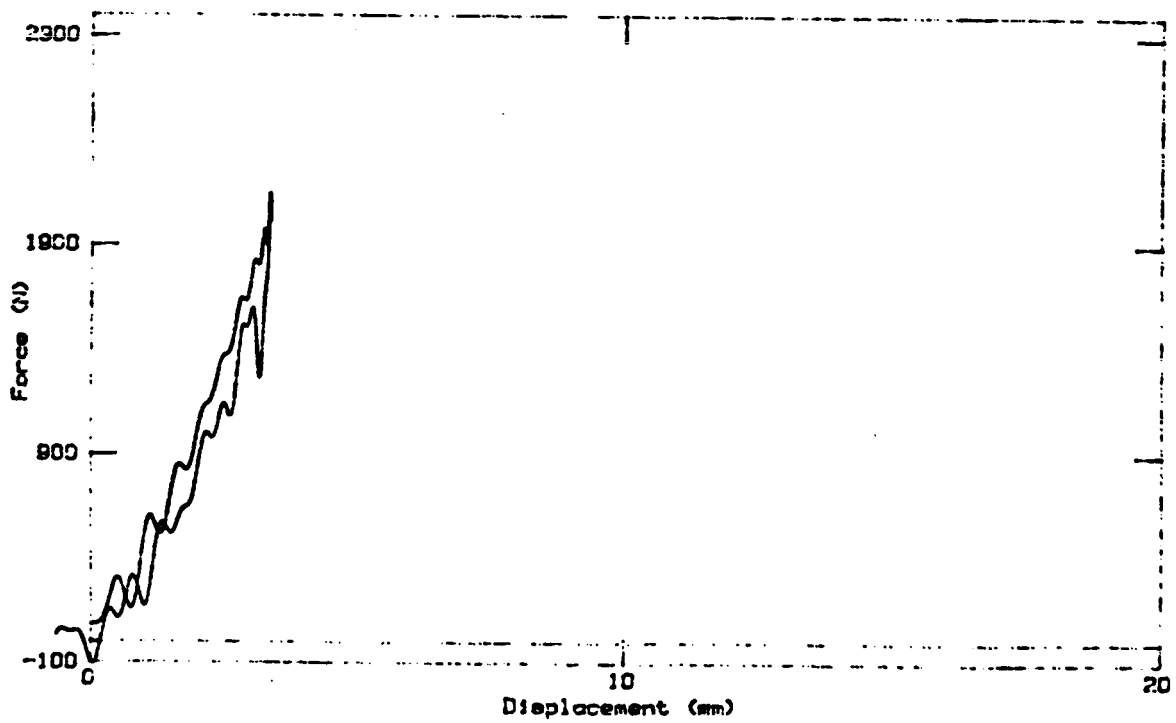
Figure 9A- Force displacement traces for the 5th (A) and 12th (B) impacts of an AS4/3501-6 laminate (Figure 8A)

A

B

Figure 9B- Force displacement traces for the 15th (A) and 23rd (B) impacts of an AS4/3501-6 laminate (Figure 8A)

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Acoustic C-scans of the damage area for a specimen impacted in the stage I region and for a specimen impacted in the stage II region are shown in Figure 10A and 10B respectively. It would appear that for these specimens the transition from stage I to stage II corresponds to the extension of the damage area to the edges of the specimen.

Three parameters of the RIT curves are of interest; the slope of the plots in stages I and II and the intersection point of the two stages. These parameters are listed in Table I.

TABLE I

| Specimen | Slope | | Intercept (J) |
|----------|---------|----------|---------------|
|          | stage I | stage II |               |
| IM6/3601-6 | | | |
| 1A | 0.225 | 0.526 | 17 |
| 1B | 0.250 | 0.500 | 17 |
| 1C | 0.225 | 0.309 | 21 |
| 2A | 0.300 | 0.357 | 61 |
| 2C | 0.274 | 0.507 | 19 |
| 3A | 0.274 | 0.510 | 23 |
| 3C | 0.238 | 0.518 | 29 |
| 4C | 0.250 | 0.385 | 45 |
| AS4/3501-6 | | | |
| 1A | 0.287 | 0.485 | 24 |
| 1C | 0.275 | 0.250 | 62 |
| 2B | 0.225 | 0.535 | 10 |
| 2C | 0.261 | 0.383 | 49 |
| Average (SD) | 0.260 ±0.026 | 0.431±0.099 | |
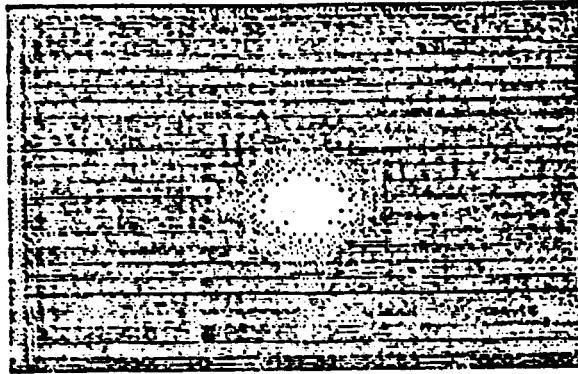
**A**
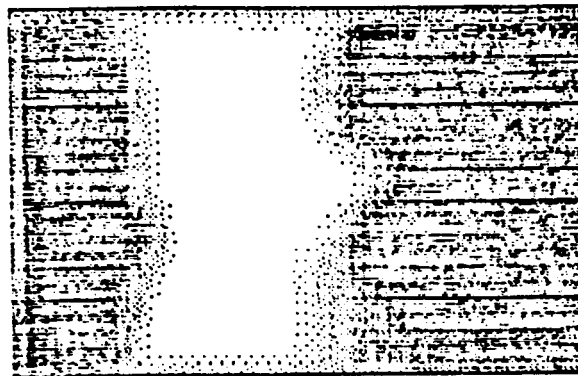


**B**

Figure 10 - Acoustic scans of impact damage to an AS4/3501-6 laminate; A - after 5 impacts. B- after 13 impacts

The slope of the data in stage I is relatively constant with a low standard deviation. The slope for stage II has a somewhat higher variance. The intercept of the two regions was quite variable and appears to be related to the position the specimen was cut from the panel. The alphabetic designation of the specimens listed in Table 1 - A,B,C - refers to the panel layout shown in Figure 11.
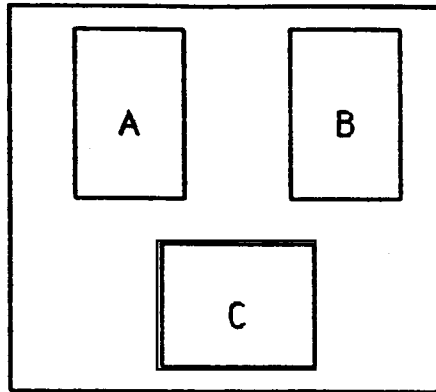
Figure 11 - Three test laminates were cut from each panel and designated as indicated

With the notable exception of the specimens cut from panel 2. the "C" specimens had higher intersections in the RIT data. Quite possibly, the differences in the intersection points in Table 1 reflect differences in specimen quality.

CONCLUSIONS AND FUTURE WORK  The repetitive impact test offers some interesting possibilities for characterizing impact damage. Clearly, the materials requirements are minimal which can be very useful in materials development studies.

The results presented here suggest that the "rate" of cumulative damage is essentially constant so long as the damage area is within the bounds of the specimen but that there is an abrupt change in rate once the damage has reached the edges of the specimen. This result is intuitively reasonable in that the mechanical response of the plate must change once the damage has extended to the boundaries.

However, in work in progress, we have found an abrupt change in the slope of the RIT data before the damage has reached the specimen edges. This was observed for 32ply specimens of IM6/3501-6 and for 32ply specimens of AS4/PEEK. The initial slope, stage 1, was the same for these materials as reported in Table 1 but the intercept was extended to much higher energies. The details of these current experiments will be reported later.

Our current thinking is that the transition from stage 1 to stage 11 represents a change in the type of mechanical response of the laminate; possibly from quasistatic behavior to dynamic behavior. This hypothesis is supported by the fact that the change in slope in the RIT corresponds to

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distinct reductions in the laminate modulus determined from the force
displacement curves (Fig 8).