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CHARACTERISTICS OF LAMINATES WITH DELAMINATION CONTROL STRIPS

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SUMMARY

Tough resin is needed to resist delamination crack propagation. However, modulus often has to be compromised because it is difficult to retain both high modulus and toughness in a matrix material. A potential solution is to use a hybrid system in which tough resin strips are included within a conventional matrix composite. By adjusting the spacing of the tough resin strips, maximum delamination size can be controlled.

In this paper, experimental results for impact damage and subsequent damage propagation in laminates containing tough resin strips obtained at Purdue University, McDonnell Aircraft Company, and the Naval Air Development Center are reported. Plain adhesive strips and fiber-reinforced tough resin composite strips were used in constructing the hybrid laminates. Test results indicated that size of delamination inflicted by impact was confined between the tough resin strips. As a result, significantly increased residual compressive strength was obtained. Impacted laminates containing tough resin strips were also fatigue tested. It was found that these strips reduced the growth of the impact damage area relative to the growth seen in coupons with no tough resin strips.

Damage growth from an open hole under tension fatigue was evaluated using both tough resin strips and glass fiber-reinforced tough resin strips. Unreinforced tough resin strips retarded delamination growth from the open hole, but did not stop matrix cracks growing in the fiber direction. Fiber reinforced tough resin strips did not contain axial delamination growth from the open hole. However, they did act as crack arresters, stopping the through-the-thickness tension crack originating from the hold.

Compression tests comparing conventional graphite/epoxy laminates to hybrid graphite/epoxy laminates which included graphite fiber reinforced tough resin strips showed similar performance under room-temperature-dry conditions, but the hybrid suffered a greater reduction in compression strength during elevated-temperature-wet tests.

INTRODUCTION

The susceptibility of graphite/epoxy laminates to impact induced delamination damage is well known. Damage tolerance for Low Energy Impact Damage (LEID) is a major criterion in aircraft design, limiting composites' design allowables which results in increased weight. The primary motivation for developing new, tough resin systems is to eliminate or reduce delamination crack propagation. Unfortunately, modulus often has to be compromised in order to improve matrix toughness, which results in degraded compressive strength. Interlaminar tensile and shear strength may also be degraded. Costs of the new tough material systems are also an issue, since they are generally significantly more expensive than conventional graphite/epoxy prepregs and may require special processing.

Delamination, in and of itself, is not necessarily undesirable. Although it can lead to widespread damage within a structure, it is a mode of failure which absorbs impact energy. If we were to eliminate delamination entirely, then more impact energy would be absorbed by the fibers, increasing the likelihood of fiber breakage which is a great deal more degrading to laminate strength. Limited amounts of delamination are acceptable in a composite structure. Manufacturing inspection criteria generally allow up to one half inch diameter delaminations in a composite part. In service, composite structure must be able to tolerate impact induced delaminations up to two inches in diameter for their remaining service life without rework or repair. Known fiber breakage, on the other hand, is always repaired.

Composites containing more than two constitutive materials (that is, another material in addition to their basic fiber and matrix) are known as "hybrid composites". The purpose of hybridization is to construct a new material which retains the best features of the constitutive materials while eliminating or reducing their disadvantages. There are several classes of hybrids: *interply* - where alternate layers of different materials are stacked in a regular manner, *intraply* - where fiber tows or strips are mixed within a layer, intimately mixed *hybrids* - where different constituent fibers are mixed in random filament-by-filament basis, and *global* - where a structural element is constructed of various materials, such as glass skins on graphite ribs. Hybrid composite structures offer the potential for improved damage tolerance, damage containment, impact resistance and lower cost. Cost reductions result from the substitution of less expensive constituent materials in non-critical locations.

An example of a successful intraply hybrid composite is laminated skins incorporating crack arrester strips [1]. As applied to graphite/epoxy laminates, within the layers oriented in the primary tension loading direction, graphite fibers are periodically replaced by glass fibers to form crack arrester strips. The glass fiber strips are softer and tougher than the adjacent graphite fiber laminate and thus form a barrier which stops a running through-the-thickness crack. By adjusting the spacing of the crack arrester strips, the size of the initial crack to be stopped can be controlled.

Another practical hybrid concept in the interply hybrid formed by including tough adhesive layers between plies in a laminate [2]. This concept has been successfully applied to reduce impact delamination in graphite/epoxy laminates. The adhesive interfere increases the impact contact area and reduces the transverse shear concentration effect. This together with the toughened interfacial properties, results in less delamination. The disadvantage of including adhesive interlayers is that the adhesive adds weight without increasing the in-plane load bearing capacity of the laminate, reduces the global stiffness and reduces the compressive strength. Moreover, suppression of delamination may result in massive fiber breakage when impact velocity exceeds a certain threshold.

Sun and Norman [3] investigated delamination and residual strength of graphite/epoxy laminates with adhesive strips subjected to transverse impact loading. The use of adhesive strips was conceived as a weight efficient means of providing delamination resistance as opposed to the use of full adhesive layers. It was also felt that the level of delamination could be controlled by the strips so that the beneficial effect of energy absorption through delamination could be gained while preventing delamination growth beyond an acceptable level. They concluded that delamination is substantially controlled by adhesive strips in laminated composites subjected to impact loading. It was shown that fabricated strength of the laminate with adhesive strips was less than the plain laminate, but residual strength after impact at higher velocities was greater for the adhesive strip hybrid. Low velocity impact studies of composite laminates with adhesive strips were also conducted in [4] with similar results.

The purpose of the research reported in this paper is to develop the concept of hybrid laminate design in which delamination is allowed to occur under impact, but its extent is limited and it is prevented from propagating under subsequent loading. A Government/Industry/University team was formed to pursue this effort cooperatively. The interests of each of the three team members were different but complementary to the overall goal of the research. Purdue University was under contract to the Office of Naval Research (ONR) to develop impact analysis and fracture methodologies for composite materials. The Naval Air Development Center (NADC), also under ONR sponsorship, was performing a program in Hybrid Composites with goals of providing a balanced hybrid laminate concept with damage growth resistance under both compression and tension loading. McDonnell Aircraft (McAir) was interested in a composite material with better damage tolerance than AS4/3501-6 but at lower cost than IM7/8551-7. McAir also required a material which could be handled and processed identically to AS4/3501-6.

DAMAGE CONTROL CONCEPT

The proposed damage control concept is to merge the adhesive delamination control strip with the crack arrester strip, Figure 1. This concept is an intraply hybrid, where the base composite material is periodically replaced by strips of fiber reinforced adhesive. The adhesive provides delamination resistance. Experience to date shows that adhesive strips must be spaced roughly 1/2 inch apart to control impact delamination. Fiberglass crack arrester strips are spaced roughly 3 inches apart to stop a running crack. Thus, we propose using two types of fibers as reinforcements in the adhesive. The base fiber is used as a reinforcement to allow the control strip to carry primary in-plane loads and improve the weight efficiency of the concept. Low modulus, high toughness fibers are periodically substituted for the base fiber as reinforcement for the adhesive to provide a through-the-thickness tension crack arrester. For example, our conceptual damage control hybrid might consist of base unidirectional graphite/epoxy plies with strips of 1/4 inch wide graphite reinforced adhesive replacing the graphite/epoxy every 3/4 inch, and S2 glass would replace the graphite fibers in every third adhesive strip.

PROGRAM PLAN

An experimental program was conducted to demonstrate the feasibility of the proposed damage control concept. The objectives were to prove impact damage reduction, crack arrester performance, damage containment under fatigue, and determine any effects of the adhesive strips on elevated-temperature-wet compression strength. Purdue University fabricated test specimens, performed air gun impact tests and post-impact compression tests. McAir performed post-impact spectrum fatigue tests on damaged specimens provided by Purdue. NADC performed tension fatigue tests to verify tension crack arrestment, compression tests to study hygrothermal effects and SACMA standard compression after impact tests.

SPECIMEN PREPARATION

Two custom batches of fiber reinforced tough adhesive prepreg were manufactured by 3M for use in this effort: AF163-2 reinforced with AS4 graphite fibers and AF163-2 reinforced with S2 glass fibers. This material was delivered to Purdue University for test specimen fabrication.

Cross-ply and quasi-isotropic AS4/3501-6 graphite/epoxy test panels were made to study impact characteristics. Some of the panels incorporated glass fiber-reinforced adhesive strips (S2/AF163-2) or graphite fiber-reinforced adhesive strips (AS4/AF163-2) to determine if they could improve the impact characteristics. Panels incorporating FM 1000 adhesive film strips were made to study tension fatigue performance.

Cross-ply Laminate

Six cross-ply 12 by 12 inch AS4/3501-6 graphite/epoxy test panels were made to study residual compressive strength characteristics. The basic layup was $[0_3/90_3/0_3/90_3/0_3]$. Four of the six cross-ply panels incorporated fiber-reinforced adhesive strips. In the test panels with fiber-reinforced adhesive strips, each group of three plies incorporated 1/4 inch wide fiber reinforced adhesive strips in the outside plies. In the following stacking sequence, "a" denotes a ply with adhesive strips, $[0_a/0/0_a/90_a/90/90_a/0_a/0/0_a/90_a/90/90_a/0_a/0/0_a]$. In these plies, the fiber-reinforced adhesive strips were spaced 1/2 inch apart.

Specimens measuring approximately 6 x 1.5 inches were cut from the test panels. The specimens were cut with the 0 degree fiber direction along the longitudinal edge of the specimen. Figure 2 depicts the fiber-reinforced adhesive strip orientation in each specimen.

Specimens were made from graphite/epoxy with adhesive strips and graphite/epoxy with glass fiber-reinforced adhesive strips to evaluate the ability of the adhesive strips to contain damage growing from an open hole during tension-tension fatigue cycling. For these specimens, graphite/epoxy strips were 1.0 inch wide and the alternating adhesive strips 0.5 inch wide. The layup geometry for these laminates was $[0_a/0/0_a/90_a/90/90_a/0_a/0/0_a/90_a/90/90_a/0_a/0/0_a]$ for specimens with FM 1000 adhesive strips and $[(0_a)_3/(90_a)_3/(90_a)_3/(0_a)_3]$ for specimens with S2/AF163-2 strips. Dimensions of the specimen were 3 inches wide, 12 inches long, with a 0.25 inch diameter hole in the center. Each specimen had 1.5 inch long fiberglass/epoxy end tabs on each end which reduced the actual test section by 3 inches. For layers containing adhesive strips, the center line of a graphite/epoxy strip coincided with the center line of the specimen. Specimens of the same dimensions and layup but without adhesive strips were made to generate baseline data.

Quasi-isotropic Laminate

Three quasi-isotropic 12 by 12 inch AS4/3501-6 graphite/epoxy test panels were prepared to study post-impact fatigue characteristics. The basic layup was $[0_2/+45_2/-45_2/90_2]_s$. Two of the three test panels incorporated fiber-reinforced adhesive strips. The following stacking sequence shows which plies contained fiber-reinforced adhesive strips, $[0/0_a/+45/+45_a/-45/-45_a/90/90_a]_s$. In these plies, 1/4 inch fiber-reinforced adhesive strips were spaced 1.25 inches apart. Specimens measuring approximately 6 x 3 inches were cut from the test panels. The specimens were cut with the 0 degree fiber direction along the longitudinal edge of the specimen.

A laminate made from graphite/epoxy with graphite-reinforced adhesive strips was used to evaluate hygrothermal effects on the compressive strength of the hybrid composite. For these specimens, graphite/epoxy strips were 1.5 inches wide, and the alternating graphite-reinforced adhesive strips 0.5 inch wide. The layup for these specimens was $[45_a/0_a/-45_a/90_a]_{3s}$. Alignment of the adhesive strips through the thickness of the laminate was random. Specimens for static compressive strength measured 3.18 inches long and 0.5 inch wide. Coupons for residual compressive strength after impact measured 6.0 inches in length and 4.0 inches wide.

Cross-ply specimens were used to study residual compressive strength characteristics. Some of the specimens were subjected to impact by a 1/2 inch diameter steel ball, while others were impacted with a 7/8 inch diameter steel ball fired from a compressed air gun. In both cases, specimens were clamped one inch on each end in a heavy test stand so that a four-inch span resulted. The specimens were impacted at their center at various velocities. After impact, a small hole (1/16 inch diameter) was drilled through the specimens at the impact center. An X-ray blocking penetrant (1.4 diiodobutane) was injected in the specimens through this hole. X-ray radiographs of the impacted specimens were then taken.

Residual compressive strength tests were performed on the specimens after they were photographed. End tabs were epoxied to the specimens so that a 1.0 inch gage length about the impact center resulted. The specimens were loaded in compression with an MTS machine, and the failure load was recorded. Careful observation of the test and the failed specimens revealed that the specimens did not buckle before failure.

Post-impact Fatigue Tests

Quasi-isotropic specimens were used for fatigue tests. Some of the specimens were subjected to impact with a 7/8 inch diameter steel ball at a velocity of 66 feet per second as described above, and X-ray photographs of the damage were taken.

Fatigue test panels were cycled to two lifetimes of spectrum fatigue (12000 Spectrum Flight Hours (SFH)) or failure, whichever was first. The F/A-18 Wing Root Spectrum was used in fatigue testing. Before fatigue testing, the test panels were bonded with fiberglass/epoxy tabs and aluminum shims using FM 300-2K (a 250^{o}F curing film adhesive) to allow for adequate grip area during testing. The tabbed test specimens were 2.75 inches wide by 10.00 inches long with a test section of 2.75 inches wide by 4.00 inches long. The specimens were gaged with back-to-back axial strain gages.

Tension Fatigue Test

Specimens made from graphite/epoxy with adhesive strips and graphite/epoxy with glass fiber-reinforced adhesive strips were cycled in tension-tension constant amplitude fatigue using a 100 KIP MTS servo-hydraulic test machine. Specimens were cycled at 5Hz at one of three maximum loads, Table 1, with a peak to valley ratio R = 10. Tests were run until failure or a maximum of 1,000,000 cycles. Damage growing from the open hole was assessed periodically using X-radiographs. Zinc-iodide penetrant was used to enhance the damaged region.

Hygrothermal Effects

Static compression testing of the graphite/epoxy coupons containing graphite reinforced adhesive strips was conducted on a 20 KIP Instron Test Machine. These tests were conducted according to the procedure detailed in [5]. Five specimens, both with and without reinforced adhesive strips, were tested at room-temperature-dry (RTD) condition. For an evaluation of hygrothermal effects (elevated-temperature-wet (ETW)), five specimens with and three specimens without reinforced adhesive strips were conditioned to one percent moisture content (by weight) and tested at $200^{\circ}F$.

Compression after Impact (SACMA Standard)

Four specimens both with and without reinforced adhesive strips were tested for residual compressive strength after impact. These tests were conducted according to the procedure detailed in [6]. All impact tests were conducted on a Dynatup Model 8200 drop tower. One specimen from each group was impacted at 3360 in-lbs/inch thickness to get through penetration. The remaining specimens were impacted at the specified energy level, 1500 in-lbs/inch thickness. Ultrasonic C-scan was used to determine damage size. Compression after impact tests were conducted on a Baldwin 60 KIP mechanical test machine.

TEST RESULTS

Residual Compressive Strength Tests

Figure 3 plots residual compressive strength versus impact velocity for those specimens impacted with the one-half inch diameter steel ball, while Figure 4 plots the same for those specimens impacted with the 7/8 inch diameter steel ball. Note that the residual compressive strength was obtained by dividing the ultimate load by the width of the specimen, resulting in units of pounds/inch. This was done to account for the slight differences in width of the specimens.

Figure 5 presents X-ray radiographs of specimens impacted with the one-half inch diameter steel ball at velocities of approximately 56, 69, 98, and 128 feet per second. Figure 6 presents the X-ray radiographs of specimens impacted with the 7/8 inch diameter steel ball at velocities of approximately 20, 26, 33, and 53 feet per second.

The fiber-reinforced adhesive strips are clearly effective in containing delamination. However, the matrix crack on the back face of the laminate due to excessive bending cannot be arrested. These bending cracks could induce local delamination along the crack path.

Post-impact Fatigue Tests

Table 2 lists the quasi-isotropic specimens impacted with the 7/8 inch diameter steel ball that were fatigue tested at McAir. Figure 7 presents X-ray radiographs of the impacted specimens.

The undamaged (no impact) specimens were fatigue cycled at a maximum spectrum compressive strain that corresponded to - 6000 microinches/inch as determined by an initial strain survey. These specimens were inspected ultrasonically before and after 12000 SFH of fatigue. No fatigue-induced damage was detected. The impact damaged specimens were fatigue cycled at a maximum sprectrum compressive strain that corresponded to -4000 microinches/inch maximum strain as determined by an initial strain survey. These specimens were inspected ultrasonically every 1500 SFH for damage growth during fatigue cycling. A plot of damage area versus cumulative spectrum flight hours is given in Figure 8, and ultrasonic NDT A-scan data are presented in Figures 9 through 11. All fatigue testing was done at room temperature. Spectrum fatigue test data are presented in Table 2.

Tension Fatigue Tests

Results show delamination growth between the 0 and 90 degree layers in the baseline laminate, Figure 12, is retarded by adhesive strips, Figure 13. However, the strips had no effect on matrix growing in the fiber direction within a layer. These matrix cracks grew through the strip regions and then served as the site for delamination initiation between the 0 and 90 degree layers beyond the adhesive strips. Figure 14 shows the cycles to failure versus the maximum equivalent strain experienced during fatigue cycling. The use of equivalent strain aids in comparing the performance of the laminates since it compensates for the change in modulus due to the adhesive strips.

With the inclusion of the glass fiber-reinforced strips, there was no reduction in strength when compared with the baseline laminate (124 KIP with glass strips, 117 KIP without). Figure 14 again shows no difference in the overall fatigue lives of the glass-reinforced adhesive interfere and baseline specimens. Using the zinc iodide enhanced X-ray to track damage growth from the notch, it was observed that the glass fiber-reinforced strips did not contain delamination originating from the notch, Figure 15, but did act as a crack arrester for the through-the-thickness crack that originated at the notch.

Hygrothermal Effect

A summary of test results for RTD and ETW conditions is shown in Table 3. No difference is observed in the mean compressive strength at the RTD condition (- 93 KIP for the baseline, and -94 KIP for the specimens containing graphite fiber reinforced adhesive strips). However, the ETW condition has a much greater effect on specimens containing graphite adhesive strips. The mean compressive strength of the baseline specimens was - 80.8 KIP; the mean compressive strength of specimens with graphite adhesive strips was - 51.7 KIP, which is a 36% reduction in strength.

Compression after Impact (SACMA Standard)

Specimens which were impact tested showed that the graphite-reinforced strips contained impact damage better than specimens without the strips, Table 4. The average damage area of specimens with the strips was 2.66 square inches while the average damage area for specimens without the strips was 5.6 square inches. As a result, the compressive strength of the specimens with the strips was greater than for the baseline specimens (-26.1 KIP with strips and -17.9 KIP for the baseline).

DISCUSSION

Results of the air gun impact tests show that at low impact energies there is little or no difference between baseline and fiber-reinforced adhesive strip laminates in either damage area or residual compressive strength. This is because the damage inflicted is smaller than the spacing of delamination control strips. As the impact energy becomes greater, the level of damage increases so that the control strips become active in inhibiting the delamination damage. At higher impact energies the delamination control strip specimens have less damage and higher compressive strength than the baseline. This result was true for both the post-impact compression tests performed by Purdue and the compression after impact test done at NADC. At higher energy impact levels, the back face matrix cracks were not arrested by the adhesive strips and may induce delamination. To reduce this type of delamination, the back face bending crack must be minimized. There are three possible methods for achieving this: using a single ply on the back face (instead of three plies in the present study), using an adhesive sheet beneath the surface ply, or using woven fabric on the surface of the laminate.

Post-impact compression dominated spectrum fatigue testing shows no detrimental effect of the strips on laminate life in undamaged specimens cycled to a maximum spectrum compressive strain of -6000 microinches/inch. Impact damaged specimens cycled to a maximum compressive strain of -4000 microinches/inch clearly showed retardation in delamination growth and increased life for fiber-reinforced adhesive strip specimens over unreinforced specimens.

Constant-amplitude tension fatigue tests of open hole specimens without strips, with adhesive only strips and with S2 glass reinforced strips yielded similar overall fatigue lives. Damage growth within each specimen was different. Under tension loading, the unreinforced strips stopped the delamination growing axially from the open hole, but was not effective against the matrix crack growing axially from the tangent to the hole along the fibers. These cracks grew in the 0 degree ply across the adhesive strip in the adjacent 90 degree layer. Since these cracks occur within the ply, it was not unexpected that the adhesive layer contacting the surface ply only at the ply interface would have little or no effect on this crack. The results from tension fatigue testing of the S2 glass reinforced adhesive strips were a surprise, since in these specimens the glass fiber strips did not stop the axial delamination crack growing from the open hole. The axial glass strips were effective as crack arrester strips in containing the through-the-thickness crack originating from the hole and propagating laterally at final failure. Overall the results of fatigue testing show improvement in performance of damaged laminates under compression fatigue and no degradation in life under tension fatigue.

The undamaged RTD compression strength of plain and graphite fiber reinforced adhesive strip specimens was similar, but the adhesive strip specimens degraded more severely than the baseline in ETW tests. We feel this is because the adhesive is more sensitive to ETW conditions than the resin matrix, and that the adhesive absorbs more moisture than the matrix. Examination of the weight gain data showed that for identical environmental conditioning, the fiber-reinforced adhesive specimens gained more moisture by weight than the baseline, 1.21% versus 1.0%.

At the initiation of this effort, we had only a limited amount of fiber-reinforced adhesive available for testing. Thus, the focus of the tests was on discovering "show-stoppers" to the hybrid damage control concept. We wanted to fabricate and test panels representative of an aircraft skin which included both the graphite-fiber-reinforce delamination control strip and glass-fiber reinforced crack arrester strip. However, after providing the initial batch of AS4/AF163-2 and S2/AF163-2 fiber reinforced adhesive, we were unable to interest any material supplier in providing further quantities of reinforced adhesive for evaluation. The amount of material needed was too large to prepreg by hand but insufficient to warrant the expense and set-up of a limited production run. We were thus unable to test the "full up" damage control hybrid, but from the results of the limited testing reported here feel we have adequately demonstrated the concept.

CONCLUSIONS

Based upon the results of our experimental investigation into the behavior of fiber reinforced adhesive strips to control damage, the following conclusions were reached.

1. The inclusion of fiber reinforced adhesive strips in a laminate yields a hybrid laminate with essentially the same RTD virgin compression strength as the baseline laminate. The presence of adhesive reduces the ETW compression strength compared with the baseline since the adhesive is more sensitive to moisture pickup than the epoxy.

2. The initial degradations of strength after impact of the plain laminate and the fiber-reinforced adhesive strip laminates tested (at lower impact velocities) are similar. At lower impact velocities, the three laminates suffer a similar amount of delamination.

3. Beyond a certain impact velocity, the plain laminate continues to steadily lose its strength as the impact velocity increases. In contrast, the two laminates containing fiber-reinforced adhesive strips are able to retain their strengths at higher impact velocities. The graphite fiber-reinforced adhesive laminate offers almost 50 percent improvement in compression after impact strength versus the baseline laminate.

4. Fiber-reinforced adhesive strips significantly reduce the growth of impact damage in compression dominated spectrum fatigue loading. The strips had no apparent effect on undamaged compression fatigue performance.

5. There is no difference in the overall tension fatigue lives between the baseline laminate, the unreinforced-adhesive strip laminate or the S2-glass fiber-reinforced adhesive strip laminate.

6. Fiberglass reinforced adhesive strips can stop through-the-thickness tension cracks when oriented in the laminate as crack arrester strips, but are ineffective in stopping axially growing delamination cracks under tension fatigue.

7. The proposed damage control hybrid laminate concept offers a practical alternative to tough resins for providing damage tolerant graphite/epoxy structures.

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Captions

Table 1. Test Results for Notched Specimens

Table 2. Spectrum Fatigue Test Data

Table 3. Compression Strength for Specimens Containing Graphite/Adhesive Strips

Table 4. Compression after Impact Test Results

Figure 1. Damage Control Concept employing graphite-reinforced adhesive strips to contain delamination damage and glass-reinforced adhesive strips to contain running tension cracks.

Figure 2. Schematic of a cross-ply specimen. Notice that the thickness is greatly exaggerated.

Figure 3. Residual compressive strength vs. impact velocity for cross-ply laminate impacted with 1/2 inch diameter steel ball.

Figure 4. Residual compressive strength vs. impact velocity for cross-ply laminate impacted with 7/8 inch diameter steel ball.

Figure 5a. X-ray photographs of cross-ply specimens impacted with 1/2 inch diameter steel ball. From left to right the specimen types are: plain graphite/epoxy, graphite/epoxy with S2/AF163-2 strips, and graphite/epoxy with AS4/AF163-2 strips.

Figure 5b. X-ray photographs of cross-ply specimens impacted with 1/2 inch diameter steel ball. From left to right the specimen types are: plain graphite/epoxy, graphite/epoxy with S2/AF163-2 strips, and graphite/epoxy with AS4/AF163-2 strips.

Figure 6a. X-ray photographs of cross-ply specimens impacted with 7/8 inch diameter steel ball. From left to right the specimen types are: plain graphite/epoxy, graphite/epoxy with S2/AF163-2 strips, and graphite/epoxy with AS4/AF163-2 strips.

Figure 6b. X-ray photographs of cross-ply specimens impacted with 7/8 inch diameter steel ball. From left to right the specimen types are: plain graphite/epoxy, graphite/epoxy with S2/AF163-2 strips, and graphite/epoxy with AS4/AF163-2 strips.

Figure 7a. X-ray photographs of quasi-isotropic specimens impacted at 66 feet per second with a 7/8 inch diameter steel ball. The specimens are plain graphite/epoxy.

Figure 7b. X-ray photographs of quasi-isotropic specimens impacted at 66 feet per second with a 7/8 inch diameter steel ball. The specimens shown here are graphite/epoxy with S2/AF163-2 strips.

Figure 7c. X-ray photographs of quasi-isotropic specimens impacted at 66 feet per second with a 7/8 inch diameter steel ball.

Figure 8. Damage growth during spectrum fatigue cycling.

Figure 9. Panels A2 (Left) and A4 not A-scan data.

Figure 10. Panels B2 (Left) and B4 NDT A-scan data.

Figure 11. Panels C2 (Left) and C4 NDT A-scan data.

Figure 12. Baseline laminate.

Figure 13. Adhesive strip laminate.

Figure 14. Equivalent strain versus cycles for baseline, adhesive strip laminate and glass-reinforced adhesive strip laminate.

Figure 15. Laminate with fiber reinforced adhesive.

Table 1. Test Results for Notched Specimens

SPECIMEN TYPE	FATIGUE OR STATIC	MAX. FATIGUE STRESS / STATIC STRENGTH *	CYCLES TO FAILURE **
BASELINE	FATIGUE	0.85	1000000
BASELINE	FATIGUE	0.85	1000000
BASELINE	FATIGUE	0.95	448954
BASELINE	FATIGUE	0.95	250241
BASELINE	FATIGUE	1	25970
BASELINE	STATIC	0.68	1
BASELINE	STATIC	1.05	1
ADHESIVE STRIP	FATIGUE	0.85	513116
ADHESIVE STRIP	FATIGUE	0.85	1000000
ADHESIVE STRIP	FATIGUE	0.95	350761
ADHESIVE STRIP	FATIGUE	0.95	1000000
ADHESIVE STRIP	FATIGUE	1	1000000
GLASS STRIP	STATIC	0.96	1
GLASS STRIP	FATIGUE	0.8	64429
GLASS STRIP	FATIGUE	0.8	225807
GLASS STRIP	FATIGUE	0.8	104699
GLASS STRIP	STATIC	1.04	1

* The static stength for baseline and adhesive strip specimens was determined by tests previously conducted at Purdue University.
Baseline static stength = 117 KSI
Specimens with adhesive strip static strength = 95 KSI
The static stength for the glass strip material was the average of the two specimens presented in this table, 124.5 KSI.

** Tests were conducted to either failure or 1,000,000 cycles, whichever came first.

Table 2. Spectrum Fatigue Test Data

SPECIMEN I.D.	THICK. (inches)	WIDTH (inches)	MATERIAL TYPE	IMPACT DAMAGED	MAXIMUM STRAIN (μin/in)	100 % TLL (lbs)	SPECTRUM FLT. HRS. COMPLETED
A2	0.085	2.850		YES	N/A	N/A	0
A4	0.089	2.851	AS-4/3501-6		-4000	-5,010	3190
A5	0.091	2.859				-7,040	
A6	0.085	2.850		NO	-6000	-6,550	
A7	0.085	2.853				-6,760	
B2	0.081	2.768		YES	-4000	-4,630	
B4	0.080	2.853	AS-4/3501-6			-4,730	
B5	0.088	2.864	WITH			-6,490	
B6	0.085	2.850	S-2/AF163-2	NO	-6000	-7,060	12000
B7	0.084	2.849	STRIPS			-6,830	
C2	0.089	2.853		YES	-4000	-4,610	
C4	0.091	2.847	AS-4/3501-6			-4,730	
C5	0.088	2.845	WITH			-7,120	
C6	0.089	2.847	AS-4/AF163-2	NO	-6000	-7,080	
C7	0.089	2.848	STRIPS			-7,590	

TEST NOTES:

1. ALL SPECIMENS WERE LOADED IN COMPRESSION DOMINATED SPECTRUM FATIGUE USING THE F/A-18 WING ROOT SPECTRUM WRFT01.
2. ALL TESTING WAS PERFORMED AT ROOM TEMPERATURE FOR TWO LIFETIMES OF FATIGUE (12000 SFH) OR FAILURE, WHICHEVER IS FIRST. THE CYCLING RATE WAS 5 HERTZ.
3. ALL SPECIMENS WERE TESTED WITH 3/8 INCH WIDE EDGE SUPPORT BARS TO PREVENT PREMATURE BUCKLING AS SHOWN BY THE TEST SETUP IN FIGURE 1.
4. SPECIMENS CONTAINING IMPACT DAMAGE WERE INSPECTED ULTRASONICALLY EVERY 1500 SFH. SPECIMENS WITHOUT DAMAGE WERE INSPECTED BEFORE AND AFTER 12000 SFH OF FATIGUE TESTING.
5. 100% TEST LIMIT LOAD (TLL) WAS CHOSEN BASED ON AN INITIAL STRAIN SURVEY OF EACH PANEL. EACH PANEL HAD BACK-TO-BACK AXIAL GAGES LOCATED AS SHOWN IN FIGURE 2. SPECIMENS WITHOUT DAMAGE WERE FATIGUE CYCLED AT A 131% TLL THAT CORRESPONDED TO -6000 μin/in MAXIMUM STRAIN AS DETERMINED BY AN INITIAL STRAIN SURVEY. SPECIMENS WITH IMPACT DAMAGE WERE FATIGUE CYCLED AT A 131% TLL THAT CORRESPONDED TO -4000 μin/in MAXIMUM STRAIN AS DETERMINED BY AN INITIAL STRAIN SURVEY.
6. SPECIMEN A2 FAILED STATICALLY DURING AN INITIAL STRAIN SURVEY TO -6000 μin/in. MAXIMUM STRAIN WAS SUBSEQUENTLY CHANGED TO -4000 μin/in FOR ALL OTHER IMPACT DAMAGED SPECIMENS.

Table 3. Compression Strength for Specimens Containing Graphite/Adhesive Strips

SPECIMEN	ENVIRONMENT (RTD OR ETW)	COMPRESSIVE STRENGTH (KSI)
BASELINE	RTD	97.2
BASELINE	RTD	94.7
BASELINE	RTD	85.9
BASELINE	RTD	88.0
BASELINE	RTD	99.0
		MEAN = 93.0
WITH GR/ADHESIVE STRIP	RTD	100.4
WITH GR/ADHESIVE STRIP	RTD	110.0
WITH GR/ADHESIVE STRIP	RTD	75.3
WITH GR/ADHESIVE STRIP	RTD	92.1
WITH GR/ADHESIVE STRIP	RTD	90.2
		MEAN = 94.0
BASELINE	ETW	78.9
BASELINE	ETW	79.8
BASELINE	ETW	83.9
		MEAN = 81.0
WITH GR/ADHESIVE STRIP	ETW	50.0
WITH GR/ADHESIVE STRIP	ETW	62.4
WITH GR/ADHESIVE STRIP	ETW	52.3
WITH GR/ADHESIVE STRIP	ETW	51.0
WITH GR/ADHESIVE STRIP	ETW	42.6
		MEAN = 52.0

Table 4. Compression after Impact Test Results

SPECIMEN	ENERGY LEVEL, IN-LB/IN (THICK.)	DAMAGE AREA, IN*IN	COMPRESSION STRENGTH AFTER IMPACT, KSI	IMPACT DEPTH, IN
BASELINE	1500	3.28	20.3	0.02
BASELINE	1500	8.22	16.1	0.021
BASELINE	1500	5.43	17.3	0.021
BASELINE	3360	5.59	16.9	THROUGH
GRAPHITE STRIP	1500	2.67	28.3	0.013
GRAPHITE STRIP	1500	2.56	24	0.01
GRAPHITE STRIP	1500	2.75	26.2	0.015
GRAPHITE STRIP	3360	3.3	18.4	THROUGH

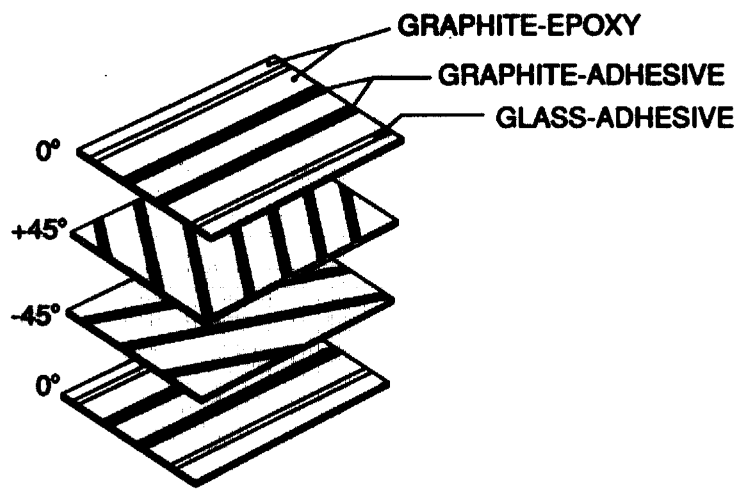
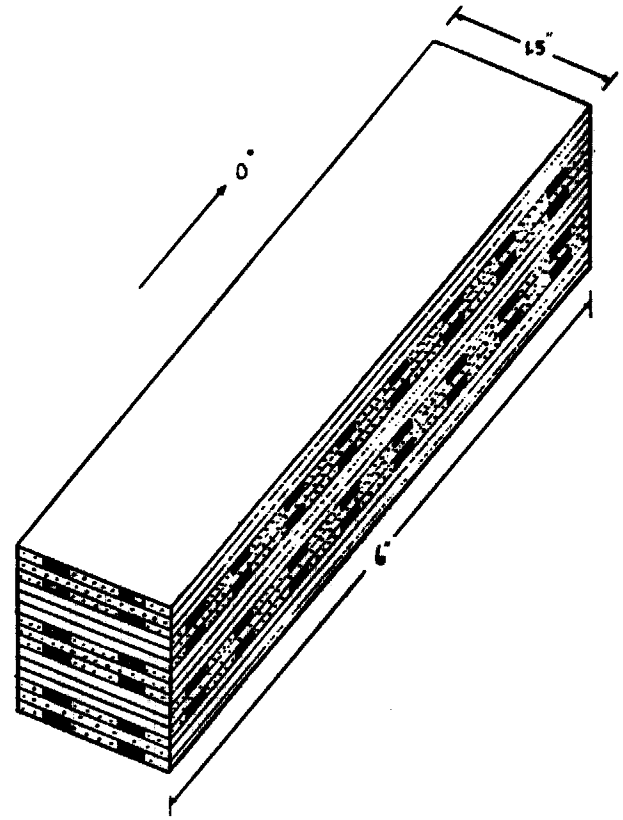


Figure 1. Damage Control Concept employing graphite-reinforced adhesive strips to contain delamination damage and glass-reinforced adhesive strips to contain running tension cracks.



layup $[0_g/0/0_g/90_g/90/90_g/0_g/0/0_g/90_g/90/90_g/0_g/0/0_s]$

1/4 inch adhesive strips with 1/2 inch spacing

Figure 2. Schematic of a cross-ply specimen. Notice that the thickness is greatly exaggerated.

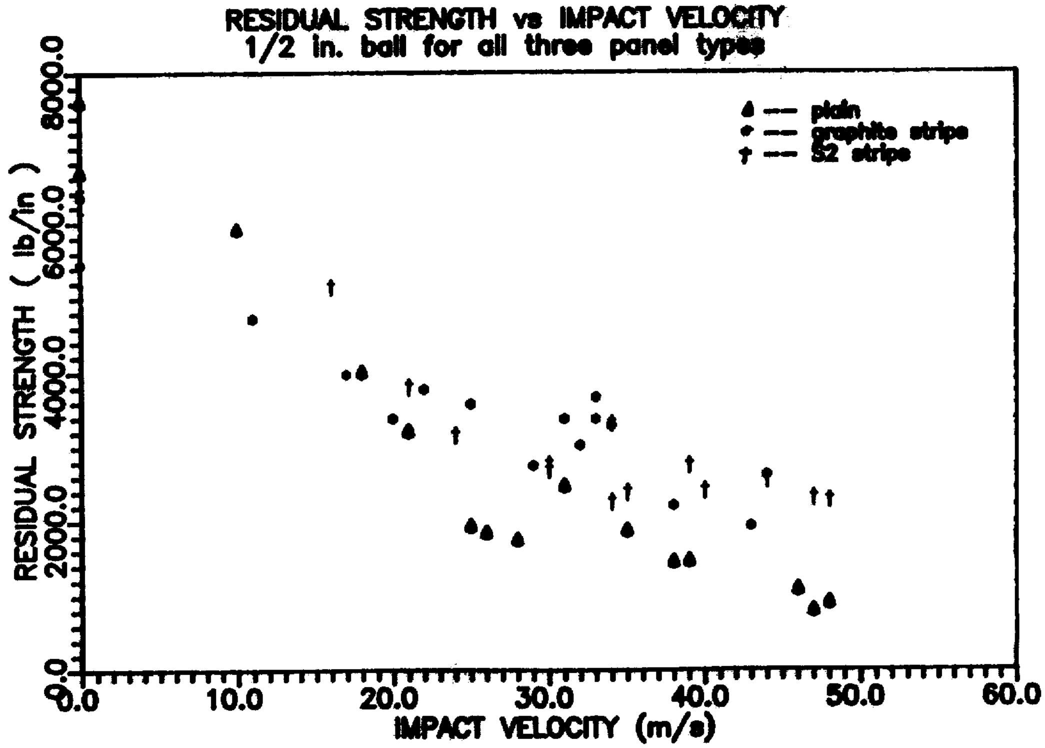


Figure 3. Residual compressive strength vs. impact velocity for cross-ply laminate impacted with 1/2 inch diameter steel ball.

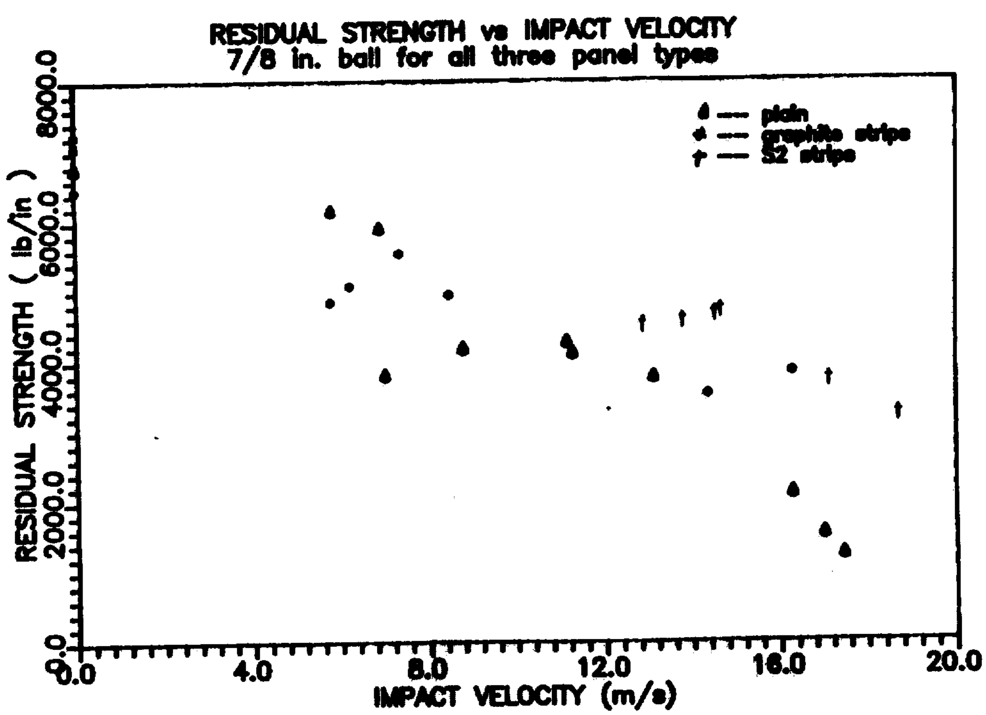


Figure 4. Residual compressive strength vs. impact velocity for cross-ply laminate impacted with 7/8 inch diameter steel ball.

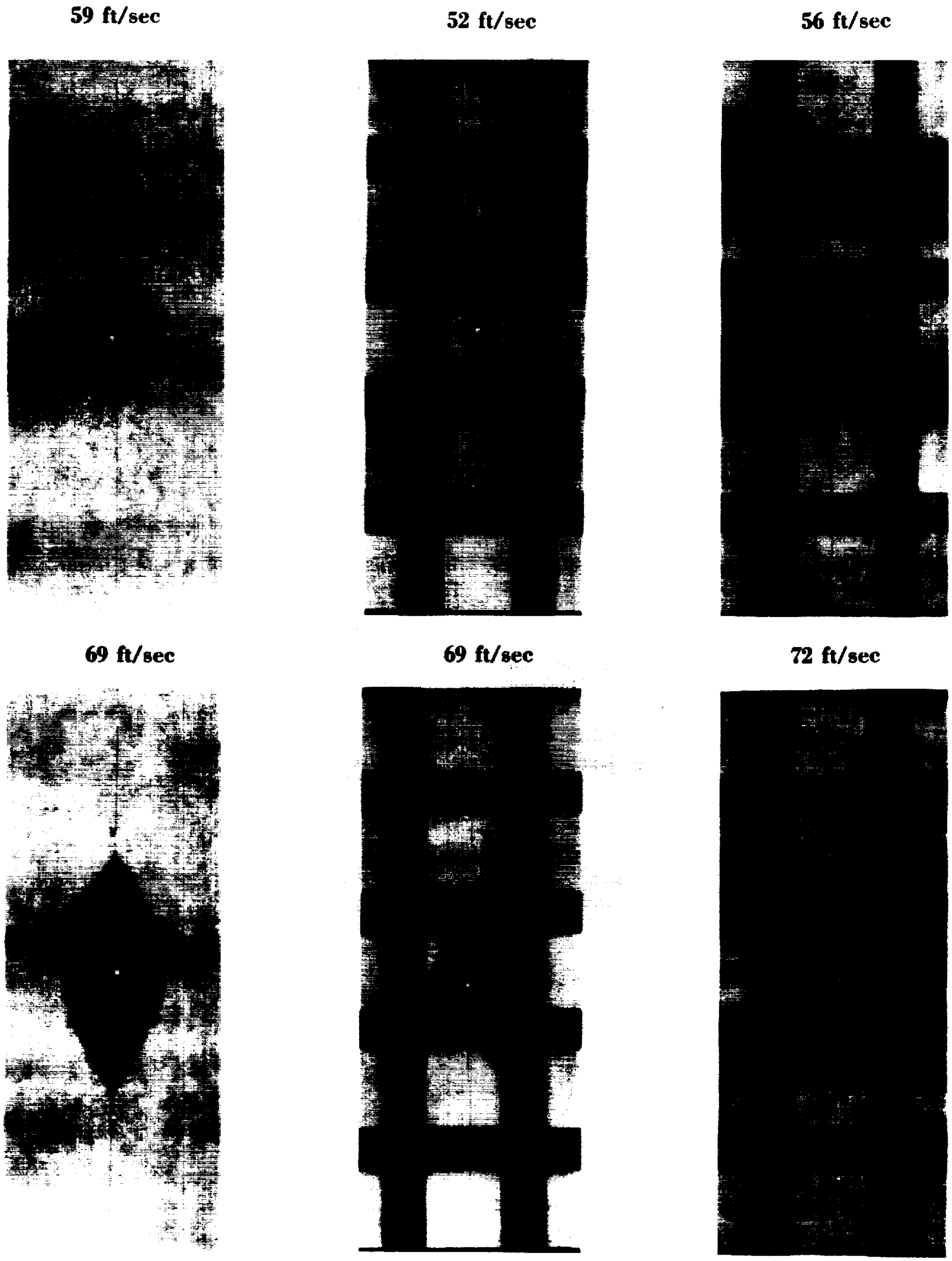


Figure 5a. X-ray photographs of cross-ply specimens impacted with 1/2 inch diameter steel ball. From left to right the specimen types are: plain graphite/epoxy, graphite/epoxy with S2/AF163-2 strips, and graphite/epoxy with AS4/AF163-2 strips.

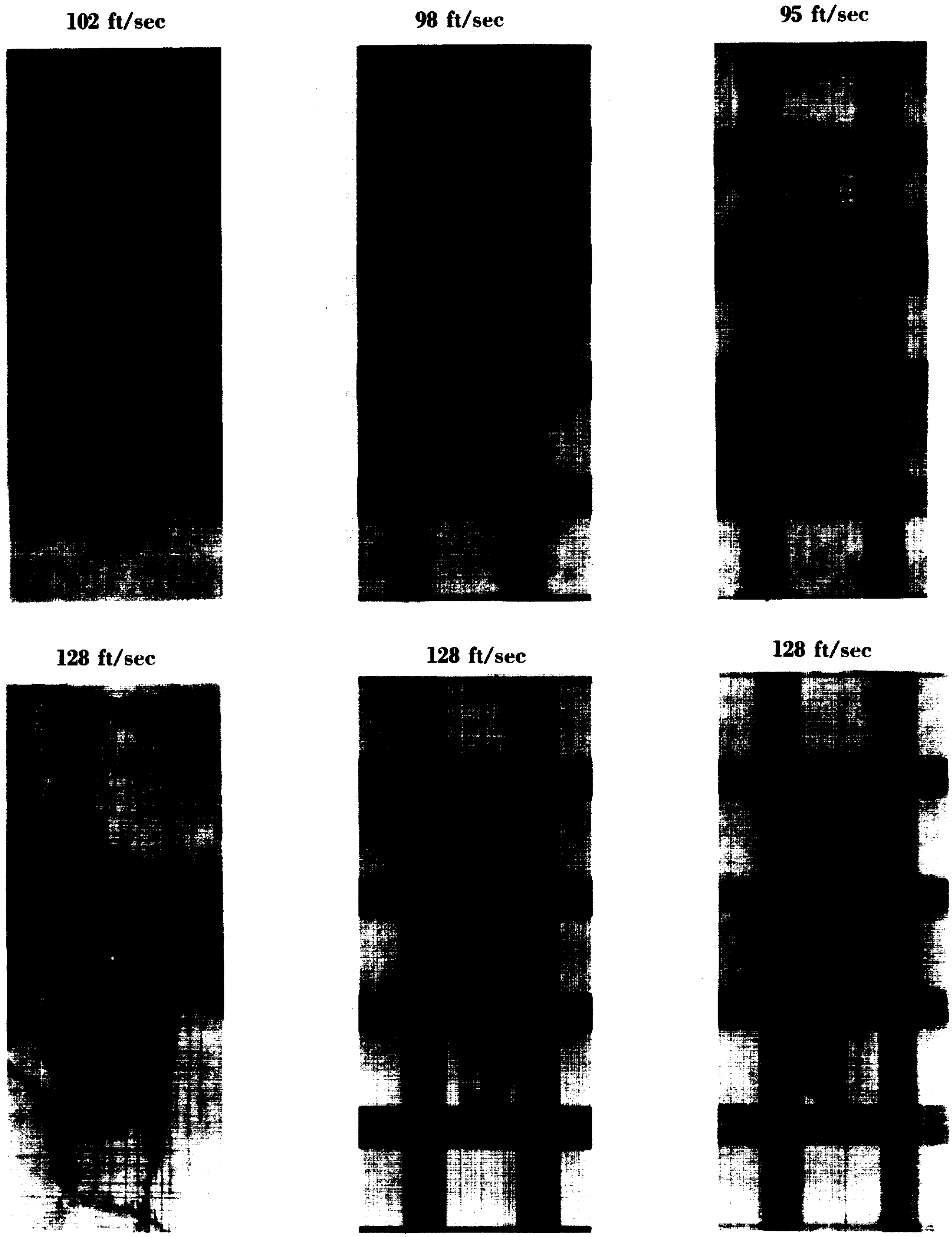


Figure 5b. X-ray photographs of cross-ply specimens impacted with 1/2 inch diameter steel ball. From left to right the specimen types are: plain graphite/epoxy, graphite/epoxy with S2/AF163-2 strips, and graphite/epoxy with AS4/AF163-2 strips.

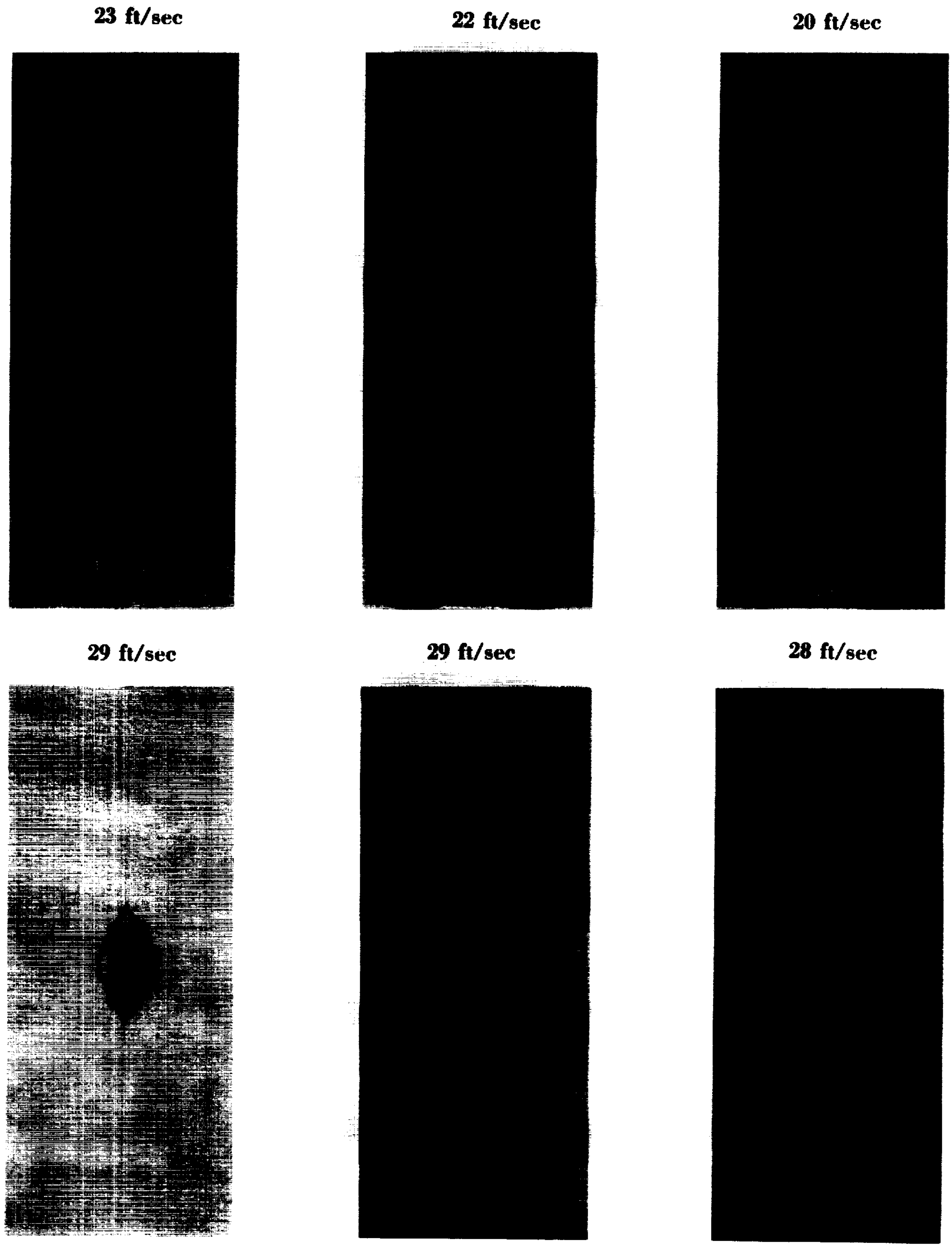


Figure 6a. X-ray photographs of cross-ply specimens impacted with 7/8 inch diameter steel ball. From left to right the specimen types are: plain graphite/epoxy, graphite/epoxy with S2/AF163-2 strips, and graphite/epoxy with AS4/AF163-2 strips.

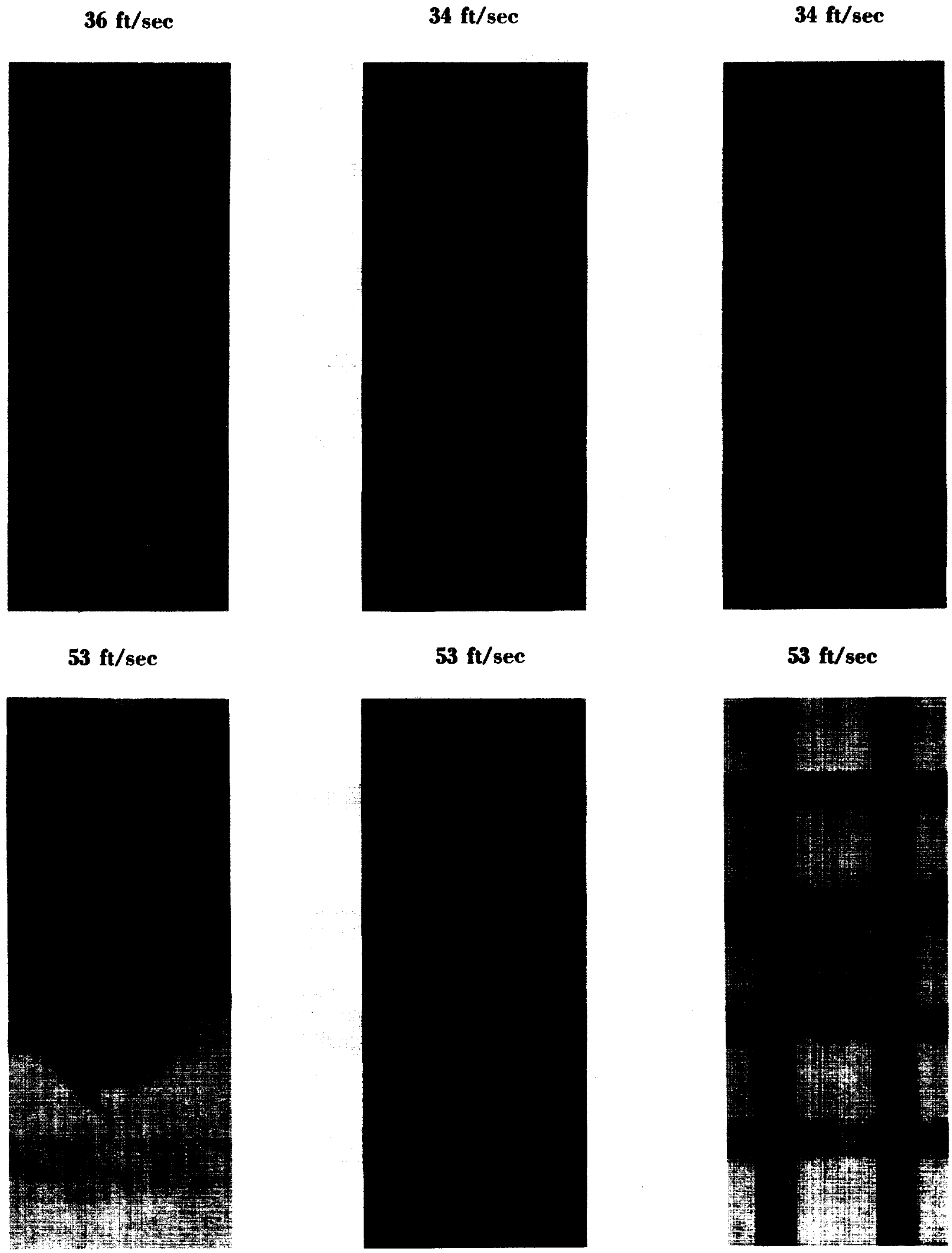


Figure 6b. X-ray photographs of cross-ply specimens impacted with 7/8 inch diameter steel ball. From left to right the specimen types are: plain graphite/epoxy, graphite/epoxy with S2/AF163-2 strips, and graphite/epoxy with AS4/AF163-2 strips.

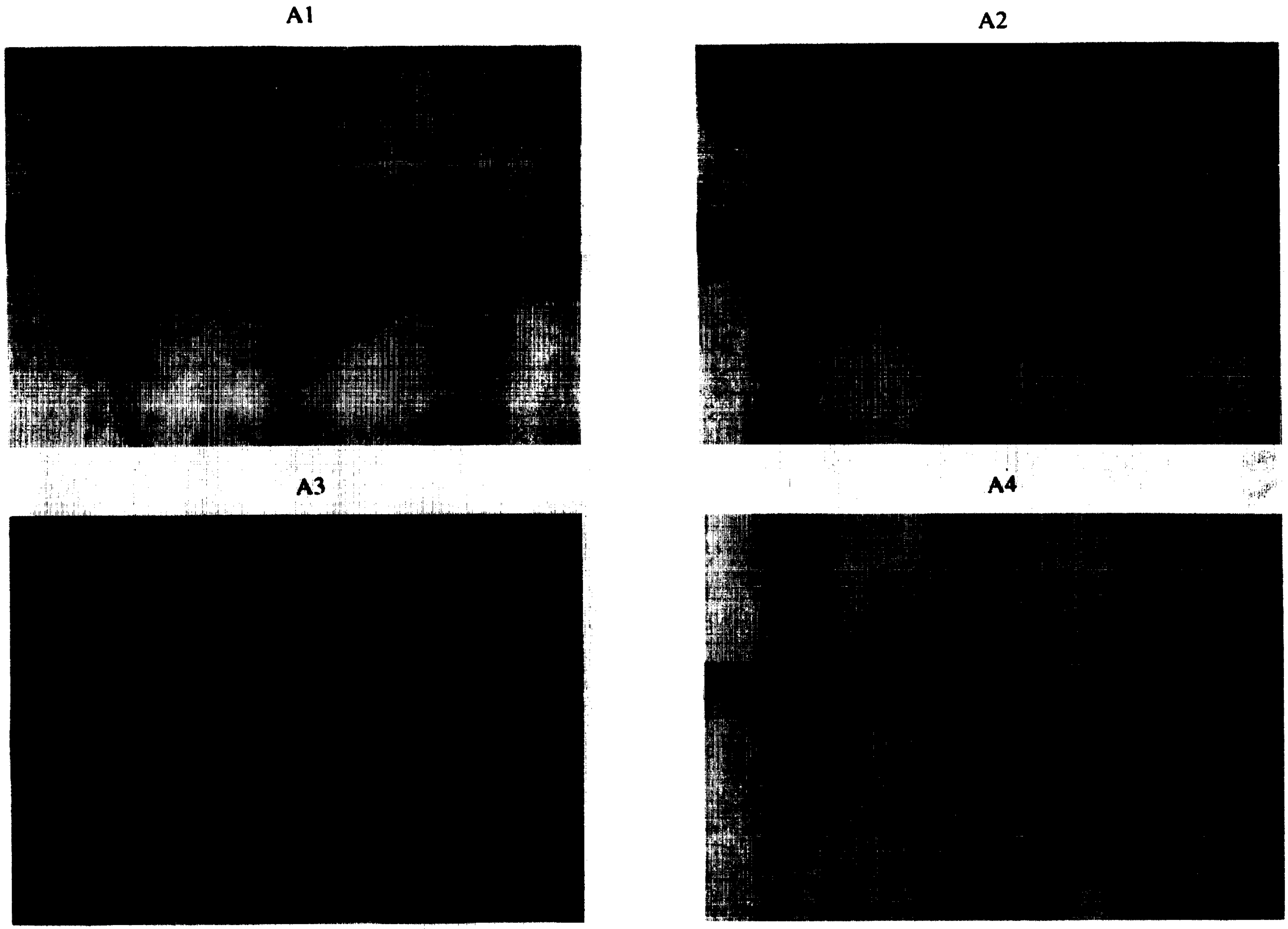


Figure 7a. X-ray photographs of quasi-isotropic specimens impacted at 66 feet per second with a 7/8 inch diameter steel ball. The specimens are plain graphite/epoxy.

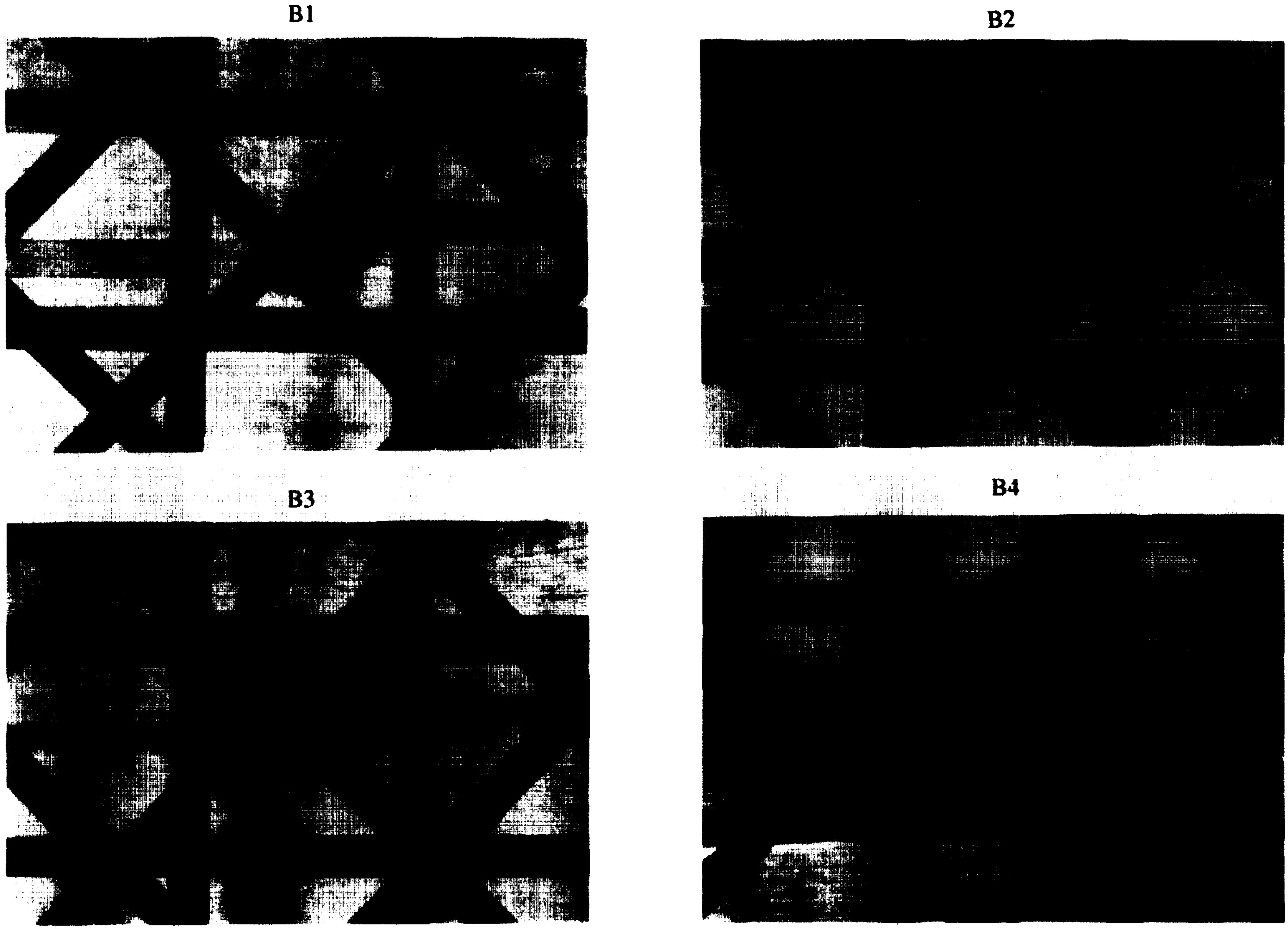


Figure 7b. X-ray photographs of quasi-isotropic specimens impacted at 66 feet per second with a 7/8 inch diameter steel ball. The specimens shown here are graphite/epoxy with S2/AF163-2 strips.

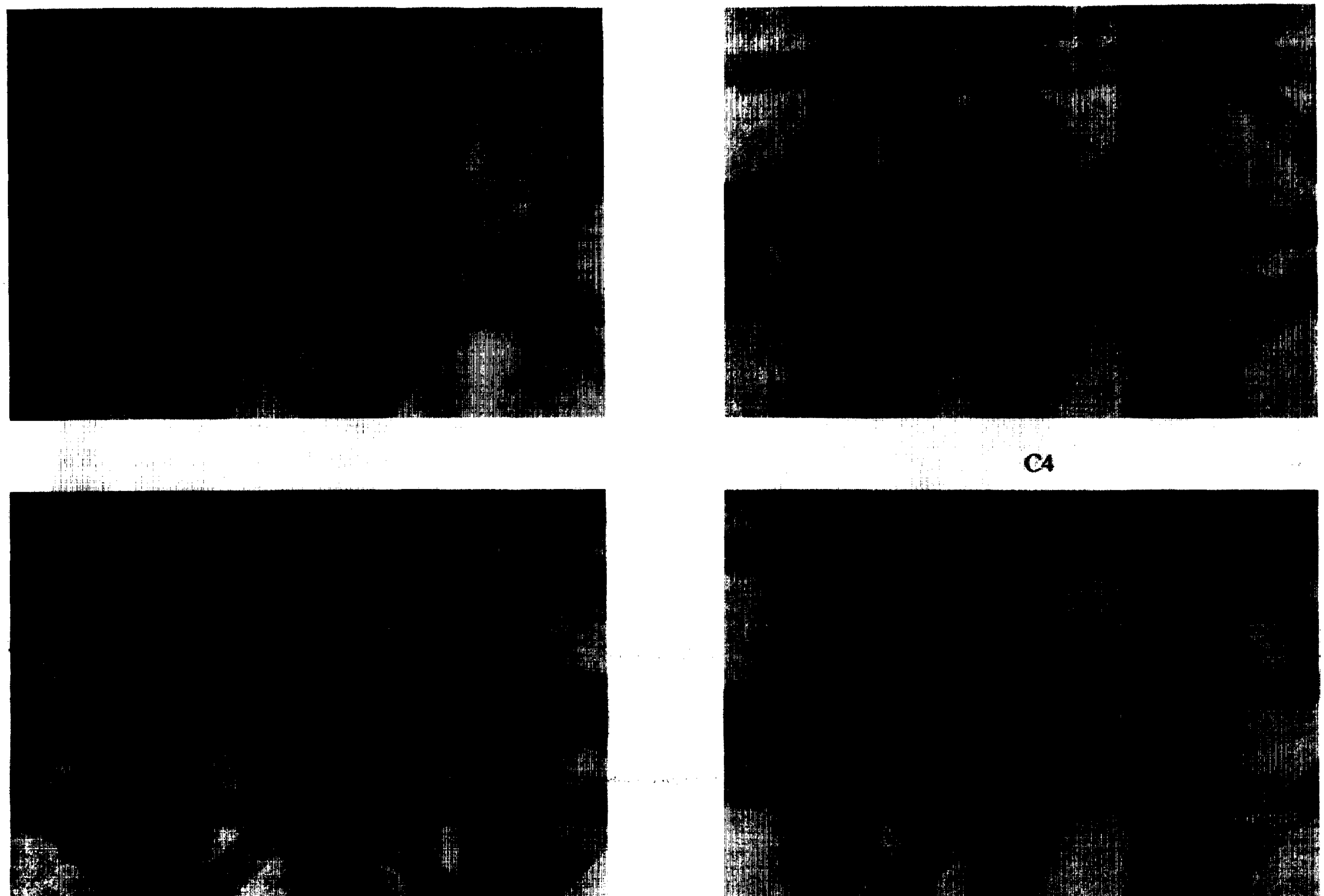
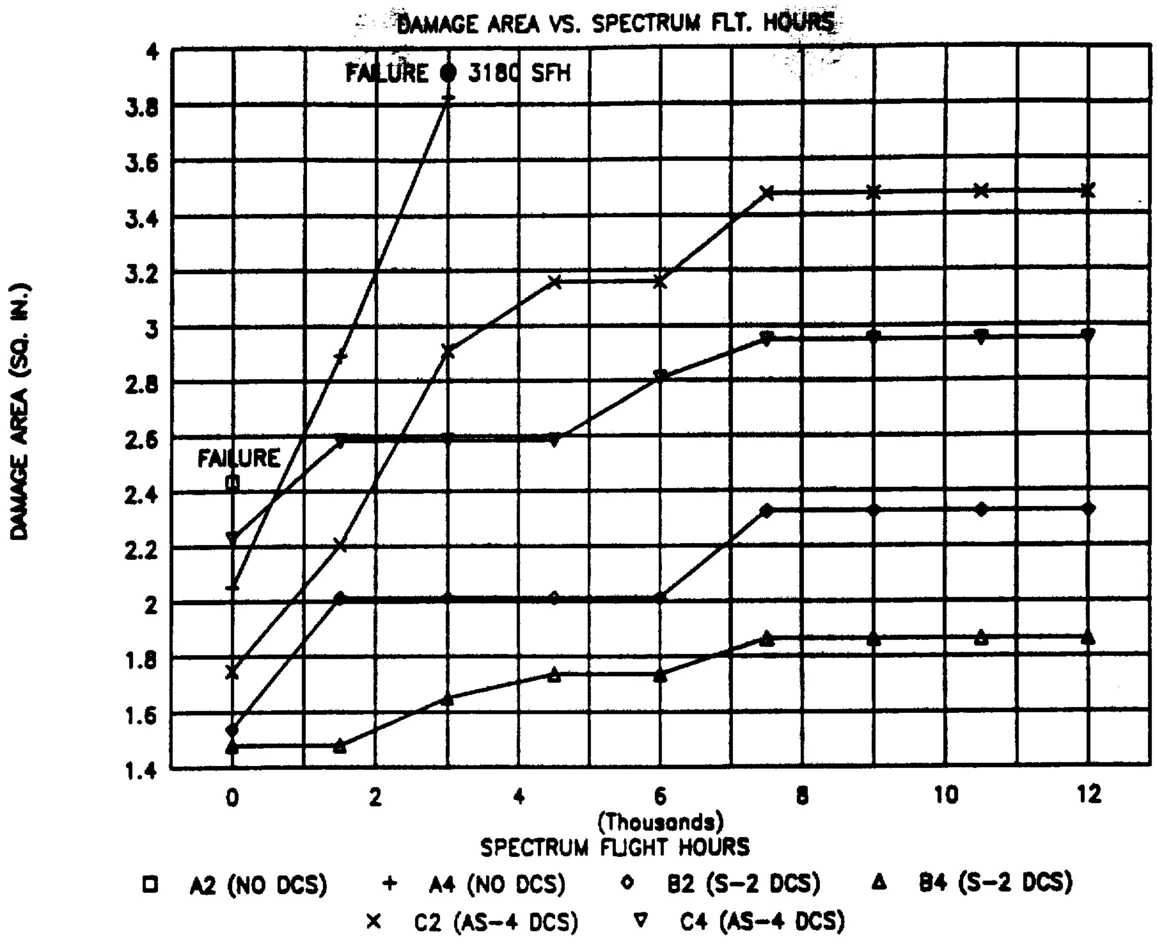


Figure 7c. X-ray photographs of quasi-isotropic specimens impacted at 66 feet per second with a 7/8 inch diameter steel ball.



SPEC. I.D.	MAXIMUM STRAIN (μin/in)	DAMAGE AREA (IN²) @ CUMULATIVE SPECTRUM FLIGHT HOURS								
		0	1500	3000	4500	6000	7500	9000	10500	12000
A2	N/A	2.434	Failed during initial strain survey to -6000 μin/in.							
A4	-4000	2.052	2.893	3.825	Failed at 3180 spectrum flight hours.					
B2	-4000	1.538	2.012	2.012	2.012	2.012	2.325	2.325	2.325	2.325
B4	-4000	1.480	1.480	1.650	1.737	1.737	1.864	1.864	1.864	1.864
C2	-4000	1.747	2.206	2.911	3.160	3.160	3.477	3.477	3.477	3.477
C4	-4000	2.228	2.582	2.582	2.582	2.808	2.948	2.948	2.948	2.948

NOTE:

1. AREAS WERE MEASURED FROM A-SCAN MYLAR TRACINGS USING CUTOUTS FROM A PAPER COPY TO DETERMINE AREAS BASED ON AREA/WEIGHT RATIOS.
2. FATIGUE TEST SPECTRUM USED WAS THE F/A-18 SPECTRUM WRFT01 WITH A MAX./MIN. OF 131%/-42% TLL WHERE 4735 CYCLES = 300 SFH BLOCK.

Figure 8. Damage growth during spectrum fatigue cycling.

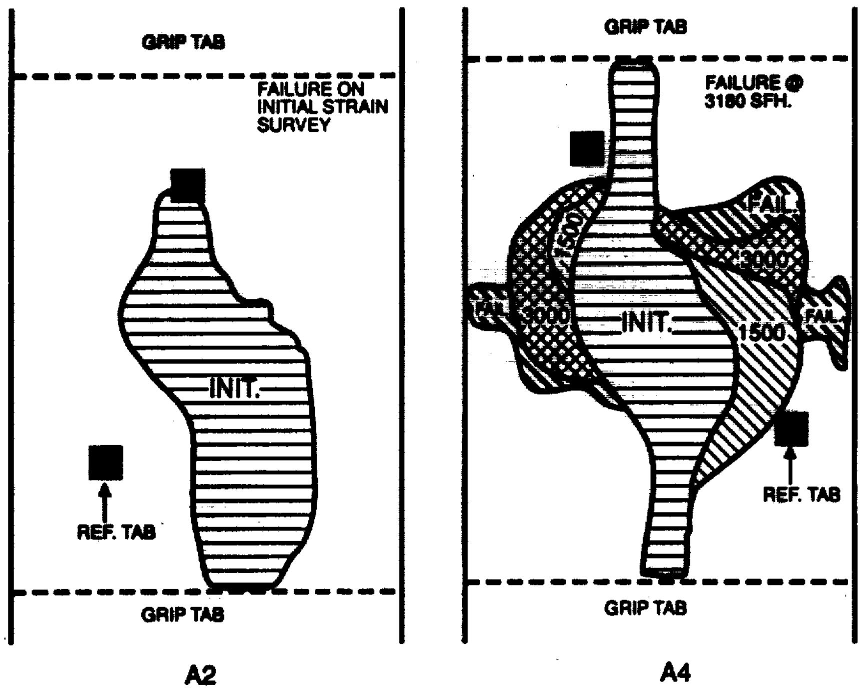


Figure 9. Panels A2 (Left) and A4 not A-scan data.

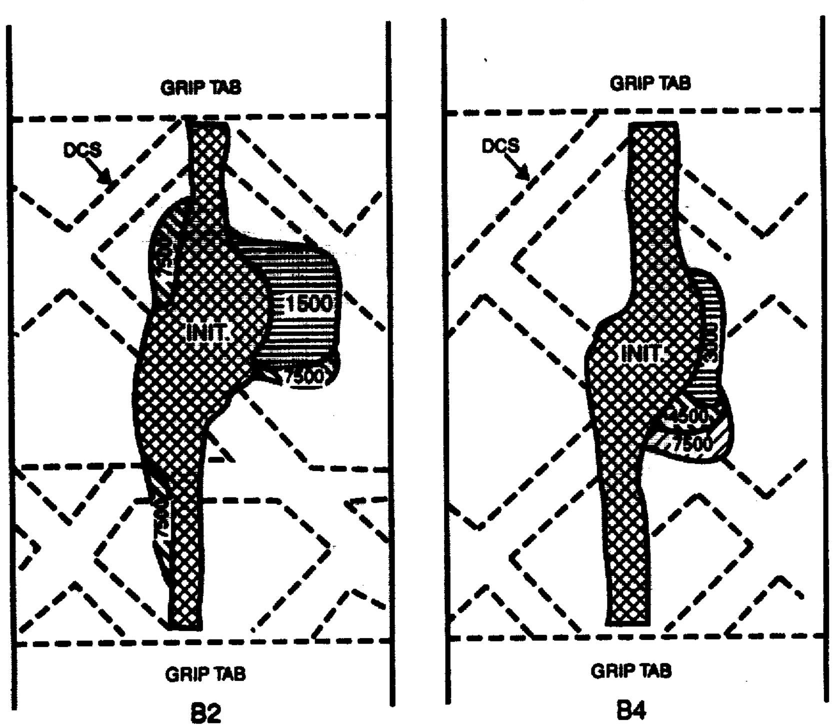


Figure 10. Panels B2 (Left) and B4 NDT A-scan data.

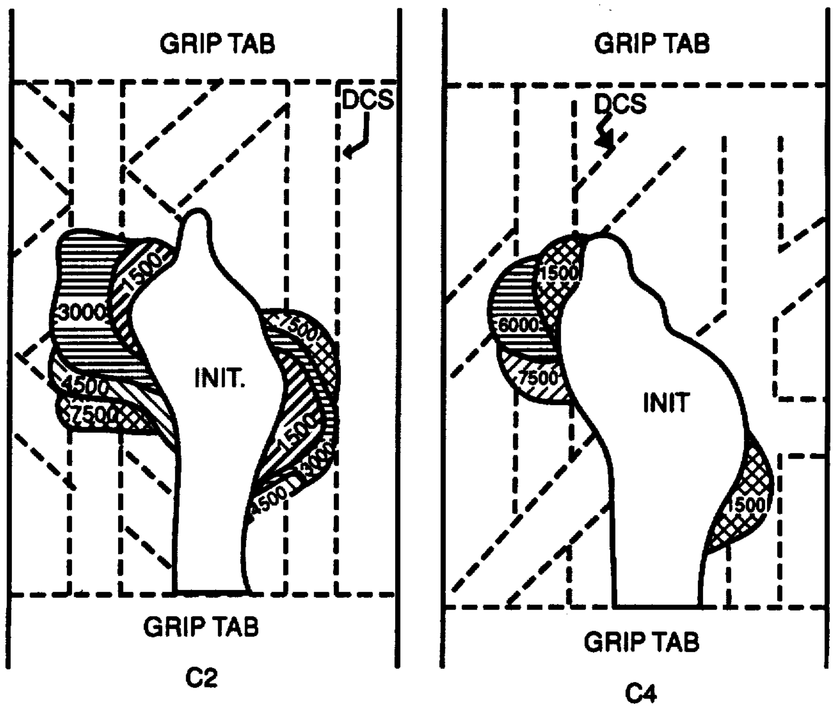


Figure 11. Panels C2 (Left) and C4 NDT A-scan data.

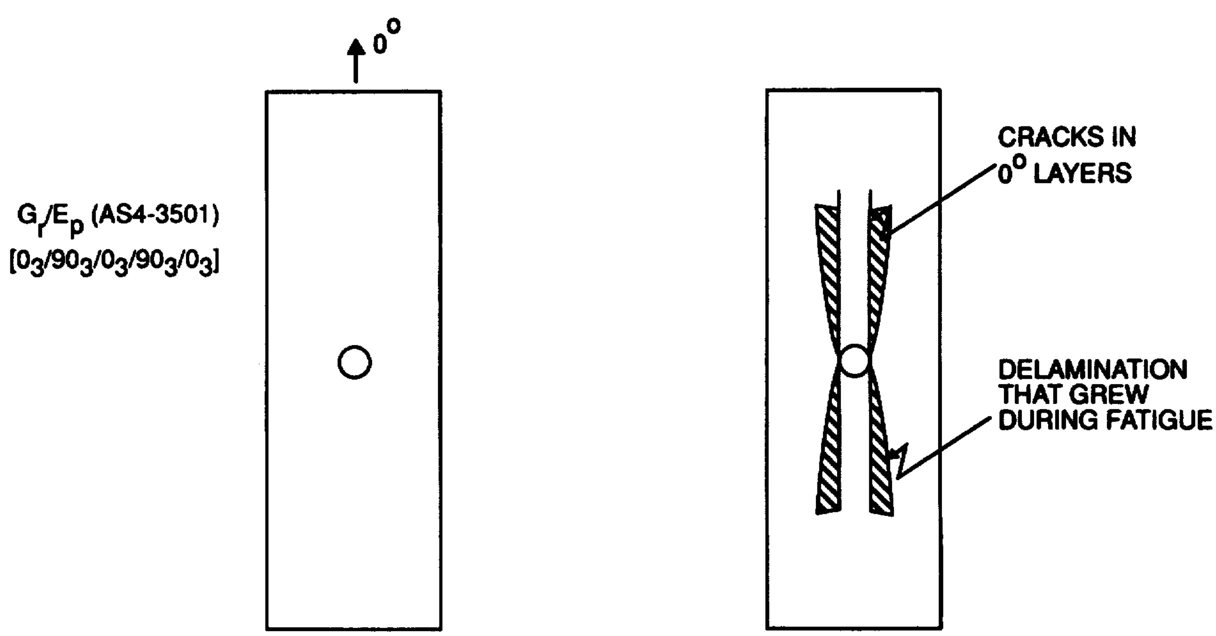


Figure 12. Baseline laminate.

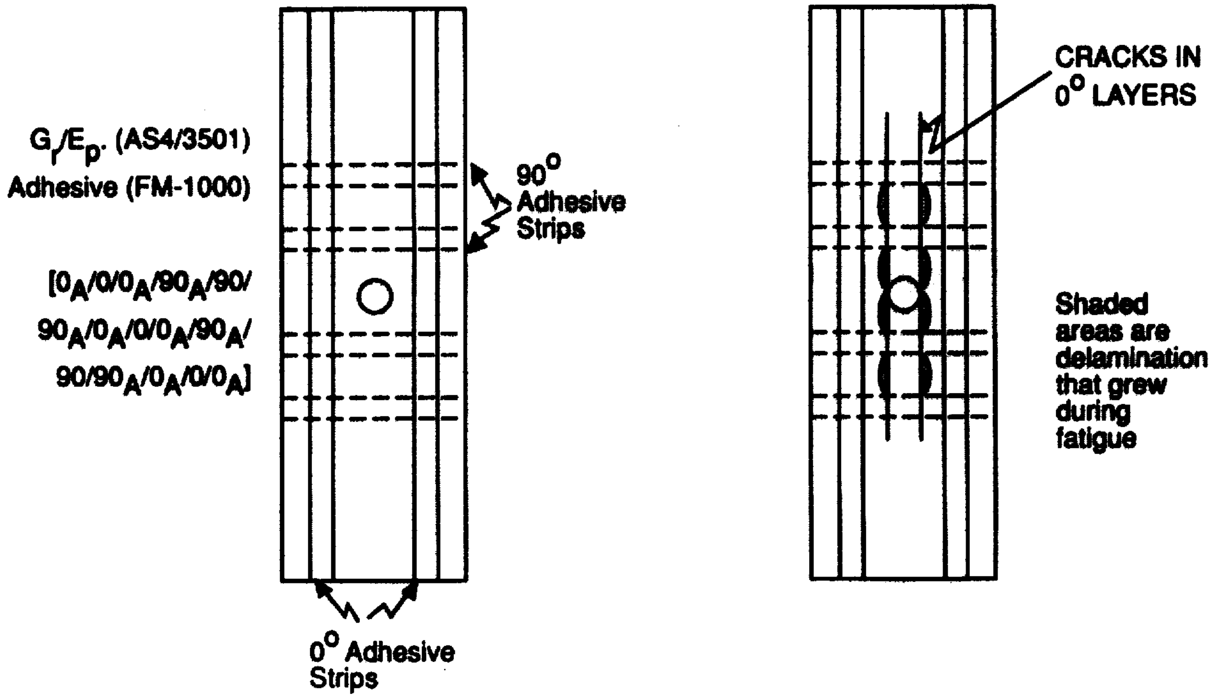


Figure 13. Adhesive strip laminate.

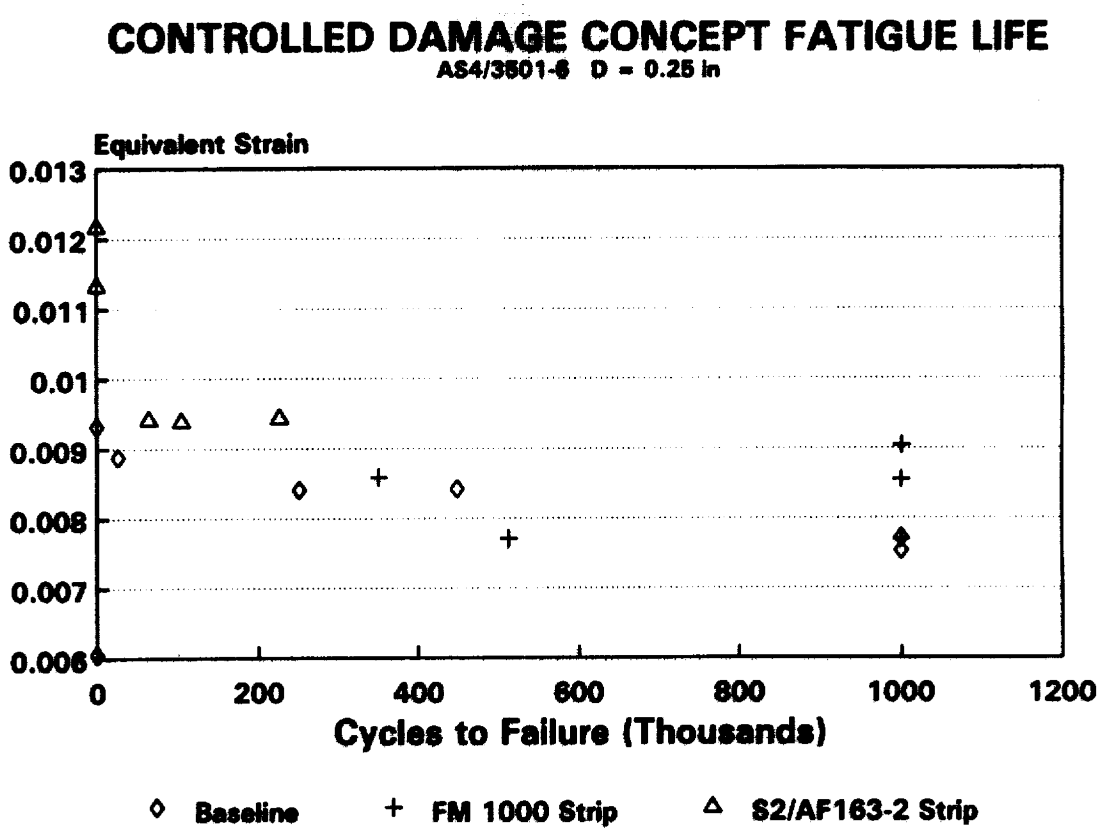


Figure 14. Equivalent strain versus cycles for baseline, adhesive strip laminate and glass-reinforced adhesive strip laminate.

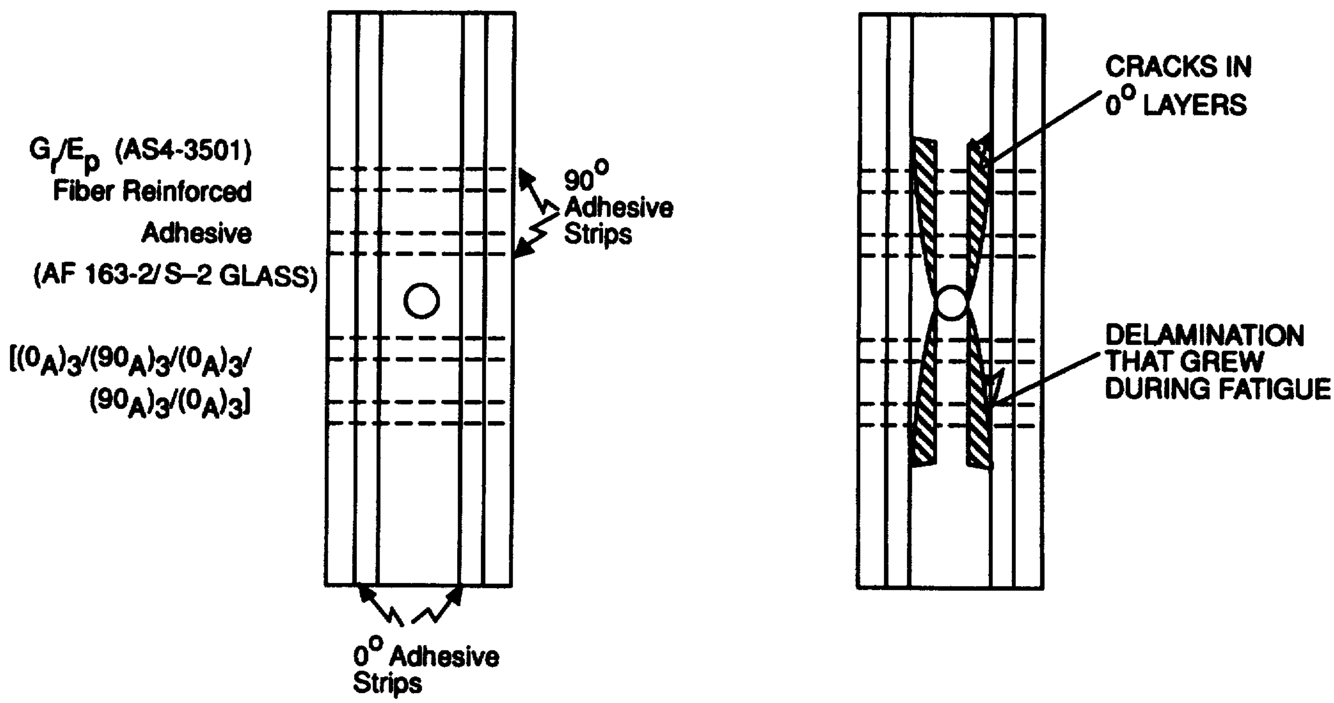


Figure 15. Laminate with fiber reinforced adhesive.

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