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EFFECT OF IMPACT DAMAGE AND OPEN HOLES ON THE COMPRESSION STRENGTH OF TOUGH RESIN/HIGH STRAIN FIBER LAMINATES

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INTRODUCTION

Past experience has shown that structural damage and design-based inclusions such as cutouts can reduce significantly the strength of graphite-epoxy laminates (ref. 1). One composite mechanics research activity at the Langley Research Center is to assess and improve the performance of composite structures damaged by impact or containing local discontinuities such as cutouts. Reductions in strength are common to both tension and compression loaded laminates, however, the problem associated with compression performance has been found to be the most illusive to solve. Compression failure involves both shear crippling and delamination modes. Small-scale coupon tests have not yet been developed which adequately predict damaged-laminate compression performance reductions. Two plate specimen configurations; however, have been developed by NASA (ref. 2) to help define the severity of the compression strength reduction problem and to assess the relative merit of proposed toughened material systems. These two test configurations, one involving impact damage and the other open hole specimens, are shown in figure 1. The test technique for impact specimens involves damaging the plate at selected energies, measuring the size of damage by ultrasonic C-scan techniques and measuring the residual strength in a compression load test. Open-hole specimen compression tests are conducted for several different hole diameters and the failure strain and load and mode of failure recorded. The plate specimen used in these tests is designed with length, width, thickness and laminate stiffness to ensure that overall plate buckling is not responsible for initiating failure.

DAMAGE TOLERANCE COMPRESSION TESTS

IMPACT AT SELECTED ENERGIES

SELECTED HOLE DIAMETERS

STRESS CONCENTRATION

• C-SCAN FOR DAMAGE
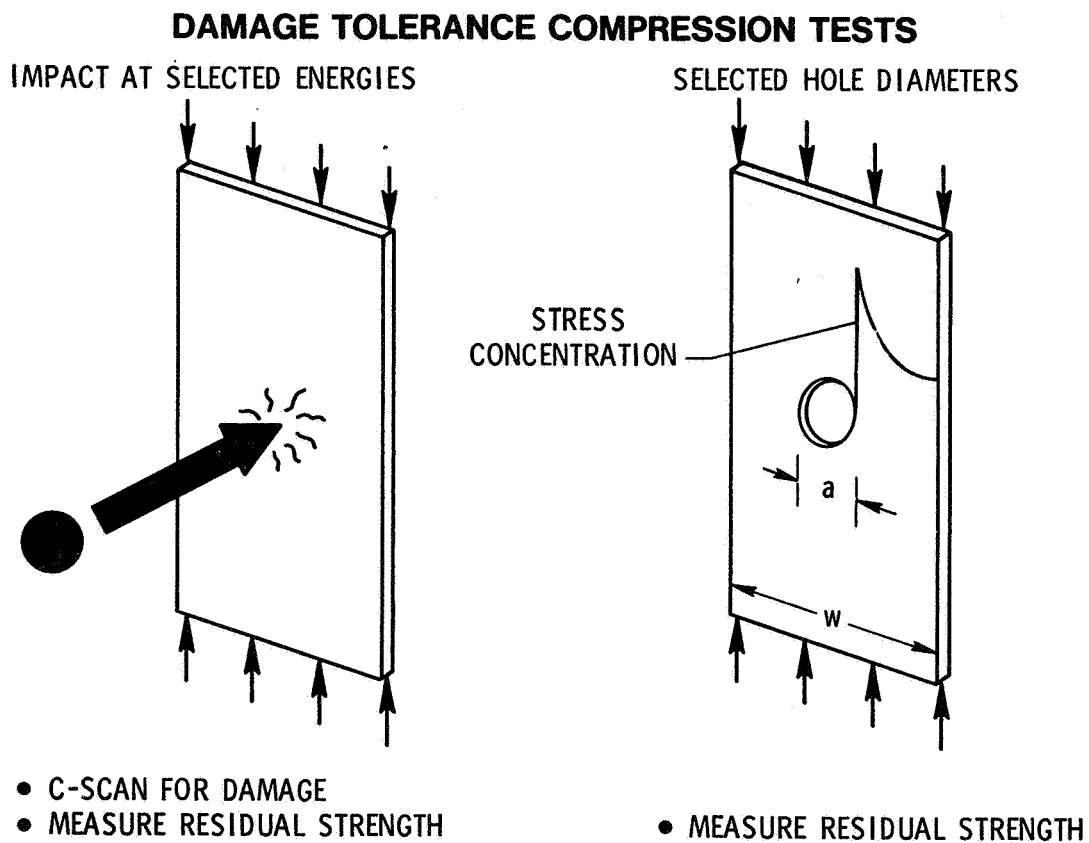• MEASURE RESIDUAL STRENGTH

• MEASURE RESIDUAL STRENGTH

Figure 1

TEST SPECIMENS AND FIXTURE

In the current investigation, several new graphite-epoxy material systems proposed for improved damage-tolerance and listed in figure 2 were studied. Material parameters included both tough resin formulations and high strain fibers. Material suppliers included Narmco (T300 fiber and 5208 resin), American Cyanamide (BP907 resin), and Hercules (AS4 and AS6 fibers and 3502, 2220-1, and 2220-3 resin). Ultimate tensile strains for these fibers are approximately: 1.2% - T300, 1.4% - AS4 and 1.8% - AS6. The T300/5208 material is used as a baseline and T300/BP907 was identified in past sudies as exhibiting improved damage-tolerance characteristics (ref. 3). All tests were conducted at room temperature and; therefore, do not address the reduction in strength of resin materials such as BP907 caused by moisture and elevated temperatures. Quasi-isotropic laminate specimens approximately 0.25 inches thick and 10 inches long by 5 inches wide were tested in the fixture shown in figure 2. The fixture imposed nearly clamped boundary conditions on the loaded ends and simple support boundary conditions on the lateral edges. Two sets of strain gages mounted back-to-back were used to measure the axial strain.
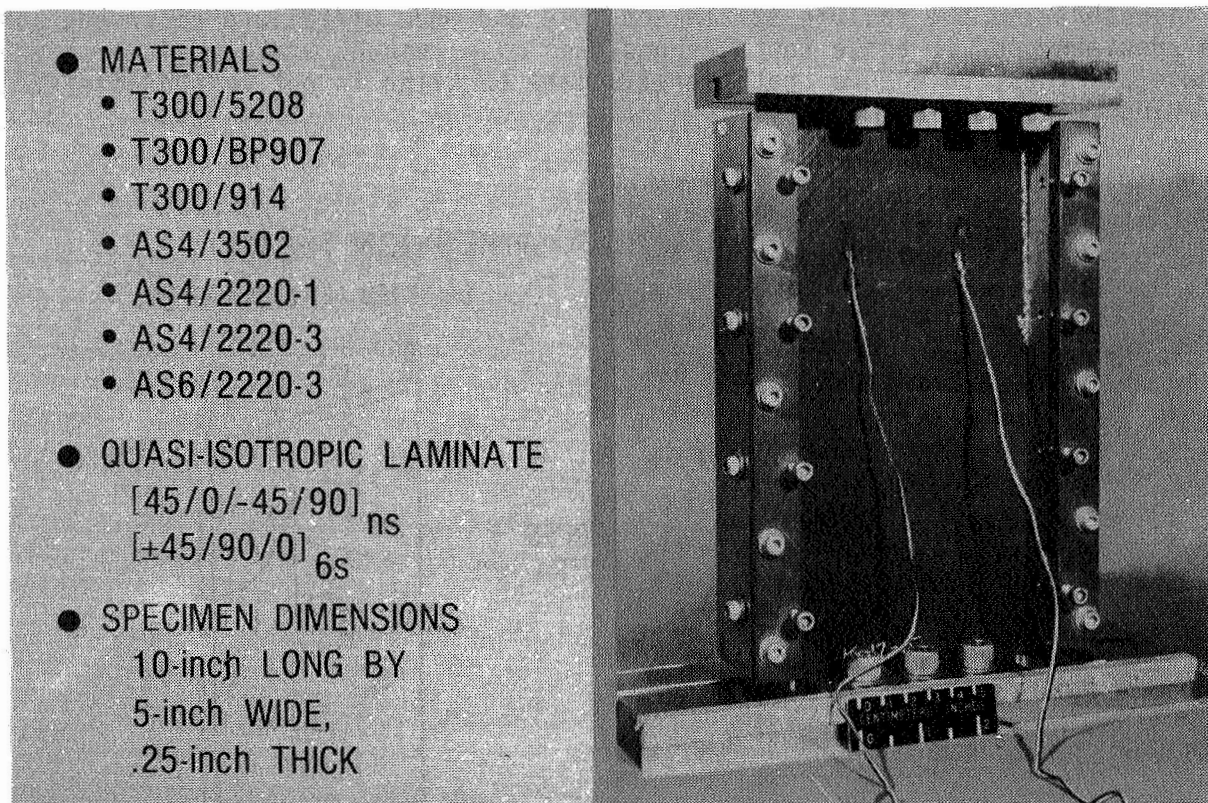

Figure 2

LAMINATE DAMAGE FOLLOWING IMPACT

An illustration of the influence the resin material has on the size and extent of damage in a graphite-epoxy laminate resulting from projectile impact is shown in figure 3. The damage following impact by a 1/2-inch diameter aluminum sphere at approximately 13 ft-lb of energy is shown on the top row for a brittle behavior resin and on the bottom row for a toughened resin system. The orthotropic laminate is approximately 0.25-inch thick. Less damage is observed for the tough resin material by visual observation of surface damage, by ultrasonic C-scan inspection and by microscopic inspection of a cross-section through the impact damage zone. This demonstration shows, therefore, that it is possible to tailor the matrix material properties to reduce the size of damage following projectile impact.
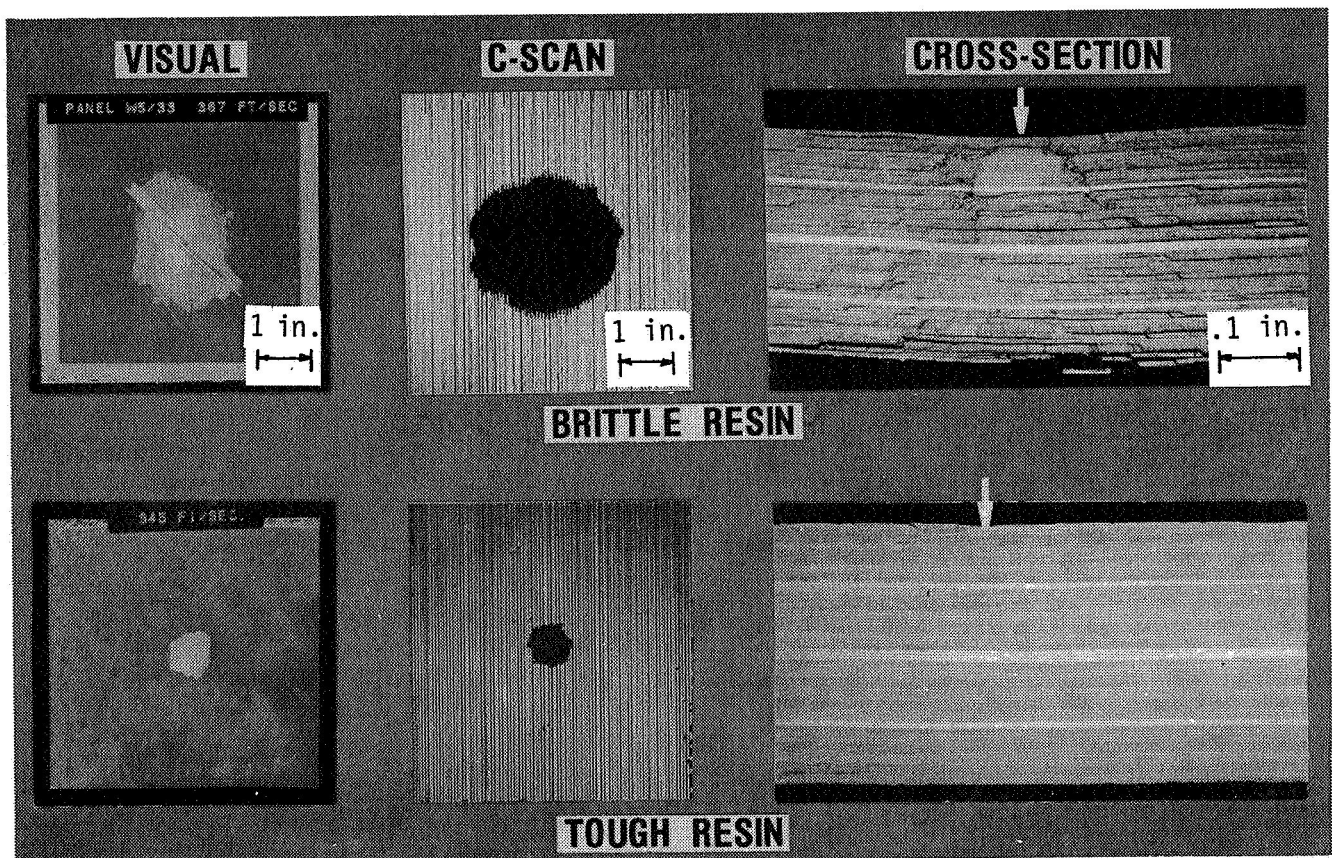

Figure 3

EFFECT OF IMPACT ENERGY ON DAMAGE SIZE

A plot of the damage area measured using ultrasonic C-scan signatures for several material systems is presented in figure 4 as a function of the projectile impact velocity and energy. The threshold energy at which damage can first be detected varies for the materials studied, however, all are in the range of three to five ft-lbs. The largest damage size was measured for the T300/914 material. One variable for this material different from the other materials was that a thicker prepreg tape was used resulting in approximately half as many plies for the 0.25-inch thick laminate. The effect of lamina thickness is not established. The results of several of the materials fall within a relatively narrow band for the energies studied. There appears to be a divergence of the results, however, at the upper energy levels, a trend which merits further study.
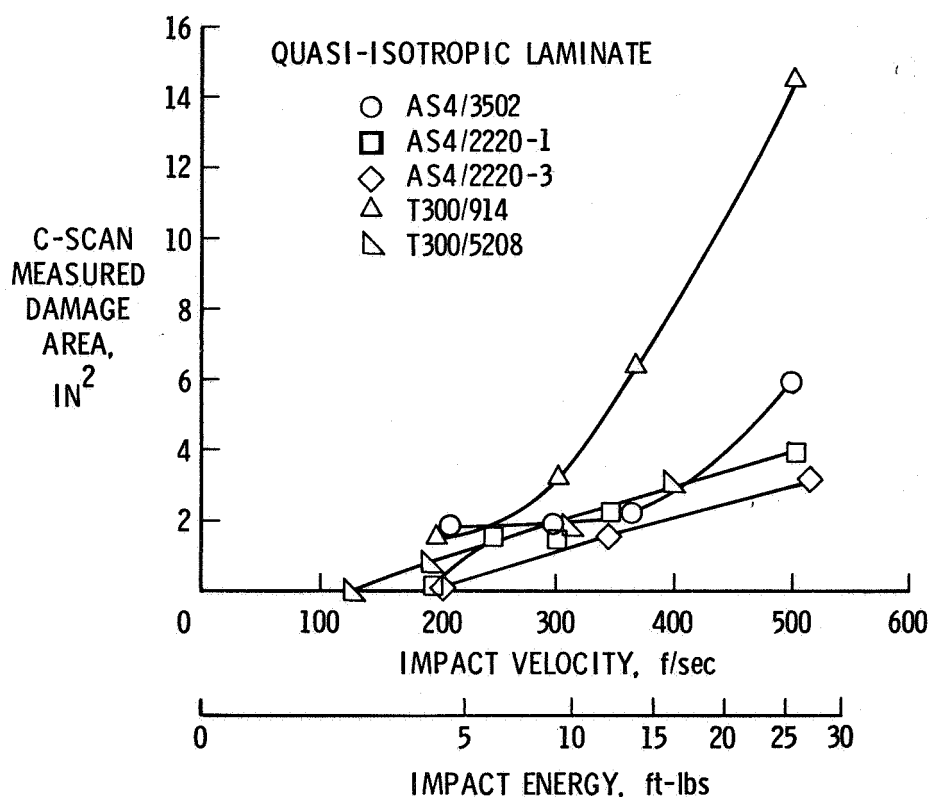

Figure 4

IMPACT INITIATED COMPRESSION FAILURE MODES

Experimental studies have shown that the failure of damaged composite laminates loaded in compression involves two primary failure mechanisms; delamination and transverse shear (ref. 4). These two failure mechanisms are illustrated in figure 5 for a brittle resin laminate and for a damage-tolerant tough resin laminate. The photographs on the right of the figure show cross-sections of failure regions which are typical for these two classes of material. The brittle resin laminate shows considerable evidence of delamination whereas the tough resin laminate cross-section is characterized by a through-the-thickness shear band which is approximately 0.07-inch wide. Closer inspection reveals, however, that both specimens actually exhibit both delamination and transverse shear failure mechanisms. The transverse shear failure mode for the brittle resin laminate develops in only a few plies before delamination occurs; while the transverse shear mode for tough resin laminates is several plies thick before it is interrupted by delamination caused by wedges of failed material prying apart the plies. Tough resin formulations improve damage tolerance by suppressing the delamination mode of failure permitting failure to occur at the next higher energy mode involving transverse shear.
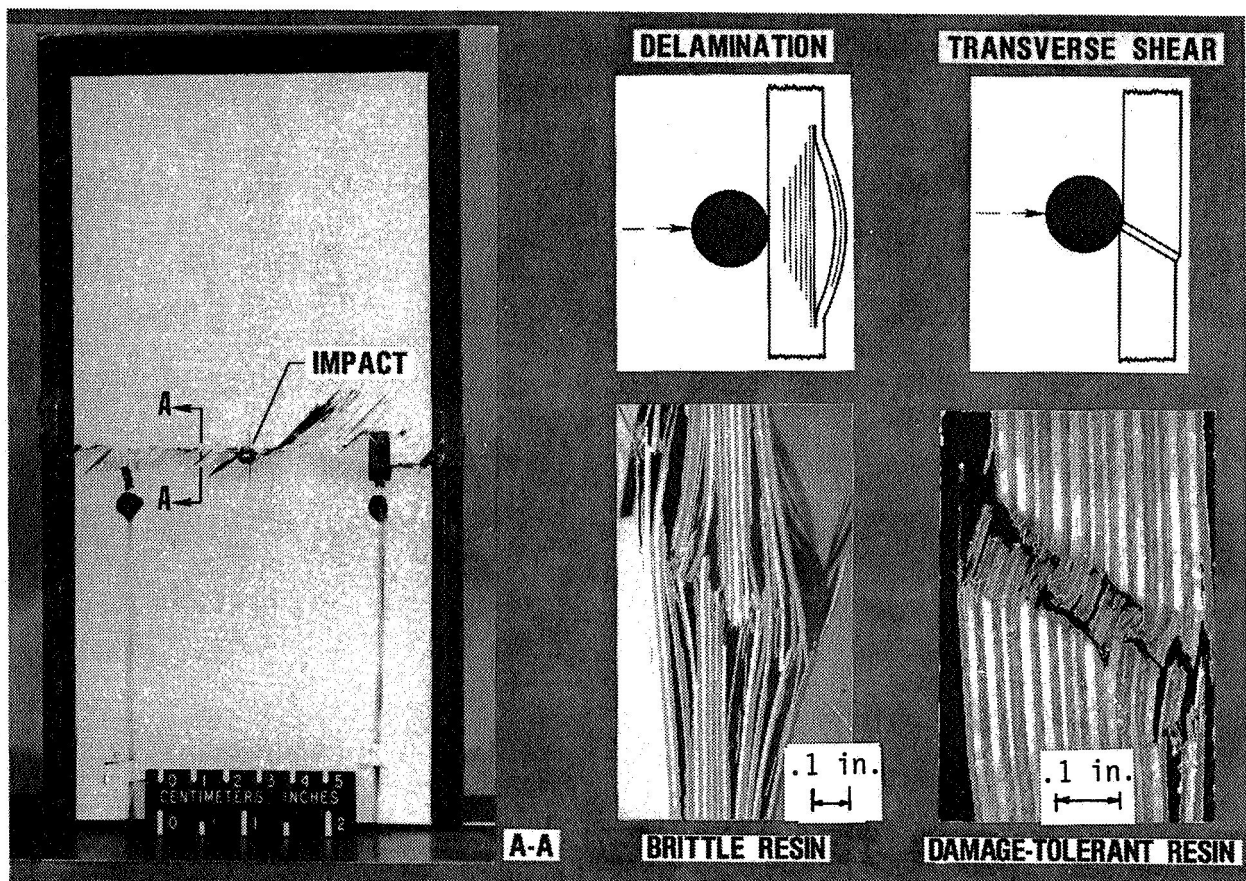

Figure 5

PROPAGATION OF IMPACT INDUCED DELAMINATION

The sequence of events which occurs when a brittle resin is damaged by impact and subsequently loaded in compression to failure is shown in figure 6. The moire fringe photographs show the local out-of-plane deformations of the laminate in the impact damaged region. Photographs presented left to right correspond to increasing load up to ultimate at which damage propagates from the center of the panel to the two lateral edges. Sublaminates caused by impact-induced delaminations have reduced bending stiffnesses compared to the undamaged laminate and, if sufficiently large, buckle at significantly lower loads than the overall plate buckles. These local buckles represented by the moire fringe contours cause high stresses in the resin at the delamination boundary. When the buckle is sufficiently advanced, these stresses cause fracture of the resin and the damage propagates.
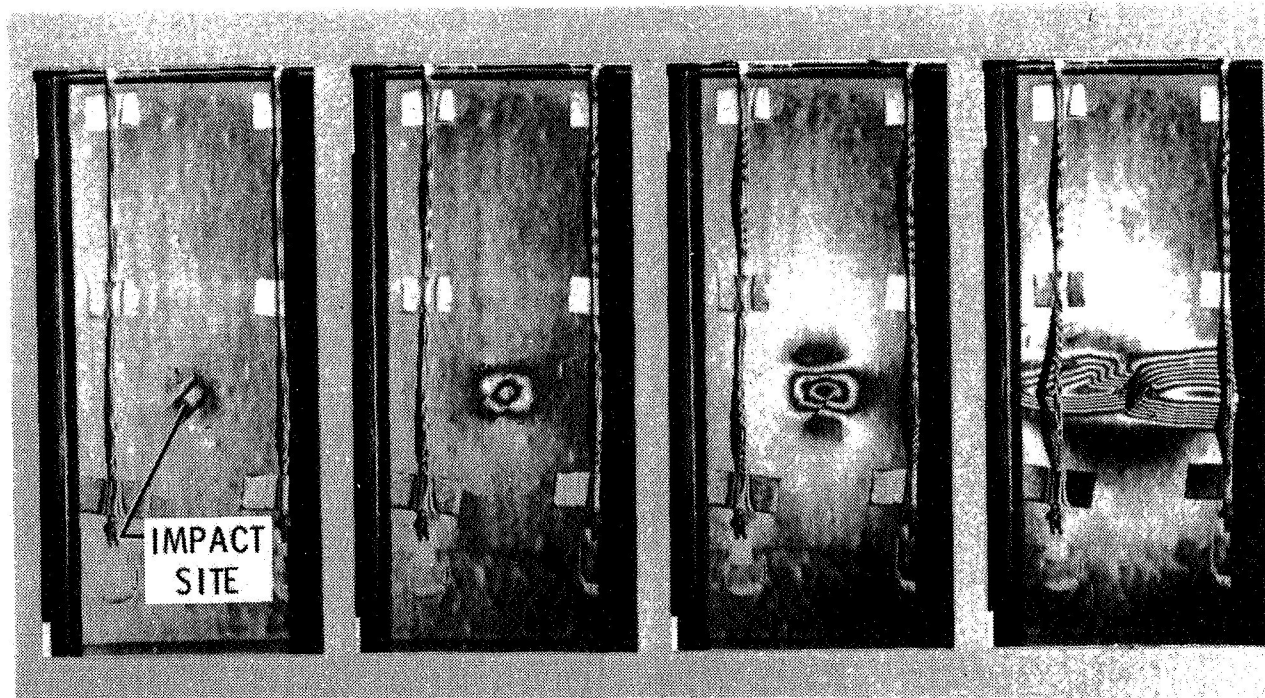

Figure 6

SHEAR CRIPPLING FAILURE MODE

The shear crippling mode of failure occurs not only at the macroscopic scale as illustrated in figure 5 but also on the microscopic scale involving individual graphite fibers as illustrated in figure 7. This tough resin orthotropic laminate was damaged by impact and loaded until the damage began to propagate across the panel. The damage propagation arrested; the load was removed and a cross-section was taken through the damaged region. Shown on the right of figure 7 is a photo-micrograph of four of the interior plies [45/0_2/-45] of the 48-ply laminate. Graphite fibers in the zero degree plies (aligned coincident with the applied load) failed by shear crippling while fibers oriented at 45-degrees are undamaged. The model proposed to explain this phenomenon is that the strain concentration in zero-degree plies located in the damage zone and the reduced support to the fibers due to matrix fracture causes the graphite fibers to microbuckle. Fracture of the fiber occurs when the axial plus postbuckling bending strains reach a critical value.

48 PLY LAMINATE
($\pm 45/0_2/\pm 45/0_2/\pm 45/0/90)_{2S}$

$\vert\leftarrow$ 45 $\rightarrow\vert\leftarrow$ 0_2 $\rightarrow\vert\leftarrow$ 45 $\rightarrow\vert$
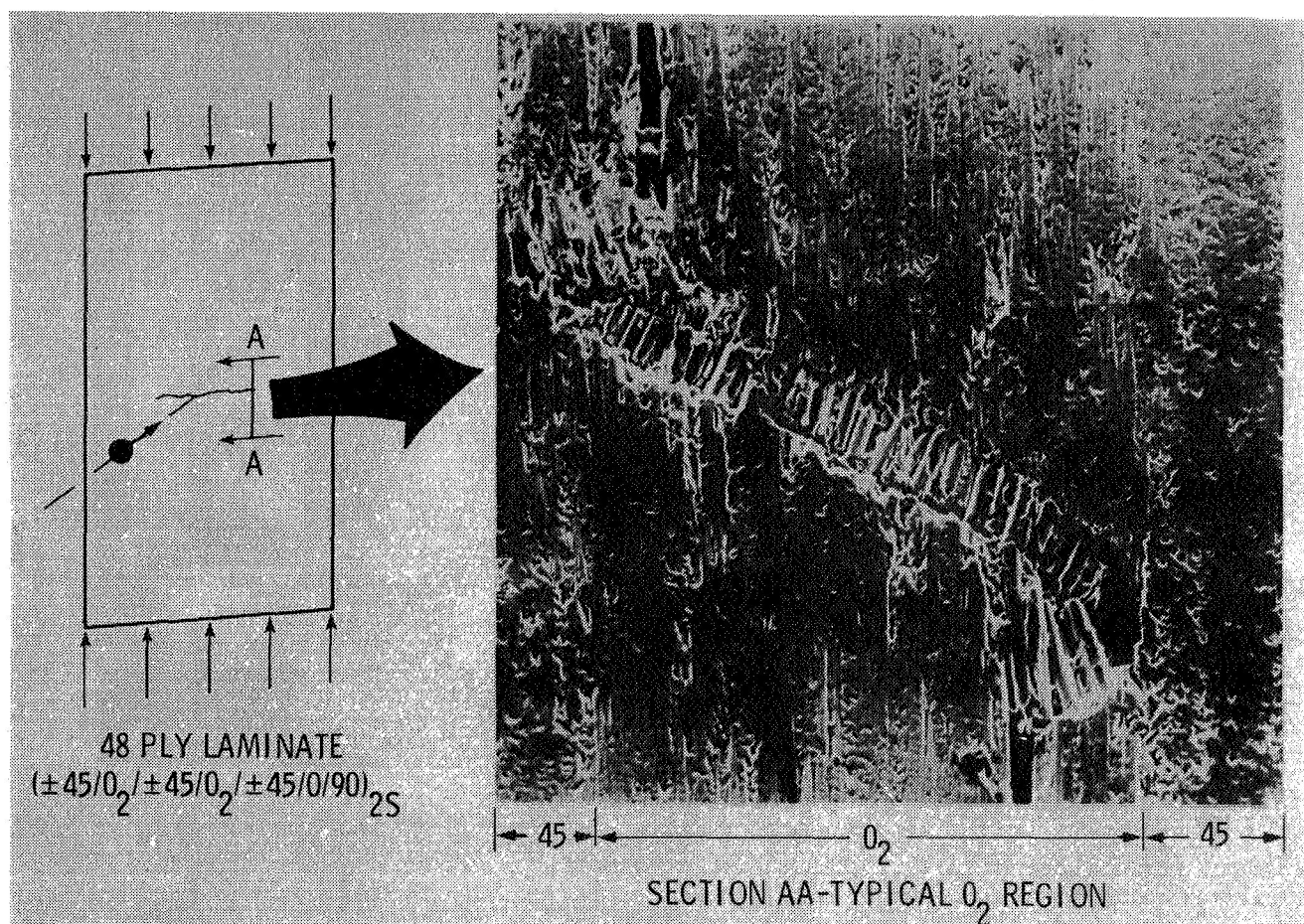
SECTION AA-TYPICAL 0_2 REGION

Figure 7

FAILURE OF OPEN-HOLE SPECIMEN LOADED IN COMPRESSION

A series of photographs showing the initiation and propagation of delamination for an open hole specimen loaded in compression is shown in figure 8. At 95.2% of the ultimate load, moire fringe photographs show no evidence of delamination around the hole boundary. At 95.4%, local fringes appear and grow in size with increasing load as can be seen comparing the photographs at 95.9% and 98.1% of ultimate. Ultimate failure occurs when damage propagates completely across the reduced section of the plate. One might conclude based on this evidence that the initiating failure mode for open hole specimens is delamination; however, as will be shown in the next figure, microscopic shear crippling occurs in the vicinity of the hole boundary in advance of delamination.
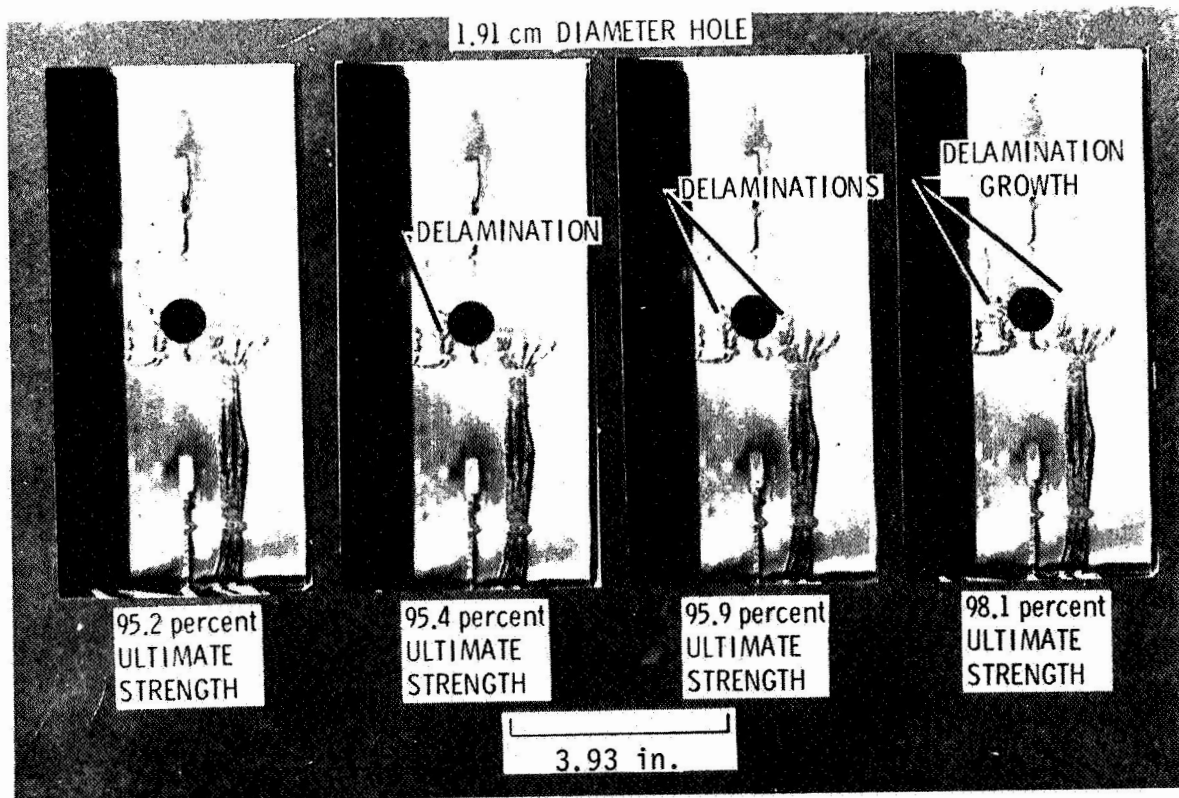

Figure 8

SHEAR CRIPPLING INITIATES OPEN-HOLE SPECIMEN FAILURE

Another specimen similar to the one shown in figure 8 was loaded to a load level just prior to the initiation of delamination (approximately 92% of ultimate) and unloaded. A small block of material adjacent to the hole boundary was cut from the specimen and surface material sanded away to expose an interior 0-degree layer. Scanning electron photomicrographs of this region are shown on the right of figure 9. Damage is the same failure of individual graphite fibers by shear crippling which was shown earlier in figure 7 for the compression failure of impact-damaged laminates. The higher magnification photomicrograph shows the failed fiber length to diameter ratio to be approximately four. The proposed failure model is the same as proposed earlier, i.e., graphite fibers microbuckle in the high strain concentration region adjacent to the hole and fail in the post-buckled state.
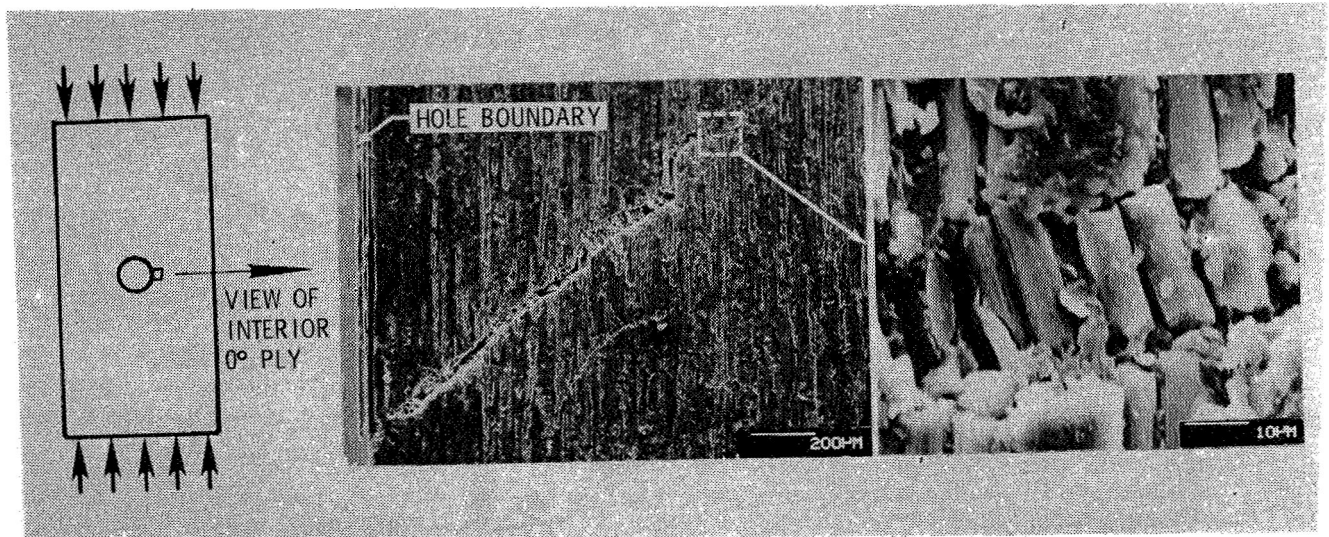

Figure 9

IMPACT-DAMAGE FAILURE THRESHOLD CURVE

The effect of impact damage on the failure strain of a compression loaded graphite-epoxy laminate constructed with a brittle-behavior resin material is presented in figure 10 (ref. 4). Filled circular symbols represent specimens which failed catastrophically when loaded to the indicated strain level and impacted by a 1/2-inch diameter aluminum sphere at the indicated velocities. Open circular symbols represent specimens which may have been damaged by impact, but the damage was contained with little loss of load. A narrow band separates open and closed symbols and a failure threshold curve has been drawn through the band, thus separating the graph into two zones. Impact conditions above and to the right of the curve result in specimen failure while the laminate survived the less severe conditions below and to the left of the curve. A severe reduction in strength occurs for impacts in the 165 to 250 ft/sec range and at 330 ft/sec the failure threshold strain is reduced to approximately 0.0028.

48 PLY LAMINATE
$(\pm 45/0_2/\pm 45/0_2/\pm 45/0/90)_{2S}$

T300/5208

STRAIN

● FAILED ON IMPACT
○ DID NOT FAIL ON IMPACT
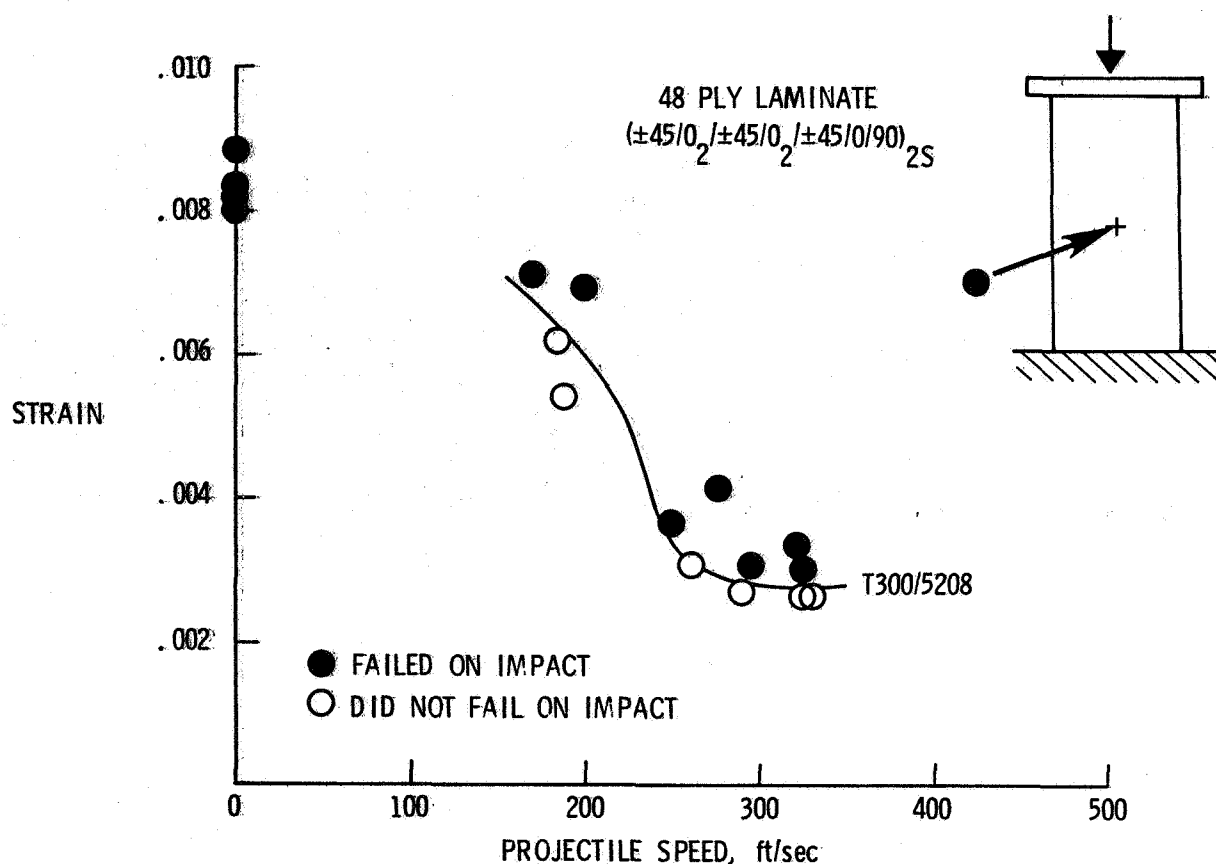
PROJECTILE SPEED, ft/sec

Figure 10

TOUGH RESIN IMPROVES LAMINATE DAMAGE TOLERANCE

Failure threshold curves for a 48-ply orthotropic graphite-epoxy laminate constructed using two different resin systems are shown in figure 11 (ref. 4). For the test conditions studied, the tough BP907 resin system shows substantial improvement relative to the brittle 5208 resin system. Similar improvements have also been observed for a 5208 resin laminate when it was reinforced by through-the-thickness stitching. The explanation for this improvement is that both the tough resin system and stitching suppress the delamination mode of failure. The delamination mode of failure has been studied using fracture toughness tests such as the double cantilever beam. Success has been achieved at correlating improved compression after impact strength and fracture toughness measurements for material systems with widely varying fracture toughness properties such as the materials compared in figure 11. As shown in figure 7, however, shear crippling is also involved in the failure of impact-damaged laminates and fracture toughness tests do not address this mode of failure.
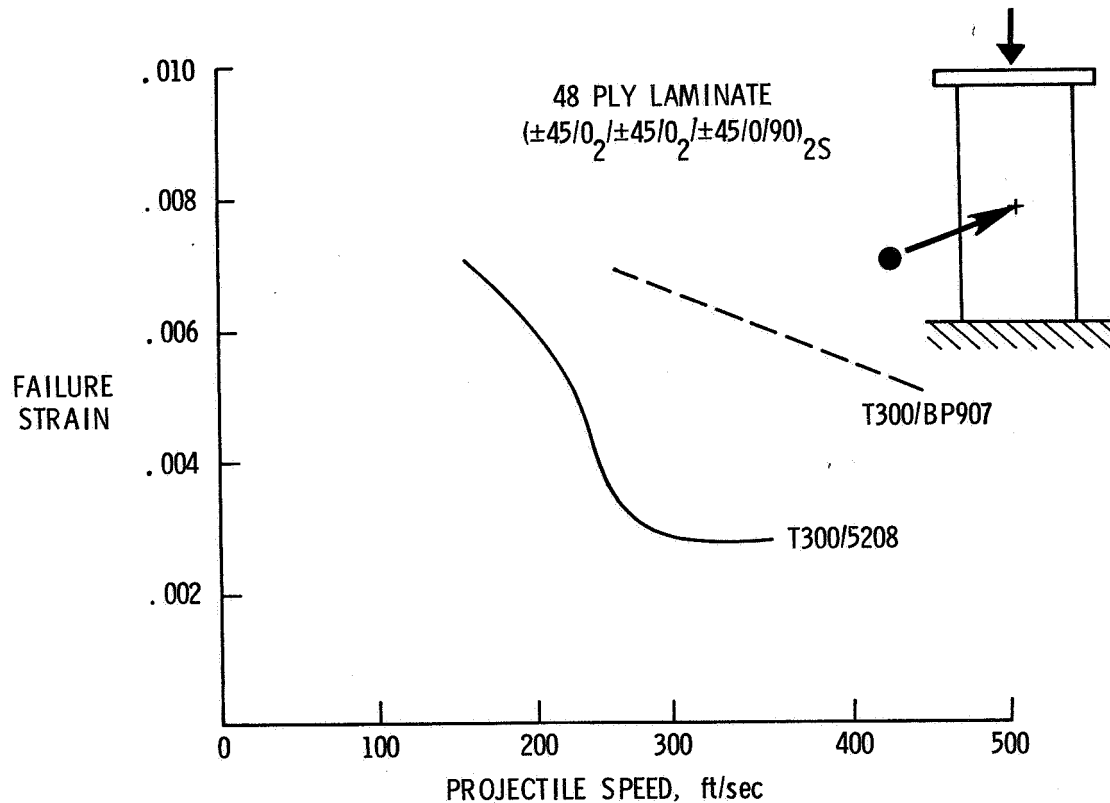

Figure 11

EFFECT OF SIZE OF IMPACT DAMAGE ON FAILURE STRAIN

A need exists for a comparison method which the composite structure designer can use to assess the effect of various impact conditions and material systems on structural strength. Trends for test data in which increasing strength losses were observed to occur with increasing impact damage size suggested the parameters used in the graph presented in figure 12. The failure strain for several different material systems constructed in a quasi-isotropic laminate is plotted as a function of the width of damage resulting from impact. The damge width was determined from ultrasonic C-scan photographs and is normalized by the specimen width (5-inches). For these laminates and impact conditions, the size of damage appears to be a parameter that reduces the test data for all four materials to a common curve. A two-parameter curve asymptotic to a/w = .24 has been drawn through the data. A large reduction in strength occurs around a/w = .24 and the failure strain for a/w < .24 is governed by conditions other than impact such as plate buckling. Additional study is required to assess the generalization of this data to other impact conditions and laminates.
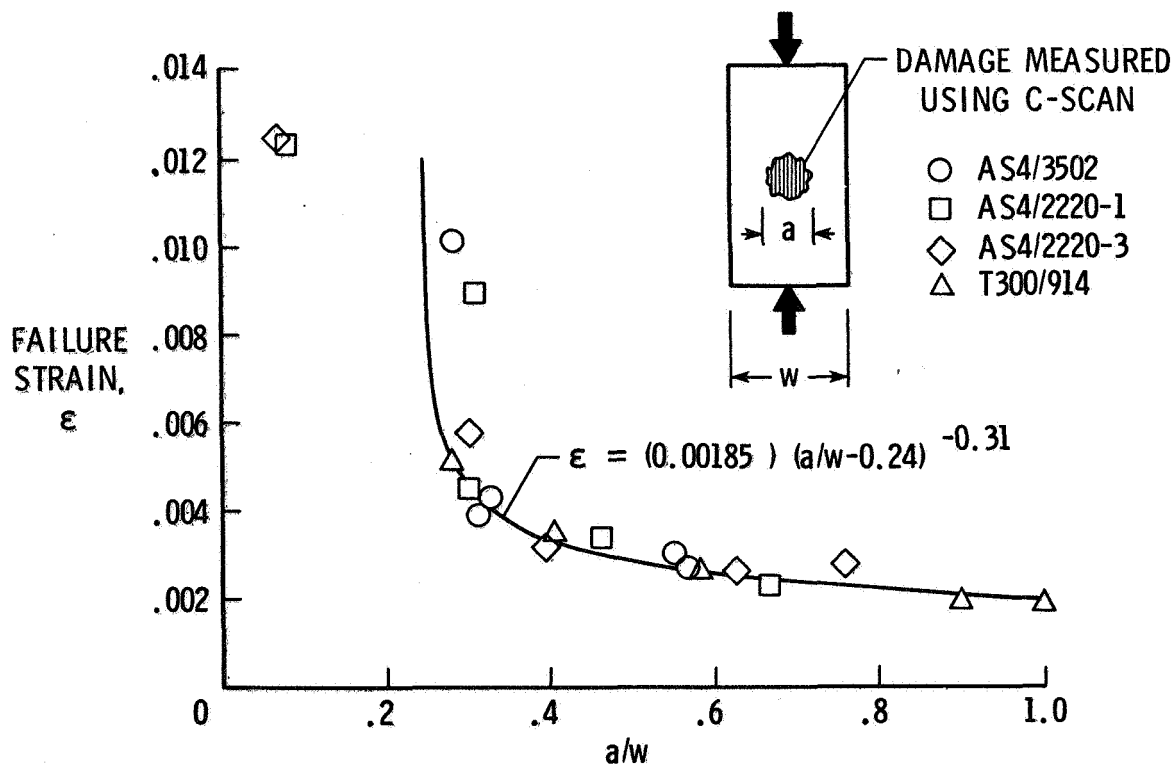

$$\varepsilon = (0.00185)(a/w - 0.24)^{-0.31}$$

Figure 12

OPEN-HOLE COMPRESSION SPECIMENS

A series of 5-inch-wide and 10-inch-long quasi-isotropic specimens with selected centrally located holes were tested for several different material systems. Photographs of some of these specimens are presented in figure 13.
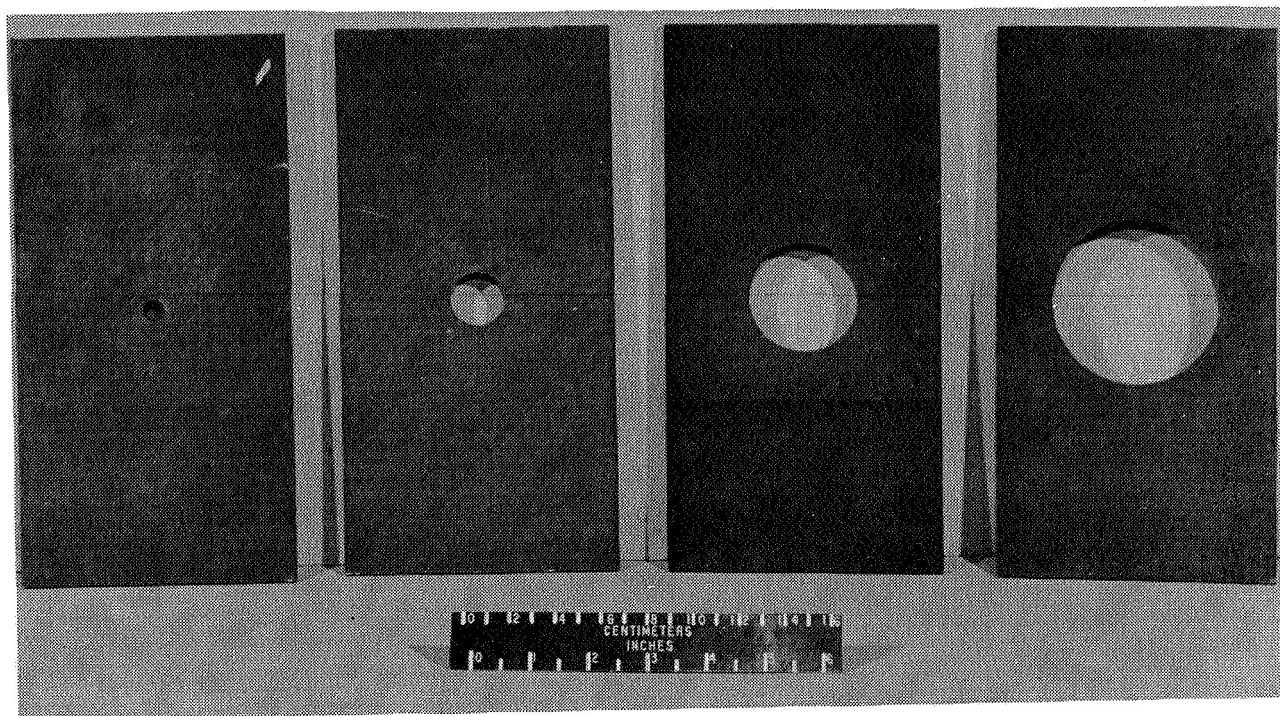

Figure 13

STRESS-STRAIN RESPONSE FOR OPEN-HOLE SPECIMENS

The stress-strain response up to failure for AS4/2220-3 quasi-isotropic 5-inch-wide specimens with selected a/w hole sizes is presented in figure 14. Strain data is taken from strain gages located near one end of the specimen. For large holes, the stress-strain response deviates from the no-hole (a/w = 0) curve. For purposes of data comparison, the failure strain for open-hole specimens reported in subsequent figures is the strain which the no-hole specimen carried at the same stress that the open-hole specimens carried at failure.
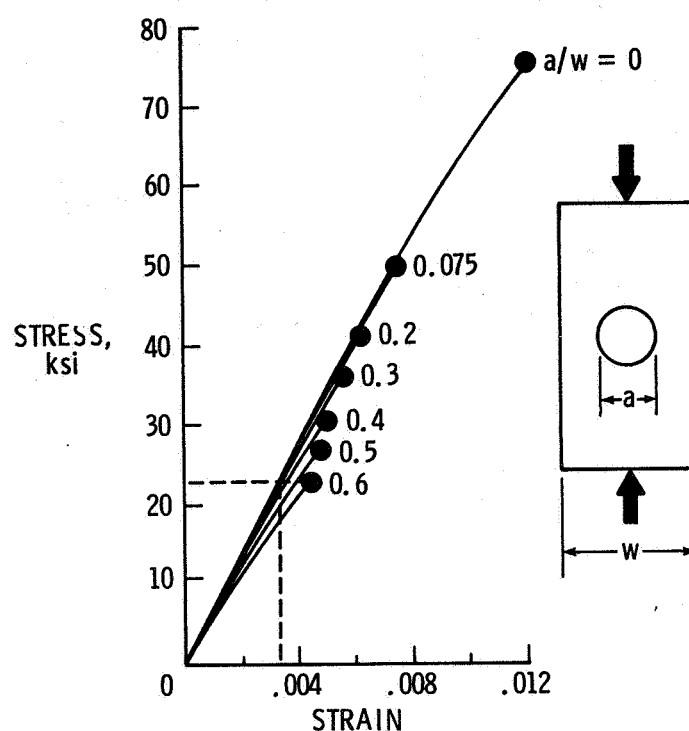

Figure 14

EFFECT OF CIRCULAR HOLES ON COMPRESSION STRENGTH

A comparison of the reduction in strength for a brittle (T300/5208) and tough (T300/BP907) resin system laminate is presented in figure 15 as a function of the hole diameter "a" normalized by the specimen width "w" (ref. 4). The curve faired through the data is a failure prediction base on the point-stress failure criterion proposed by Whitney and Nuismer (ref. 5). The curve is bounded on the top by a net-area notch-insensitive curve and on the botton by a notch-sensitive curve in which failure is assumed to occur when the stress at the hole edge reaches the critical value for an unnotched specimen. The different resin formulations appear to have had no effect on the failure strain for these two orthotropic laminates. The explanation for this apparent paradox in which the tough resin improved the strength of impact damaged specimens (fig. 11) but not open-hole specimens involves understanding the governing failure mechanisms. For impact damage, tough resins improved the performance by suppressing the delamination mode of failure. For open hole specimens as was shown in figure 9, the failure initiation mechanism involves fiber microbuckling and shear crippling of highly stressed material adjacent to the hole. Fiber microbuckling is governed by the stiffness properties of the matrix and fiber and by other factors such as the integrity of the matrix-to-fiber bond. Similar strength reductions for these two material systems with holes occur since the same fiber was used in both laminates and because the two resin systems have similar initial elastic modulus properties.
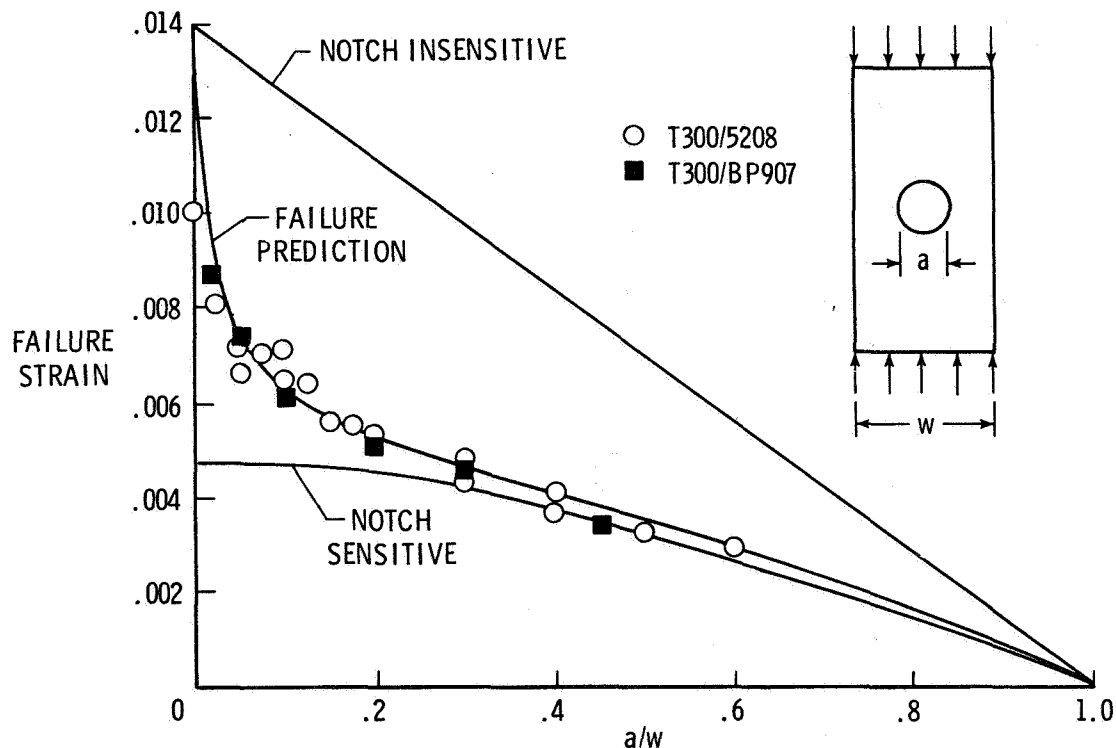

Figure 15

EFFECT OF HIGH STRAIN FIBER ON FAILURE STRAIN OF OPEN-HOLE SPECIMENS

The influence of hole size "a/w" on the failure strain of several quasi-isotropic laminates constructed with selected resin systems and two graphite fiber materials is presented in figure 16. The two theoretical failure curves are point stress failure predictions with the indicated characteristic parameters. The lower theoretical curve is taken from reference 6 and represents the best fit to date for T300/5208 graphite-epoxy. The data appear to group according to fiber reinforcement type with the AS4 fiber laminates exhibiting higher failure strain than T300 fiber laminates. The ultimate tension strains for T300 and AS4 are approximately 0.012 and 0.015, respectively. Recall from figure 15 that laminates with two different resin systems and the same fiber had identical strengths. If as hypothesized, high bending strains in a buckled fiber initiate local failure, then one might expect a higher tension strain fiber to exhibit a higher laminate strength as was observed in this series of tests. Several material and structural properties govern fiber micro-buckling and failure including the fiber extensional and bending stiffnesses and strength and the stiffness and strength properties of the matrix. Theoretically, a high shear modulus property of the resin should also increase the strain at which microbuckling would occur. All of the factors which affect microbuckling and compression strength need to be better understood in order to better tailor material and laminate properties for optimum performance.
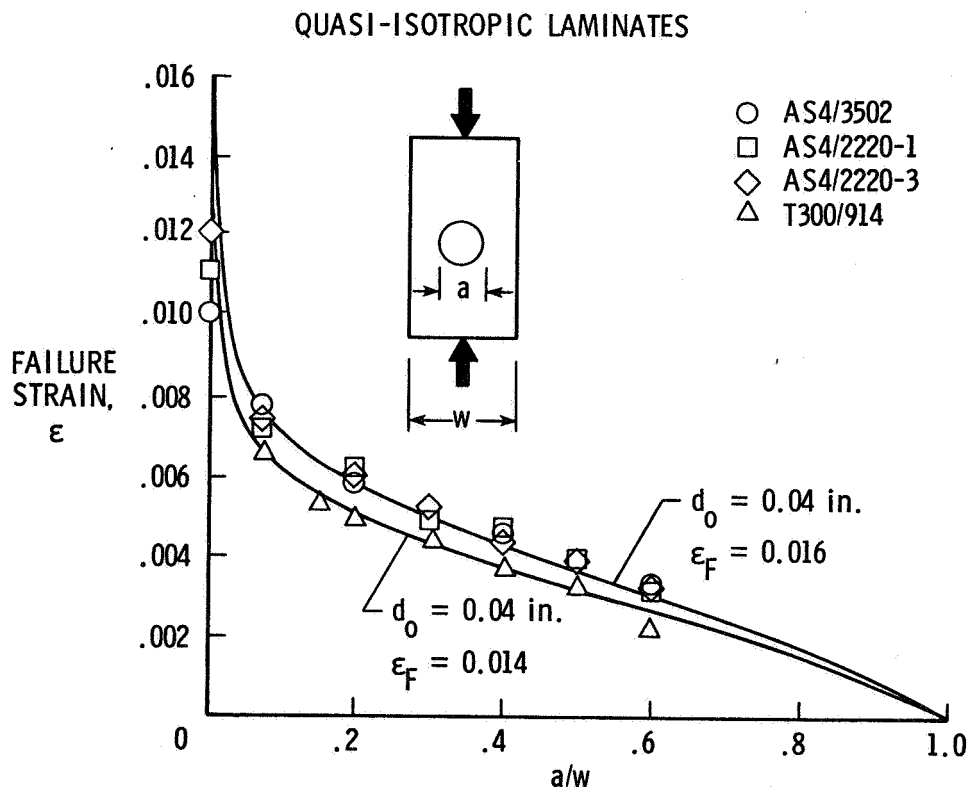

QUASI-ISOTROPIC LAMINATES

Figure 16

OPEN-HOLE VERSUS IMPACT STRENGTH REDUCTION

Designers of composite structures must address the effects of both holes and impact
on design allowables and are interested in the range of conditions in which each
factor governs structural performance. A comparison is made in figure 17 of the
effect of these two types of local discontinuities. The open hole curves are taken
from figure 16 for AS4 and T300 fiber laminates and the impact curve is taken from
figure 12 in which the damage size was determined from C-scan measurements. The
open hole causes the greatest reduction in strength for a/w < .3 (w = 5 inches) and
impact damage causes the greatest reduction for a/w > .3. Additional curves need
to be defined for other plate widths and laminates to establish the generality for
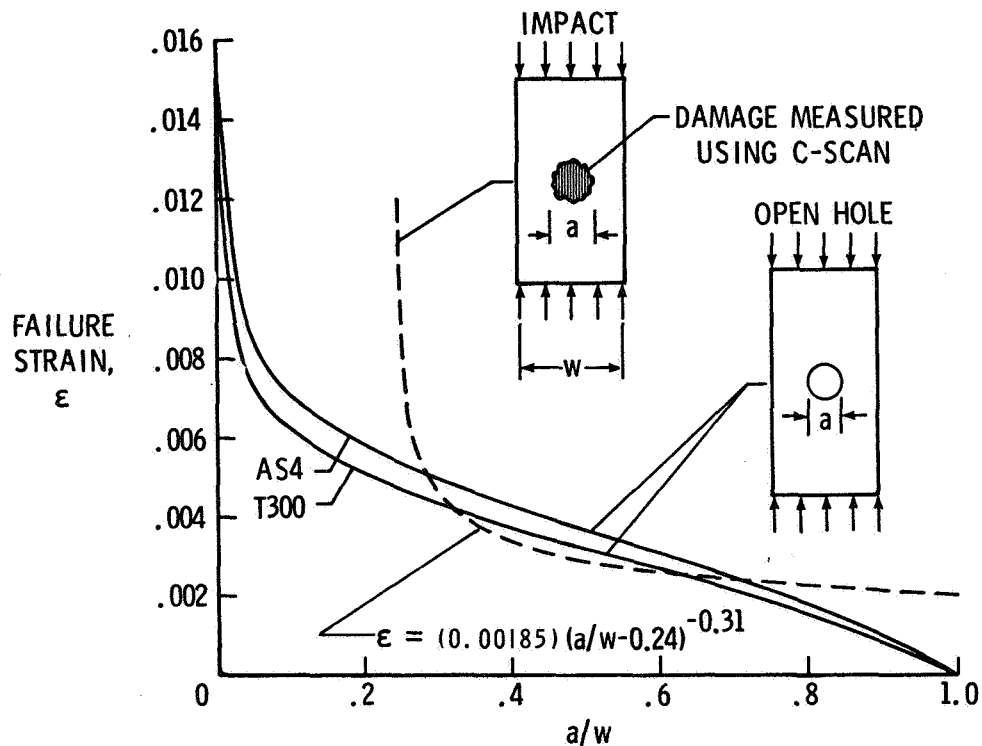design purposes of these findings.

Figure 17

CONCLUSIONS

1. Tough resin system can reduce the size of the damage zone caused by impact.

2. Delamination and shear crippling are two fundamental mechanisms involved in the compression failure of graphite-epoxy laminates.

3. Tough resins (compared to brittle resins) can improve the compression strength of impact-damaged laminates by suppressing the delamination mode of failure.

4. Tough resins do not provide similar improvement in the performance of laminates with open holes where shear crippling is the dominant failure mechanism.

5. Several graphite-epoxy material systems were found to exhibit common strength reductions for equal size impact damage.

6. Higher strain fiber provided increase in failure strain of open hole specimens.

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16. Abstract

Past experience has shown that structural damage and design-based inclusions such as cutouts can reduce significantly the strength of graphite-epoxy laminates. One composite mechanics research activity at the Langley Research Center is to assess and improve the performance of composite structures damaged by impact or containing local discontinuities such as cutouts. Reductions in strength are common to both tension and compression loaded laminates, however, the problem associated with compression performance has been found to be the most illusive to solve. Compression failure involves both shear crippling and delamination modes. In the current investigation, several new graphite-epoxy material systems proposed for improved damage-tolerance were studied. Material parameters included both tough resin formulations and high strain fibers.

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