

**NASA  
Technical  
Paper  
2981**

January 1990

**Instrumented Impact and  
Residual Tensile Strength  
Testing of Eight-Ply  
Carbon/Epoxy Specimens**

A. T. Nettles

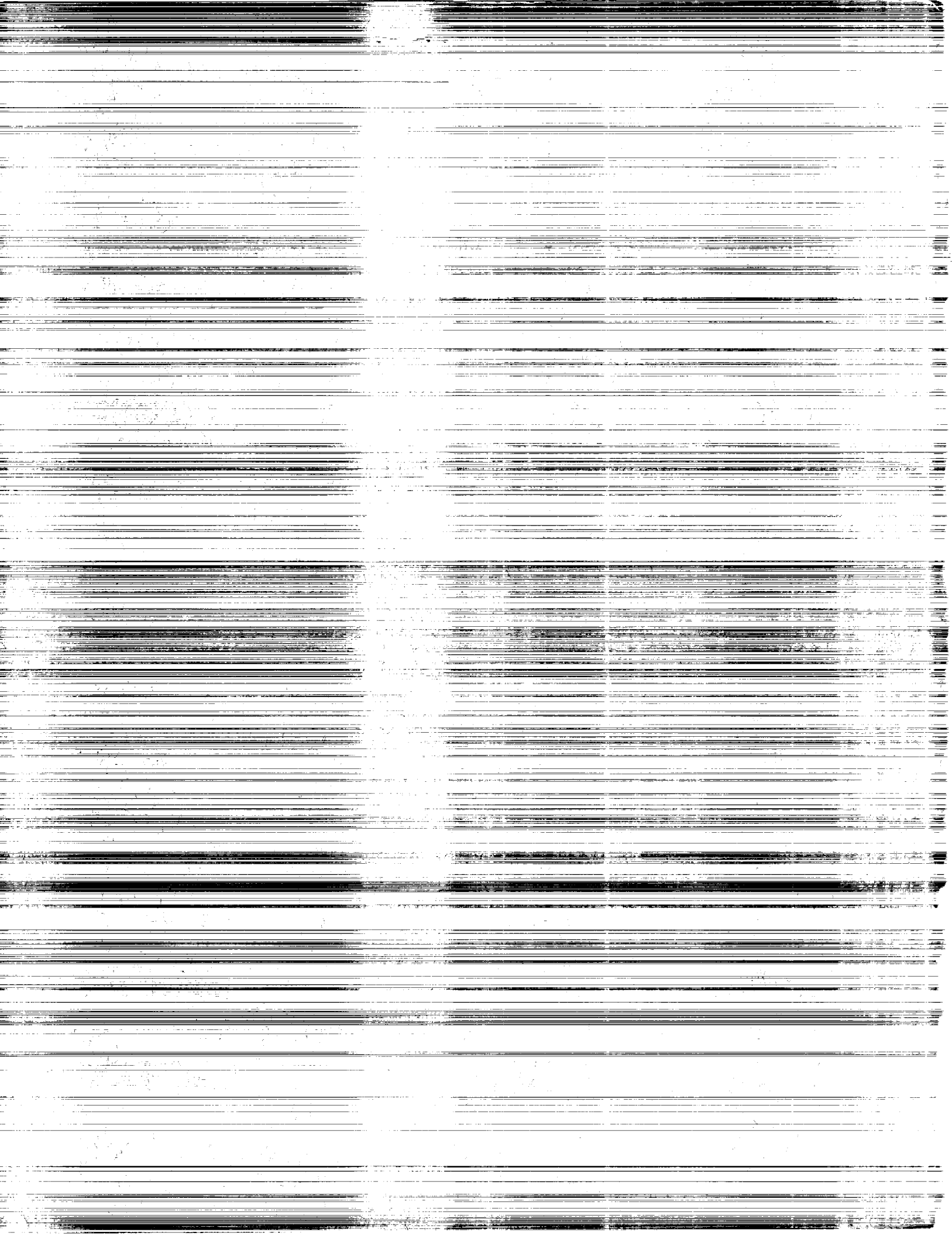
(NASA-TP-2981) INSTRUMENTED IMPACT AND  
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N90-16007

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Marshall Space Flight Center, Alabama*



National Aeronautics and  
Space Administration  
Office of Management  
Scientific and Technical  
Information Division

## **ACKNOWLEDGMENTS**

The author would like to acknowledge the technical support of Mr. Frank E. Ledbetter, without whose knowledge of the employed equipment this project could not have been performed. Thanks are also extended to Dr. Jerry Patterson and Dr. Dennis Tucker for their support throughout this study. This final report was completed with the help of Andrew Hodge.

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## TECHNICAL PAPER

# INSTRUMENTED IMPACT AND RESIDUAL TENSILE STRENGTH TESTING OF EIGHT-PLY CARBON/EPOXY SPECIMENS

## I. INTRODUCTION

Foreign object impact damage to carbon-fiber composite materials has been the focus of many studies since a low-damage tolerance level has been associated with this class of materials. Much research still needs to be performed to better classify and understand damage phenomena in this type of material if it is to be more widely accepted and utilized as primary structural members. Previous studies have utilized instrumented drop weight impact testing to better understand the impact behavior of composites [1,2] since this kind of test can provide such information as initial impact energy, energy lost during impact, and force-time or force-displacement plots.

Most impact studies utilizing the drop weight test method have supported the test specimens either as a simple beam (see, for example, Refs. 3 and 4) or as a membrane clamped between edge supports (see Refs. 1 through 5). A simple beam type of support will produce significant bending of the specimen, thus producing fiber breakage along the tension (bottom) side and ply delaminations due to the high bending shear developed within the specimen. The membrane type supports usually allow less deflection and cause more damage to the impacted sides of the specimens. Back-face fiber breakage and ply delaminations also occur with this type of support. The membrane type of support is more representative of real structures, and virtually all impact testing now performed uses this type of support system. These tests usually use an impacting striker (tup) that is a cylinder with a 12.7-mm diameter with a hemispherical end and a specimen support system which produces a membrane with an area many times that of the tup cross-sectional area (a 76.2-mm diameter circular membrane is commonly used).

In order to study what effects would result from a puncture type of impact on carbon fiber composites, this study utilized a smaller tup (4.2-mm diameter) with a much smaller (10.3-mm diameter) membrane size than in previous studies. This test set-up produces more transverse shear due to the close proximity of the supporting circular edge to the outer edges of the tup.

One method of assessing the damage inflicted to an impacted composite is to test the residual tensile strength of the specimen. Other methods used are residual compression strength testing, cross-sectional examination, ultrasonic scanning, and other forms of nondestructive evaluation (NDE) techniques. One previous study that has evaluated tensile strength after impact [6] has shown that there exists a critical impact energy level at which strength begins to rapidly decrease with increasing impact energy. Much scatter tends to exist in impact data, thus giving rise to the need for testing many different impact energies and a number of specimens at each energy level.

Husman [7] has shown that, in general, a specimen width to projectile diameter ratio must be greater than six to eliminate edge effects so an infinite plate analysis can be used. In this study a specimen width of 25.4 mm would be sufficient to meet this requirement.

The current research had the following objectives: to examine the trend of residual tensile strength versus impact energy for a puncture type of damage, to see how different carbon fiber composite systems would respond to this type of damage, to examine three different material lay-ups for comparisons, and to determine the usefulness of instrumented impact testing for interpreting the damage inflicted upon the specimen.

## II. DESCRIPTION

### A. Materials and Test Methods

1. Material. A total of four different prepreg systems were used. Two of the prepreps were AS4/3501 and IM7/8551, supplied by Hercules Incorporated, with the other two being G40/F584, supplied by Hexcel, and T40/1962, supplied by Amoco Performance Products. All of the materials, with the exception of the AS4/3501, were claimed to have superior impact resistance. Ultimate tensile strength and modulus data for the material systems used are given in Figure 1.

Three types of lay-up configurations were used; unidirectional  $(0)_8$ , bidirectional  $(0/90)_{2S}$ , and quasi-isotropic  $(0, +45, -45, 90)_S$ , all being of eight plies. Panels were formed and cured according to the suppliers' recommendations. Measurements of the cured panels showed all had thicknesses between 10.4 and 11.9 mm.

Specimens of dimension 2.54 x 25.4 cm were cut from the panels along the direction of the outer fibers (i.e., the outer fibers ran lengthwise down the strips). The specimens were then end tabbed for tensile testing.

Due to a limited amount of material available for this study, only a unidirectional lay-up was used for the G40/F584 and unidirectional and bidirectional lay-ups for the AS4/3501.

2. Impact Testing. Specimens were impacted using a TMI 43-21 drop weight instrumented impact tester (Fig. 2) with data being acquired with a Dynatup 730 system. The impacting head weighed 1.5 kg and had a hemispherically ended tup with a diameter of 4.2 mm.

The specimens were clamped in place between two aluminum plates, as shown in Figure 3. A hole of 10.3-mm diameter was present in the center of each plate to allow the tup to pass through. To avoid having the edge of the bottom hole cutting the fibers upon impact, the hole was chamfered to 12.7 mm in diameter, as shown in Figure 4. A bubble level capable of measuring levelness in  $360^\circ$  was placed on the top plate to assure an even clamp. The specimens were aligned so as to be impacted at their centers. Impact energy was varied by changing the drop height, with at least three specimens being impacted at each drop height.

3. Tensile Testing. Tensile testing was conducted on an Instron 1125 testing machine at a crosshead speed of 2.54 mm/min. All impacted and some undamaged specimens of each type of material were tested for tensile strength.



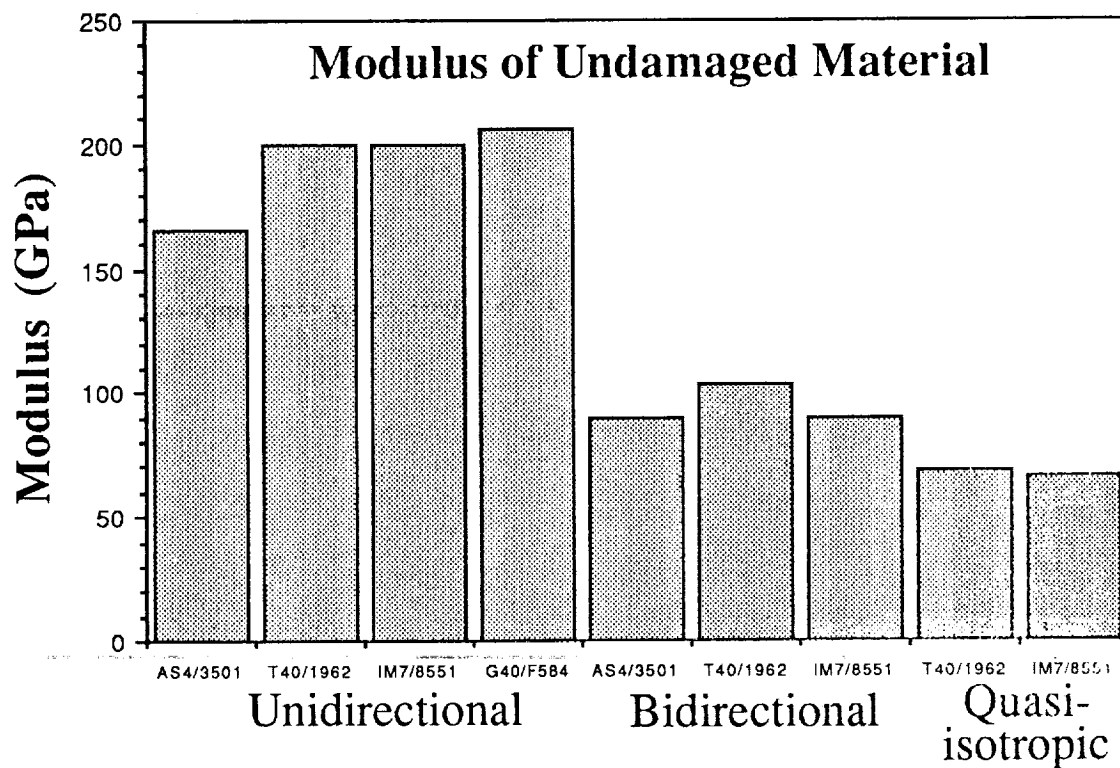
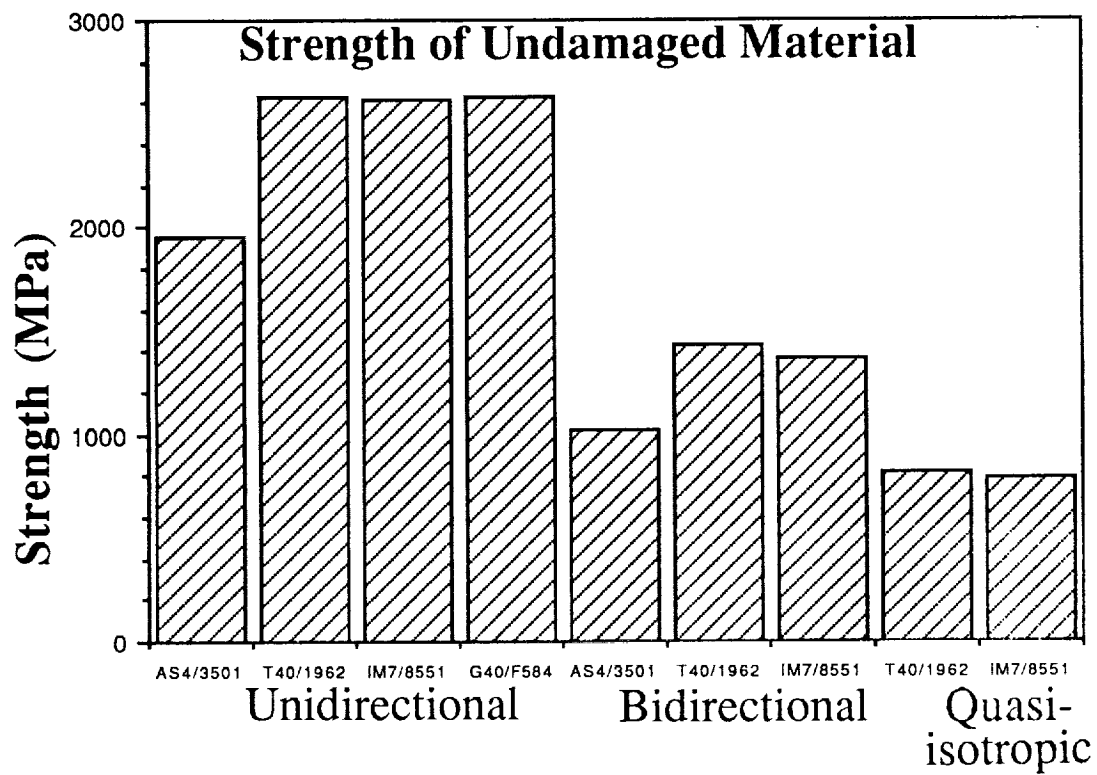


Figure 1. Undamaged properties of materials tested.

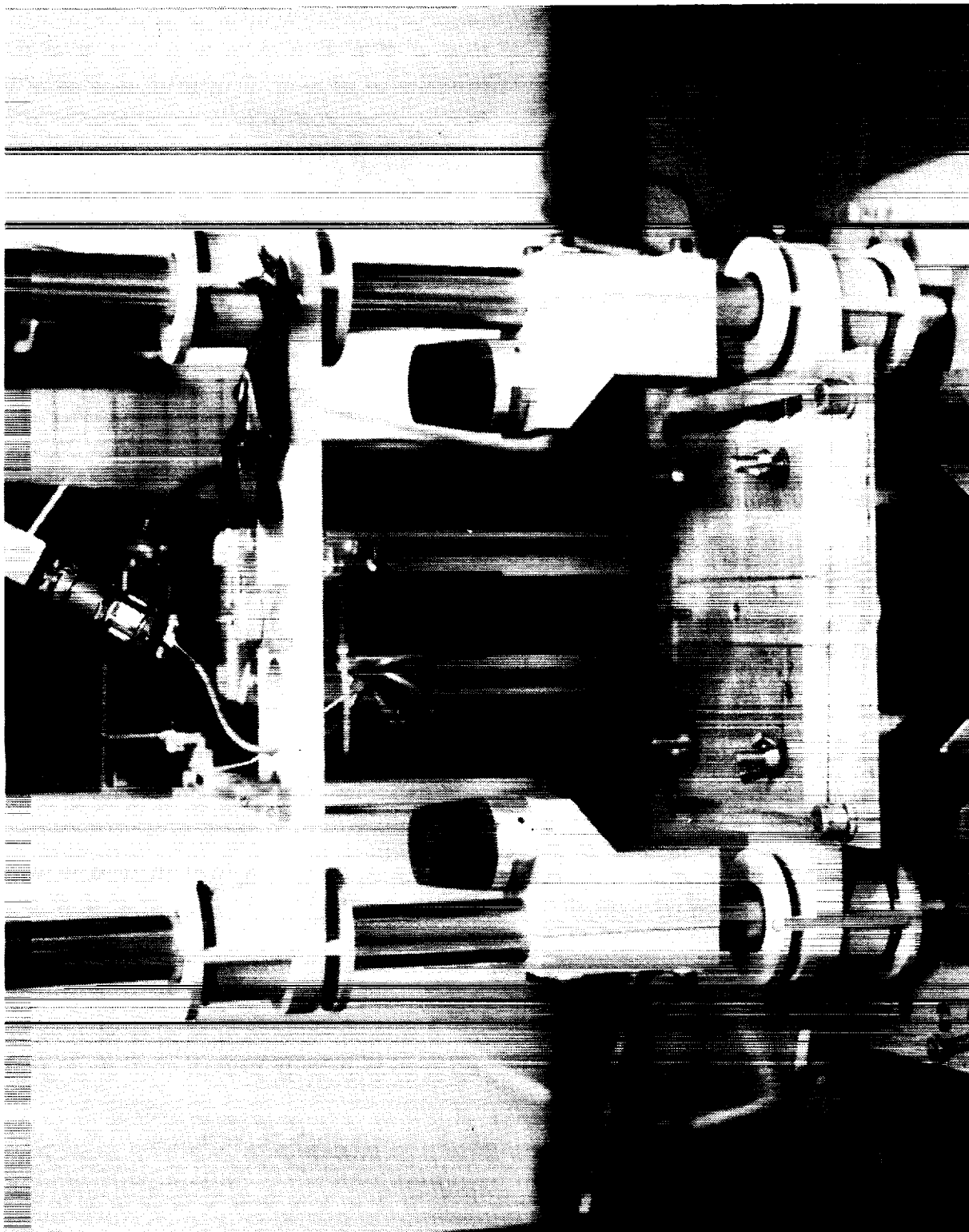


Figure 2. Instrumented impact apparatus used.

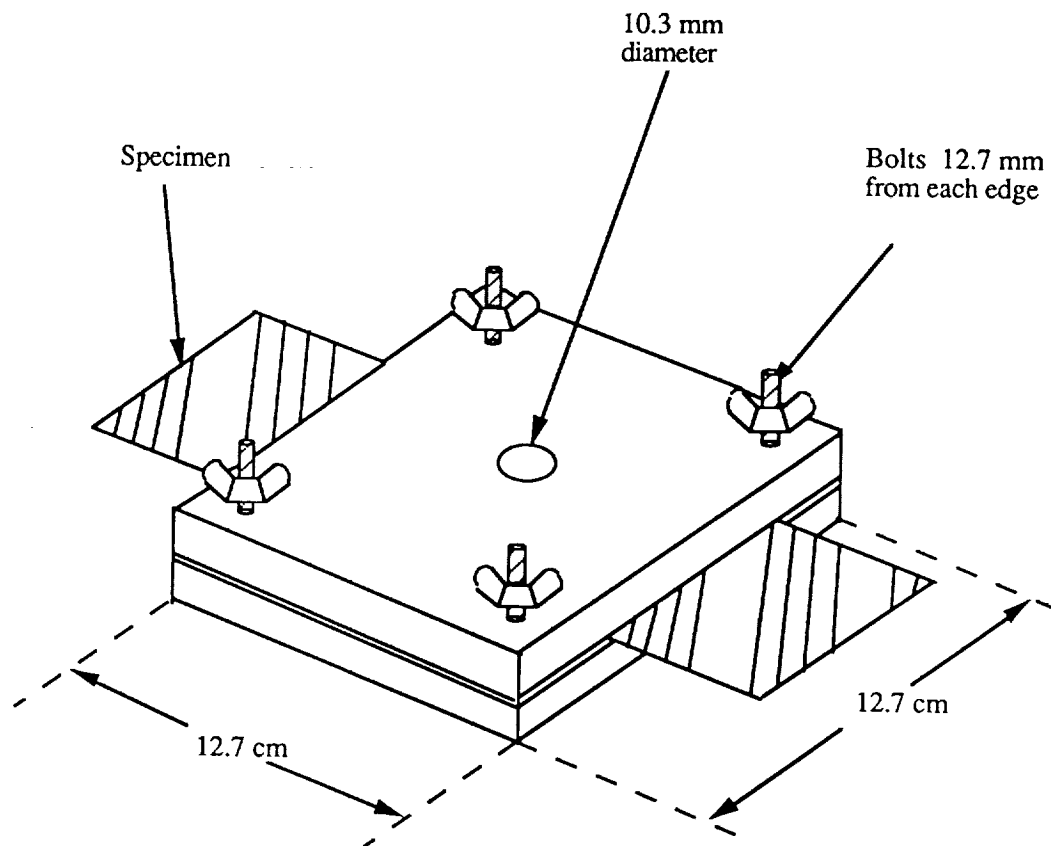


Figure 3. Method of clamping specimens.

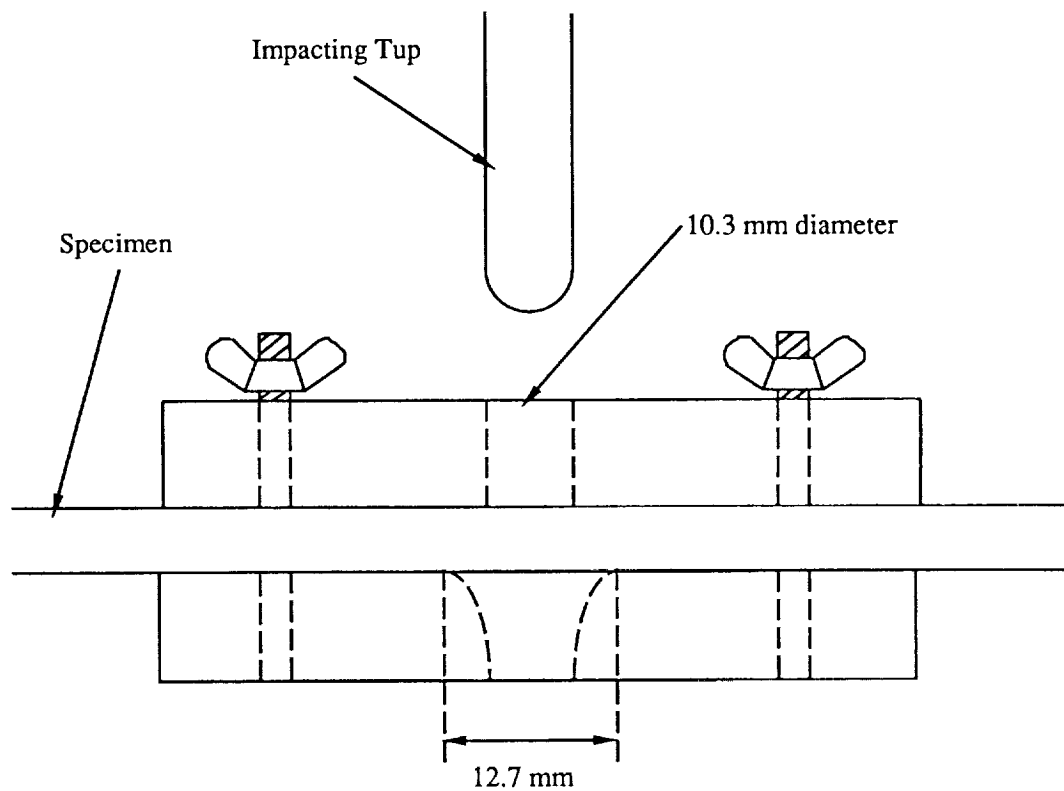


Figure 4. Side view of clamping mechanism.

## B. Impact Test Results and Discussion

1. Force-Time Plots From Impact Tests. The force-time plots of each specimen tested exhibited a small drop in force that occurred at the early stage of the impact event as shown on the sample plot in Figure 5. This "incipient damage," as it has been called, can be seen even at drop heights which produce no visible damage when the impacted zone is cross-sectioned and microscopically examined. This "incipient damage" was also found by other investigators, most notably Aleska [2], and has also been seen on aluminum samples that were impacted by the author. It is difficult to say with any certainty what causes this small drop in force, and future investigation is needed before any conclusions can be drawn.

At drop heights which produce fiber breakage, a large drop in force can be seen on the force-time plots at the peak force, as shown in Figure 6. This drop in force occurs at roughly the same load level for any given material system and also has about the same amount of drop in load.

2. Maximum Force Versus Impact Energy Plots. A more detailed examination of maximum force of impact can be formulated by plotting these values, as given by the instrumented output, versus initial impact energy. An examination of these plots (given in Appendix A) shows that the maximum force varies somewhat linearly with increasing impact energy up to a critical impact energy level, at which point the maximum force begins to level out and then decrease slightly. These results are surprising since theoretically the maximum load should be proportional to the square root of the impact energy, as outlined in Appendix B, thus giving an inverse parabolic shape. Actually this shape is seen on some of the plots, most notably the T40/1962 quasi-isotropic and bidirectional lay-ups, and the AS4/3501 bidirectional lay-up. The leveling out of the maximum force as damage becomes more severe is expected since any given material system can only withstand a certain load before failure. The small decrease in maximum force is associated with complete penetration of the specimen but is not an expected result. One possible explanation is that a different damage mechanism takes place at the higher impact velocities. At lower velocities the specimen will bend more and produce a back-face tension type failure, whereas at a higher velocity the tup will penetrate with more of a shear type force since the specimen does not have as much time to deflect the amount of distance the tup has traveled through the specimen.

It should be noted that for each impact energy level, all of the specimens tested at that level had their maximum force of impact values averaged, and this is the value used in the plots.

A comparison of the different materials used shows that the AS4/3501 had the lowest maximum force values for the two lay-up configurations used. This is not surprising given the fact that this system has less fiber strength than the others tested.

For any given material, the unidirectional samples could not support the amount of load that the bidirectional and quasi-isotropic lay-ups could. This occurs because the unidirectional samples can no longer support a load when the matrix material fails by splitting parallel to the direction of the fibers. In the bidirectional and quasi-isotropic lay-ups, the transverse fibers help prevent the matrix from failing in shear, as shown in Figure 7.

3. Absorbed Energy Data. The smooth curves superimposed on the force-time curves in Figures 4 and 5 are absorbed energy-time curves. For all of the specimens tested, between 73 and 85 percent of the initial impact energy was lost during the impact event, the percentage being a constant for a given material system. This trend held true up to the point of fiber breakage where a larger amount of

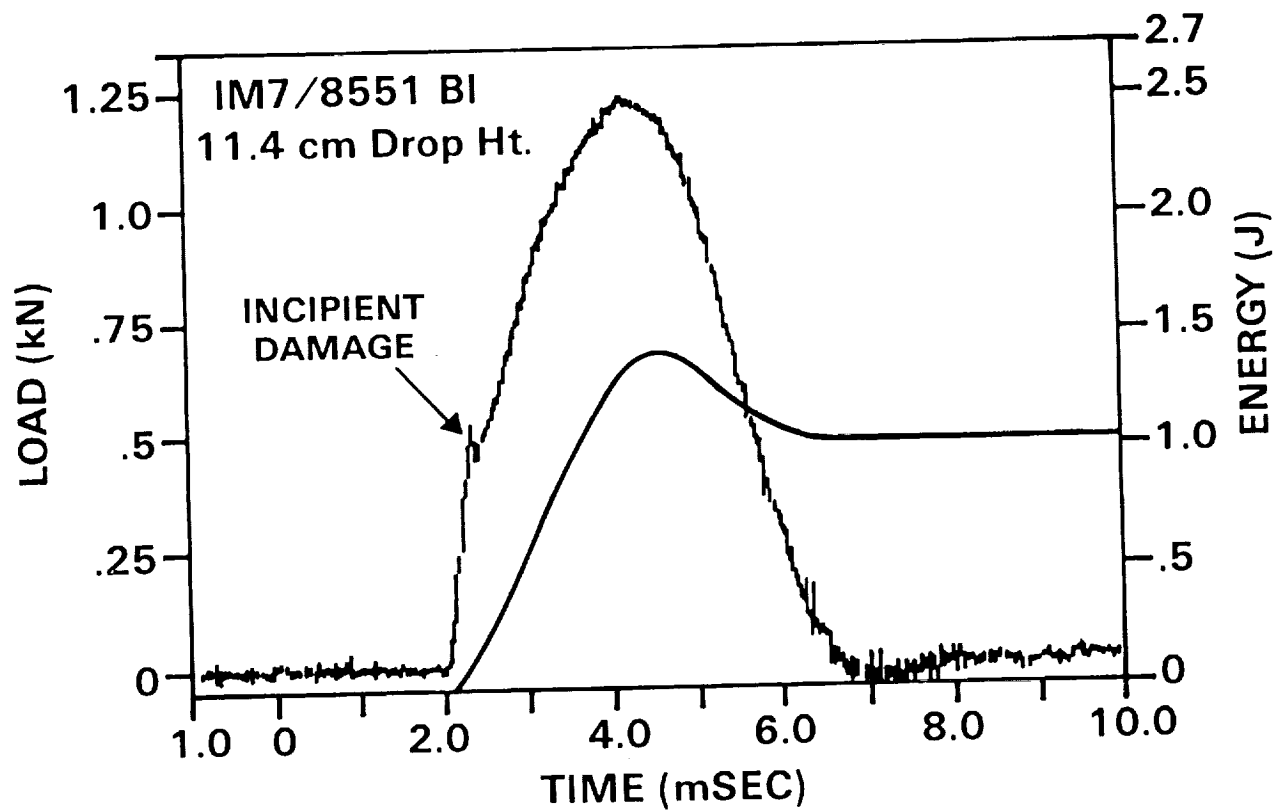


Figure 5. Instrumented impact output showing little damage.

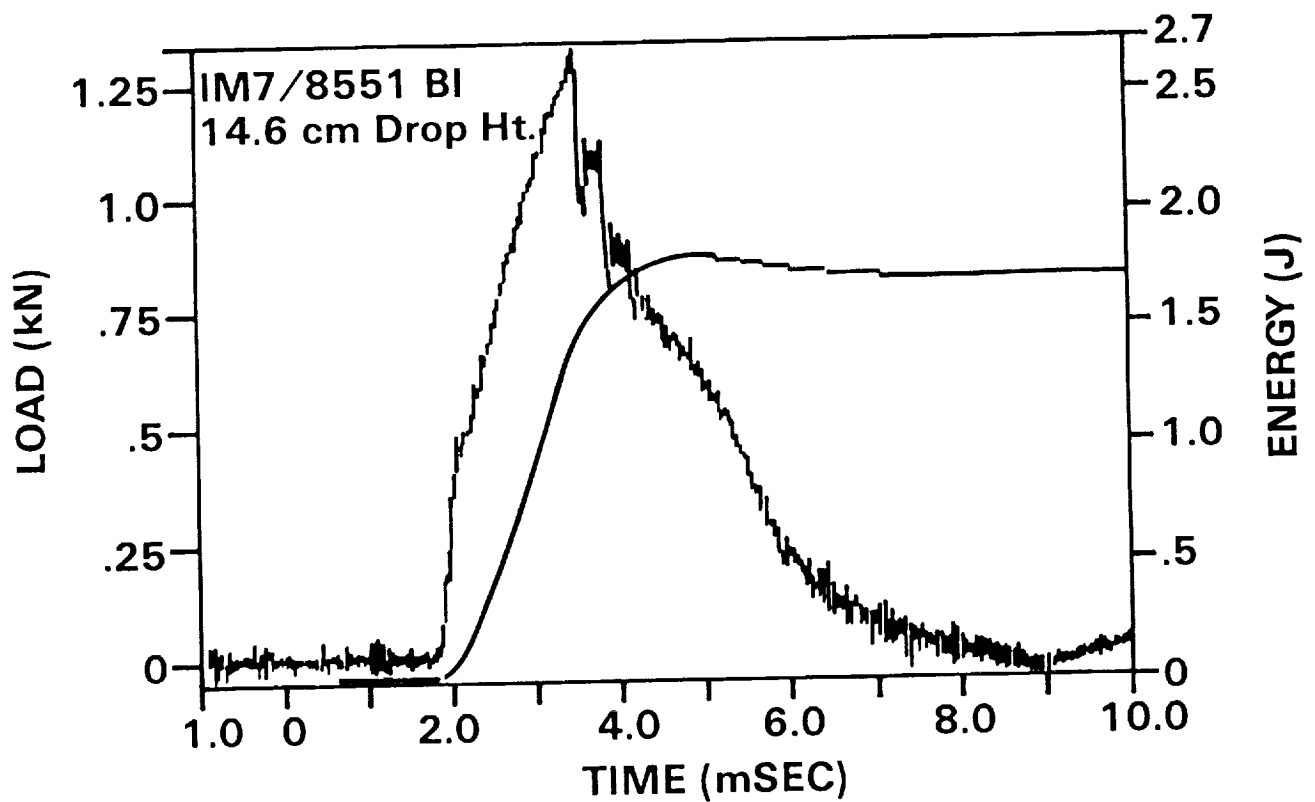
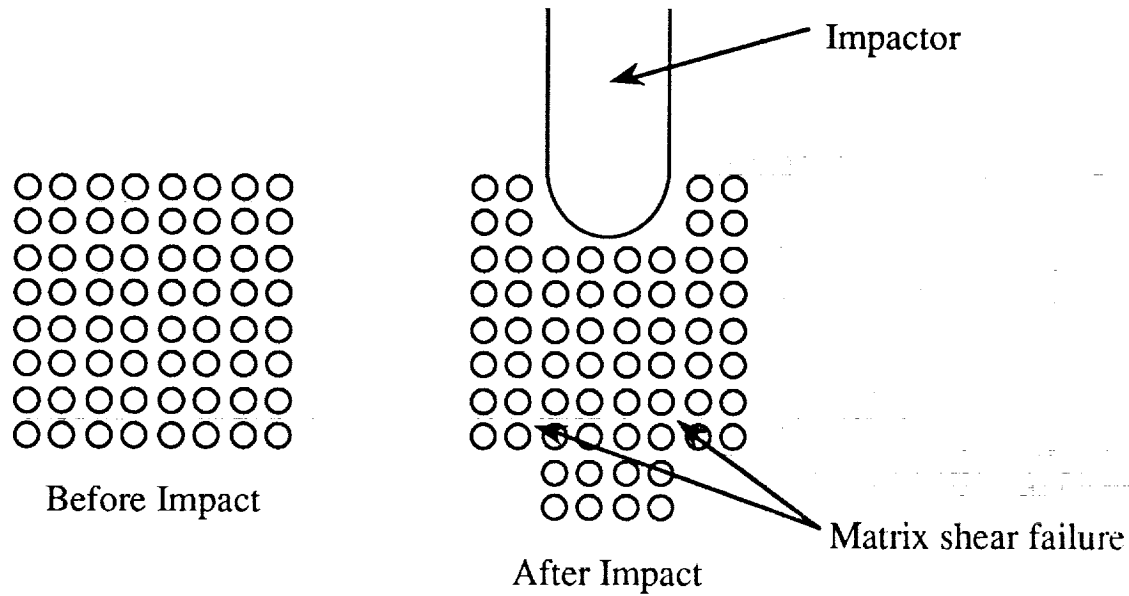


Figure 6. Instrumented impact output showing large damage.

## Unidirectional Material



## Bidirectional Material

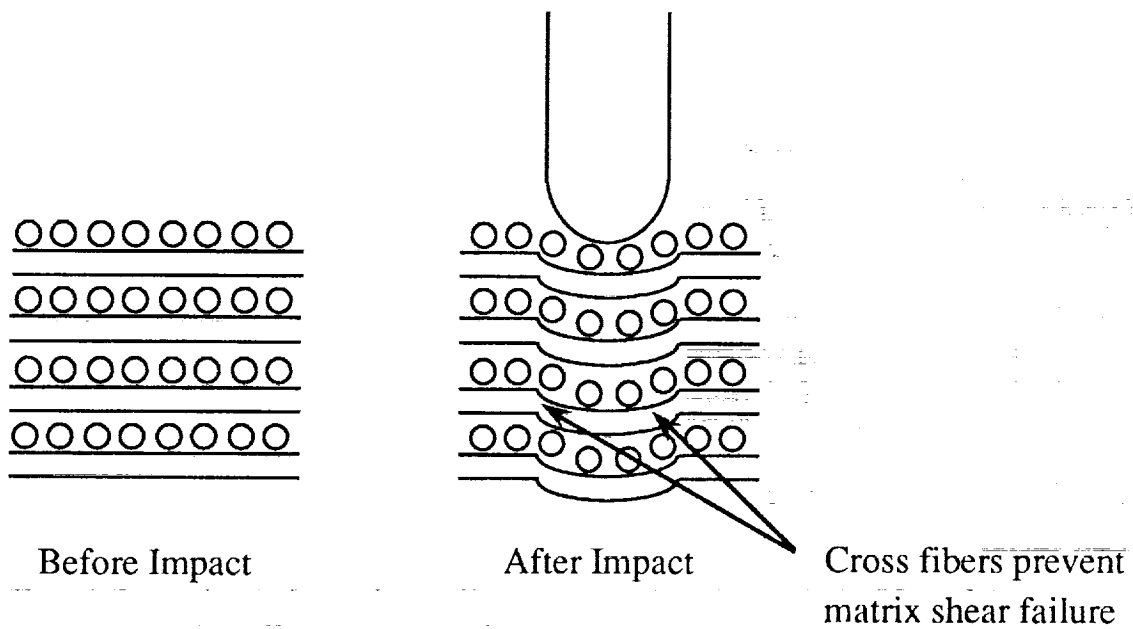


Figure 7. Damage mechanisms for unidirectional and bidirectional samples.

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energy was lost. Care must be taken not to interpret this data to mean that this loss of energy is in the form of damage to the specimen. It is suspected that a substantial amount of energy is lost in the form of vibrational waves. These waves have been shown to be quite large in long slender objects impacted at their ends and in thin plates impacted on the surface [8], both of which exist in this study.

Plots of lost energy versus supplied energy were made for all of the materials tested and are presented in Appendix C. The results show that a distinct linear region exists on all of the plots with the slope being the percentage of energy lost. A deviation from this linearity occurs at the impact energy level at which fiber damage first occurs, that also corresponds to the energy level at which tensile strength begins to rapidly decrease which will be discussed later in this paper. This absorbed energy behavior was also noted in another study [9]. These results imply that instrumented impact test data can be used to predict, with good accuracy, the point at which damage can produce a rapid loss in tensile strength, thus reducing the need for time consuming residual strength testing.

4. Visual Surface Damage. All samples showed initial visible damage in the form of a small dent on the impacted side of the specimen, as shown in Figure 8. As the impact energy was increased, matrix cracking and fiber breakage was observed on the back face of the specimens, as shown in Figure 9. A hole was formed as impact energy was increased even farther.

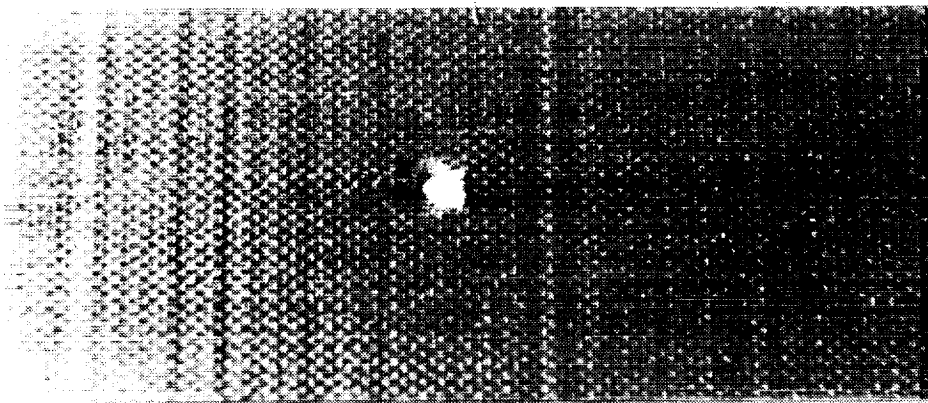


Figure 8. Typical top surface damage to impacted specimens.

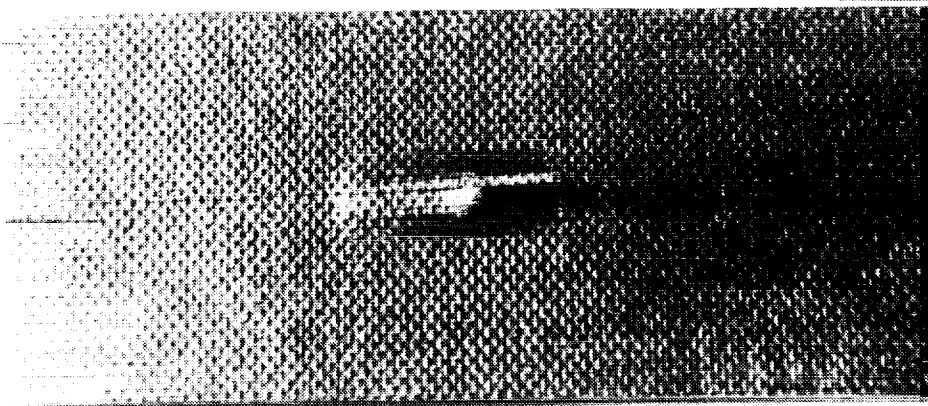


Figure 9. Typical back surface damage to impacted specimens.

5. Cross-Sectional Visual Examination. A selected number of specimens were cross-sectionally sliced through the impacted area with a diamond wheel cutter. The specimens were then observed at 16X magnification and photographed. Figures 10, 11, 12, and 13 show the AS4/3501 bidirectional material impacted at 0.80 J, 1.13 J, 1.32 J, and 1.76 J, respectively. Comparing these to the residual strength curves given in Appendix D, it can be seen that the 0.80 J energy level shows no damage and has not experienced a loss of strength. At 1.13 J, the specimen shows delaminations and corresponds to the point at which strength begins to decrease. Fiber breakage is evident at 1.32 and 1.76 J and, according to the residual strength curve, at least 80 percent of the undamaged strength has been lost at this point. Quasi-isotropic samples show similar damage, while the unidirectional samples exhibit more matrix splitting parallel to the fibers. A complete report on cross-sectional examination of impact damaged specimens is currently being prepared but is too lengthy to be included in this report. The results presented are given to give an idea of what types of damage can be expected and how they may correspond to the residual strength.

### C. Residual Strength Testing

1. Residual Strength Versus Impact Energy Plots. All impacted specimens were tested in tension for ultimate strength. Normalized residual tensile strength (the ratio of damaged to undamaged tensile strength) was plotted versus impact energy, and the results are given in Appendix D. The plots all show that very little or no loss in strength takes place until a critical impact energy level is reached, at which point a sharp reduction in strength occurs. The residual strength then reaches a minimum value as a hole is created in the material. The only exception to this trend was with the T40/1962 quasi-isotropic material which showed little decrease in strength even at impact energy levels which would produce obvious fiber breakage. Before any conclusions could be drawn, more testing would need to be performed to determine if this held true with another batch of samples. No reason for this unique behavior can be given at this time.

2. Comparisons of Residual Strength Plots. Comparisons of residual strength versus impact energy plots can be made on the basis of either differing ply configurations involving the same material system or differing material systems with the same ply configuration.

Figure 14 shows a comparison of the bidirectional samples tested. It is clear that the T40/1962 material was superior in retaining strength at a given impact energy level. The toughened IM7/8551 and the standard AS4/3501 had very similar results, indicating that perhaps fiber strain to failure is the dominant factor since the T40 fiber has a 0.2 percent higher strain to failure than the IM7 fiber and a 0.27 percent higher strain to failure than the AS4 fiber.

The unidirectional samples showed no clearly superior system (Fig. 15). At impact energies above 1.3 J, the IM7/8551 had a significantly lower strength retention than the other material systems. This is surprising since the 8551 resin is a toughened system. As mentioned before and shown in Figure 7, the unidirectional samples fail by matrix shear, thus implying that no resin system was superior to the standard 3501 resin on the basis of unidirectional tests alone.

In order to compare the three different lay-up configurations used, the IM7/8551 material system was chosen since the only other material system tested with all three chosen configurations, the T40/1962, showed strange behavior for the quasi-isotropic lay-up, as mentioned earlier. As expected, the



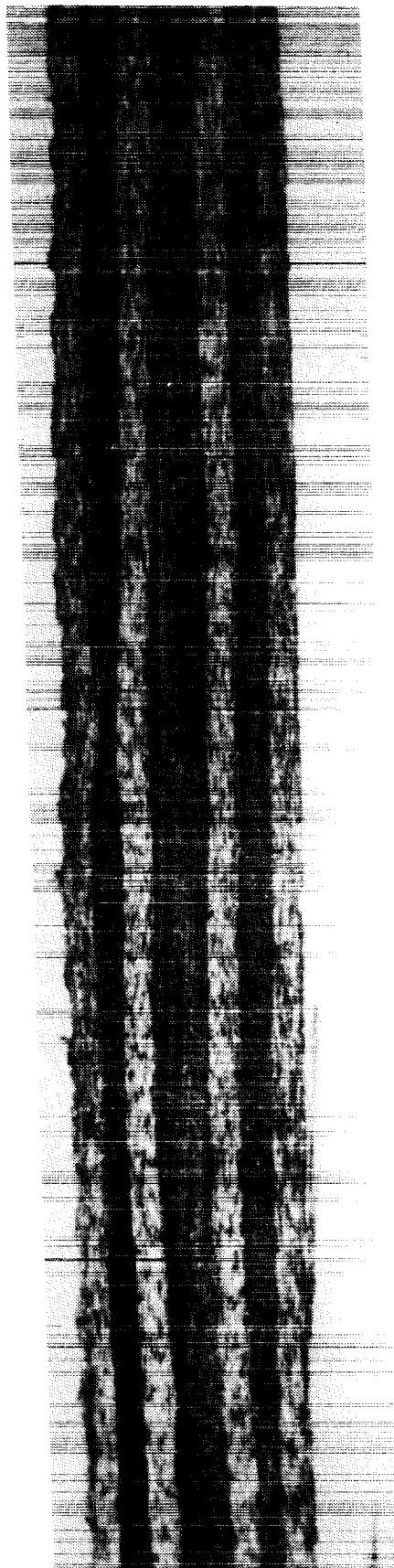


Figure 10. Cross-sectional 16X magnified view of AS4/3501 bidirectional specimen impacted at 0.80 J.

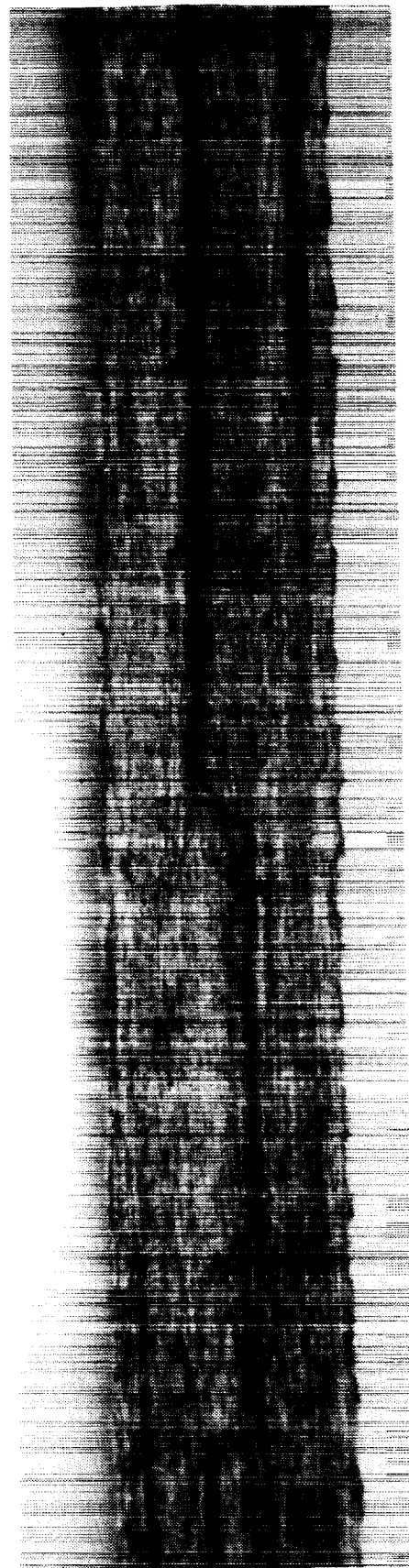


Figure 11. Cross-sectional 16X magnified view of AS4/3501 bidirectional specimen impacted at 1.13 J.

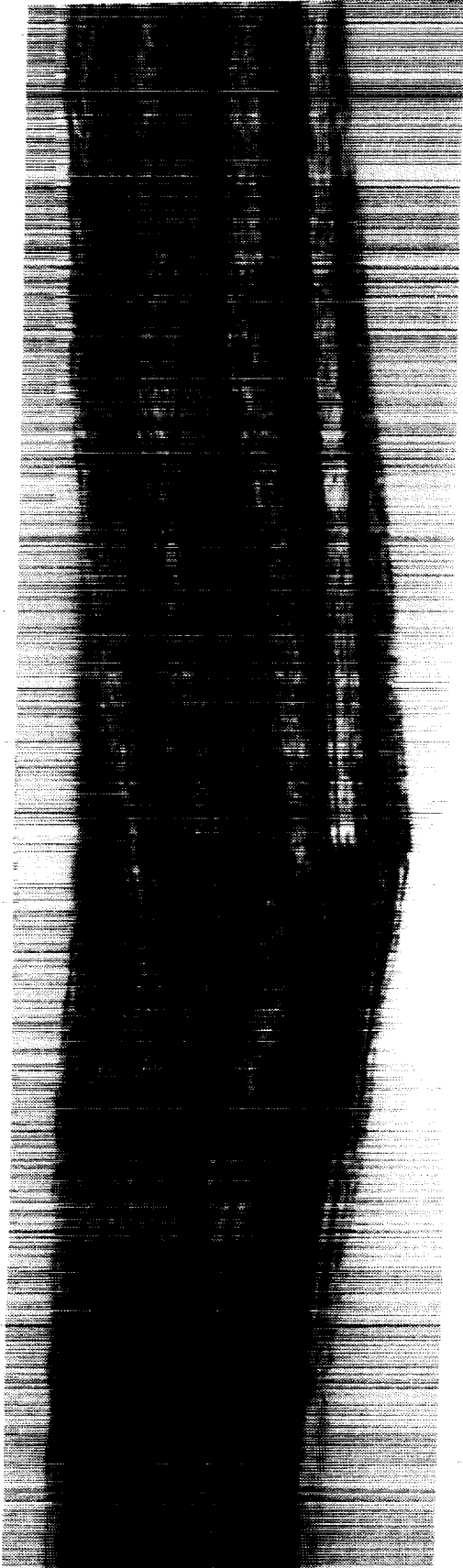


Figure 12. Cross-sectional 16X magnified view of AS4/3501 bidirectional specimen impacted at 1.32 J.

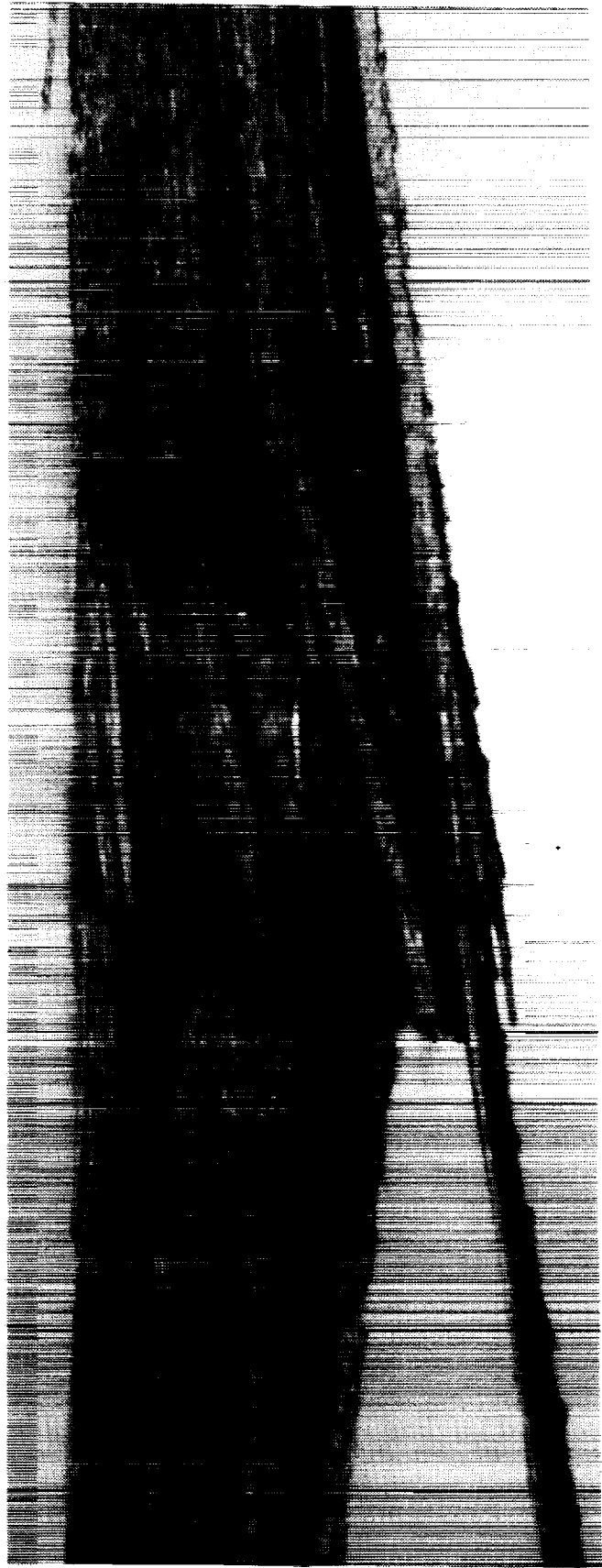


Figure 13. Cross-sectional 16X magnified view of AS4/3501 bidirectional specimen impacted at 1.76 J.

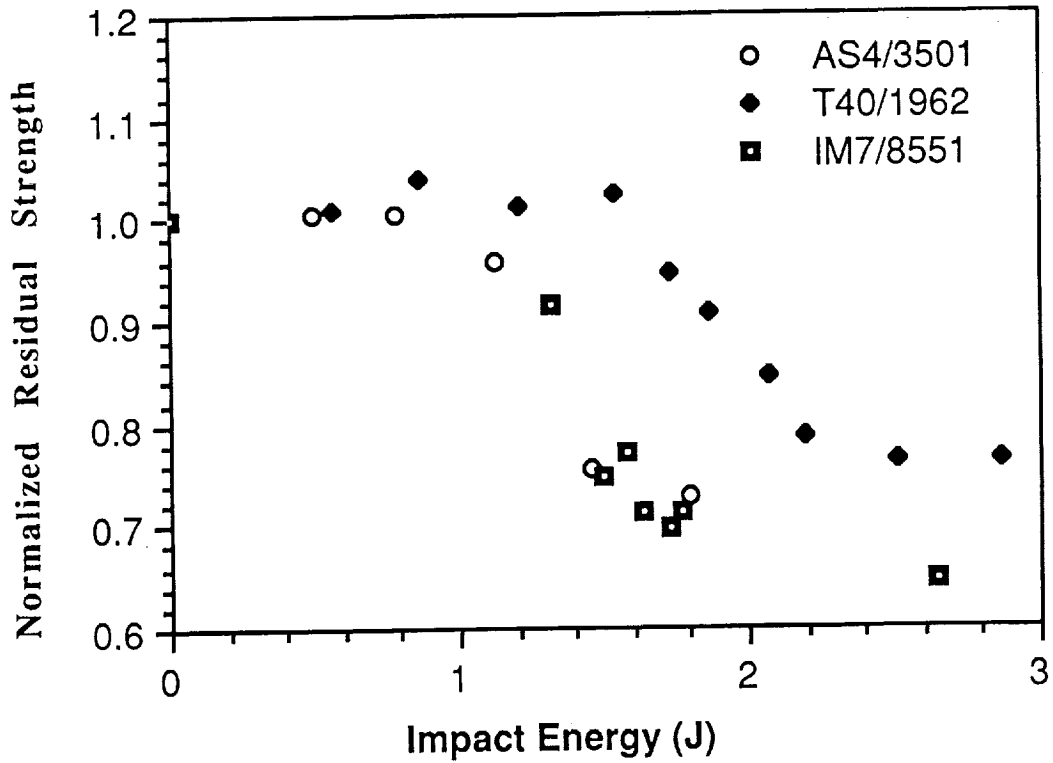


Figure 14. Residual strength versus impact energy for bidirectional samples.

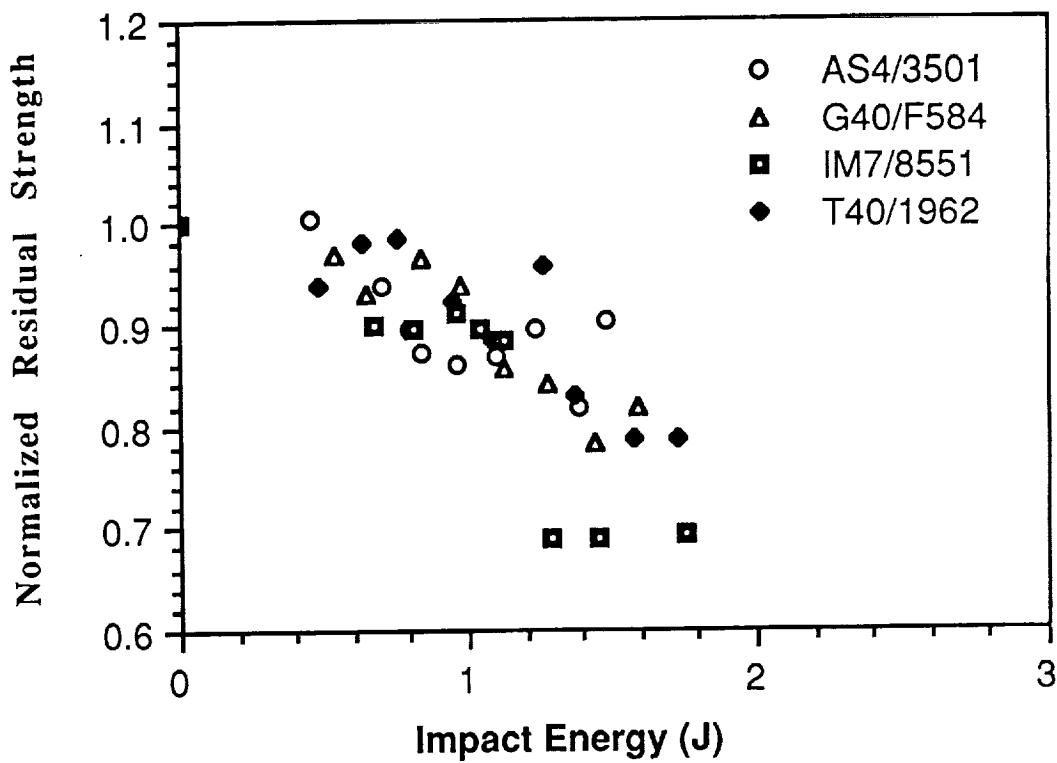


Figure 15. Residual strength versus impact energy for unidirectional samples.

unidirectional samples showed the most strength reduction with the quasi-isotropic lay-up having the most amount of strength retention for a given impact energy. This is probably due to the larger number of fiber directions in the quasi-isotropic lay-up contributing to more freedom for cracks to change direction, taking the path of least resistance, and thus blunting sooner.

These types of plots and comparisons can be of great use to the designing engineer in the material screening process for parts that may be subjected to change.

### III. CONCLUSIONS

It is difficult to predict the residual tensile strength of an impacted composite material. Large amounts of scatter exist in the data, making a prediction from just one impact test impossible. A large number of impact energy levels and a large number of samples at each energy level must be used if a residual strength versus impact energy plot is to be of any use. This type of testing involves a large amount of material and time.

Characteristic curve shapes of residual strength versus impact energy plots were detected for all but one of the material systems tested. All materials exhibited a range of impact energy levels, beginning at zero, during which no loss of strength occurred, even though small amounts of damage could be detected on some of these specimens. Furthermore, all of the materials showed a sharp decrease in residual tensile strength at a critical energy level, which also coincided with the first signs of visible damage. It is also at this critical energy level that a deviation from linearity was seen on absorbed energy versus impact energy plots, thus providing a much easier method of finding this critical energy than by residual tensile strength testing.

The thinness of the samples tested produced a very small energy range in which residual tensile strengths were exhibiting a decrease in value, making an examination of this region difficult.

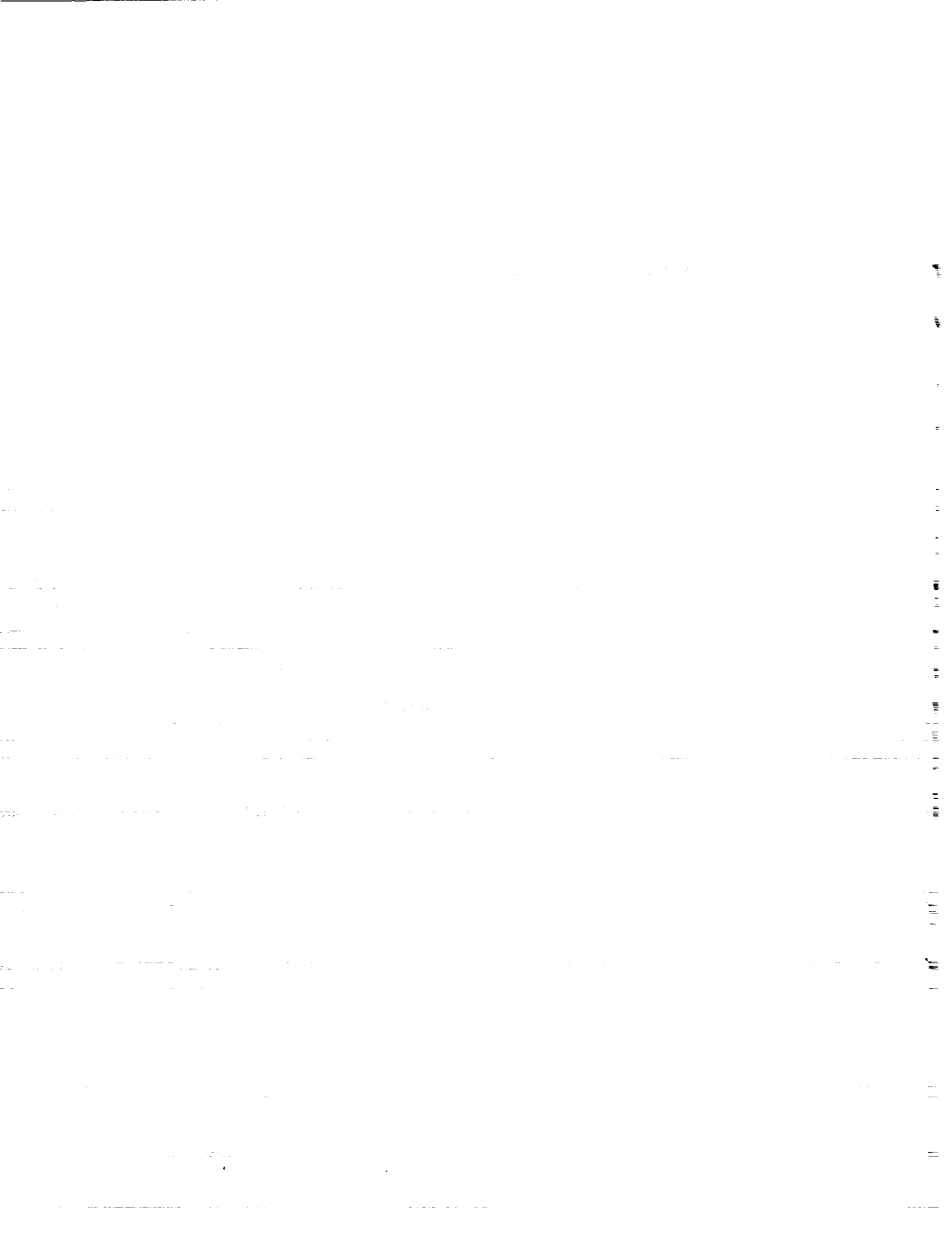
Fiber strain to failure appears to be the dominating factor in impact resistance for thin samples. The T40/1962 material could withstand higher impact energy levels and showed a larger retention of strength at each impact energy level. The major difference between this material system and the others tested is that the T40 fiber has a strain to failure 0.2 percent larger than the others tested. The unidirectional samples, which sustained damage mostly in the form of matrix cracking, showed no significant differences in impact damage at a given impact energy level. The thinness of the samples probably accounts for this, and it is difficult to say if the toughened matrices actually perform better than the untoughened 3501 matrix for other specimen geometries.

Instrumented impact testing can provide useful data on a material system. Plots of absorbed energy versus impact energy can show the critical energy level at which point major tensile strength reduction begins, thus eliminating the need for many residual strength tests.

Force-time plots of the impact event can show the ultimate force the specimen can withstand before fiber breakage takes place, given a certain specimen support geometry. This information could prove very useful in design purposes since the types of impact a part may encounter can usually be predicted.

This study was intended as an empirical approach and no mathematical models are attempted. It shows how experimental data can be used to determine trends in material behavior after a predescribed type of damage. This type of study is to benefit the designing engineer by showing the response of various material systems to a puncture type of impact.

Finally, compression strength after impact has been shown to be a much more critical parameter than tension strength after impact, since matrix cracking and ply delaminations will greatly reduce the compression strength of a composite material. However, residual tensile strength needs to be understood as well since many parts are tension critical.

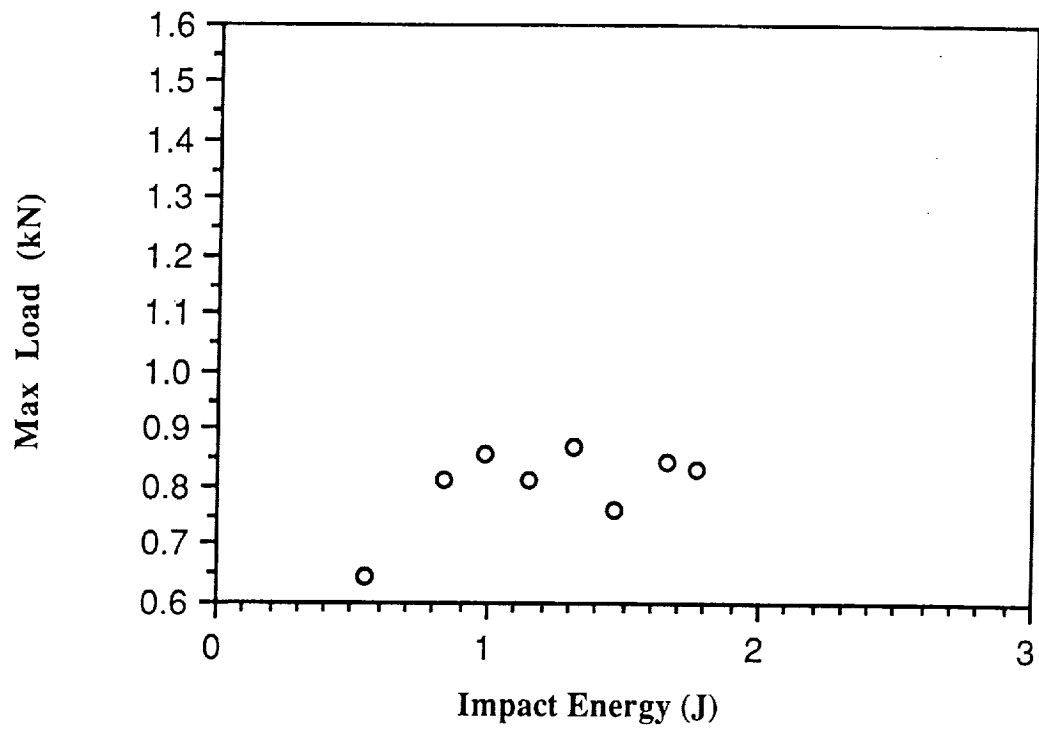


## **APPENDIX A**

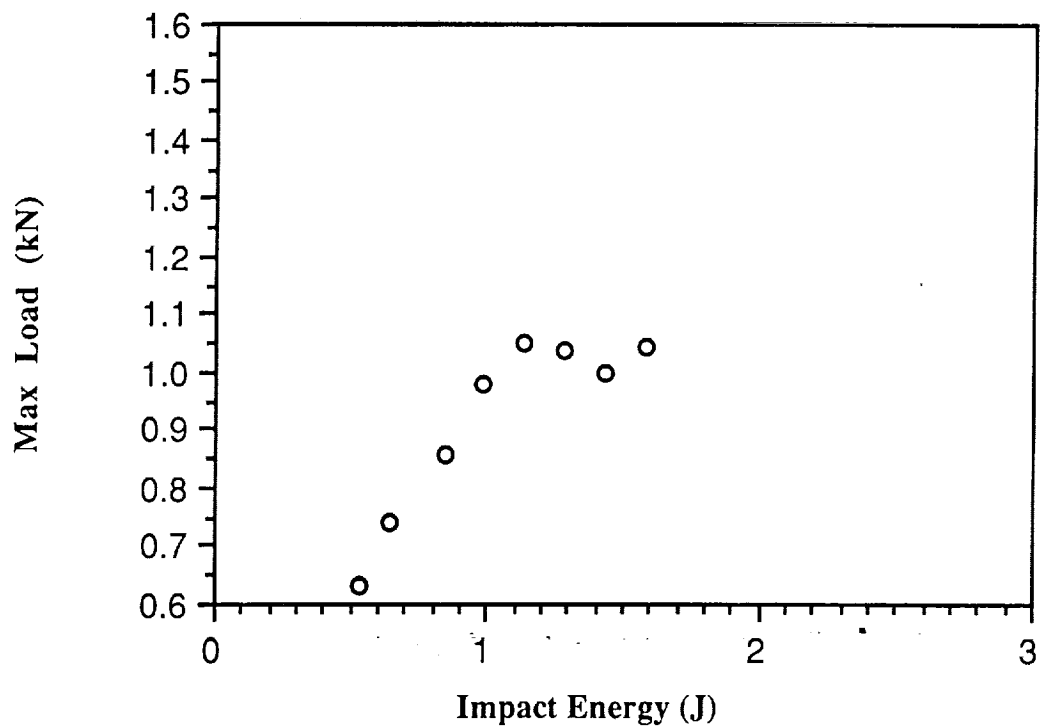
### **Maximum Force of Impact Versus Impact Energy Plots**

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**Max Load vs Impact Energy  
AS4/3501 Unidirectional**

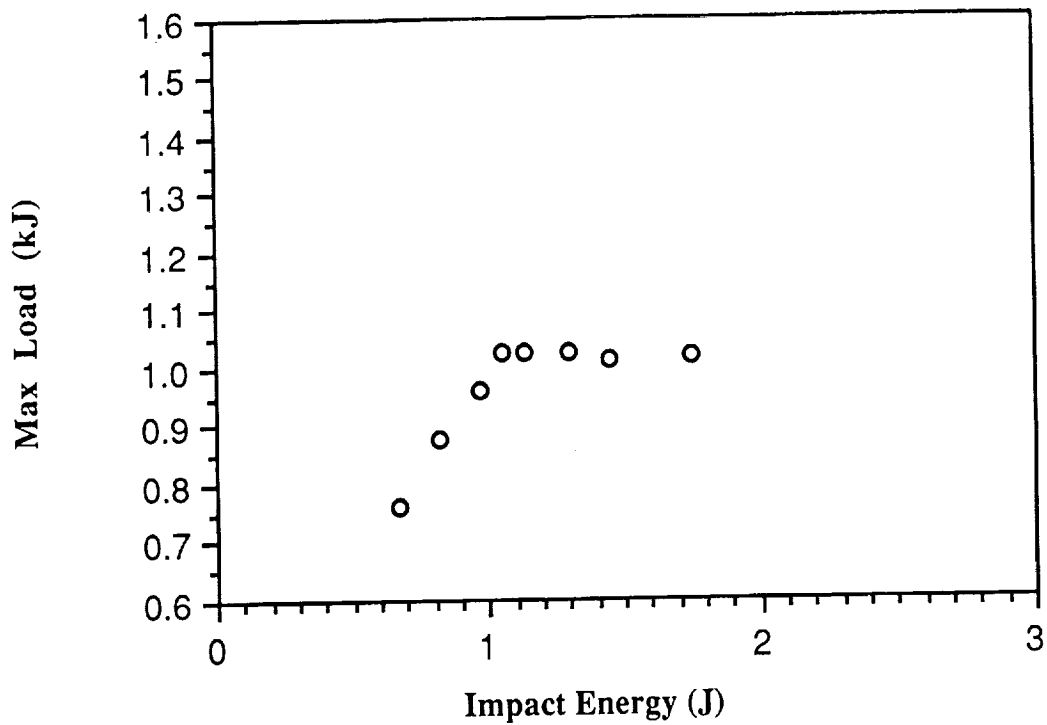


**Max Load vs Impact Energy  
G40/F584 Unidirectional**

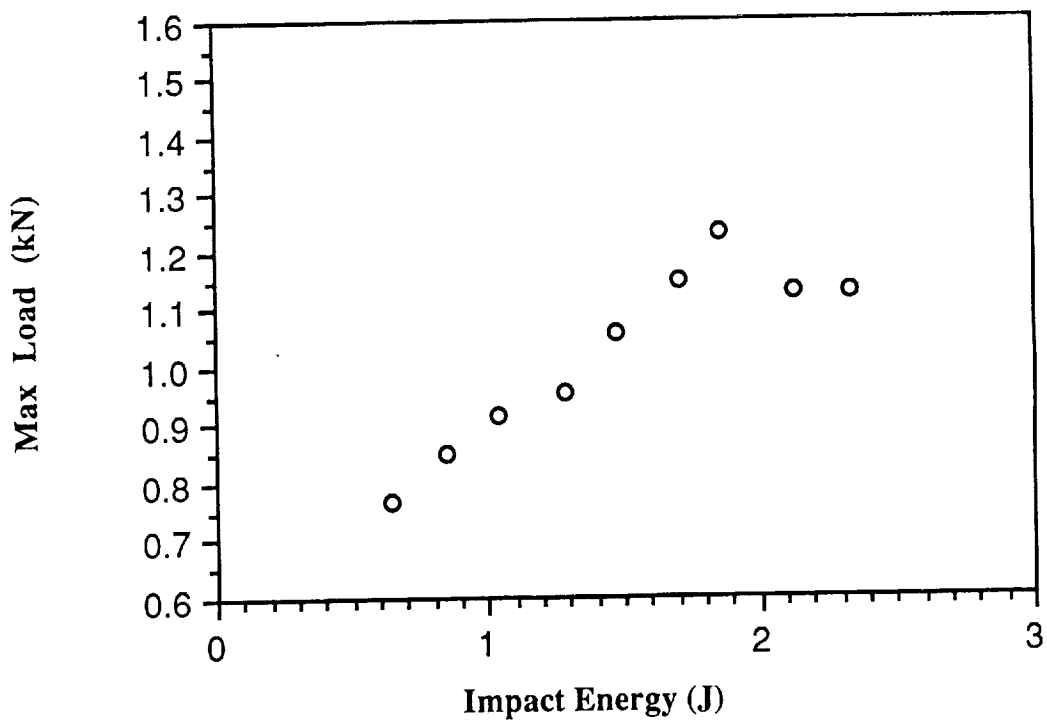




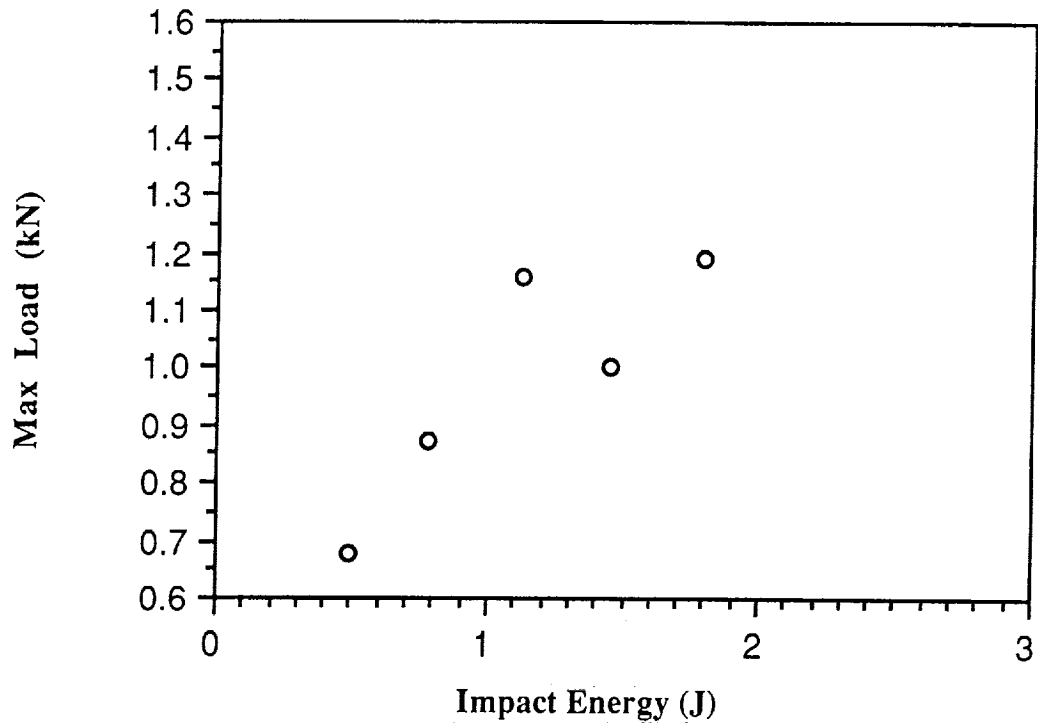
**Max Load vs Impact Energy**  
**Im7/8551 Unidirectional**



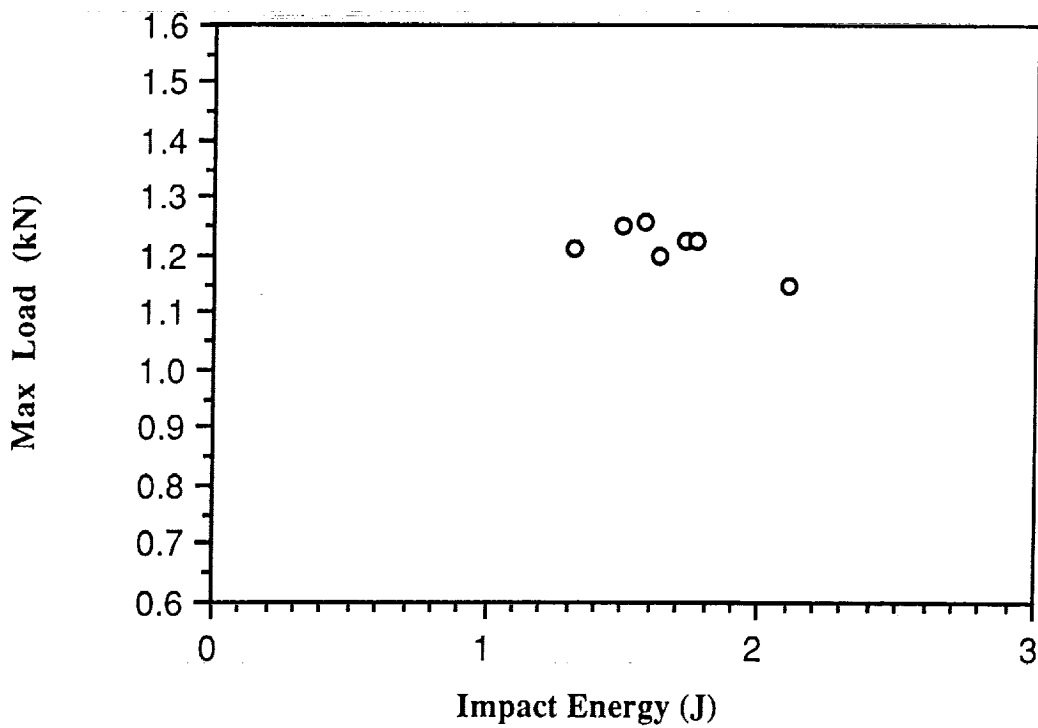
**Max Load vs Impact Energy**  
**T40/1962 Unidirectional**



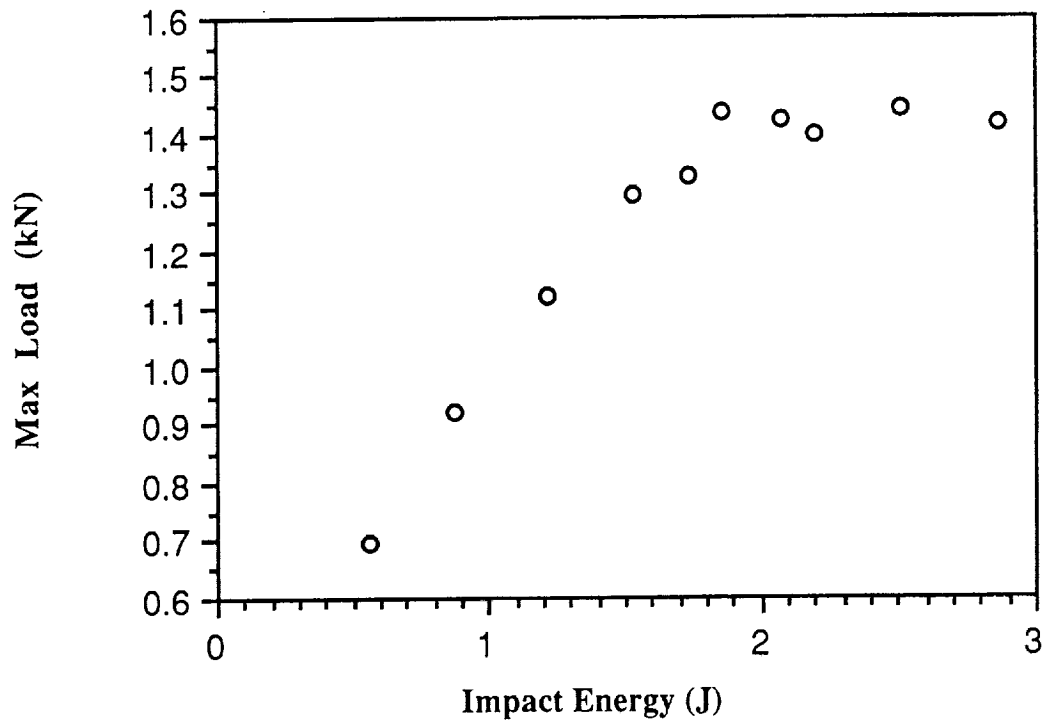
**Max Load vs Impact Energy**  
**AS4/3501 Bidirectional**



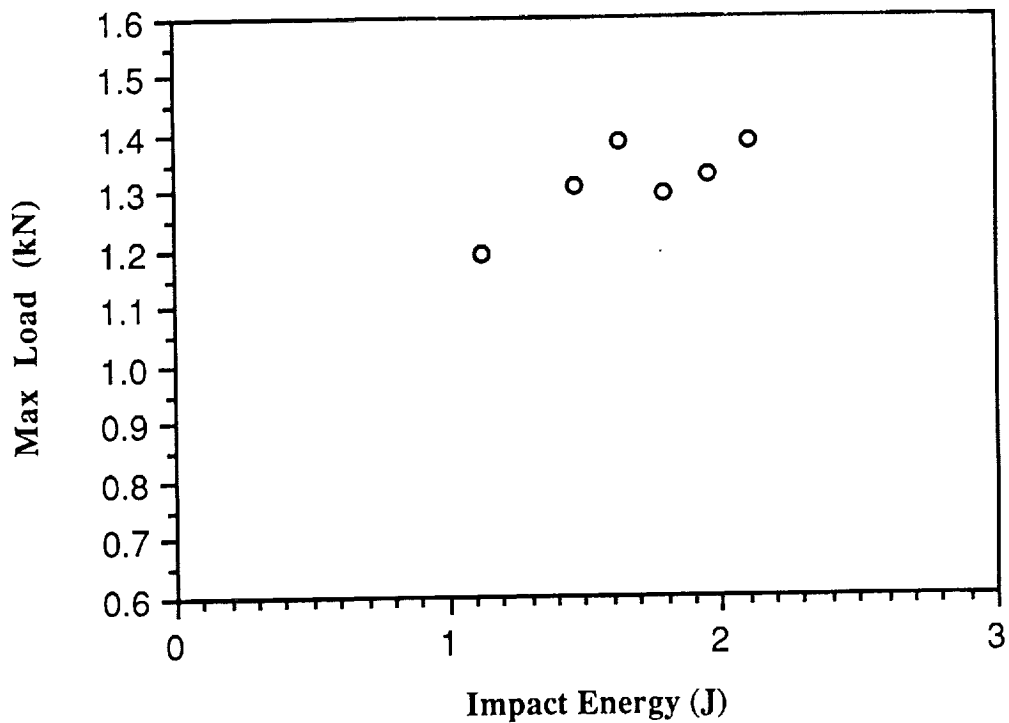
**Max Load vs Impact Energy**  
**IM7/8551 Bidirectional**



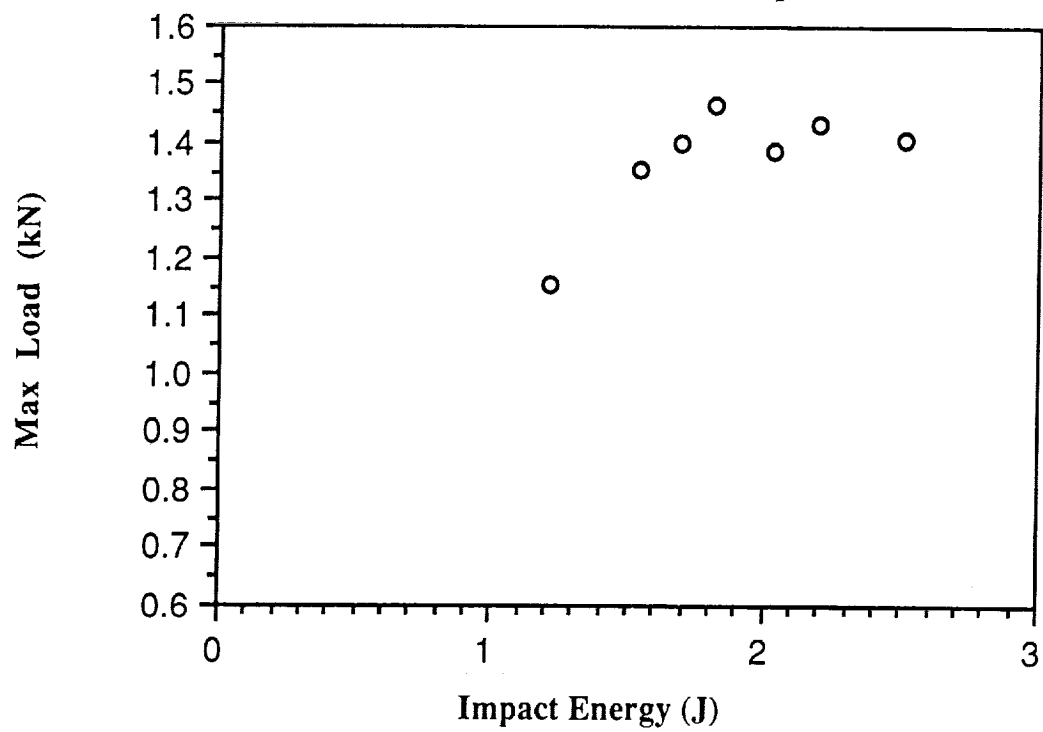
**Max Load vs Impact Energy  
T40/1962 Bidirectional**



**Max Load vs Impact Energy  
IM7/8551 Quasi-isotropic**



# Max Load vs Impact Energy T40/1962 Quasi-isotropic



## APPENDIX B

### Derivation of Relationship Between Load and Impact Energy

According to data from an Instron loading frame, as an indenter is pressed onto a composite plate or honeycomb structure, the load is proportional to the displacement:

$$F(x) = C \cdot X \quad (1)$$

where

$F(x)$  = force supplied by indenter

$C$  = material constant

$X$  = displacement of specimen directly under indenter.

By classical mechanics,

$$E = \frac{1}{2} mv^2$$

so,

$$E_i = \frac{1}{2} mv_i^2 \quad (2)$$

where

$E_i$  = energy of falling weight impactor

$m$  = mass of impactor

$v_i$  = velocity of indenter upon impact.

Assumption: If no damage has occurred to the composite plate then at the maximum load, all energy is stored as elastic potential energy.

Therefore,

$$E_e = \int_0^d F(x)dx \quad , \quad (3)$$

where,

$E_e$  = stored elastic energy

$d$  = maximum deflection of plate

$F(x)$  = force supplied by indenter at any deflection distance  $X$

$dx$  = incremental change in deflection.

Substituting equation (1) into equation (3),

$$E_e = \int_0^d F(x)dx = \int_0^d C \cdot X dx \quad (4)$$

Solving this integral yields,

$$E_e = \left. \frac{1}{2} C \cdot X^2 \right|_0^d = \frac{1}{2} C \cdot d^2 \quad (5)$$

Since we assume  $E_i = E_e$ ,

$$E_i = E_e = \frac{1}{2} C \cdot d^2 \quad (6)$$

From equation (1) at  $X = d$ ,

$$F(d) = C \cdot d \quad \text{or} \quad d = \frac{F(d)}{C} \quad (7)$$

Putting equation (7) into equation (6) gives,

$$E_i = \frac{1}{2} C \left( \frac{F(d)}{C} \right)^2 = \frac{1}{2C} (F(d))^2 \quad (8)$$

Rearranging;  $F(d) = \sqrt{2CE_i}$  or  $F(d)$  is proportional to the square root of the impact energy.



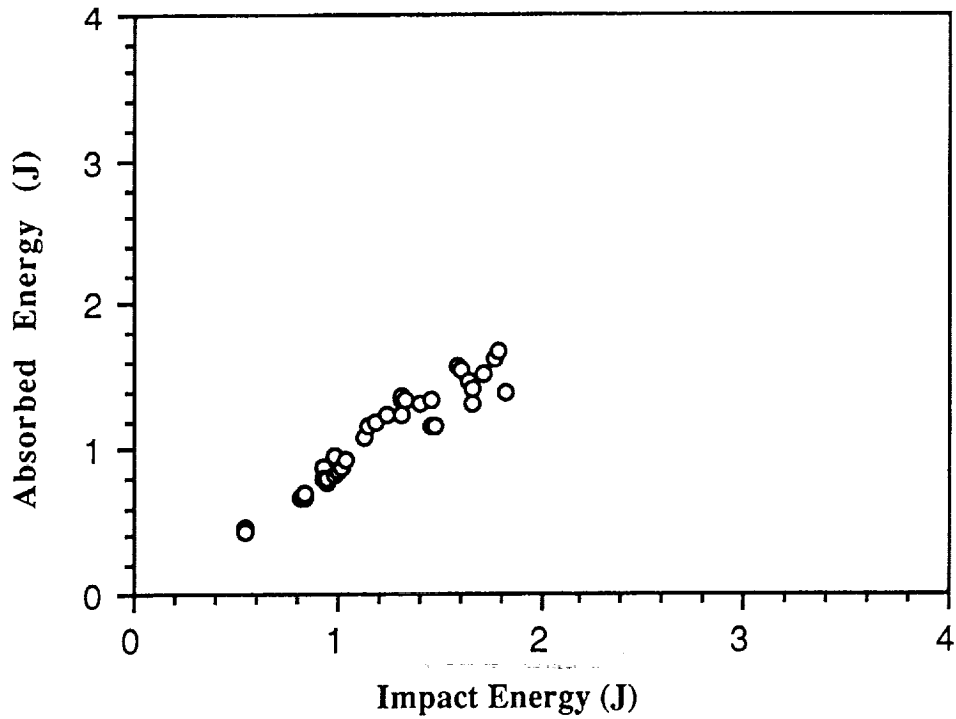


## **APPENDIX C**

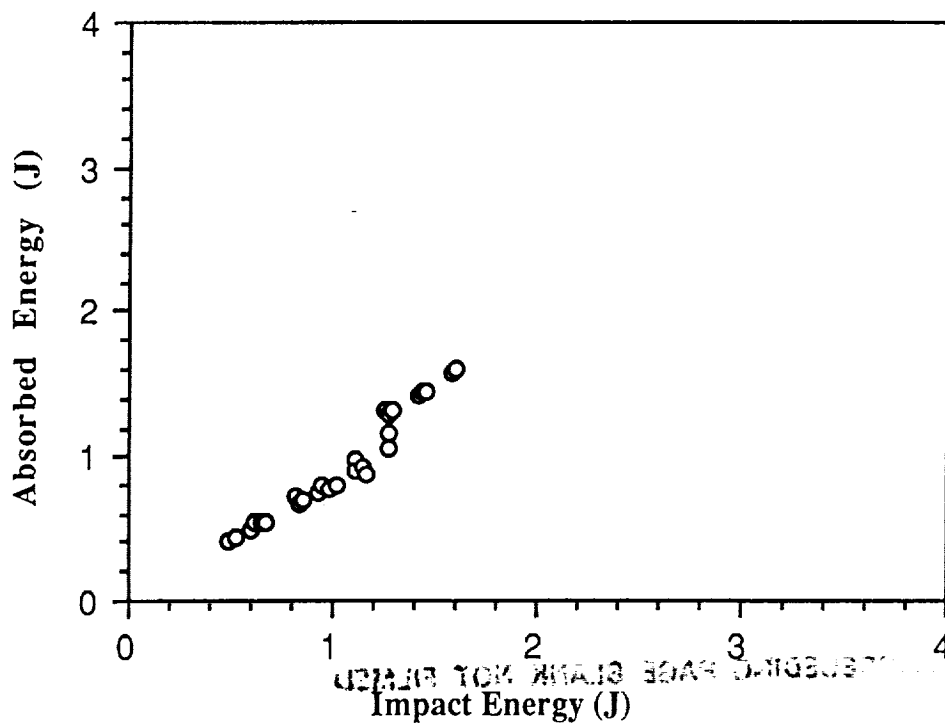
### **Energy Lost During Impact Versus Energy of Impact**

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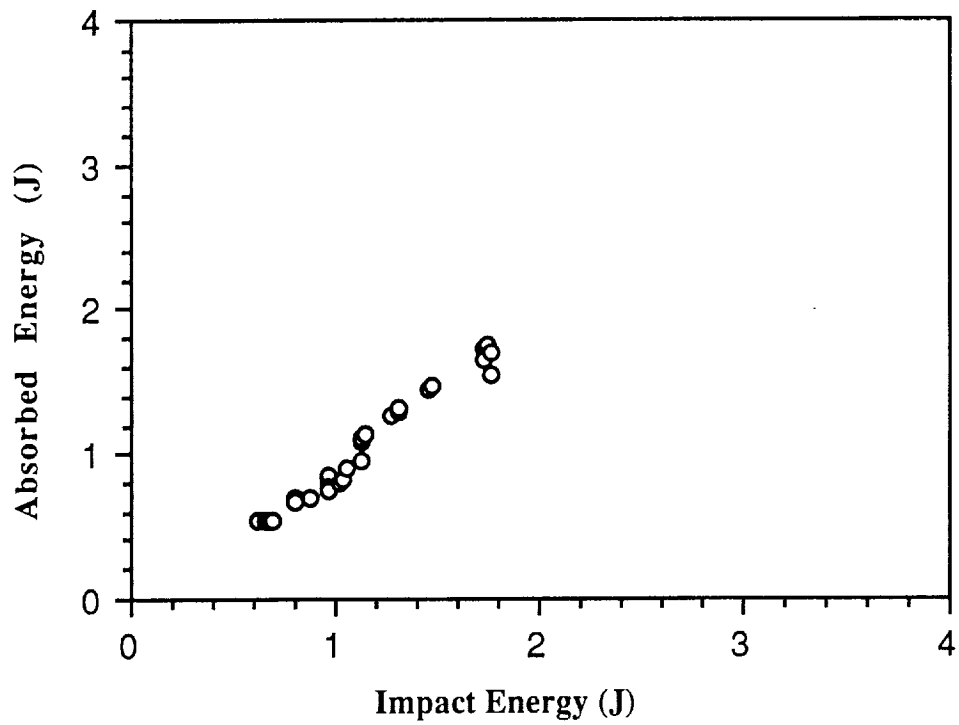
## Absorbed Energy vs Impact Energy AS4/3501 Unidirectional



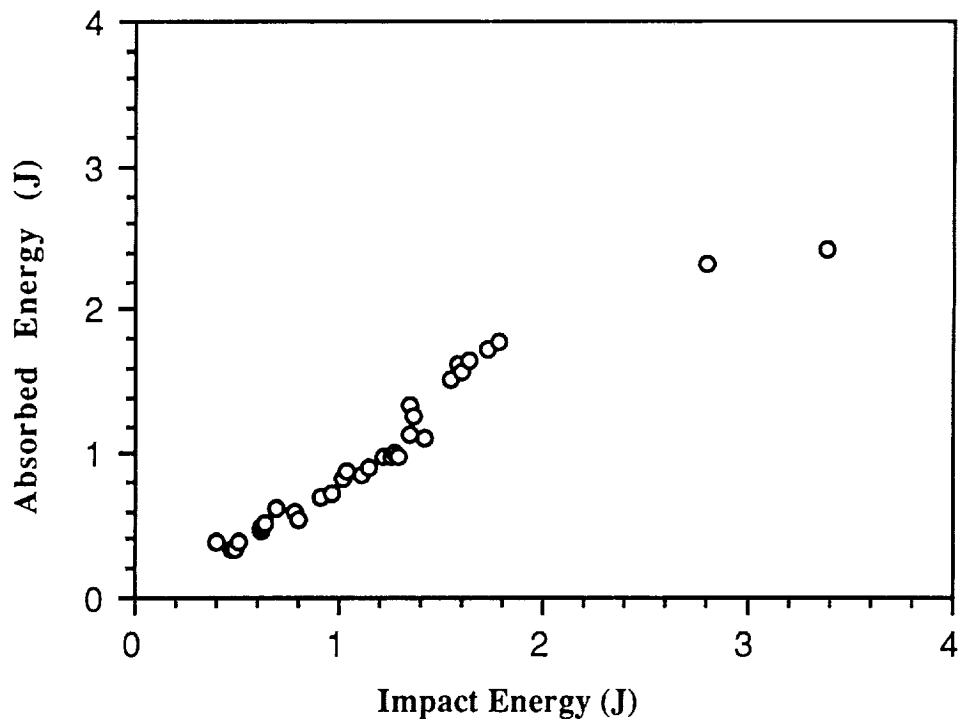
## Absorbed Energy vs Impact Energy G40/F584 Unidirectional



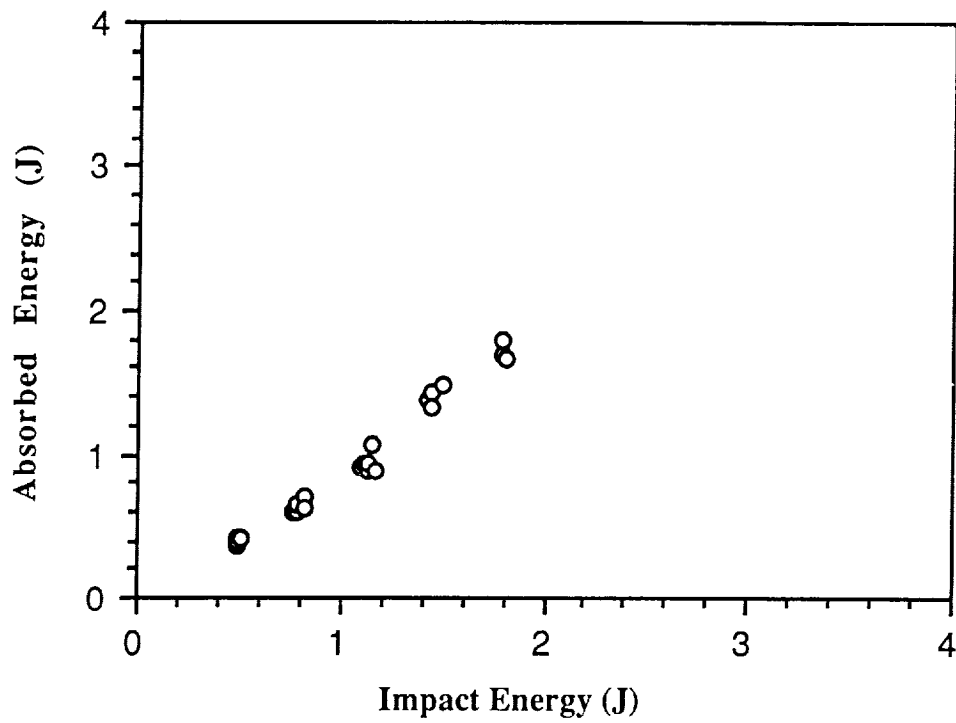
Absorbed Energy vs Impact Energy  
IM7/8551 Unidirectional



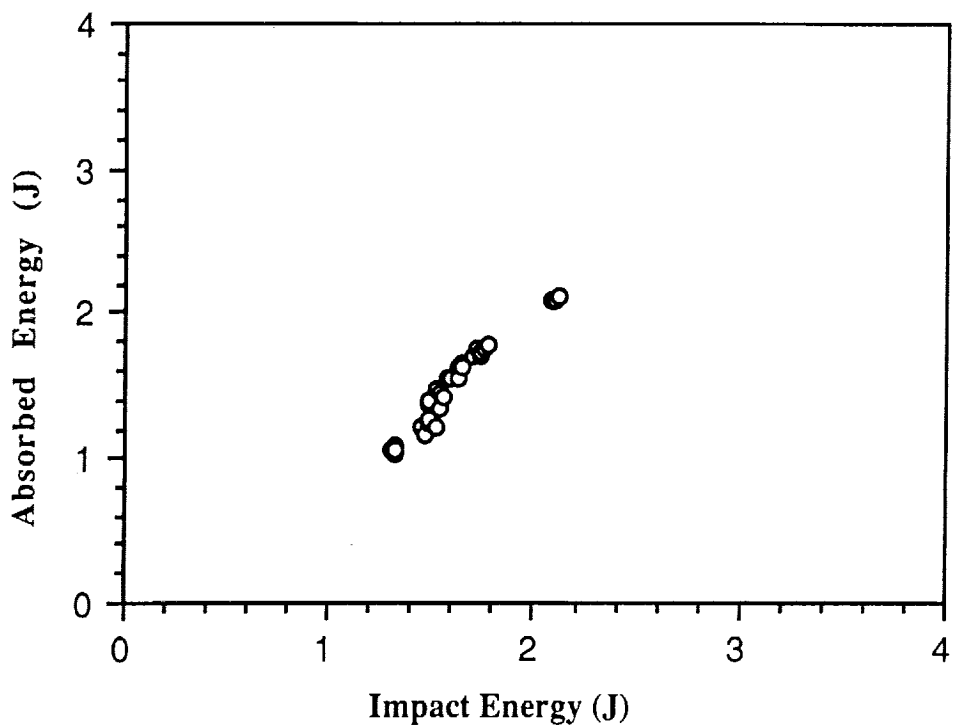
Absorbed Energy vs Impact Energy  
T40/1962 Unidirectional



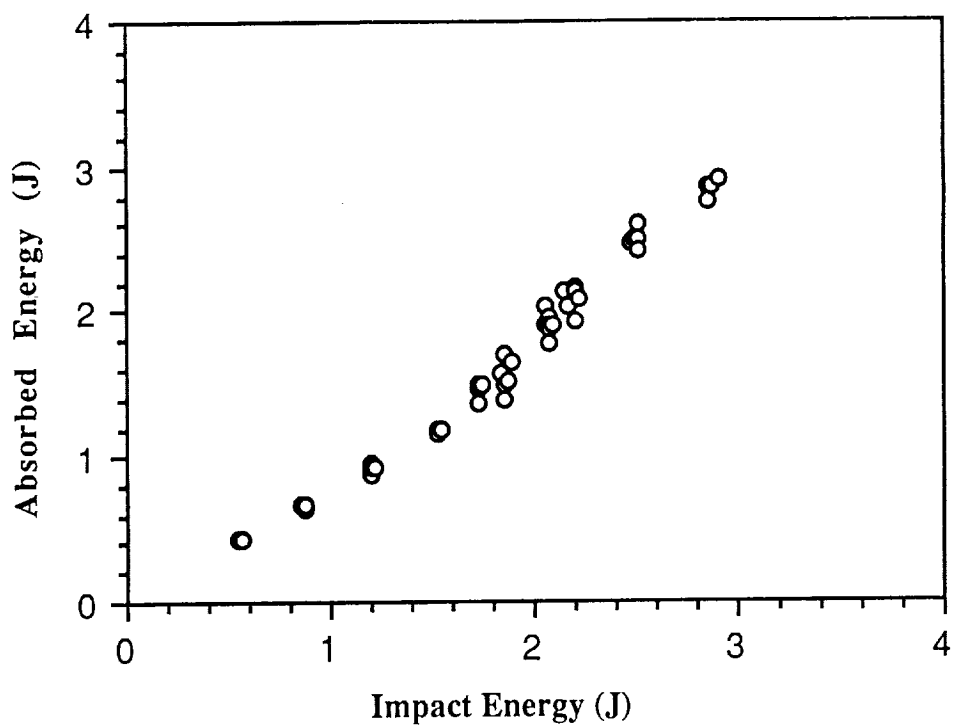
**Absorbed Energy vs Impact Energy**  
**AS4/3501 Bidirectional**



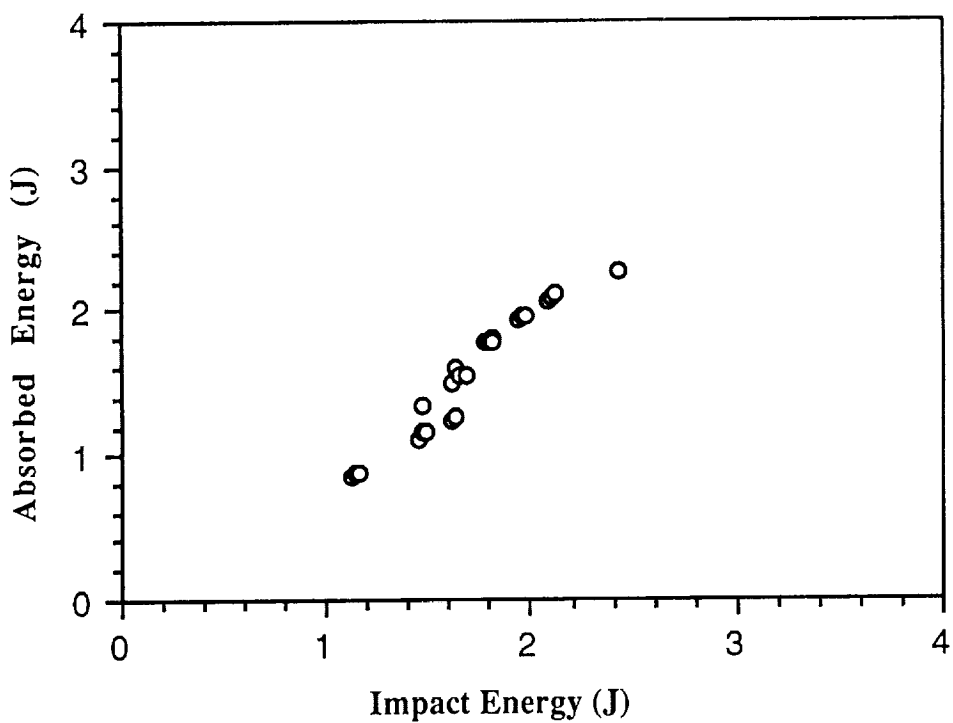
**Absorbed Energy vs Impact Energy**  
**IM7/8551 Bidirectional**



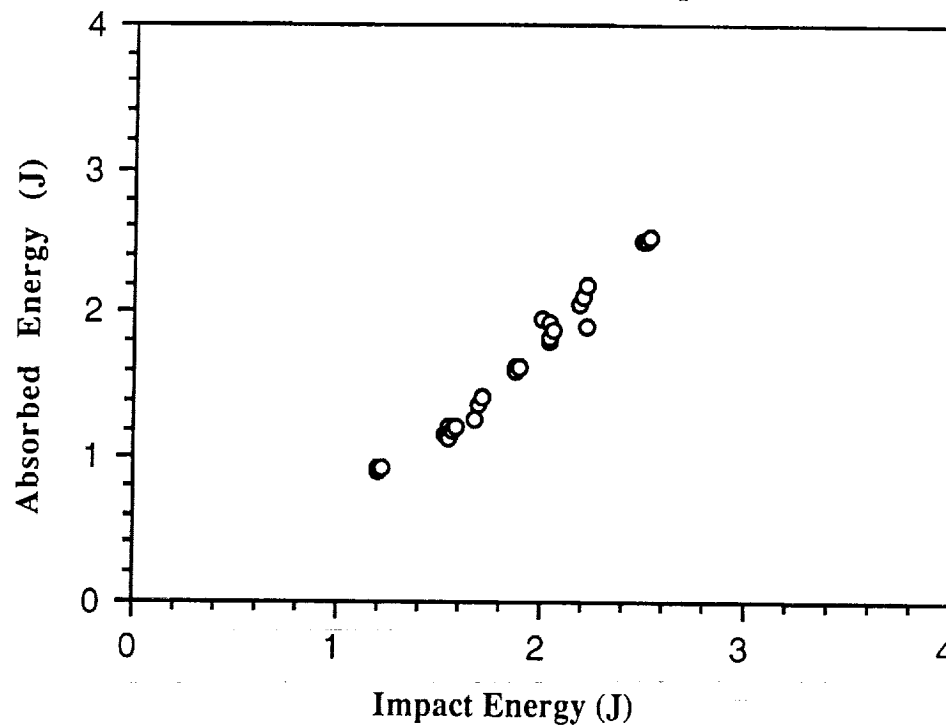
**Absorbed Energy vs Impact Energy**  
**T40/1962 Bidirectional**



**Absorbed Energy vs Impact Energy**  
**IM7/8551 Quasi-isotropic**



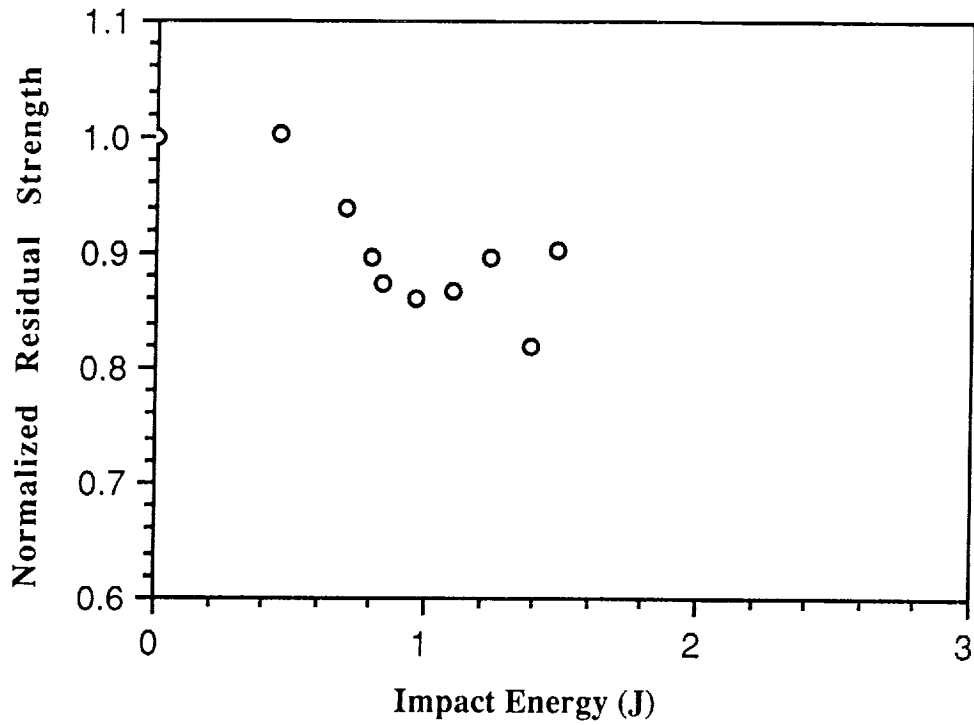
# Absorbed Energy vs Impact Energy T40/1962 Quasi-isotropic



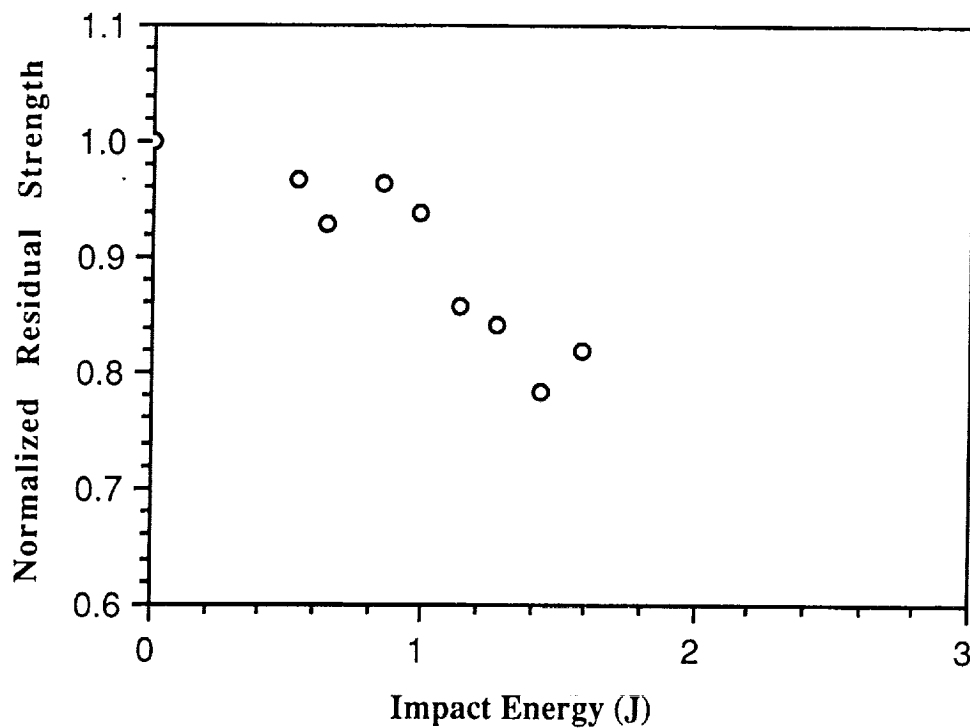
## **APPENDIX D**

### **Residual Tensile Strength Versus Energy of Impact**

**Residual Strength vs Impact Energy**  
**AS4/3501 Unidirectional**

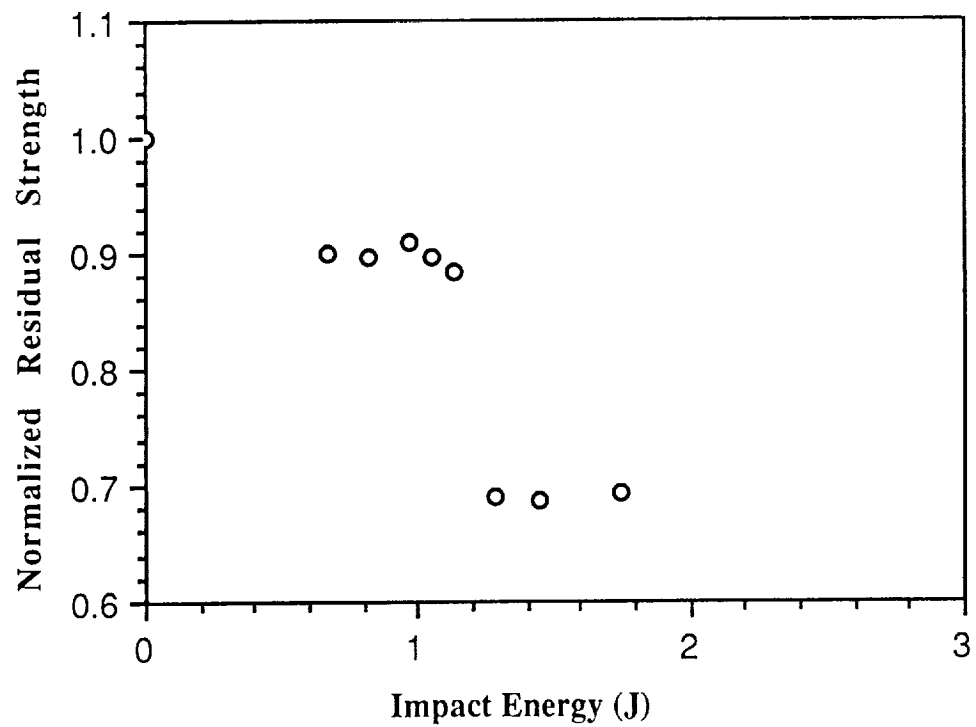


**Residual Strength vs Impact Energy**  
**G40/F584 Unidirectional**

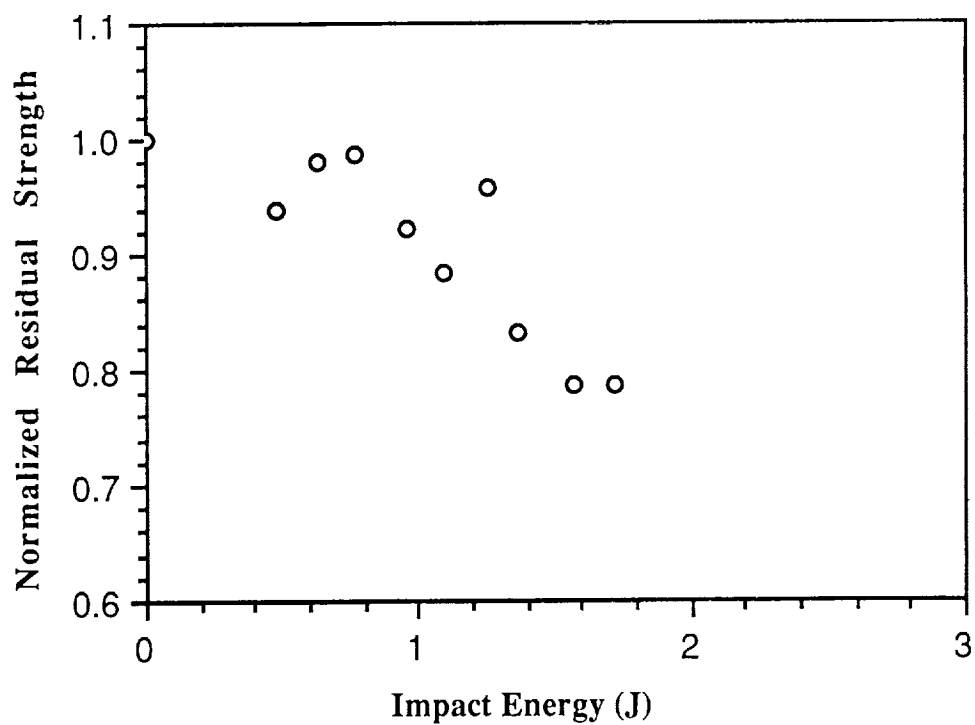




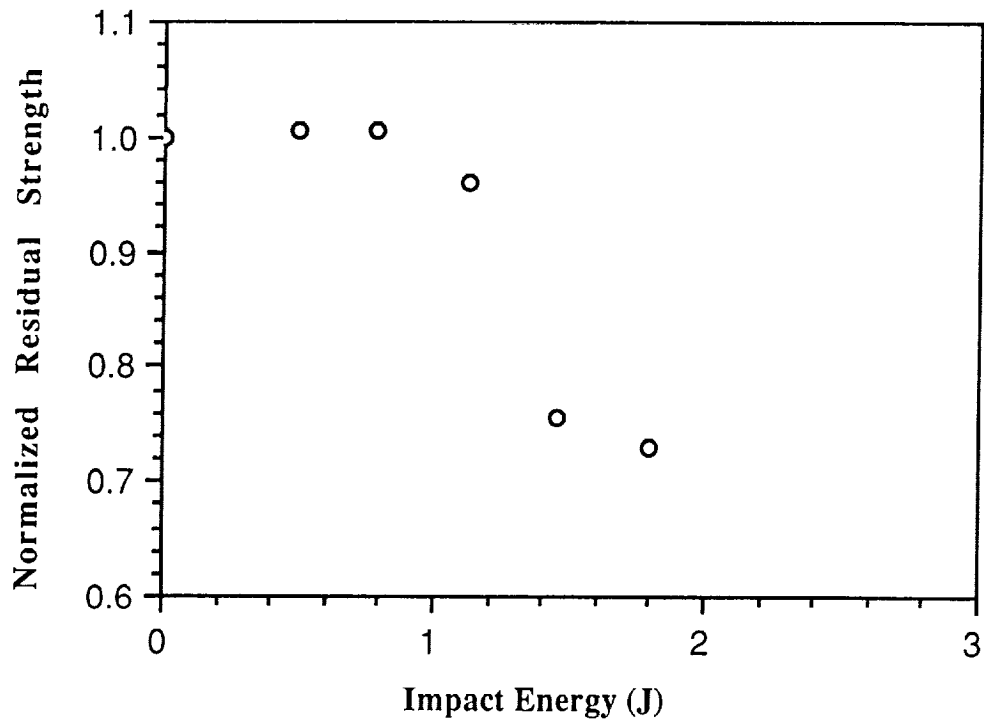
**Residual Strength vs Impact Energy**  
**IM7/8551 Unidirectional**



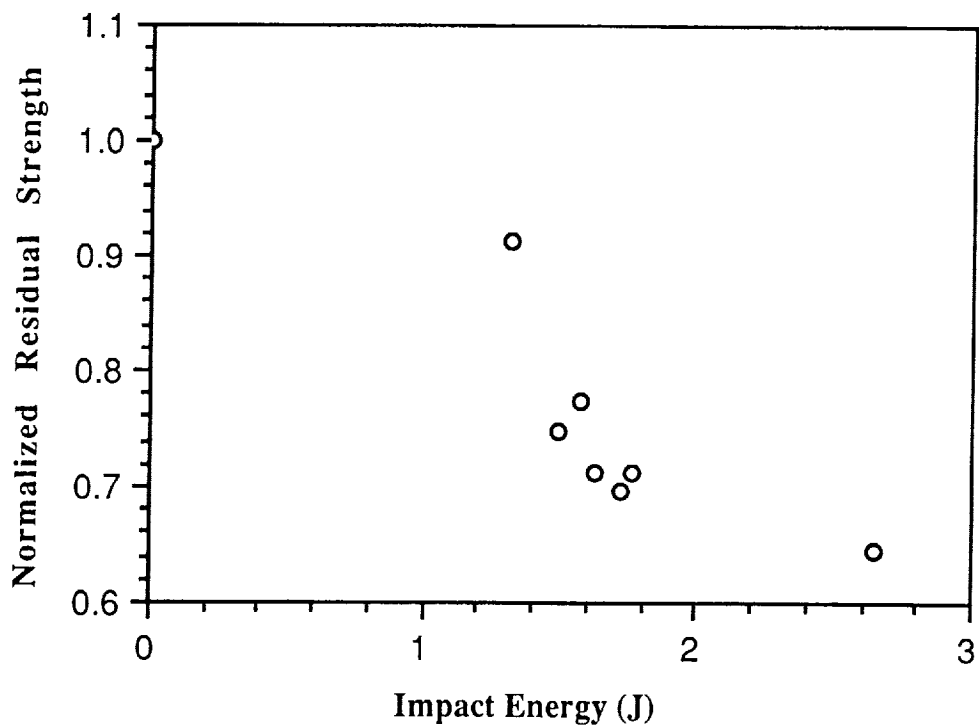
**Residual Strength vs Impact Energy**  
**T40/1962 Unidirectional**



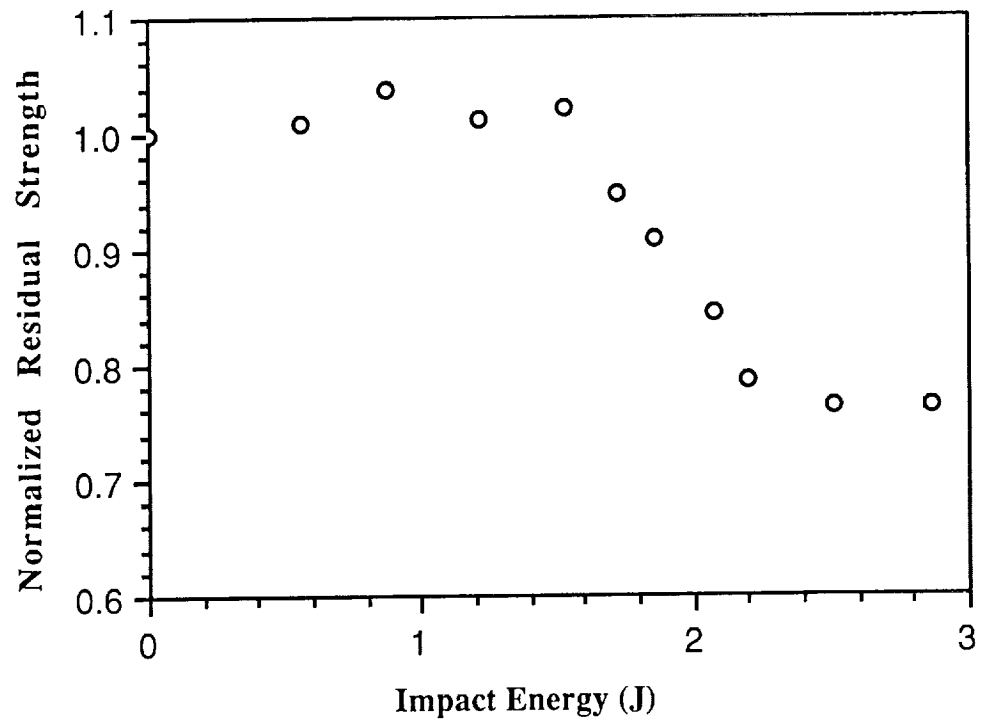
**Residual Strength vs Impact Energy**  
**AS4/3501 Bidirectional**



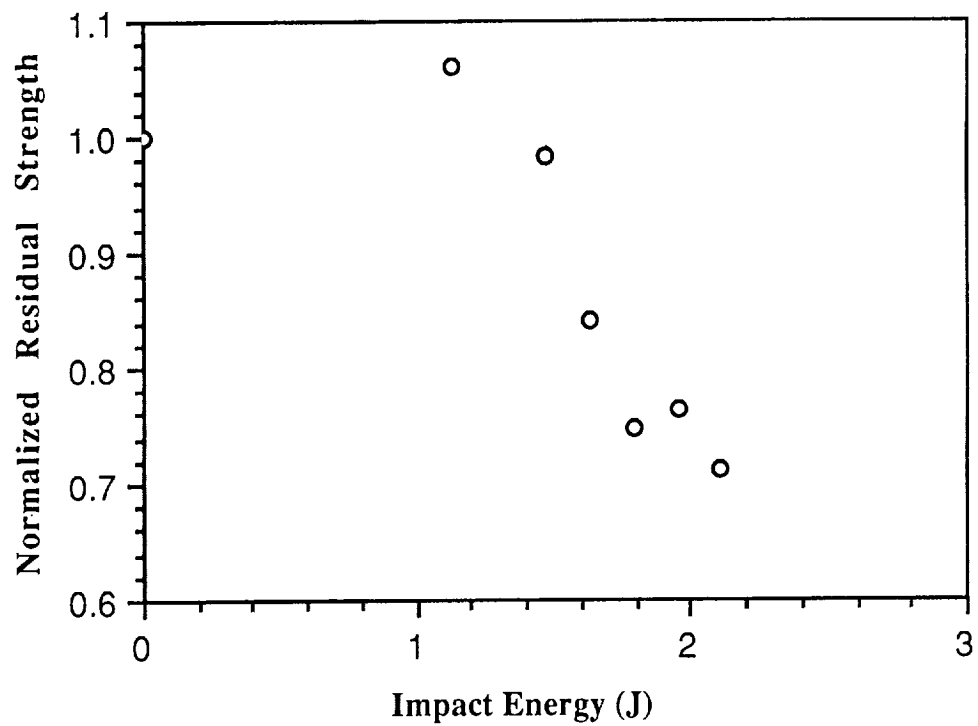
**Residual Strength vs Impact Energy**  
**IM7/8551 Bidirectional**



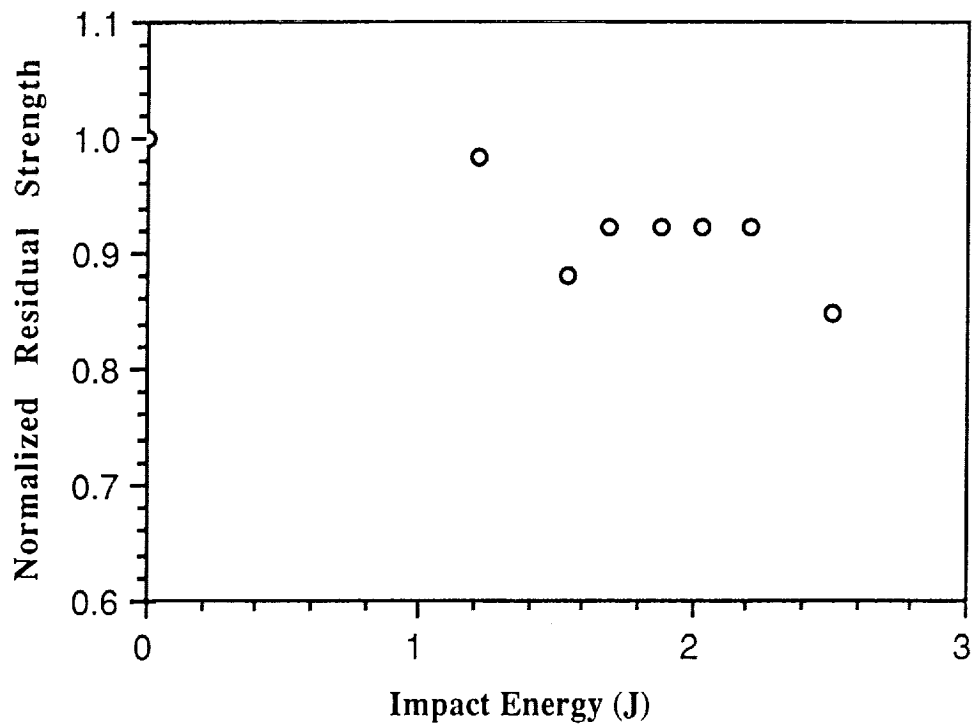
**Residual Strength vs Impact Energy**  
**T40/1962 Bidirectional**



**Residual Strength vs Impact Energy**  
**IM7/8551 Quasi-isotropic**



# Residual Strength vs Impact Energy T40/1962 Quasi-isotropic



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## Report Documentation Page

1. Report No. <b>NASA TP-2981</b>	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle  <b>Instrumented Impact and Residual Tensile Strength Testing of Eight-Ply Carbon/Epoxy Specimens</b>		5. Report Date <b>January 1990</b>	
		6. Performing Organization Code	
7. Author(s)  <b>A.T. Nettles</b>		8. Performing Organization Report No.	
		10. Work Unit No.  <b>M-623</b>	
9. Performing Organization Name and Address  <b>George C. Marshall Space Flight Center Marshall Space Flight Center, Alabama 35812</b>		11. Contract or Grant No.	
		13. Type of Report and Period Covered <b>Technical Paper</b>	
12. Sponsoring Agency Name and Address  <b>National Aeronautics and Space Administration Washington, D.C. 20546</b>		14. Sponsoring Agency Code	
15. Supplementary Notes  <b>Prepared by Materials and Processes Laboratory, Science and Engineering Directorate.</b>			
16. Abstract  <p>Instrumented drop weight impact testing was utilized to examine a puncture-type impact on thin carbon/epoxy coupons. Four different material systems with various eight-ply lay-up configurations were tested. Specimens were placed over a 10.3-mm diameter hole and impacted with a smaller tup (4.2-mm diameter) than those used in previous studies. Force-time plots as well as data on absorbed energy and residual tensile strength were gathered and examined. It was found that a critical impact energy level existed for each material tested, at which point tensile strength began to rapidly decrease with increasing impact energy.</p>			
17. Key Words (Suggested by Author(s))  <b>Composite Materials, Instrumented Impact Testing, Carbon Fibers, Epoxy Resins, Tensile Strength</b>		18. Distribution Statement  <b>Unclassified - Unlimited</b>  <b>Subject Category: 24</b>	
19. Security Classif. (of this report)  <b>Unclassified</b>	20. Security Classif. (of this page)  <b>Unclassified</b>	21. No. of pages  <b>43</b>	22. Price  <b>A03</b>