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# IMPACT RESISTANCE OF COMPOSITE FAN BLADES

by

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## FOREWORD

This report describes the work accomplished on Contract NAS 3-16763 by the Pratt & Whitney Aircraft Division of United Aircraft Corporation for the Lewis Research Center of the National Aeronautics and Space Administration. The work was initiated 13 July 1972 and completed on 15 May 1973.

Mr. Robert H. Johns of the National Aeronautics and Space Administration Materials and Structures Division was Project Manager.

Mr. Emile J. Premont was the Pratt & Whitney Aircraft Program Manager and Mr. K. R. Stubenrauch was the principal investigator. Mr. A. T. Weaver and Mr. L. A. Davis conducted the spin impact testing. Mr. G. B. Fulton contributed to the analysis of the test results, and Mr. J. L. Preston, Jr. conducted the material quality assurance testing and contributed also to the analysis of test results.

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## SUMMARY

The objective of this program was to determine the ability of current-design composite fan blades to resist damage from foreign object ingestion, to permit evaluating their adaptation to advanced STOL engines. The program was divided into four tasks to achieve this objective: (1) blade fabrication, (2) quality assurance, (3) impact testing, and (4) foreign object damage evaluation.

Ten blades were produced using an existing P&WA design and fabrication procedures previously developed for the composite fan blade. Five blades were constructed of Modmor II graphite fiber/BP-907 epoxy resin, and five blades were made from boron fiber/BP-907 epoxy resin. Both types of blades had a metal leading edge sheath for added protection from foreign object damage.

Quality assurance testing was performed on the composite prepreg tape before it was used for blade fabrication. Various non-destructive inspections including density, ultrasonic, radiography, frequency, and dimensional were performed both during and after completion of blade fabrication to insure their quality before being impact tested.

The composite fan blades were individually impact tested in a spin pit under conditions simulating STOL engine operation. The impact velocity was 216 m/sec (708 ft/sec) with the angle of impact being 30 degrees. Each of the five graphite/epoxy and five boron/epoxy blades were impacted with one of five foreign objects. The impacting objects were ice balls, two sizes of gelatin balls simulating birds, starlings, and gravel. The blade impact was documented by the use of high speed photography and closed circuit television.

Both the graphite/epoxy and boron/epoxy blades behaved similarly under impact, and damage was confined to the impact area. The damage threshold was determined to be between 40g (1.4 oz) and 105g (3.7 oz) slice size for graphite/epoxy blades and between 45g (1.6 oz) and 130g (4.6 oz) slice size for boron/epoxy blades. The composite fan blades had inadequate resistance to foreign object damage when impact tested under simulated STOL engine conditions.

# INTRODUCTION

The successful development of an improved military and commercial air transportation system is dependent upon a continuing effort to advance the present state of technology. The meeting of design requirements for aircraft, such as the STOL, requires the exploration of new materials and the testing of engine components before integration and assembly. The use of composite material for future engines is being evaluated and analyzed. The fiber-reinforced composite fan blades have demonstrated that they now meet many of the design requirements for STOL applications. The composite materials have high strength, high stiffness, and low density. Graphite or boron fiber/resin-matrix composite has the potential for lightweight STOL engine fan blades.

The gas turbine engine is designed to accept foreign object ingestion. The failure of a fan blade can cause a variety of detrimental effects which could endanger the safety of the aircraft. The severity of damage done to fan blades when impacted by a foreign object is related to the size, weight, velocity and impact angle of the object when ingested. The ability of a composite fan blade to withstand impact damage is a critical design requirement.

The objective of this program is to determine the ability of current design composite fan blades to resist damage from foreign object ingestion at STOL low tip speed conditions. To achieve this objective, ten low aspect ratio composite fan blades were manufactured and tested at Pratt & Whitney Aircraft. Existing equipment and techniques were used to fabricate five graphite fiber-reinforced epoxy composite and five boron fiber-reinforced epoxy composite wide-chord fan blades. Both types of blades have a nickel plated stainless steel leading edge protection sheath. The blades were impacted with foreign objects (ice balls, gravel, simulated birds and starlings) in an existing vacuum whirlpit spin test rig. Evaluation of the foreign object damage (FOD) which occurred was complemented by high-speed photographic movies of the testing.

## TEST BLADES

### Description of Blades

The ten blades used for this program were fabricated from an existing design developed previously at Pratt & Whitney Aircraft. The fan blade was designed for a high by-pass ratio gas turbine engine, requiring a 430 m/sec (1410 ft/sec) tip speed, compared to the 244 m/sec (800 ft/sec) tip speed for an advanced STOL blade. The composite fan blade is 81.0 cm (31.9 inches) long and has an airfoil root chord of 23.4 cm (9.2 inches) and tip chord of 30.8 cm (12.1 inches). The maximum thickness tapers from 2.0 cm (.79 inch) at the airfoil root to .7 cm (.27 inch) at the tip. The airfoil is twisted 61 degrees. A completed blade is pictured in Figure 1.

Five blades were manufactured from Modmor II graphite fiber/BP-907 epoxy resin composite prepreg tape. The other five blades were fabricated from .014 cm (5.6 mil) diameter boron fiber/type 104 fiber glass scrim/BP-907 epoxy resin composite prepreg tape. Other than these material differences, construction is identical for the two types of blades. The composite tape is arranged in plies such that the center, or core, of the blade consists of fibers at angles of plus and minus ten degrees from the radial direction, as shown in Figure 2. The core thickness is 40 percent of the airfoil maximum thickness at any radial section. Surrounding the core is a shell of ±40 degree fiber plies. A pair of ±25 degree fiber plies is placed between the core and shell to act as a transition. The fiber orientation used provide the desired strength and vibration characteristics to the blade.

Only the ±10 degree plies are extended into the blade root where they are splayed by ten aluminum wedges, as illustrated in Figure 3. The root configuration is determined by the blade strength requirements. Two titanium pads provide the bearing surfaces of the dovetail root.

The leading edge of the blade is protected from root to tip by a metal sheath. An 0.013 cm (5 mil) thick stainless steel sheath wraps around the leading edge and extends chordwise 8 cm (3 inches) from the edge on the pressure (concave) surface and 3 cm (1 inch) on the suction (convex) surface. The sheath is hard nickel plated for additional protection.

### Composite Material Quality Assurance

The composite prepreg tape received from vendors for use in this program was put through a series of quality assurance tests. Samples from each prepreg tape lot were visually inspected for uniformity of resin content, fiber alignment and fiber spacing. The prepreg tape was also tested for resin content, volatile content, resin flow, and gel time. These properties were determined on the as received tape and repeated after storing samples at ambient conditions for one week. (Note: The prepreg material is normally refrigerated for storage). The procedure used in this quality control work is described in Appendix A.

Samples from the prepreg tape were also used to fabricate panels (composite laminates) from which mechanical test specimens were machined. Longitudinal tensile strength, modulus and short beam interlaminar shear strength were determined at room temperature for each material lot. The composite laminates were also used for fabrication process verification. The cured ply thickness, fiber volume percent, and composite density were determined for each panel. The procedures used for fabrication and test of the laminates are described in Appendix B.

The Modmore II graphite/BP-907 epoxy prepreg tape, received on 30 cm (12 inch) wide continuous rolls, was of acceptable quality. Quality assurance test results are presented in Tables I and II. The boron/BP-907 epoxy prepreg tape, received on 8 cm (3 inch) wide continuous rolls, was also of acceptable quality. Quality assurance test results for this material are shown in Tables III and IV.

**TABLE I**
**QUALITY ASSURANCE TEST RESULTS**
**MODMOR II GRAPHITE/BP-907 EPOXY PREPREG TAPE**

| | Required | Lot #449 Roll #1 | Roll #3 | Roll #5 |
|---|---|---|---|---|
| Resin Content - Weight% | 38-42 | 38.3 | 39.7 | 40.2 |
| Volatile Content - As Received - Weight% | < 2 | .62, .55 | .38, .46 | .42, .52 |
| Volative Content - After One Week - Weight% | - | .49, .49 | .60, .53 | .47, .47 |
| Resin Flow - As Received - Weight% | 9-18 | 12.4, 11.2 | 12.9, 12.5 | 12.4, 12.4 |
| Resin Flow - After One Week - Weight% | | 10.8, 10.4 | 11.2, 11.2 | 10.4, 11.1 |
| Gel Time - As Received - Minutes | - | 83.2 | 83.1, 91.8 | 89.2, 83.4 |
| Gel Time - After One Week - Minutes | | 67.4, 75.2 | 77.4 | 84.2 |

**TABLE II**
**QUALITY ASSURANCE TEST RESULTS**
**MODMOR II GRAPHITE/BP-907 EPOXY LAMINATES**

| | Lot #449 Roll #1 | Roll #3 | Roll #5 |
|---|---|---|---|
| **Longitudinal Tension** | | | |
| Panel Code | FM | FN | FO |
| Cured Ply Thickness - cm/ply (mils/ply) | .019(7.3) | .018(7.0) | .018(7.1) |
| Density-g/cc | 1.48 | 1.48 | 1.48 |
| Fiber Content - Volume % | 56 | 57 | 56 |
| Resin Content - Volume % | 41 | 40 | 41 |
| Void Content - Volume % | 3 | 3 | 3 |
| Strength - GN/m$^2$(10$^3$ psi) | 1.30(189), 1.24(180), 1.21(176) | 1.29(187), 1.13(164), 1.25(182) | 1.20(174), 1.26(183), 1.14(166) |
| Modulus - GN/m$^2$(10$^6$ psi) | 146(21.2), 150(21.8), 143(20.8) | 141(20.4), 153(22.2), 150(21.7) | 142(20.6), 142(20.6), 135(19.6) |
| **Short Beam Interlaminar Shear** | | | |
| Panel Code | FQ | FR | FS |
| Cured Ply Thickness - cm/ply (mils/ply) | .018(7.2) | .018(7.1) | .018(7.2) |
| Density - g/cc | 1.47 | 1.47 | 1.47 |
| Fiber Content - Volume % | 55 | 58 | 58 |
| Resin Content - Volume % | 42 | 38 | 37 |
| Void Content - Volume % | 3 | 4 | 5 |
| Strength - GN/m$^2$(10$^3$ psi) | .0820(11.9), .0814(11.8), .0834(12.1) | .0848(12.3), .0855(12.4), .0903(13.1) | .0779(11.3), .0814(11.8) .0800(11.6 |

**TABLE III**
**QUALITY ASSURANCE TEST RESULTS**
**BORON/BP-907 EPOXY PREPREG TAPE**

| | Required | Lot #257 | Lot #259 | Lot #265 |
|---|---|---|---|---|
| Resin Content - Weight % | 30-34 | 31.9 | 31.8 | 33.1, 33.4 |
| Volatile Content - As Received - Weight % | < 2 | .36, .39 | 1.10, .54 | .28, .20 |
| Volatile Content - After One Week - Weight % | - | .12, .16 | .33, .30 | .21, .18 |
| Resin Flow - As Received - Weight % | 9-18 | 14.6, 14.6 | 17.0 | 21.4, 21.1 |
| Resin Flow - After One Week - Weight % | - | 4.8, 4.9 | 16.8, 16.8 | 17.8, 17.2 |
| Gel Time - As Received - Minutes | - | 70.0, 73.0 | 84.3 | 74.8, 78.1 |
| Gel Time - After One Week - Minutes | | 71.5, 70.8 | 77.8, 79.5 | 70.0, 73.0 |

**TABLE IV**
**QUALITY ASSURANCE TEST RESULTS**
**BORON/BP-907 EPOXY LAMINATES**

| | Lot #257 | Lot #259 | Lot #265 |
|---|---|---|---|
| **Longitudinal Tension** | | | |
| Panel Code | FP | FV | GD |
| Cured Ply Thickness - cm/ply (mils/ply) | .019(7.6) | .017(6.7) | .020(7.8) |
| Density - g/cc | 1.82 | 1.94 | 1.87 |
| Fiber Content - Estimated Volume % | 46 | 51 | 44 |
| Strength - $GN/m^2(10^3 psi)$ | 1.25(182),1.32(192),1.44(209) | 1.36(198),1.36(198),1.37(199) | 1.42(206),1.16(168),1.29(187) |
| Modulus - $GN/m^2(10^6 psi)$ | 213(30.9),204(29.6),210(30.5) | 221(32.0),215(31.2),218(31.7) | 220(31.9),213(30.9),200(29.0) |
| **Short Beam Interlaminar Shear** | | | |
| Panel Code | FT | FW | GC |
| Cured Ply Thickness -cm/ply (mils/ply) | .016(6.4) | .017(6.7) | .020(7.9) |
| Density - g/cc | 1.99 | 1.94 | 1.86 |
| Fiber Content - Estimated Volume % | 54 | 51 | 43 |
| Strength - $GN/m^2(10^3 psi)$ | .105(15.3),.105(15.3),.103(15.0) | >.108(15.7)*,>.106(15.4)*, >.109(15.8)* | >.0945(13.7)*,>.0952(13.8)*, >.0938(13.6)* |

* Failed in tension

## Blade Fabrication Procedure

The composite fan blades fabricated for use in this program were produced using techniques equipment developed previously by Pratt & Whitney Aircraft. There were only minor modifications to and improvements upon the established procedures. The composite materials used in this program required that new ply templates be made because of the thinner cured-ply thickness. The new ply shapes were computer generated.

Fabrication procedures are identical for both the graphite/epoxy and boron/epoxy fan blades. The first step in the blade fabrication is to trace the ply shapes from templates onto the prepreg tape, maintaining the proper fiber orientation for core, shell, and transition plies. The plies are cut from the tape using scissors or razor blades. Tvpical plies are shown in Figure 4. After the plies are cut they are ready for lay-up on the molding die. The ten aluminum root wedges must be prepared for lay-up by grit blasting and chemically cleaning the surfaces. The wedges are then given a thin coating of BP-907 epoxy resin, and then oven dried.

Plies and wedges are layed-up on the convex surface of the molding die maintaining the proper sequence and position. A vacuum bag is intermittently used during and upon completion of the lay-up to debulk the ply lay-up. The die side plates, end plates, and punch are then assembled, and the die is loaded into a hydraulic press. The mold is gradually closed using a maximum pressure of 5.34 $MN/m^2$ (775 psi) as the punch and die are heated by steam to 422°K (300°F). Temperatures are read from thermocouples placed within the blade lay-up. The temperature is increased to 450°K (350°F) and held for two hours. The pressure is then reduced and the blade is held for an additional two hours at 450°K, before a slow cool to room temperature. A blade is shown in the molding die in Figure 5.

The flash is removed from the blade edges, and the blade is put through a series of nondestructive inspections. The blade tip and root are trimmed, the root area is roughened and cleaned in preparation for root pad bonding. The titanium pads are grit blasted and chemically cleaned. RMI-380 adhesive is applied to the blade and pad surfaces to be bonded. The pads are positioned on the blade root, the assembly is clamped in a holding fixture, and the adhesive is allowed to cure for 24 hours at room temperature. The blade root is then finish machined by conventional methods.

The stretch-formed .013 cm (5 mil) thick stainless steel sheath is fitted to the blade leading edge. Chordwise slots on the concave side of the sheath facilitate its forming over the airfoil surface. The blade and sheath surfaces to be bonded are roughened and cleaned. AF-111 film adhesive is positioned on the blade leading edge and the sheath is placed over the film. This assembly is then placed in a vacuum bag, which in turn is placed in an oven at 394°K (250°F). After the first 10 and 20 minutes in the oven, the leading edge is rolled with a hard rubber roller to insure contact between the blade and sheath. The assembly is held in the oven for an additional 1.5 hours at 394°K. Figure 6 shows a blade with the leading edge sheath bonded to it.

The leading edge sheath is then electroplated with hard nickel (Rc50) using the fixture shown in Figure 7. This plating fixture provides a .064 cm (25 mil) build-up of nickel at the leading edge which tapers to near zero thickness at the sheath edges. Plating completes the composite fan blade fabrication. The blade is now ready for non-destructive inspections.

## Blade Quality Assurance

Non-destructive inspections (NDI) were performed on the composite fan blades during and after completion of blade fabrication to insure blade quality. Following molding, the composite densities of the blades were determined. The densities for the graphite/epoxy blades (numbered C-1 through C-5) and the boron/epoxy blades (numbered B-1 through B-5) are presented in Table V.

TABLE V

COMPOSITE FAN BLADE DENSITIES

| Blade Number | Density (g/cc) |
|---|---|
| C-1 | 1.46 |
| C-2 | 1.46 |
| C-3 | 1.46 |
| C-4 | 1.46 |
| C-5 | 1.45 |
| | |
| B-1 | 1.93 |
| B-2 | 1.92 |
| B-3 | 1.92 |
| B-4 | 1.96 |
| B-5 | 1.96 |

Also after molding, the blades were ultrasonically inspected for indications of delamination or high porosity within the airfoil. The equipment used for these inspections of composite consolidation is pictured in Figure 8. Graphite/epoxy blades C-1, C-3, and C-5 had indications of porosity or delamination in the areas shown in Figures 9, 10, and 11. Boron/epoxy blade B-2 had an ultrasonic signal decrease, indicating possible porosity, as shown in Figure 12. The remaining six composite blades had no ultrasonic indications.

Radiography inspection was performed after blade molding. The X-ray technique was used to detect fiber breakage and density variation. All ten blades were of acceptable quality based on this radiographic inspection.

Upon completion of blade fabrication, the root pad bond and leading edge sheath bond were both inspected by ultrasonic techniques. The blade root was also checked with fluorescent penetrant for defects. Results of all inspections were satisfactory for all ten blades.

The blade natural frequencies in the first bending, second bending, and first torsional modes were determined. A blade is pictured on the shaker table in Figure 13, and the frequency test results are presented in Table VI.

TABLE VI
COMPOSITE FAN BLADE
NATURAL FREQUENCIES (HERTZ)

| Blade Number | First Bending | Second Bending | First Torsion |
|---|---|---|---|
| C-1 | 45 | 103 | 262 |
| C-2 | 45 | 103 | 263 |
| C-3 | 41 | 97 | 233 |
| C-4 | 40 | 97 | 270 |
| C-5 | 45 | 103 | 282 |
| B-1 | 51 | 111 | 319 |
| B-2 | 50 | 109 | 307 |
| B-3 | 50 | 110 | 311 |
| B-4 | 51 | 110 | 314 |
| B-5 | 51 | 110 | 316 |

The airfoil section (K-K) to be impacted was charted for each of the ten completed blades. Section K-K is illustrated in Figure 14, and the measurements from the blade charts are presented in Table VII.

TABLE VII
COMPOSITE FAN BLADE
AIRFOIL IMPACT LOCATION INSPECTION RESULTS
Section K-K, 98.4 cm (38.8 in) Radius
18.5 cm (7.3 in) from blade tip

| Blade Number | Chord Angle Degrees | Maximum Thickness cm (Inch) | Leading Edge Radius cm (Inch) |
|---|---|---|---|
| C-1 | 29.2 | 1.10 (.433) | .132 (.052) |
| C-2 | 28.9 | 1.13 (.443) | .132 (.052) |
| C-3 | 29.1 | 1.04 (.410) | .132 (.052) |
| C-4 | 28.6 | 1.10 (.433) | .132 (.052) |
| C-5 | 28.6 | 1.14 (.450) | .132 (.052) |
| B-1 | 28.7 | 1.11 (.437) | .132 (.052) |
| B-2 | 29.0 | 1.07 (.423) | .122 (.048) |
| B-3 | 28.7 | 1.09 (.430) | .132 (.052) |
| B-4 | 28.6 | 1.09 (.430) | .132 (.052) |
| B-5 | 29.1 | 1.08 (.427) | .127 (.050) |

## IMPACT TESTING

### Description of Tests

The composite fan blade impact tests were performed under conditions simulating a typical STOL engine environment. A STOL take-off flight condition, aircraft speed 41 m/sec (80 knots) and blade tip speed 244 m/sec (800 ft/sec), was used. It was assumed that the foreign object would strike the STOL blade at an airfoil section where the chord angle is 38 degrees (80% span) and the blade tangential velocity is 212 m/sec (695 ft/sec). It was further assumed that the object enters the engine at the aircraft velocity of 41 m/sec (135 ft/sec). These velocities give a resultant impact velocity of 216 m/sec (708 ft/sec) at an angle of 27 degrees from the airfoil section chord line.

In the actual testing of the composite fan blades in the spin pit, the foreign object speed is negligible since the object is merely dropped and accelerated only a short distance by gravity. The airfoil impact section (K–K) has a chord angle of 30 degrees including dynamic untwist with no air loading. The three degree difference from the desired 27 degree angle was considered acceptable for this test program. A rotational speed of 219 rad/sec (2090 rpm) is necessary to provide a 216 m/sec (708 ft/sec) velocity at Section K-K, which is at an engine radius of 98.4 cm (38.8 in). These conditions, illustrated in Figure 15, were used throughout the impact testing program.

One blade of each composite material, graphite/epoxy and boron/epoxy, was used in each of five types of impact tests. The foreign objects used were ice balls, gelatin balls (two sizes), quartz gravel, and starling birds. Sample impacting objects are pictured in Figure 16. Except in the case of the gravel tests, the impacting object was timed to be struck approximately at its mid point by the blade leading edge at Section K-K [18.5 cm (7.3 in) from blade tip] and thereby sliced in half. The impact tests were set up to allow only one impact per object, so that the blade damage from first impact could be evaluated. High speed photography was used to document the blade impacts.

Graphite/epoxy blade C-1 and boron/epoxy blade B-1 were each impacted with an ice ball. The ice balls were molded from distilled water with a blue dye added for photographic purposes and strands of string inserted to suspend them during impact testing. The 5.1 cm (2.0 in) diameter balls were removed from the mold approximately six hours before testing and kept frozen at 270°K (25°F). The set-up time required for the test was approximately thirty minutes, during which time some melting of the ice ball occurred. However, the weight loss was determined to be only three percent of the original 75g (2.6 oz) weight and therefore acceptable.

Gelatin balls were molded one day before the test using four parts of water (by weight) and one part of pigskin gelatin powder (250 bloom size). Again red dye and supporting strands were used for the test. Two sizes of gelatin balls were produced, 165g (5.8 oz) and 320g (11.2 oz), to simulate birds of different size. Graphite/epoxy blade C-2 and boron/epoxy blade B-2 were impacted with the larger gelatin balls, while blades C-3 and B-3 were tested using the 165g balls. Blades C-3 and B-3 were each strain gaged to check the response of the leading edge impact area and the airfoil root, when the blade was struck with the 165g gelatin ball.

The quartz gravel used for the testing of blades C-4 and B-4 was of irregular shape with a nominal diameter of .64 cm (.25 in). Approximately 130 pieces of gravel were required for the 30g (1.1 oz) used in each test. The gravel was dropped on the blades from mid-span to tip with a greater concentration of stones being dropped at the Section K-K impact area. The impacts between gravel and blade took place during approximately fourteen revolutions.

Starlings were killed within two weeks of the test date and frozen until the day before testing. After thawing, each bird was tied into a compact bundle, as shown in Figure 17. A bird weighing 75g (2.6 oz) was used in the test of graphite/epoxy blade C-5. Boron/epoxy blade B-5 was impacted with a 80g (2.9 oz) starling.

## Test Apparatus and Procedure

The composite fan blades were individually impact tested using the rotating arm rig shown in Figure 18 with a blade installed. Blades were painted with a blue and white striped pattern and Section K-K was targeted to aid in analyzing movies of the testing. The blades were spun about a vertical axis with the rig mounted in an evacuated spin pit and driven by a steam turbine, as pictured in Figure 19. Spin rig rotational speed and the test events were monitored and controlled at the test stand control panel shown in Figure 20.

Color high-speed movies of each impact were taken using two cameras. Camera No. 1 was operated at 5200 frames per second and gave a close-up view of the blade impact area. Camera No. 2, with an over-all view of the blade at impact, operated at 5500 frames per second. This photography proved invaluable in setting up the test system, in correcting system malfunctions, and in showing the manner in which blade damage occurred from impact. Closed circuit television with video tape recording was also used to monitor testing system operation.

For each test, the blade was timed to slice the ice ball, gelatin ball, or starling in half. This required an accurately timed drop mechanism for each impacting object. The object was held by a string 25 cm (10 in) above the blade leading edge at Section K-K as shown schematically in Figure 21. When the spin rig was at the proper speed and the test was to be initiated, a control was actuated which released the opposite end of the string into the path of the blade which then cut the string allowing free fall of the impacting object. The circumferential location at which the string was cut in the spin pit was calculated to provide the proper timing for the object to be sliced in half. The start-up of the high-speed cameras was also timed with the string release such that the film was at full speed when impact occurred. The time duration from start to completion of the test sequence was approximately one-half second. Figure 22 shows a gelatin ball set-up in the drop mechanism.

Additional provisions in the test system were included to prevent more than one impact between blade and foreign object. A plate of barbed spikes were placed above the object drop location so that when the top half of the object rebounded from the blade, it would be impaled on the spikes and thus kept from striking the blade again. As a back-up for this catching method, a string shortener was also used. This device, which was automatically activated after impact, retracted the string holding the object so that the top half of the object would be above the level of the blade leading edge, and therefore prevent a second impact. The top portion of the object could be retrieved after testing and the slice size thus determined.

Test trials using gelatin balls were performed on a titanium fan blade of comparable size to check the test timing systems and object catching systems. The equipment was adjusted and calibrated until satisfactory results were obtained.

The impact tests using ice balls and starlings were set up in the same manner as for the gelatin ball tests. The gravel tests used a hopper which spread the stones over the outer half of the blade. Timing in the gravel tests was not critical since impacts occurred throughout several revolutions of the blade.

## Test Results and Discussion

One composite fan blade of each material type was impact tested with one of the five impacting objects used in the program. Table VIII summarizes the tests conditions. Graphite/epoxy blades are numbered C-1 through C-5 and boron/epoxy blades are serialized B-1 to B-5. Ultrasonic inspection was performed on each blade following testing. The test conditions shown in Table VIII are discussed in detail in the following paragraphs.

TABLE VIII

COMPOSITE FAN BLADE
IMPACT TEST CONDITIONS

| Blade Number | Impacting Object | Object Diameter cm. (in.) | Object Weight g. (oz.) | Slice Size g. (oz.) | Notes |
|---|---|---|---|---|---|
| C-1 | Ice ball | 5.1 (2.0) | 75 (2.6) | – | |
| B-1 | Ice ball | 5.1 (2.0) | 75 (2.6) | – | |
| C-2 | Gelatin ball | 8.4 (3.3) | 320 (11.2) | 110 (3.8) | First Impact |
| C-2 | Gelatin ball | 8.4 (3.3) | 320 (11.2) | 210 (7.4) | Second Impact |
| B-2 | Gelatin ball | 8.4 (3.3) | 320 (11.2) | 210 (7.4) | |
| C-3 | Gelatin ball | 6.8 (2.7) | 165 (5.8) | 105 (3.7) | Strain Gaged |
| B-3 | Gelatin ball | 6.8 (2.7) | 165 (5.8) | 25 (.9) | Strain Gaged |
| B-3 | Gelatin ball | 6.8 (2.7) | 165 (5.8) | 130 (4.6) | Strain Gaged |
| C-4 | Gravel | .64 (.25) | 30 (1.1) | – | 130 pieces |
| B-4 | Gravel | .64 (.25) | 30 (1.1) | – | 130 pieces |
| C-5 | Starling | – | 75 (2.6) | 40 (1.4) | |
| B-5 | Starling | – | 80 (2.9) | 45 (1.6) | |

- Ice Ball Tests

In the 5.1 cm (2.0 in) diameter ice ball impact tests of blades C-1 and B-1, the high speed movies showed that the ice ball shattered upon contact with the blade leading edge in each case. Visual damage to the two blades after impact with the 75g (2.6 oz) ice balls is shown schematically in Figures 23 and 24 and pictured in Figures 25 and 26. The small area of composite delamination on blade C-1 was in the area where ultrasonic indications of poor consolidation was found during pre-test NDI. This ultrasonic area grew during testing, as shown in Figure 27. The tip deflection caused by the impact tends to further loosen any existing delamination. Due to the designed thinness of the composite at the blade tip leading edge, the impact has an increased effect on this area.

The damage to blade B-1 from the ice ball impact was more severe, however, no post-test ultrasonic indications were found. High speed movies show that blade B-1 took a large slice of the ice ball (approximately three-quarters of the ball), whereas blade C-1 hit the ice ball at its mid-point. This seems to be the only factor which affected the amount of damage sustained by each blade. The difference in FOD was not expected due to the composite material differences. The FOD threshold is very likely close to the ice ball weight of 75g (2.6 oz).

- Gelatin Ball Tests

Four composite blades were impact tested with gelatin balls of two different sizes. The impact sequence for blade C-2, taken from the high-speed movies, is shown in Figure 28. The manner in which the ball is sliced and in which the blade is damaged is typical for all of the gelatin ball tests. As the ball is cut in half, the blade begins tearing chordwise from the leading edge impact location. As this tearing continues, the blade material around the tear lifts up and away from the tear causing additional tearing in the radial direction. This material then breaks loose from the blade as some of the gelatin from the lower half of the ball pushes through the torn areas of the blade. The top half of the gelatin ball remains intact after going through severe distortions from the impact.

The 320g (11.2 oz) gelatin ball impact caused damage to graphite/epoxy blade C-2 as sketched in Figure 29 estimated from the final sequence photo of Figure 28. The high-speed movies revealed that the slice size for this first impact was approximately 110g (3.8 oz). In this test, the object catching system failed to prevent a second impact. The remaining 210g (7.4 oz) piece of gelatin ball hit the blade inboard of Section K-K where the airfoil chord angle is greater. The damage from both impacts is sketched in Figure 30 and pictured in Figure 31. Post-test ultrasonic indications correspond to the delaminated area shown in Figure 30.

Blade C-3 sliced 105g (3.7 oz) from the 165g (5.8 oz) gelatin ball which impacted the blade leading edge at Section K-K. Visual damage is shown in Figures 32 and 33. Ultrasonic indications after testing were in the areas labeled as delamination in Figure 32.

The gelatin ball impact tests revealed that the FOD threshold is below a 105g (3.7 oz) slice size for graphite/epoxy blades. The leading edge sheath offers little protection to the blade and the composite material cannot withstand gelatin ball impacts above 105g (3.7 oz) slice size, at the angle and velocity used in these tests.

In the test of boron/epoxy blade B-2, a slice greater than one-half of the 320 g (11.2 oz) gelatin ball was taken. The 210g (7.4 oz) slice impact caused the damage shown in Figures 34 and 35. No ultrasonic indications were found on blade B-2 following testing.

Boron/epoxy blade B-3 was impacted with a 165 g (5.8 oz) gelatin ball, however, a malfunction in the drop mechanism caused only a 25g (.9 oz) slice to be taken. The blade was visually and ultrasonically inspected following this impact and found to be undamaged. Blade B-3 was then retested with a new 165g gelatin ball. A 130g (4.6 oz) slice was cut from this ball and blade damage did occur as shown in Figures 36 and 37. Post-test ultrasonic indications correspond to the area shown as delaminated in Figure 36.

The FOD threshold for boron/epoxy blades was determined to be below a 130g (4.6 oz) gelatin ball slice size from the B-3 impact test. However, the severity of damage with the 210g (7.4 oz) slice taken by blade B-2 was not significantly worse than the B-3 damage.

- Strain Gaged Tests

Graphite/epoxy blade C-3 and boron/epoxy blade B-3 were each instrumented with nine strain gages (S/G) to check the blade response from impact with the 165g (5.8 oz) gelatin ball. The strain gage locations are shown in Figure 38. The gages at the airfoil root were situated to give maximum response to blade bending and torsional vibration in fundamental modes. The gages at the impact section were oriented to show response to chordwise bending and higher plate modes.

During impacting, strain versus time for all nine gages was recorded on a magnetic tape system with a flat frequency response from 20 Hz to 20 KHz. For the first instrumented test, the outputs of gages 5, 6, 7 and 8 were also displayed on an oscilloscope system with a flat frequency response up to 2 MHz. This oscilloscope coverage showed that there were no very-short duration pulses from stress wave propagation due to impact. Therefore, the magnetic tape system had adequate frequency response to accurately record strain versus time, and the use of the oscilloscope was discontinued.

The time traces from the oscillograph film play-back of the magnetic tape recording of the impact events are shown in Figures 39 and 40 for blades C-3 and B-3, respectively. The physical separation between tracks on the magnetic tape leads to the possibility of timing errors. The magnetic tape/oscillograph system was calibrated in time using a step input, and the results are shown in Figure 41. The appropriate corrections have been applied to each channel in Figures 39 and 40, so that the channels are comparable in time.

A correlation of time of first gage disturbance versus gage distance from the leading edge impact location is presented in Figure 42, for the five gages at Section K-K. The inverse slopes of the curves in this graph give characteristic disturbance velocities of 706 m/sec (2320 ft/sec) for graphite/epoxy blade C-3 and 509 m/sec (1670 ft/sec) for boron/epoxy blade B-3.

Maximum strains, recorded for the four airfoil root gages were significantly lower than the impact section gage readings, before impact gage failure, as shown in Table IX. A graph of peak strain versus gage distance from the impact location is plotted in Figure 43 for the Section K-K gages.

**TABLE IX**
**COMPOSITE FAN BLADE**
**IMPACT TESTING STRAIN GAGE RESULTS**

| Strain Gage Number | Maximum Strain-Microns/m. ($\mu$ in/in) Blade C-3 | Blade B-3 |
|---|---|---|
| 1 | 307 | 502 |
| 2 | 316 | 658 |
| 3 | 583 | 1820 |
| 4 | 53 | 479 |
| 5 | 1760 | 2160 |
| 6 | 1140 | 2720 |
| 7 | 3040 | 6130 |
| 8 | 5050 | 4670 |
| 9 | 3170 | - - |

Table X shows the characteristic frequencies measured during each strain gaged impact test. Also listed for comparison are the pre-test fundamental mode blade natural frequencies. For each blade, the lowest frequency at impact is the resultant first bending frequency after increases due to rotational speed and material loss. The second bending and first torsional vibratory modes were not excited by the gelatin ball impacts. The frequencies at impact indicate that except for first bending, high frequency plate modes predominate after impacting. It was possible to see these various blade vibrations, which occurred to significant amplitudes, in the high-speed movies of the impact tests.

**TABLE X**
**COMPOSITE FAN BLADE**
**EXCITATIONS FROM IMPACT TESTING**

| | Blade C-3 | Blade B-3 |
|---|---|---|
| Pre-Test First Bending (Hz) | 41 | 50 |
| Pre-Test Second Bending (Hz) | 97 | 110 |
| Pre-Test First Torsion (Hz) | 233 | 311 |
| Frequencies at Impact (Hz) | 68 | 63 |
| | 2290 | 350 |
| | 3500 | 610 |
| | 4000 | 730 |
| | | 1350 |
| | | 2000 |
| | | 2300 |
| | | 2850 |

- **Gravel Tests**

Blade C-4 and B-4 were each impacted with 30g (1.1 oz) of gravel. The leading edge sheath on the concave side of C-4 came off the blade as shown in Figures 44 and 45. This failure indicates the possibility of a poor bond between the blade and sheath, although pre-test NDI showed no lack of bonding. Post-test ultrasonic inspection showed indications in the two areas illustrated in Figure 46.

The gravel impact results on blade B-4 are shown in Figures 47 and 48. No ultrasonic indications were found after testing. Damage at the leading edge is negligible, even though the high-speed movies show that impacts did occur at this location. However, the concave side sheath, aft of the leading edge, was nicked, gouged, and unbounded, as pictured in Figure 49. The gravel apparently strikes the sheath causing compressive stresses on the sheath exterior surface. The stress differential within the sheath is great enough to break the sheath-to-blade bond and then lift the sheath from the surface of the blade. Therefore it is concluded that with a better bond between sheath and blade, the leading edge sheath could offer satisfactory protection from small amounts of gravel ingestion.

- **Starling Tests**

Blade C-5 and B-5 were impacted with 75g (2.6 oz) and 80 g (2.9 oz) starlings, respectively. The 40g (1.4 oz) slice taken by C-5 and the 45g (1.6 oz) slice cut by B-5 caused only slight damage in each case. The damage which occurred seems to be related to blade fabrication problems. Both blades are pictured in Figures 50 and 51 respectively.

The visually delaminated area of C-5 shown in Figure 52, which also corresponds to post-test ultrasonic indications, is in a location where a pre-test ultrasonic indication was present. The starling impact caused this area of delamination to grow. If the blade had been well consolidated in this area, possibly no damage would have occurred from the impact.

Only a small amount of leading-edge sheath unbonding, as shown in Figure 53, resulted from B-5 starling impact. Better bonding of the sheath to the blade could perhaps prevent such damage. No post-test ultrasonic indications were found on this blade.

The two starling tests indicate that graphite/epoxy and boron/epoxy blades of sound construction are capable of withstanding a starling slice size of at least 40g (1.4 oz) and 45g (1.6 oz) respectively.

- **Blade Damage Summary**

A tabulation summarizing the test conditions and the extent of damage sustained by each blade during the impact tests is shown in Table XI.

TABLE XI

COMPOSITE FAN BLADE TEST SUMMARY

| | | Impact Test Conditions | | | Extent of Blade Damage | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Blade Number | Impacting Object | Object Diameter cm. (in.) | Object Weight g. (oz.) | Slice Size g. (oz.) | Delamination | Partial L.E. Sheath Unbond | Partial L.E. Sheath Loss | Approx. L.E. Loss sq. cm (sq. in.) | Ref. Figure |
| C-1 | Ice ball | 5.1 (2.0) | 75 (2.6) | 37 (1.3)* | Minor | – | – | – | 23 |
| B-1 | Ice ball | 5.1 (2.0) | 75 (2.6) | 56 (2.0)* | – | X | X | 32 (5) | 24 |
| C-2 | Gelatin ball | 8.4 (3.3) | 320 (11.2) | 110 (3.8)* | [1] | [1] | [1] | 129 (20)* | 29 |
| C-2 | Gelatin ball | 8.4 (3.3) | 320 (11.2) | 210 (7.4) | Severe [2] | – | X [2] | 213 (33) [2] | 30 |
| B-2 | Gelatin ball | 8.4 (3.3) | 320 (11.2) | 210 (7.4) | Severe | – | X | 232 (36) | 34 |
| C-3 | Gelatin ball | 6.8 (2.7) | 165 (5.8) | 105 (3.7) | Severe | – | X | 251 (39) | 32 |
| B-3 | Gelatin ball | 6.8 (2.7) | 165 (5.8) | 25 (.9) | – | – | – | – | – |
| B-3 | Gelatin ball | 6.8 (2.7) | 165 (5.8) | 130 (4.6) | Severe | – | X | 155 (24) | 36 |
| C-4 | Gravel | .64 (.25) | 30 (1.1) | 130 pieces | Minor | X | X | – | 44 |
| B-4 | Gravel | .64 (.25) | 30 (1.1) | 130 pieces | – | X | – | – | 47 |
| C-5 | Starling | – | 75 (2.6) | 40 (1.4) | Minor | – | – | – | 52 |
| B-5 | Starling | – | 80 (2.9) | 45 (1.6) | – | X | – | – | 53 |

*Estimated from high speed movies.

[1] Unknown for first impact.

[2] After two impacts.

- **Post-Test Inspections**

In addition to the post-test ultrasonic inspection done on each blade and discussed in the preceeding sections, several other inspections were performed on the blades following impacting. The five boron/epoxy blades were x-rayed after testing. No change from the pre-test condition, other than the gross damage, was indicated in the radiographs.

Four blades which lost little or no material due to impacting were frequency checked following testing. As can be seen in Table XI, the changes in blade natural frequencies before and after impacting are low. In most cases they are within the accuracy band of the measurement except for blade C-5 torsional frequency. No explanation is evident from the post-test inspection. Possibly a pre-test reading error is the cause.

Three blades (C-1, C-5 and B-5) which had little damage from impacting were charted at the impacted airfoil section (K-K) to check for permanent deformation of the blade. Only blade C-1 showed such a deformation. The leading edge of C-1 was distorted approximately .05 cm (.02 inch) for a distance of 3 cm (1 inch) from the leading edge.

Graphite/epoxy blade C-3 was sectioned in the area of the impact damage for metallographic study. Two chordwise sections were examined, as illustrated in Figure 54. Section 1 revealed a shear crack of approximately .41 cm (.16 in) length angled at 40° from the concave blade surface as shown in Figure 55. Section 2, pictured in Figure 56, revealed five interlaminar separations which propagated for a length of .10 cm (.04 in) to .66 cm (.26 in) in the chordwise direction. No internal composite damage was found further away from the broken area of the blade.

TABLE XII

COMPOSITE FAN BLADE
NATURAL FREQUENCIES (HERTZ)

| Blade Number | First Bending | | Second Bending | | First Torsion | |
|---|---|---|---|---|---|---|
| | Pre-Test | Post-Test | Pre-Test | Post-Test | Pre-Test | Post-Test |
| C-1 | 45 | 44 | 103 | 101 | 262 | 255 |
| C-5 | 45 | 45 | 103 | 101 | 282 | 248 |
| B-4 | 51 | 50 | 110 | 107 | 314 | 309 |
| B-5 | 51 | 51 | 110 | 106 | 316 | 298 |

# CONCLUSIONS

The following conclusions have been drawn based upon the test results reported herein of the composite fan blades impacted at simulated STOL takeoff conditions.

- Both graphite/epoxy and boron/epoxy blades behave similarly under small object impact and FOD is confined to the impact area.

- Based on gelatin ball and starling impacts, the FOD threshold for these graphite/epoxy blades is between 40g (1.4 oz) and 105g (3.7 oz) slice size, while the boron/epoxy blade FOD threshold is between 45g (1.6 oz) and 130g (4.6 oz) slice size.

- An adequately bonded leading edge sheath could protect the composite blade from small amounts of gravel ingestion.

- The fact that a 5.1 cm (2.0 in) diameter ice ball weighing 75g (2.6 oz) damaged a boron/epoxy blade and not a graphite/epoxy blade may be attributable to blade scatter and testing close to the blade FOD threshold.

- The composite fan blades tested in this program have inadequate resistance to FOD when impact tested under simulated STOL engine conditions.

- To date a satisfactory demonstration of FOD capability on composite fan blades has not been achieved. A large concentrated and integrated FOD development program on real blades is required if the FOD problem is to be solved.

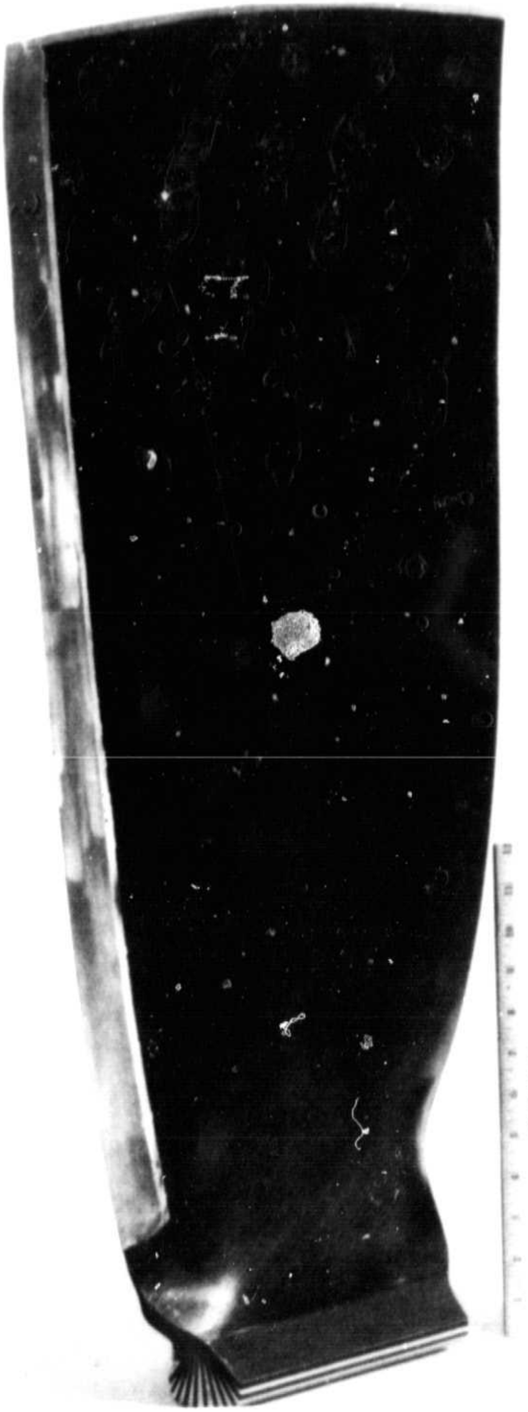



Figure 1   Composite Fan Blade

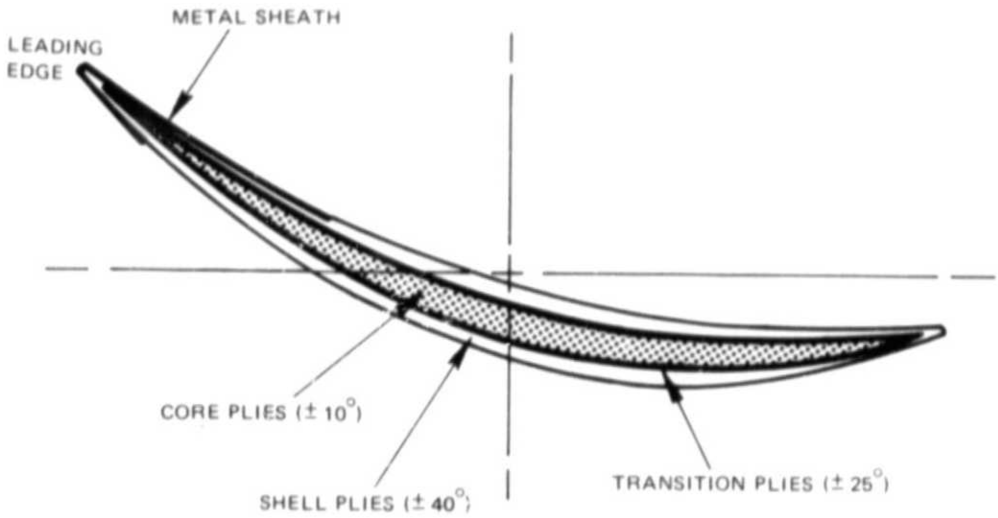



Figure 2 Composite Fan Blade - Typical Airfoil Section

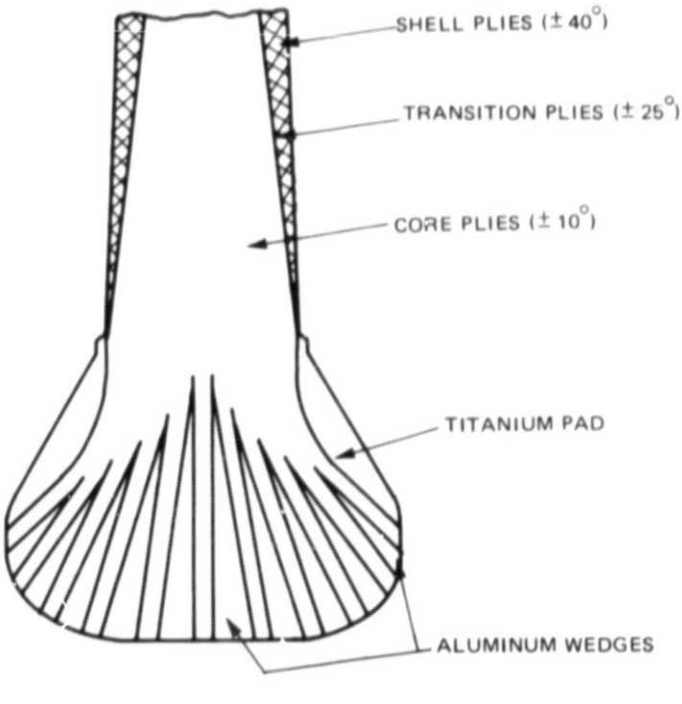



Figure 3 Composite Fan Blade - Typical Root Section

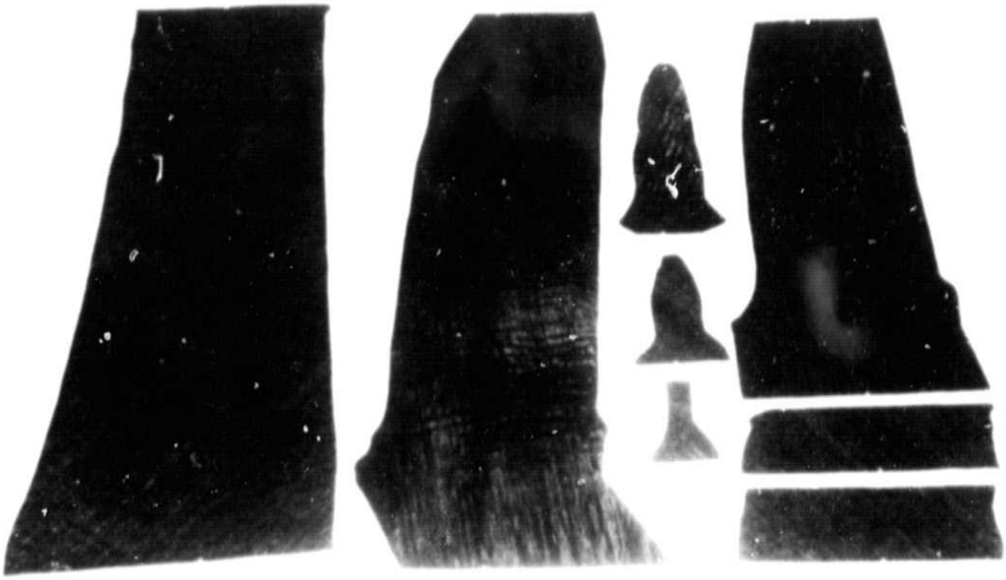


Figure 4   Composite Fan Blade - Typical Prepreg Tape Plies

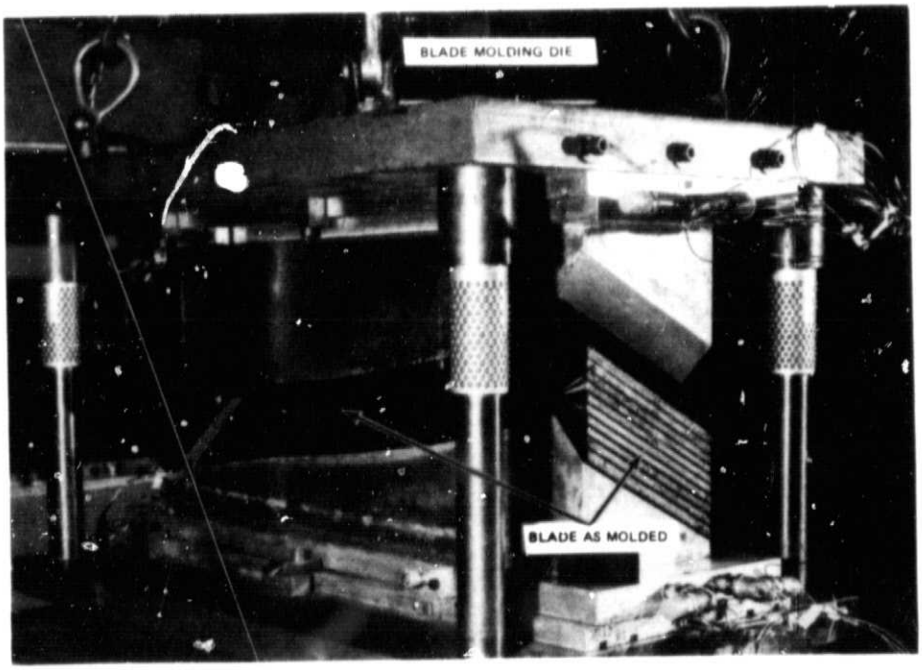



Figure 5   Composite Fan Blade in Molding Die

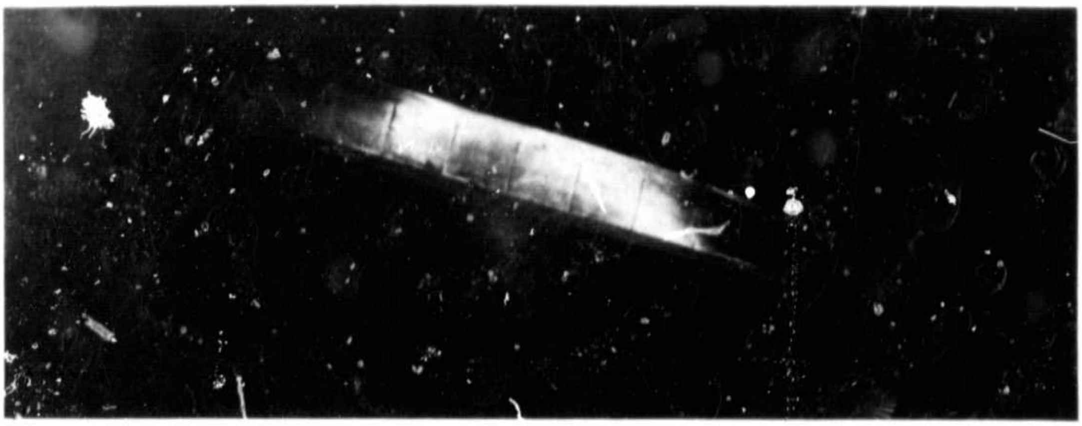


Figure 6 Composite Fan Blade Following Leading Edge Sheath Bonding

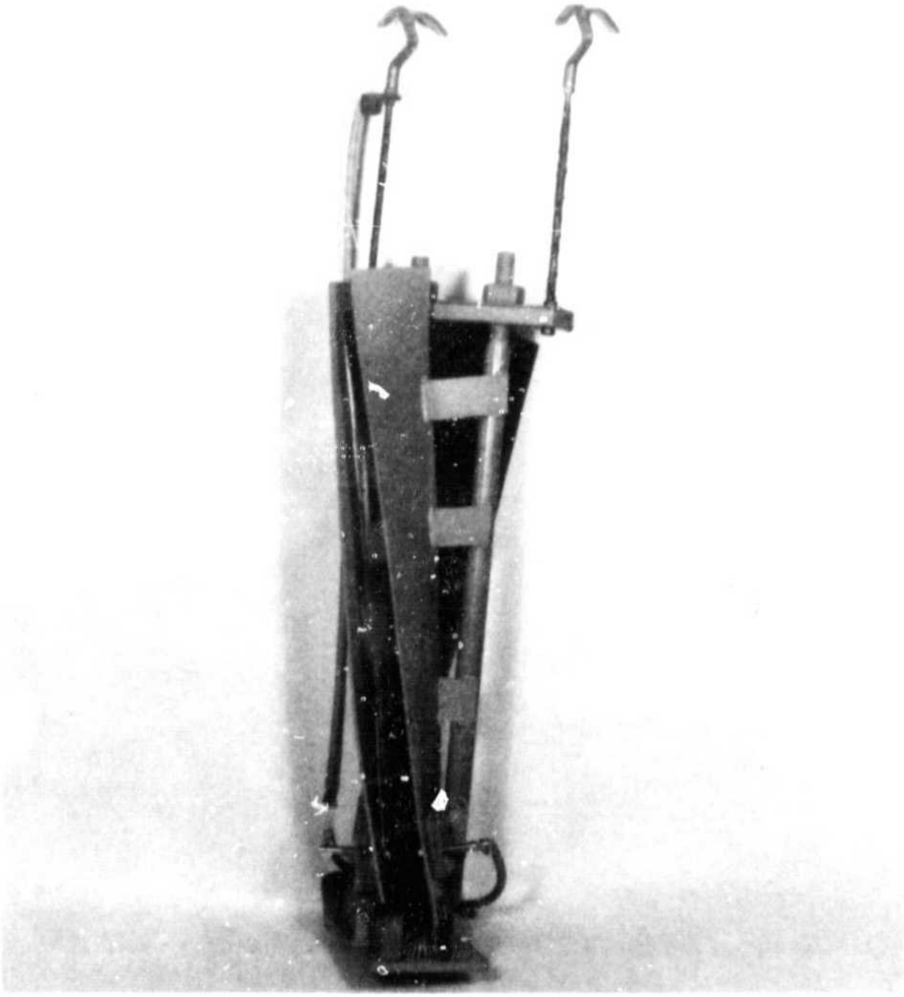


Figure 7 Composite Fan Blade in Leading Edge Sheath Plating Fixture

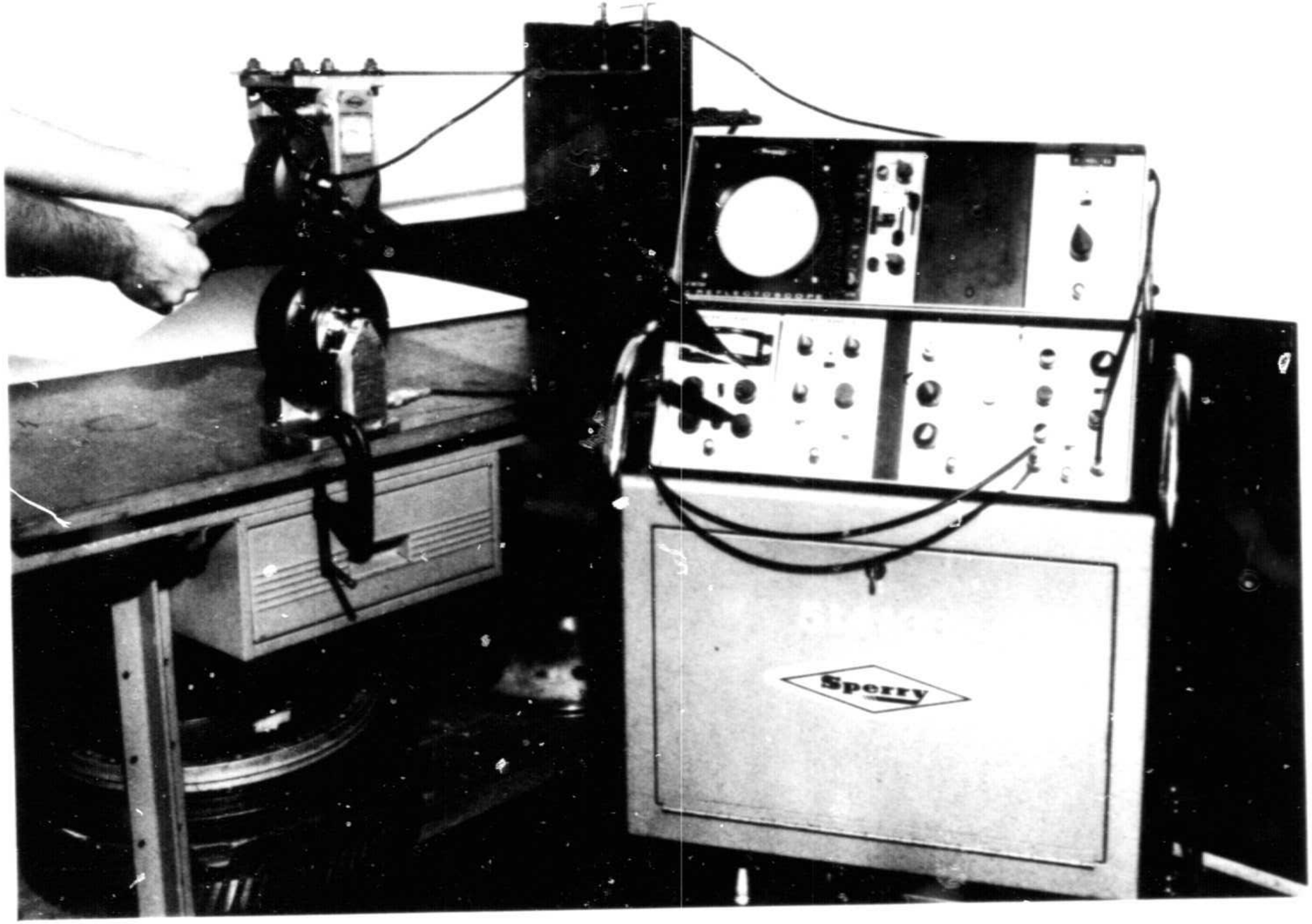



Figure 8 Composite Fan Blade - Airfoil Ultrasonic Inspection

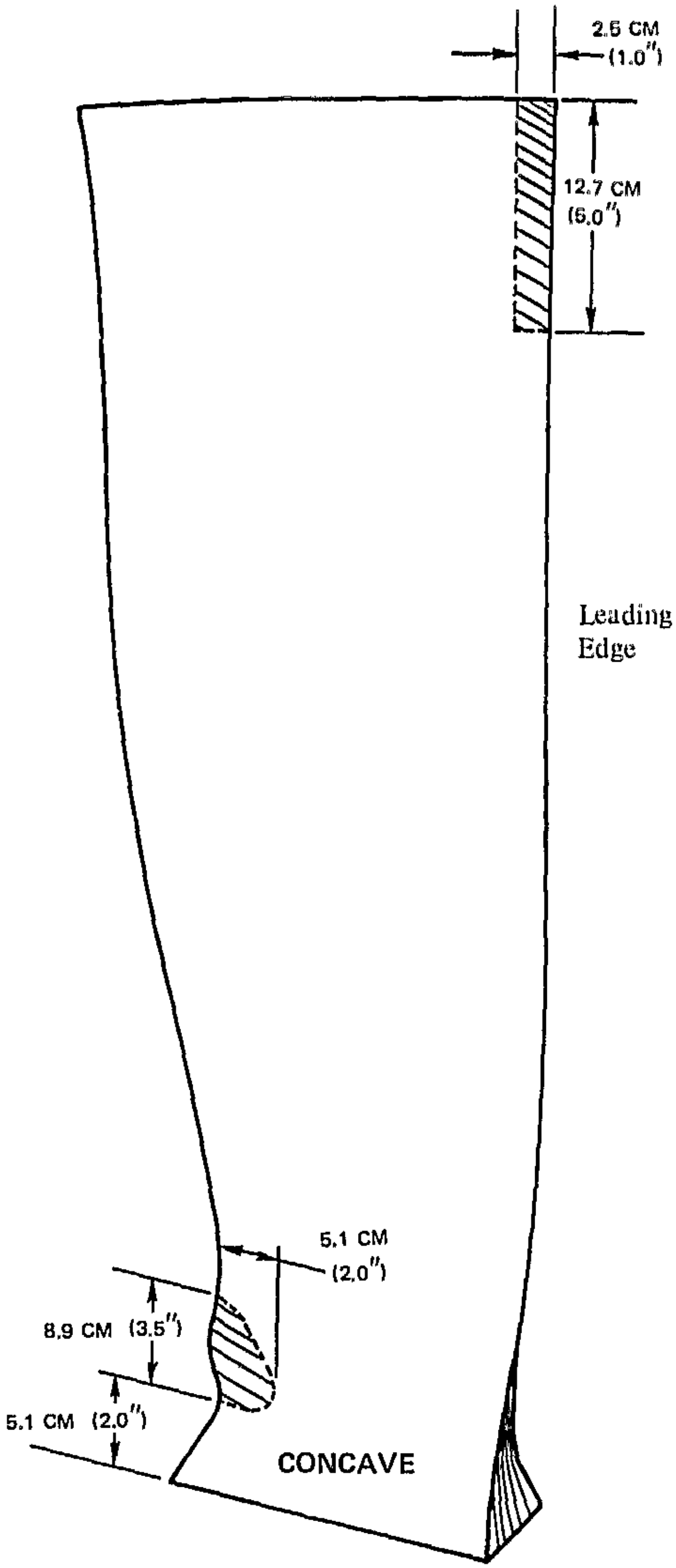



Figure 9 Ultrasonic Indications on Graphite/Epoxy Blade C-1 Before Impact.

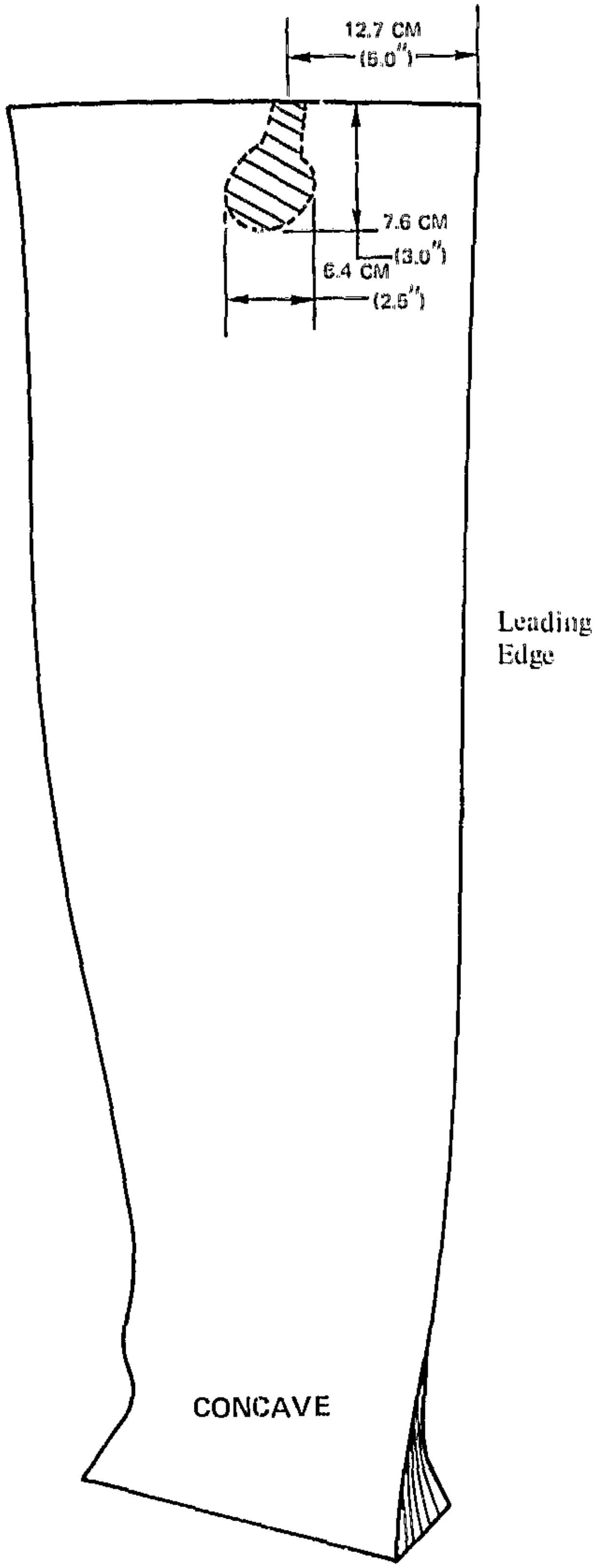



Figure 10 Ultrasonic Indications on Graphite/Epoxy Blade C-3 Before Impact.

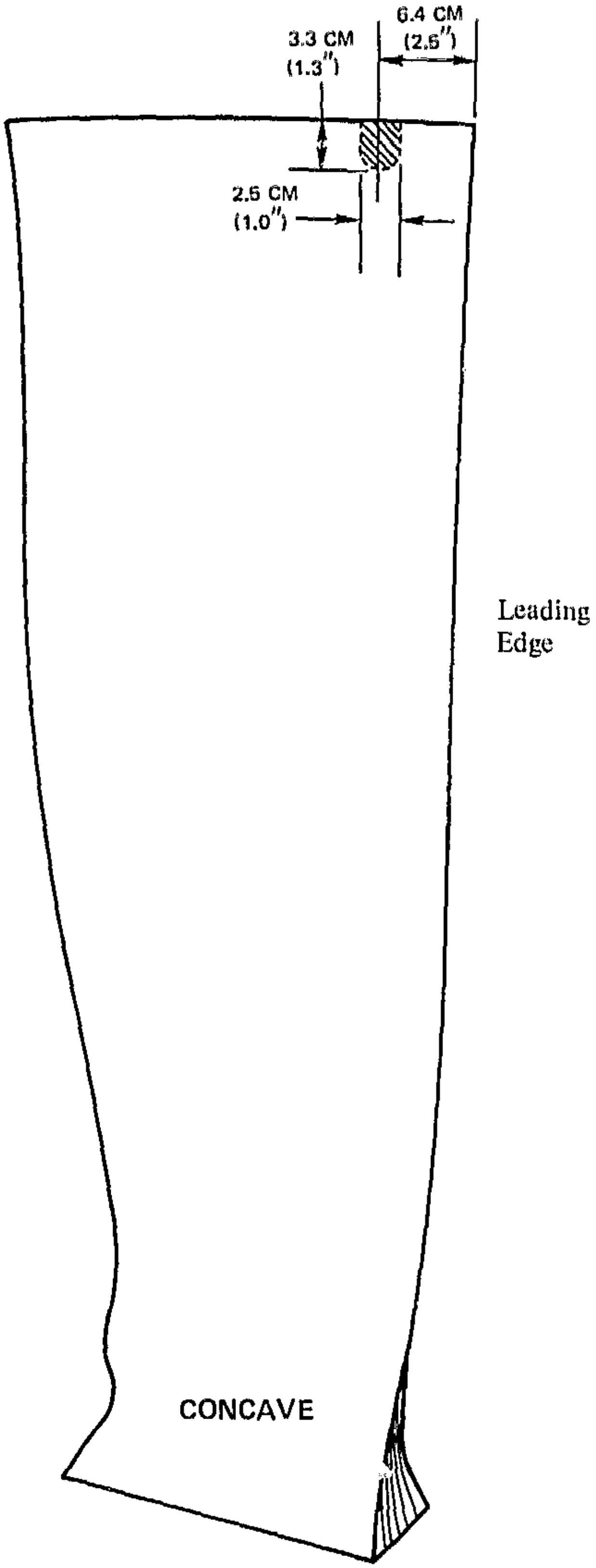



Figure 11 Ultrasonic Indications on Graphite/Epoxy Blade C-5 Before Impact.

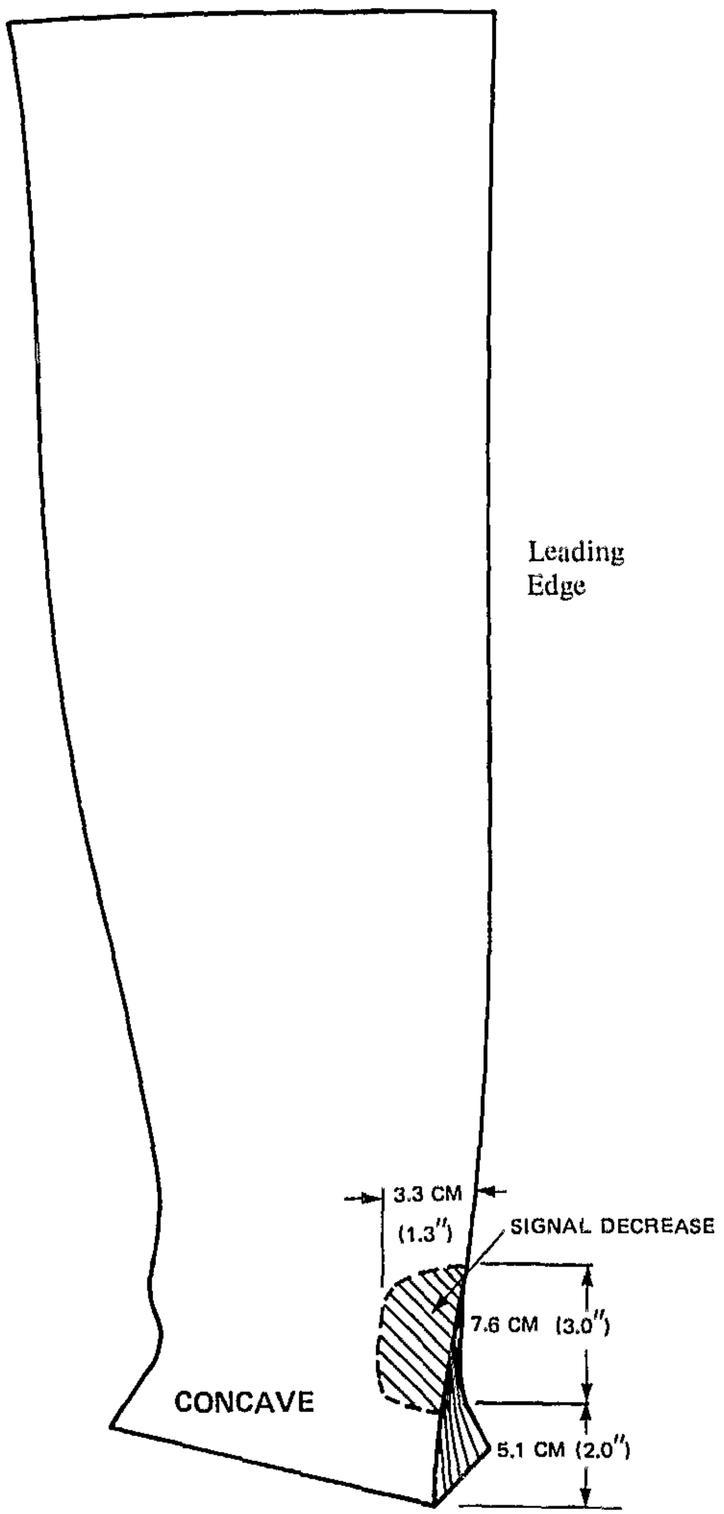



Figure 12 Ultrasonic Indications on Boron/Epoxy Blade B-2 Before Impact.

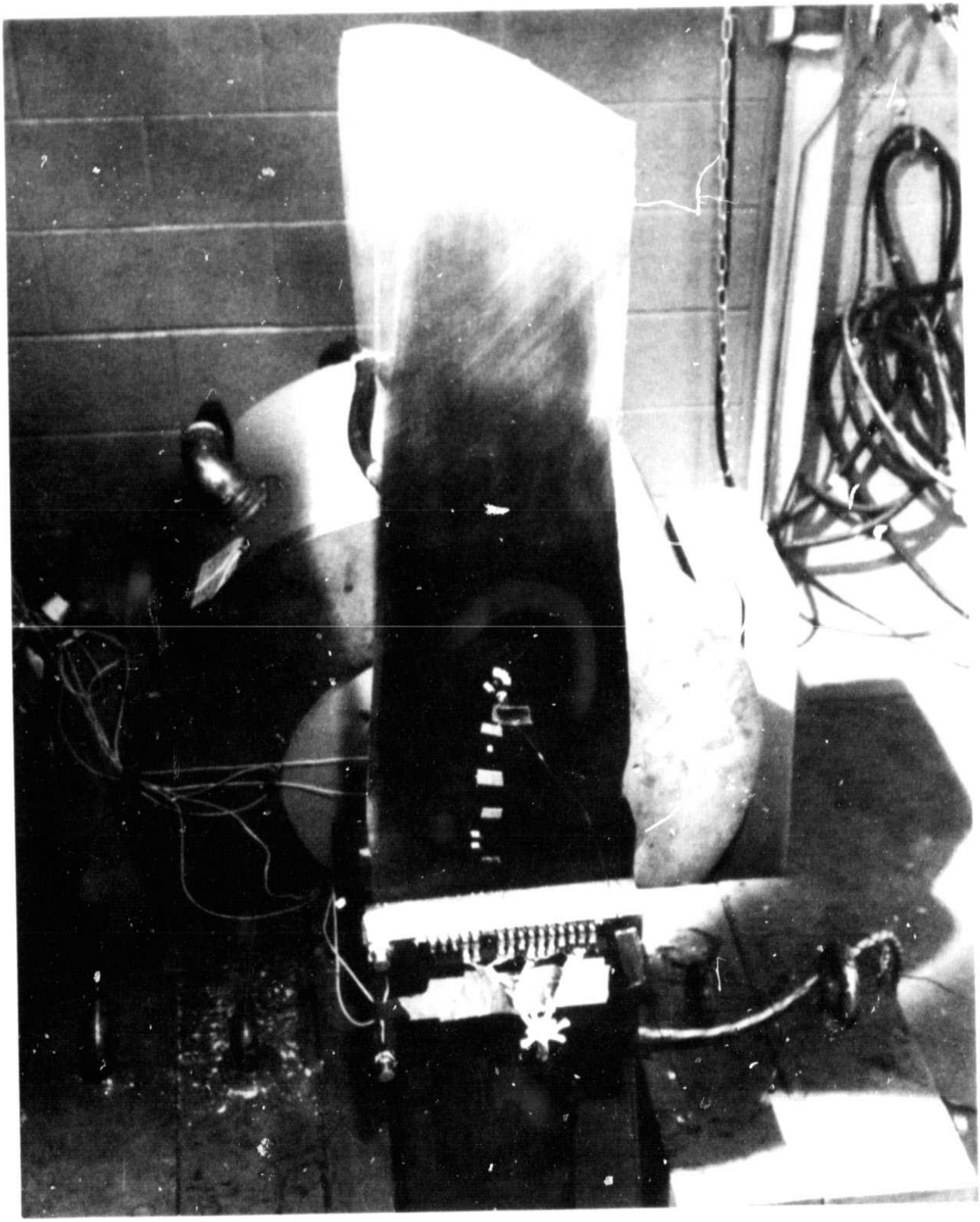


Figure 13 Composite Fan Blade - Natural Frequency Determination

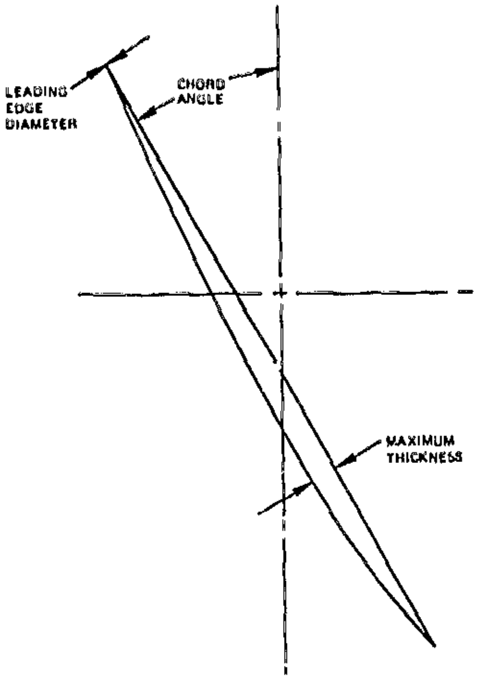



Figure 14 Composite Fan Blade - Airfoil Impact Section K-K
18.5 cm (7.3 in) from blade tip

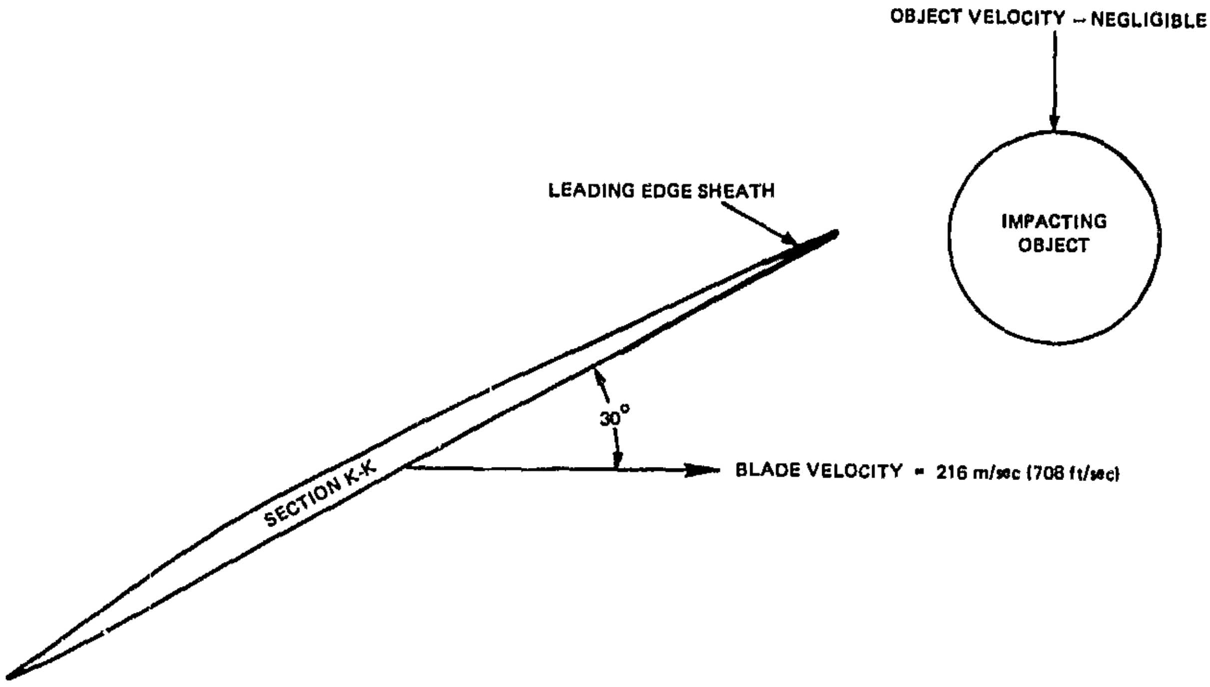



Figure 15 Composite Fan Blade - Impact Testing Condition

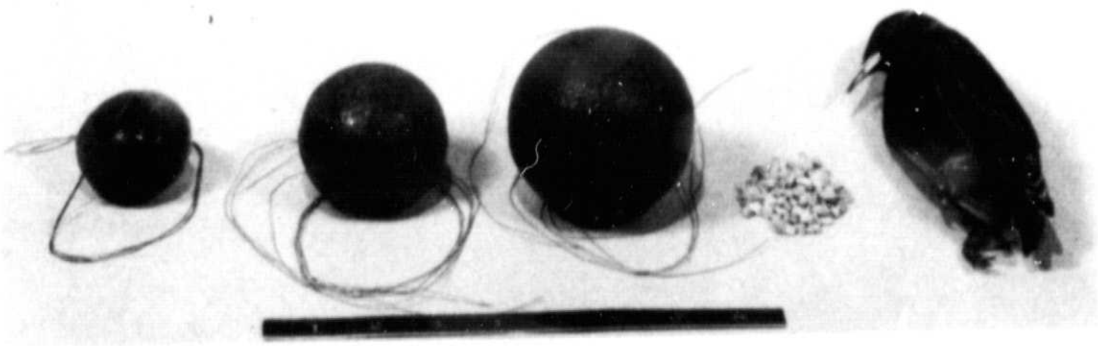


Figure 16    Impacting Objects - Left to Right, Ice Ball, Gelatin Ball (165g), Gelatin Ball (320g), Gravel, Starling

Figure 17    Starling Before and After Bundling for Test

Figure 18    Composite Fan Blade in Spin Test Rig

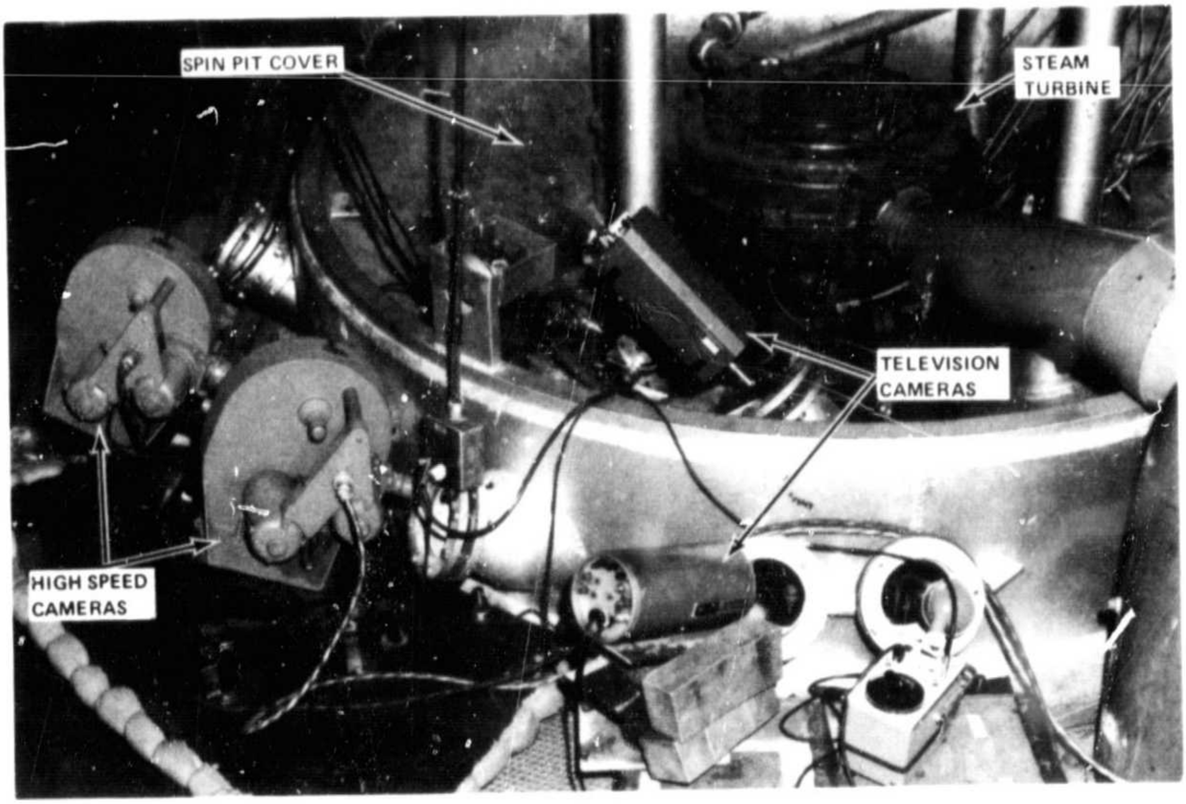



Figure 19    Spin Pit Set-up for Impact Testing

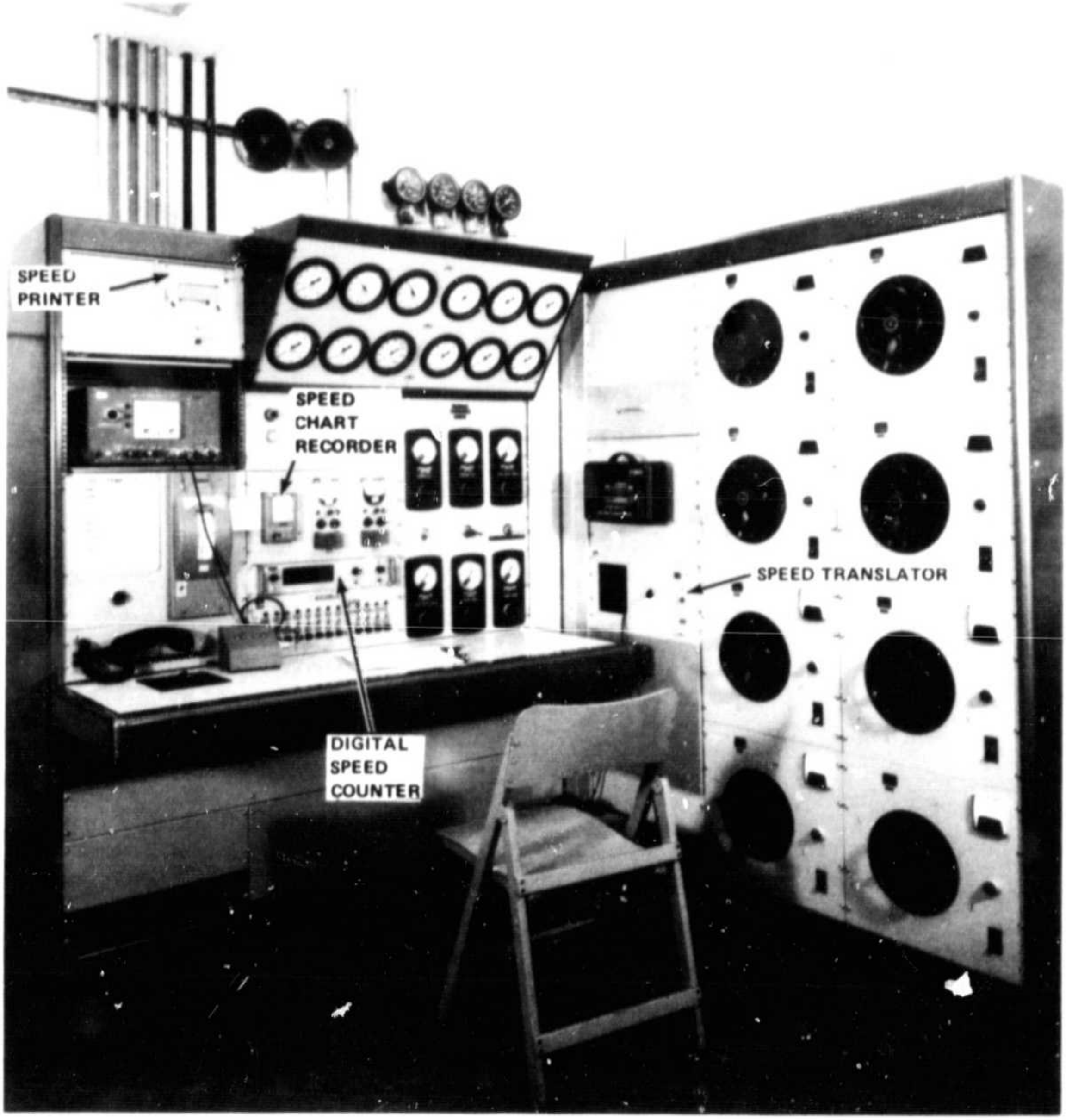



Figure 20 Spin Pit Test Stand Control Panel

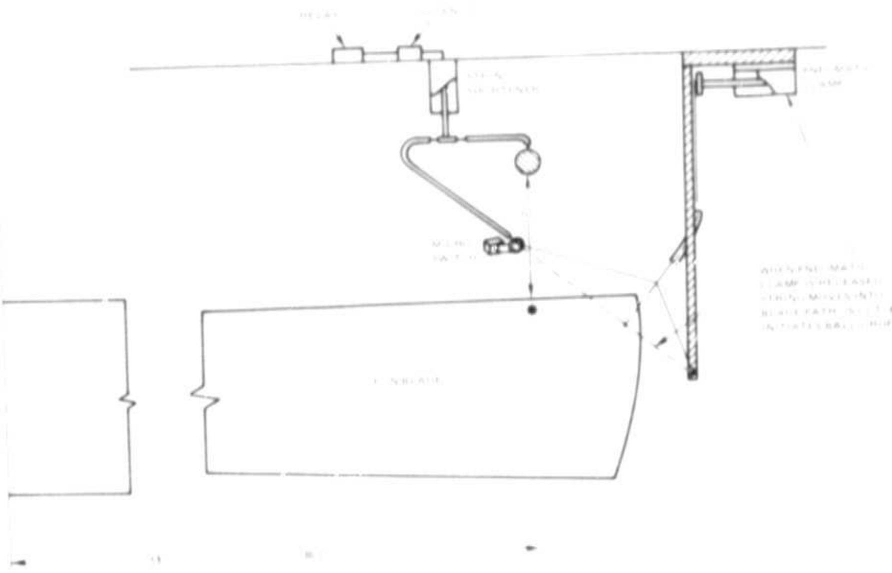


Figure 21     Schematic of Impact Object Drop Mechanism

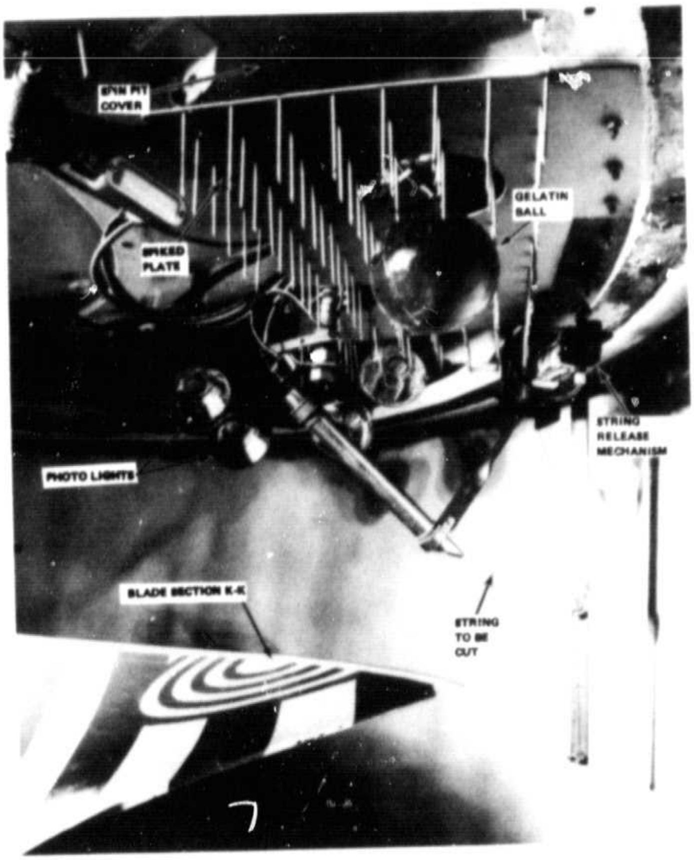



Figure 22     Drop Mechanism For Impact Testing

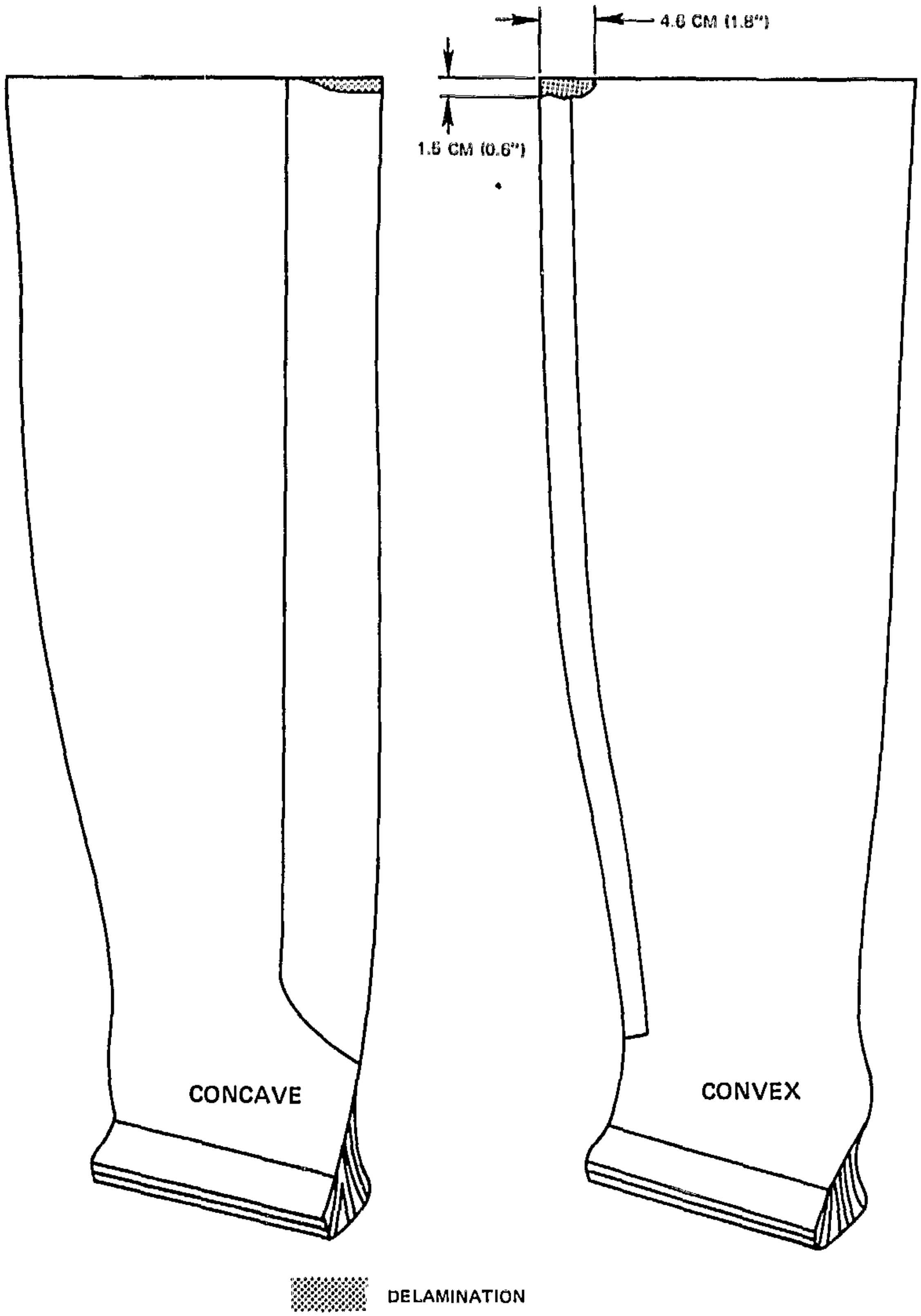



Figure 23 Visual Damage to Graphite/Epoxy Blade C-1 Following Impact with Ice Ball

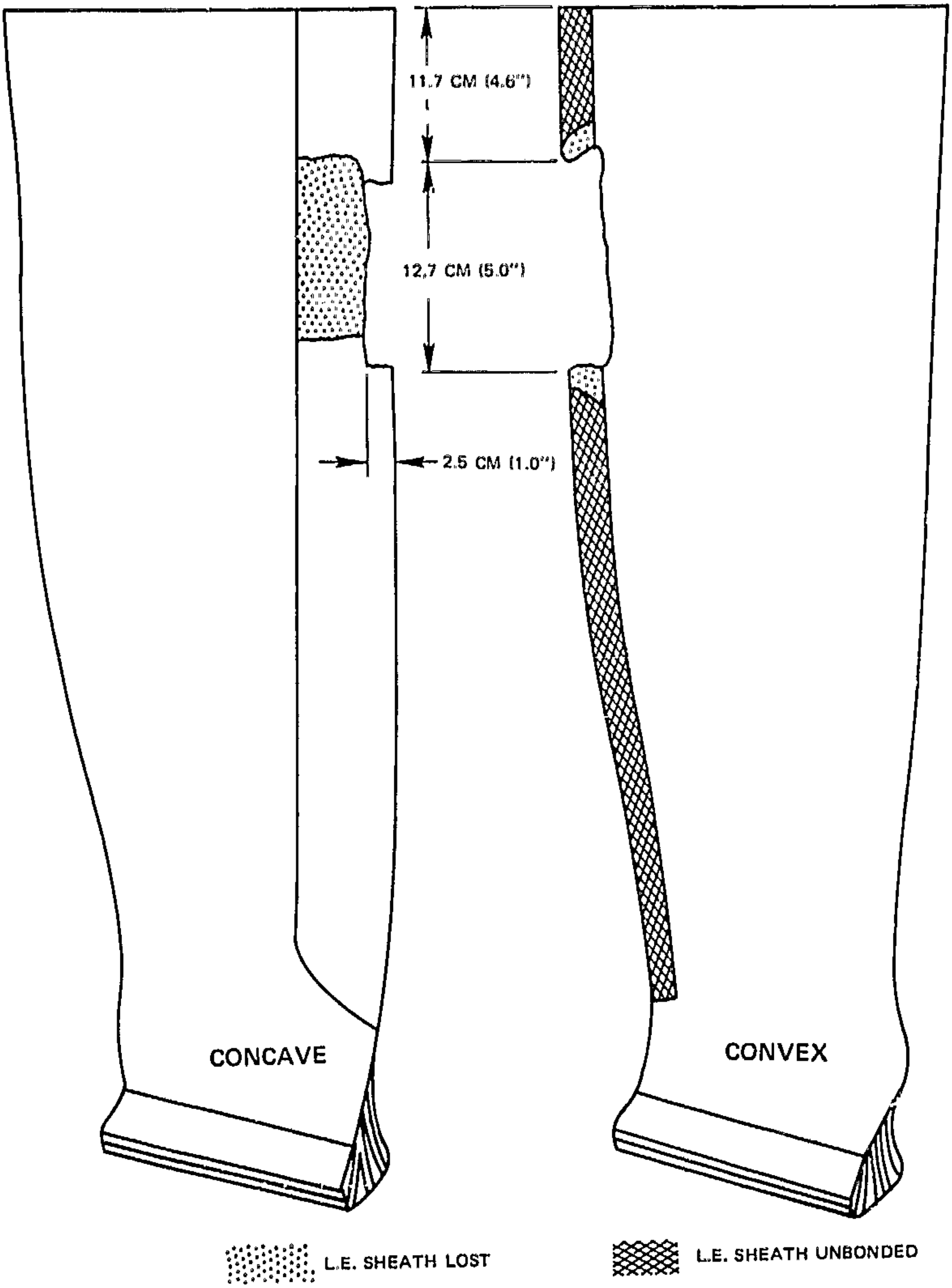



Figure 24 Visual Damage to Boron/Epoxy Blade B-1 Following Impact with Ice Ball

CONVEX CONCAVE

Figure 25 Graphite/Epoxy Blade C-1 Following Impact with Ice Ball


CONVEX CONCAVE

Figure 26 Boron/Epoxy Blade B-1 Following Impact with Ice Ball

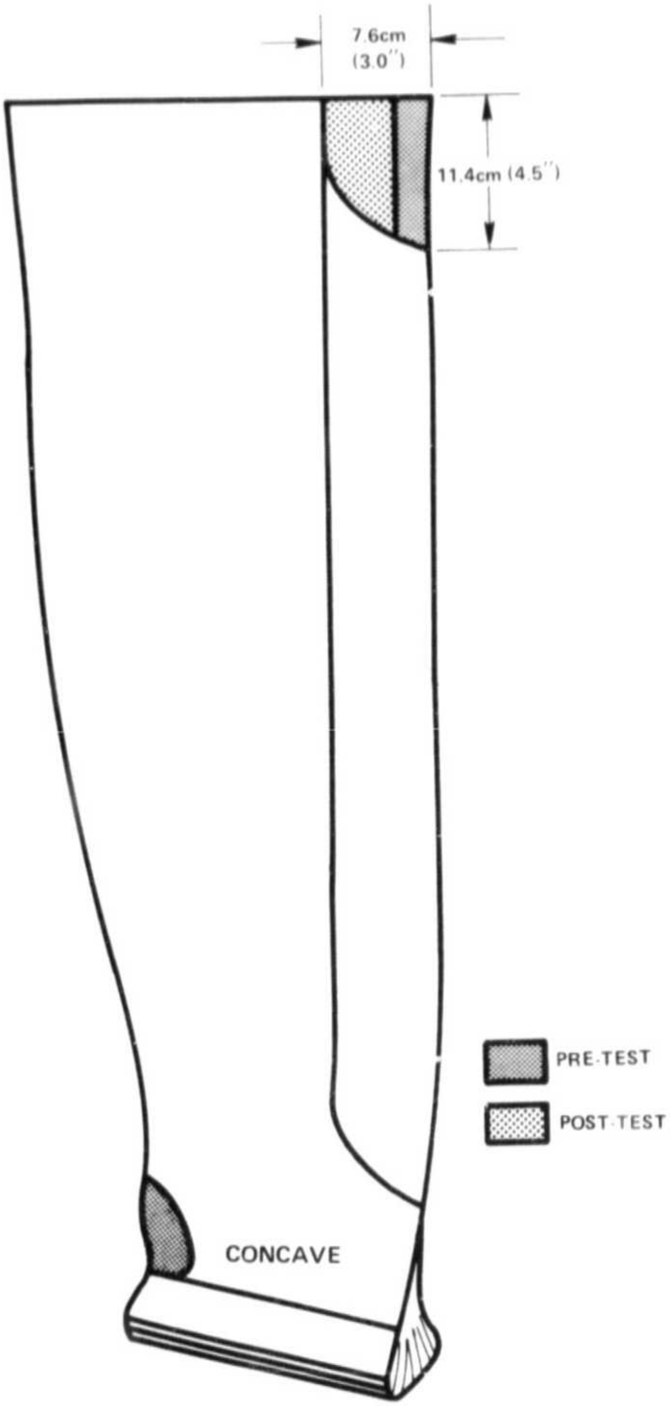



Figure 27 Ultrasonic Indications on Graphite/Epoxy Blade C-1

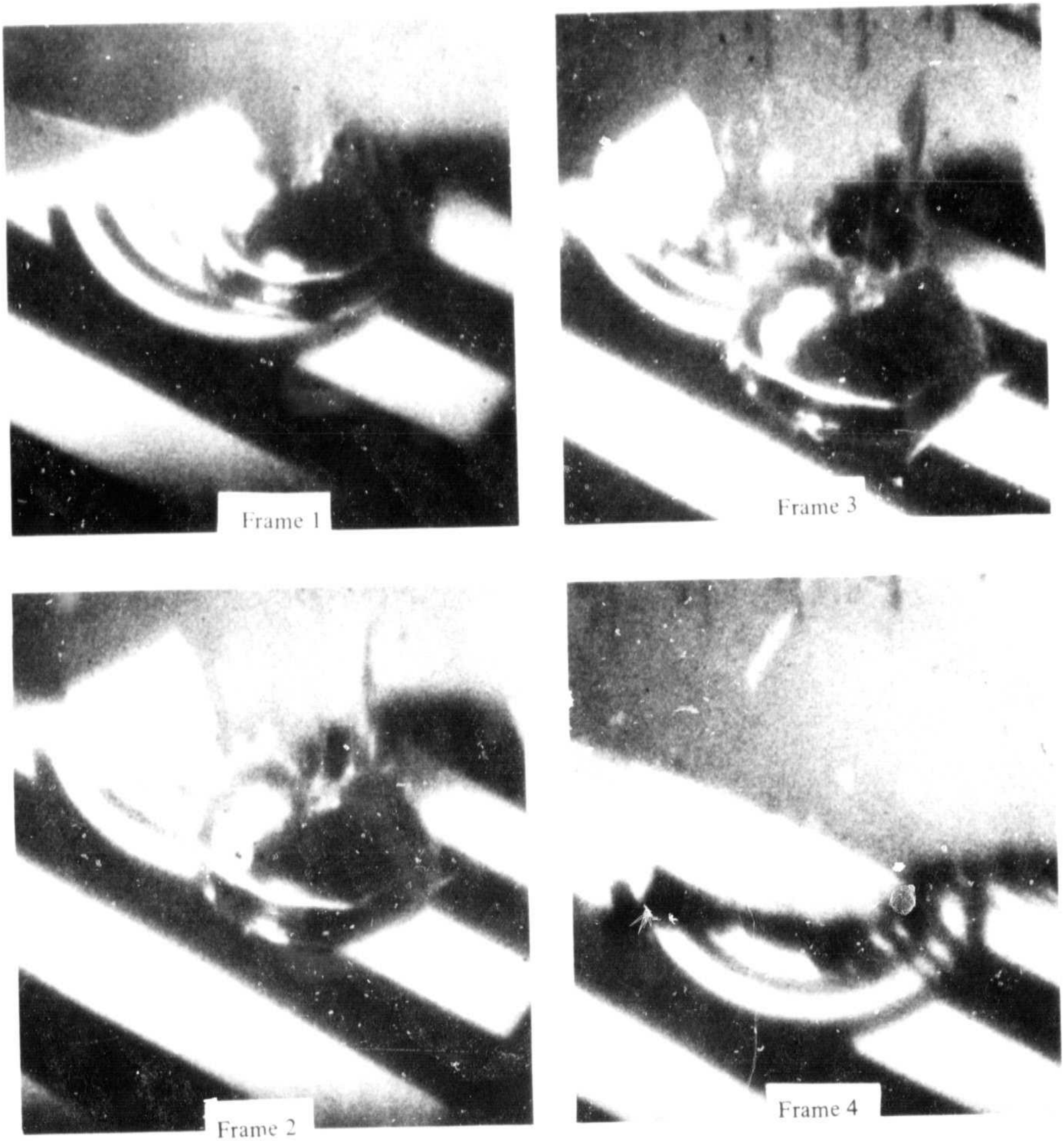



Figure 28 Gelatin Ball Impact on Graphite/Epoxy Blade C-2. (Photo's from high speed film)

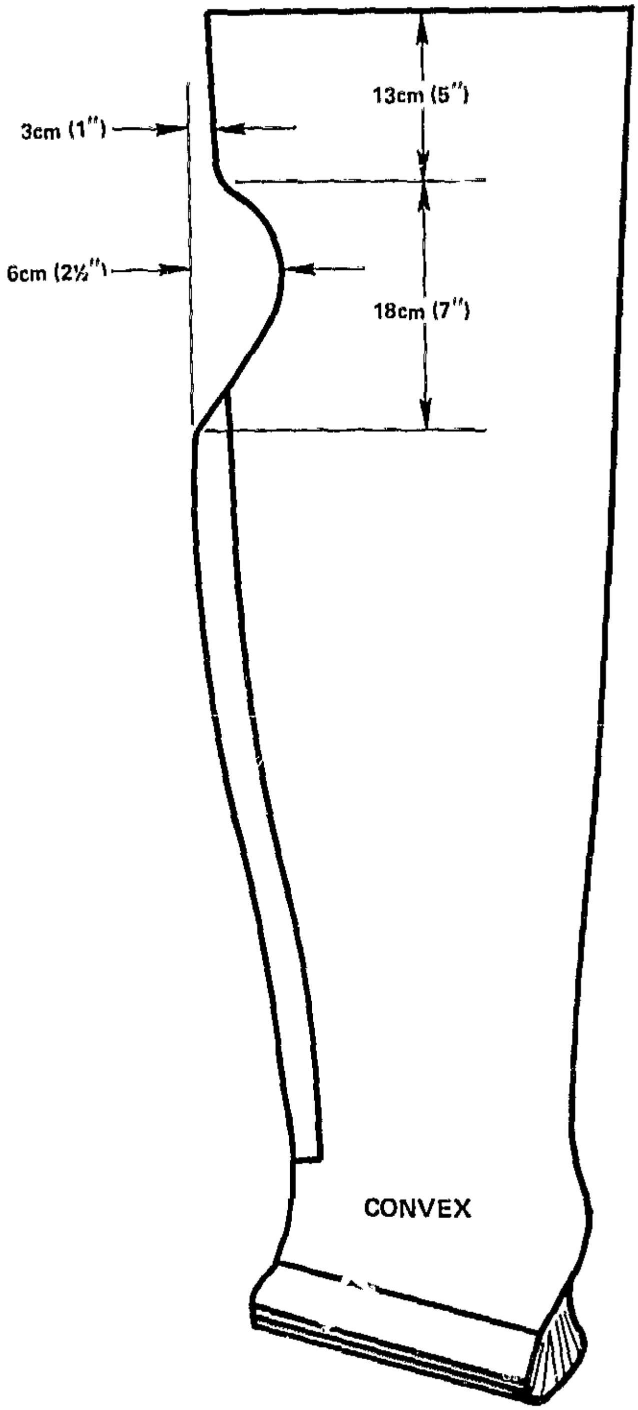



Figure 29 Estimated Damage to Graphite/Epoxy Blade C-2 Following the First Impact with 320g Gelatin Ball

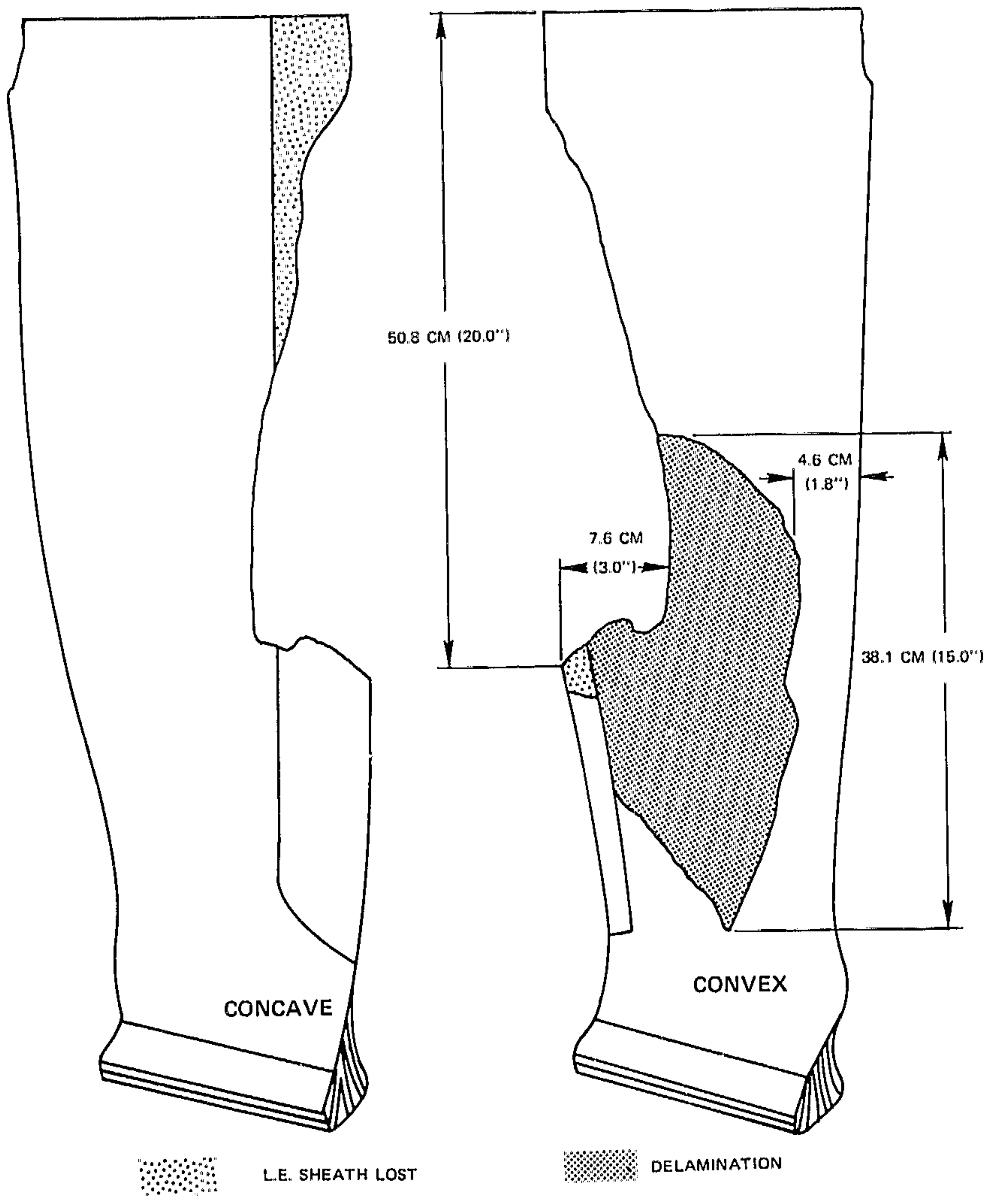
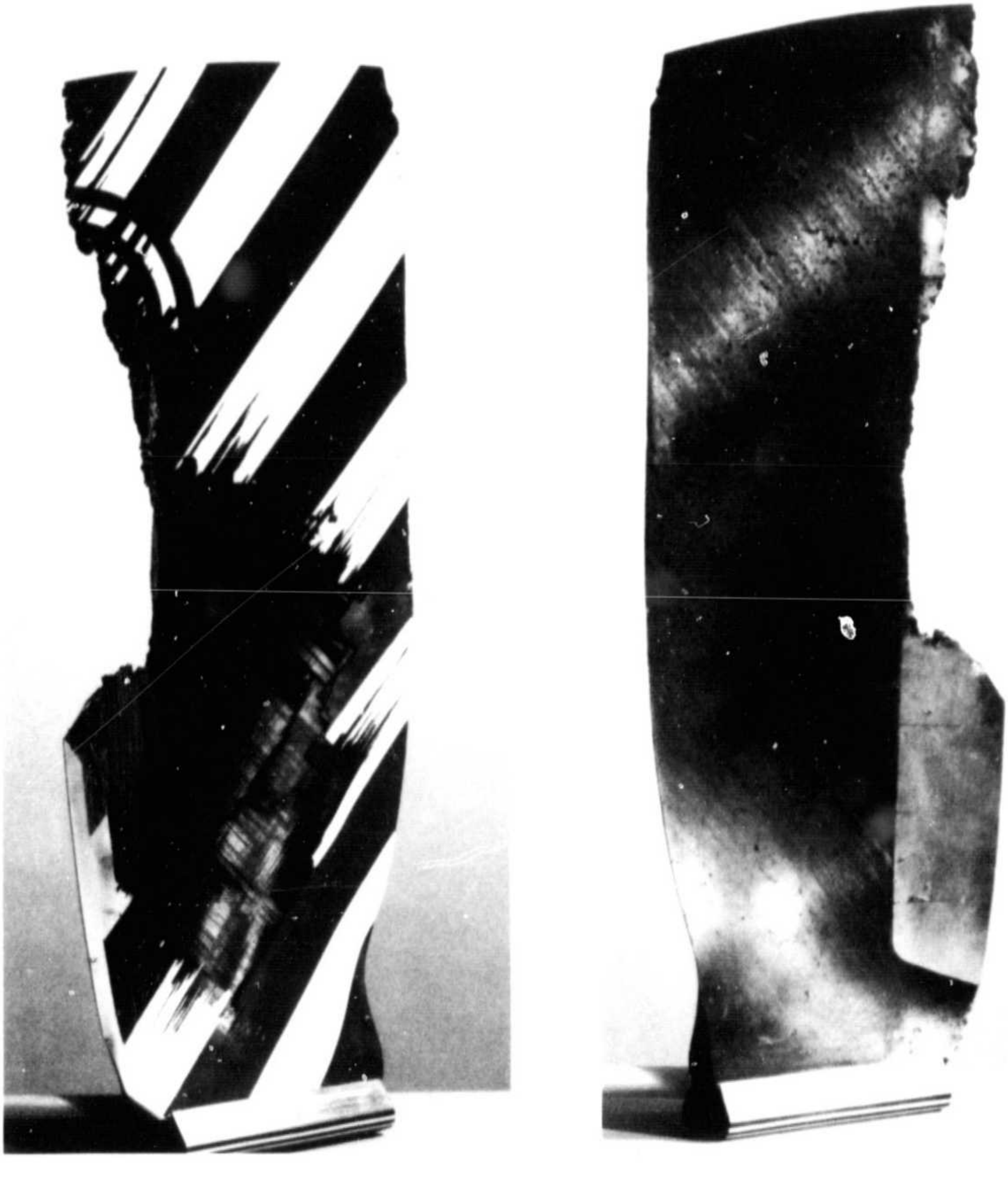



Figure 30 Visual Damage to Graphite/Epoxy Blade C-2 Following Two Impacts with 320g Gelatin Ball



CONVEX CONCAVE

Figure 31 Graphite/Epoxy Blade C-2 Following Two Impacts with 320g Gelatin Ball

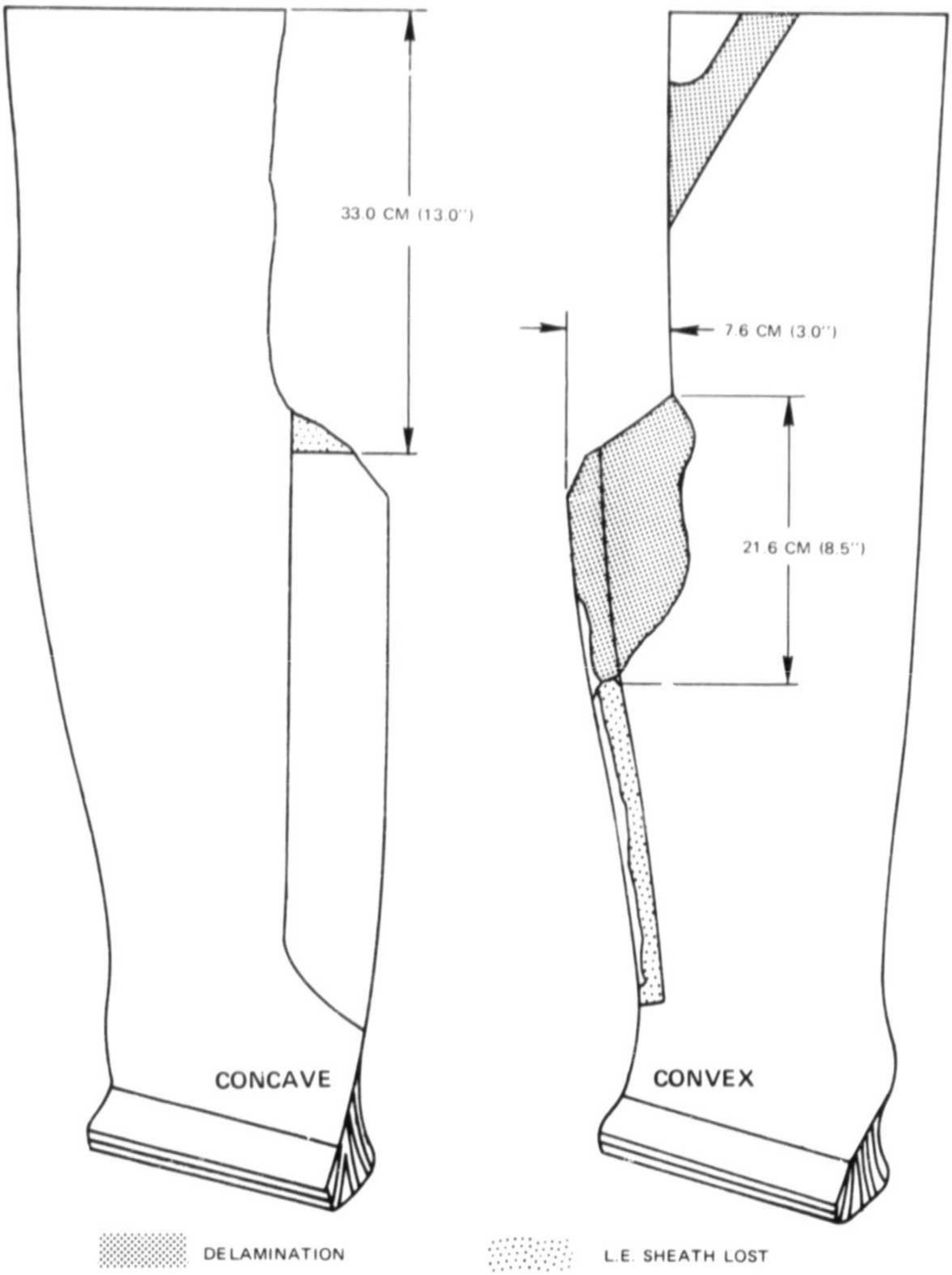



Figure 32 Visual Damage to Graphite/Epoxy Blade C-3 Following Impact with 165g Gelatin Ball


CONVEX CONCAVE

Figure 33 Graphite/Epoxy Blade C-3 Following Impact with 165g Gelatin Ball

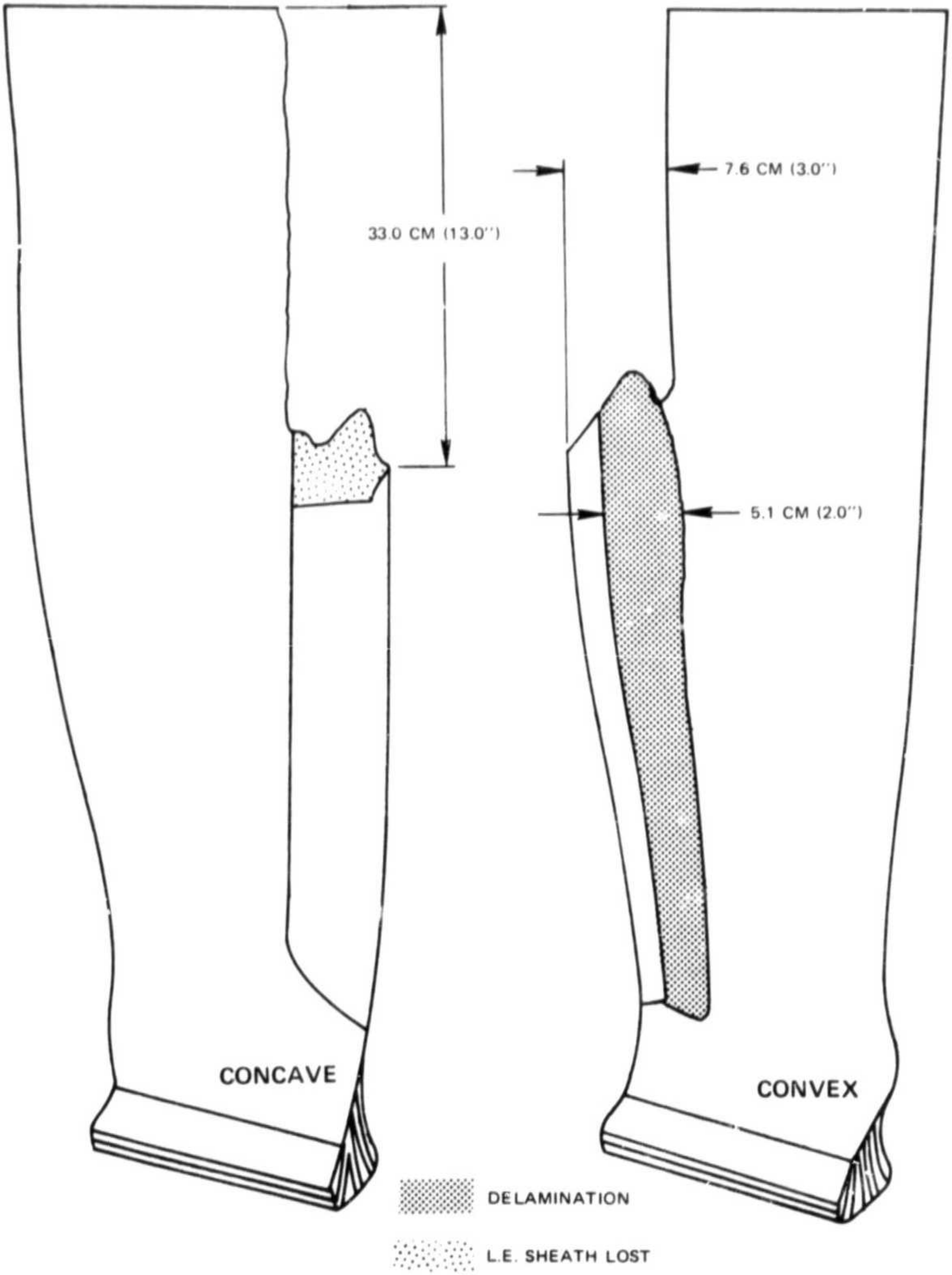
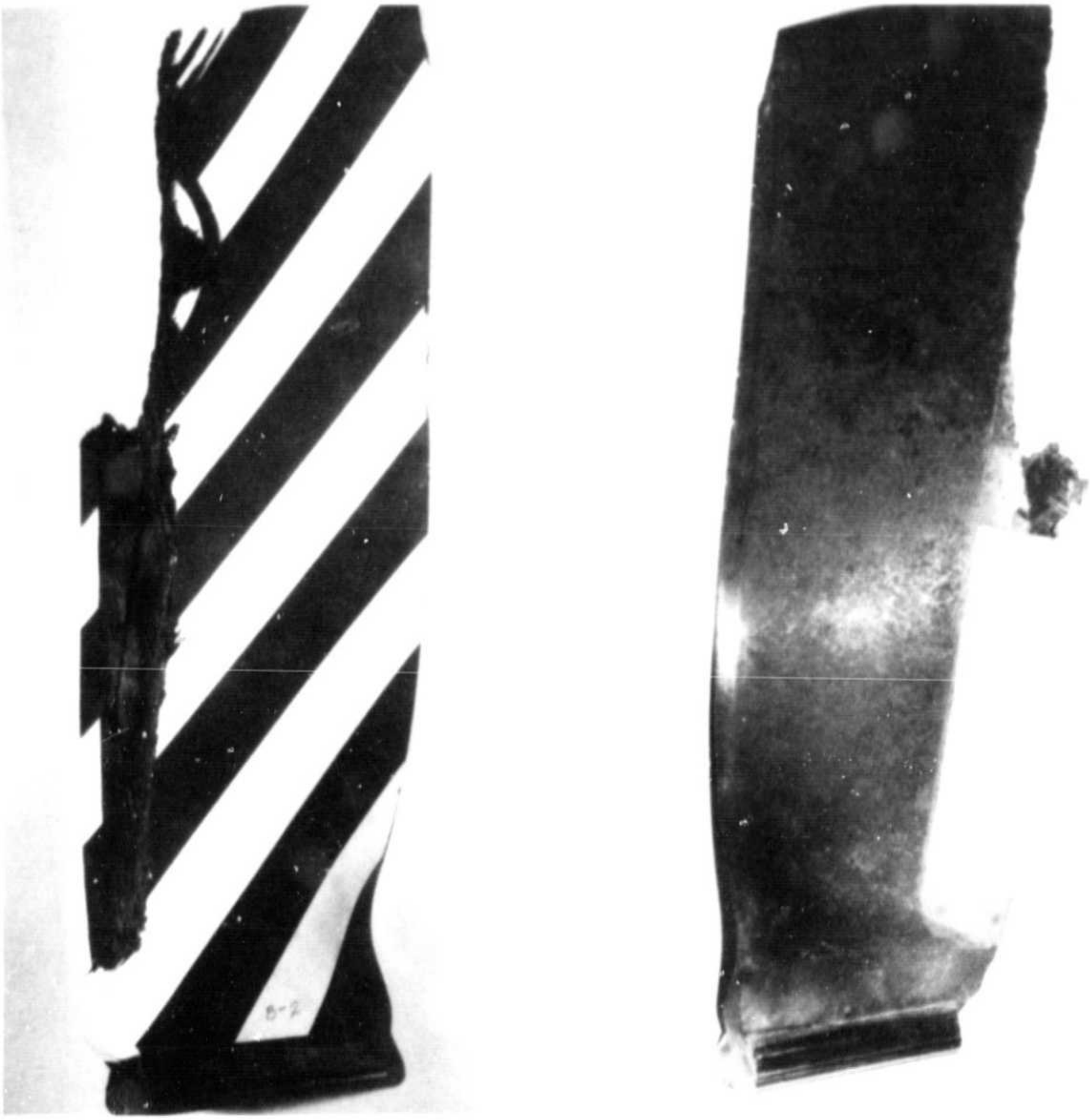



Figure 34 Visual Damage to Boron/Epoxy Blade B-2 Following Impact with 320g Gelatin Ball



CONVEX CONCAVE

Figure 35 Boron/Epoxy Blade B-2 Following Impact with 320g Gelatin Ball

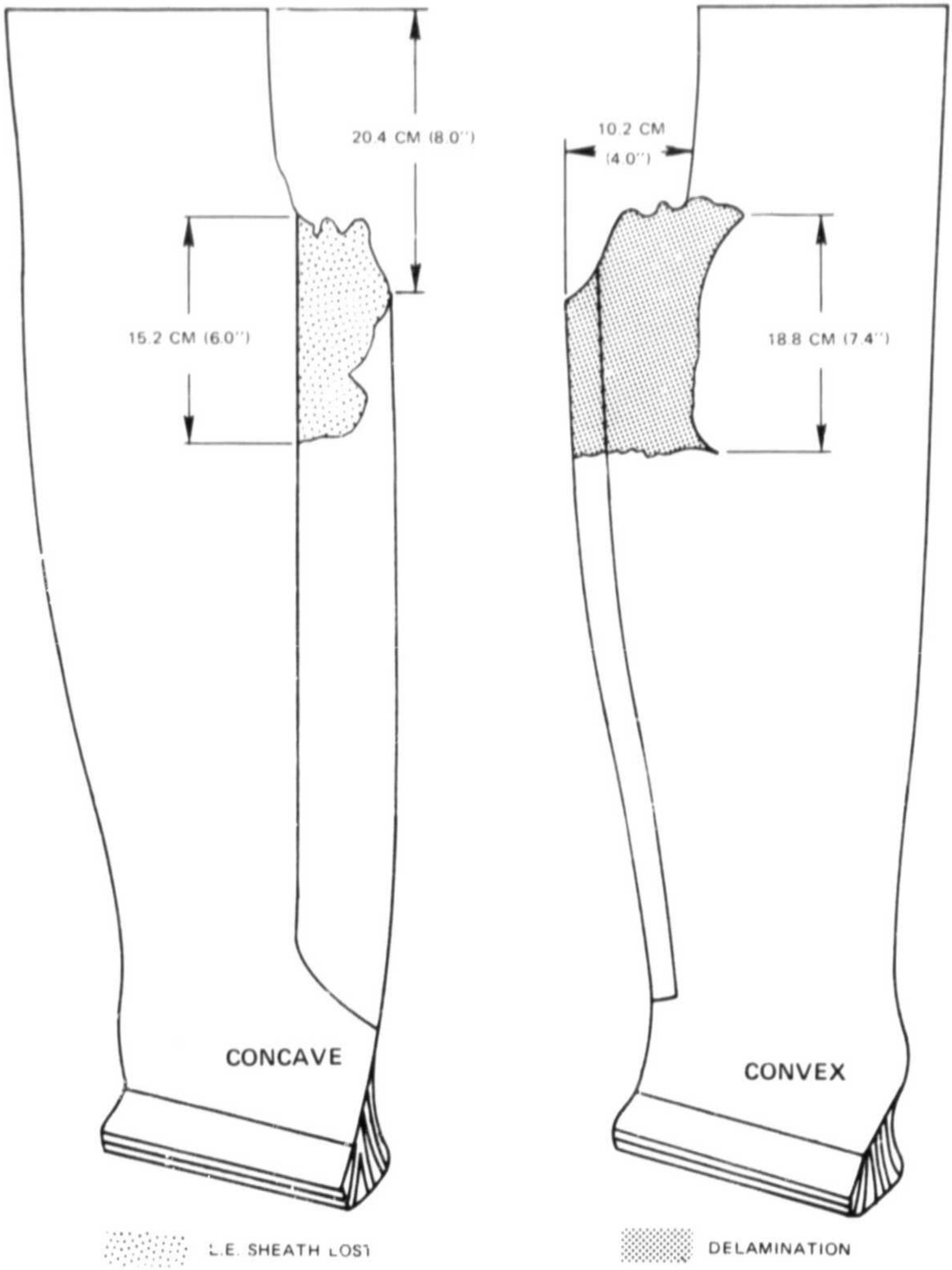



Figure 36 Visual Damage to Boron/Epoxy Blade B-3 Following Impact with 165g Gelatin Ball


CONVEX

CONCAVE

Figure 37    Boron/Epoxy Blade B-3 Following Impact with 165g Gelatin Ball

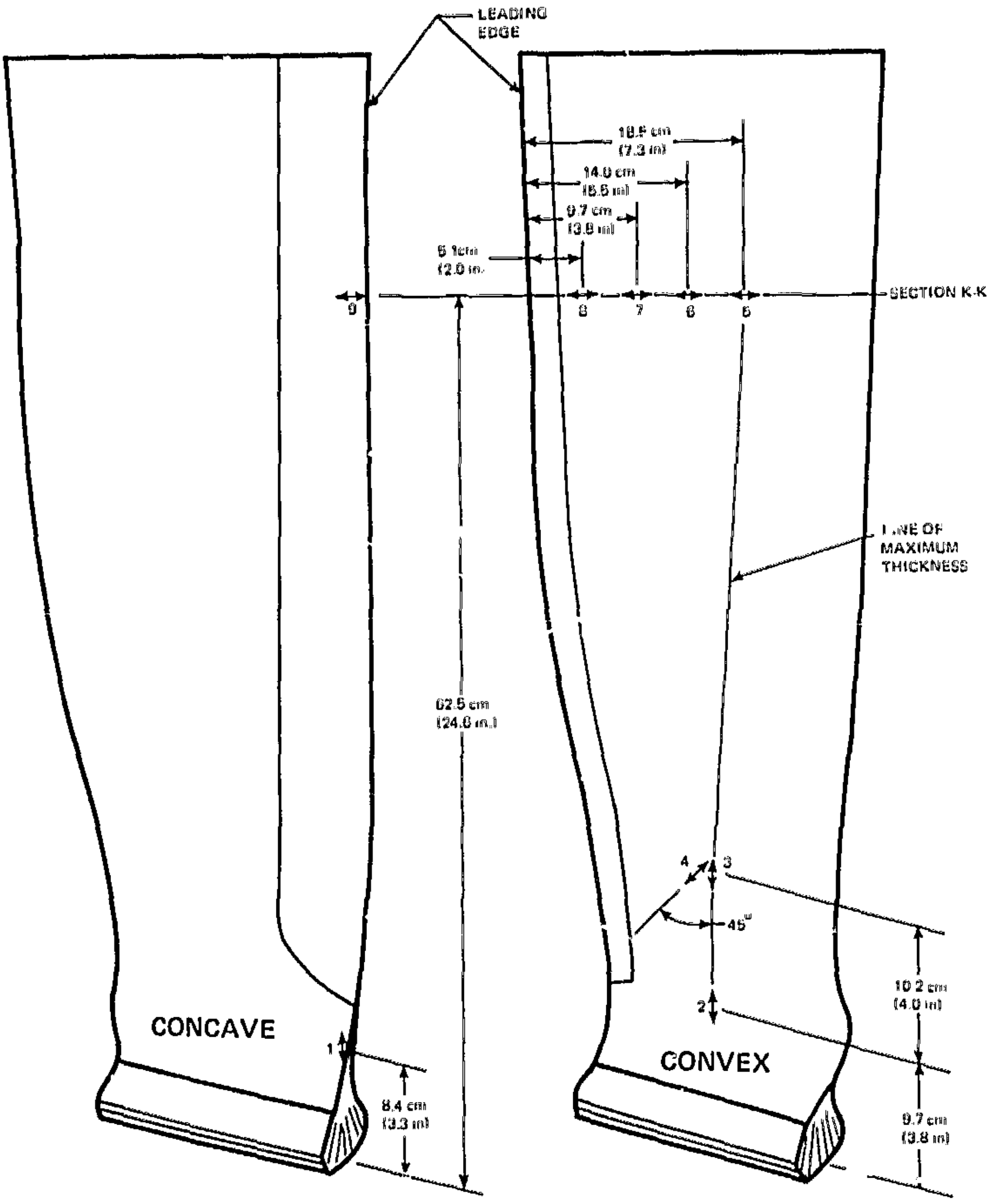



Figure 38    Strain Gage Locations on Blades C-3 and B-3

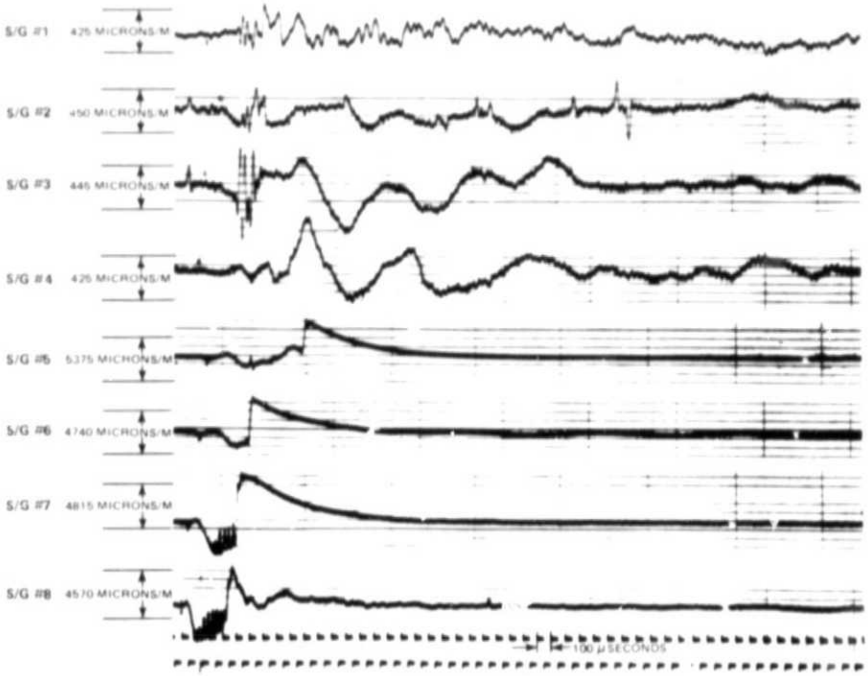



Figure 39 Strain Gage Oscillograph Record from Impact Test of Graphite/Epoxy Blade C-3

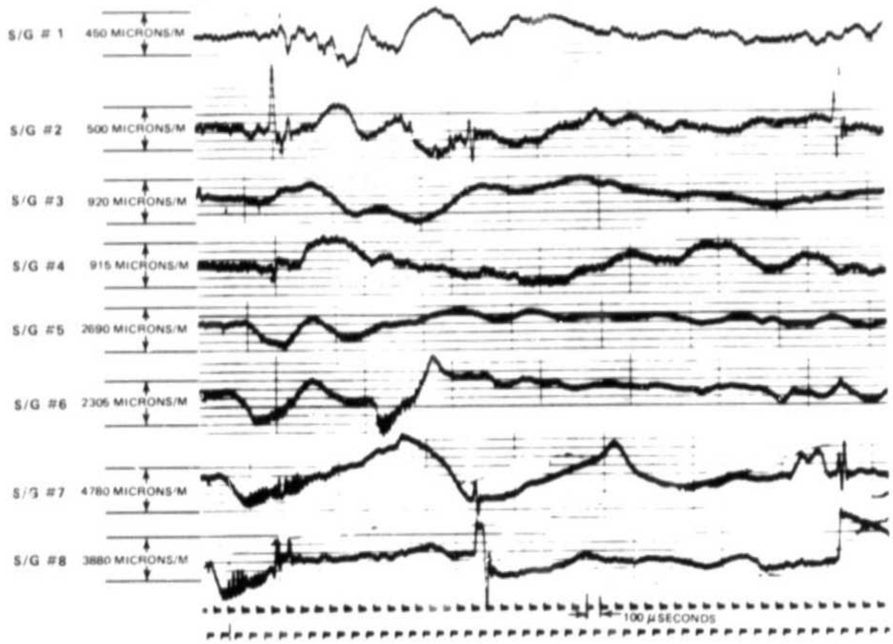



Figure 40 Strain Gage Oscillograph Record from Impact Test of Boron/Epoxy Blade B-3

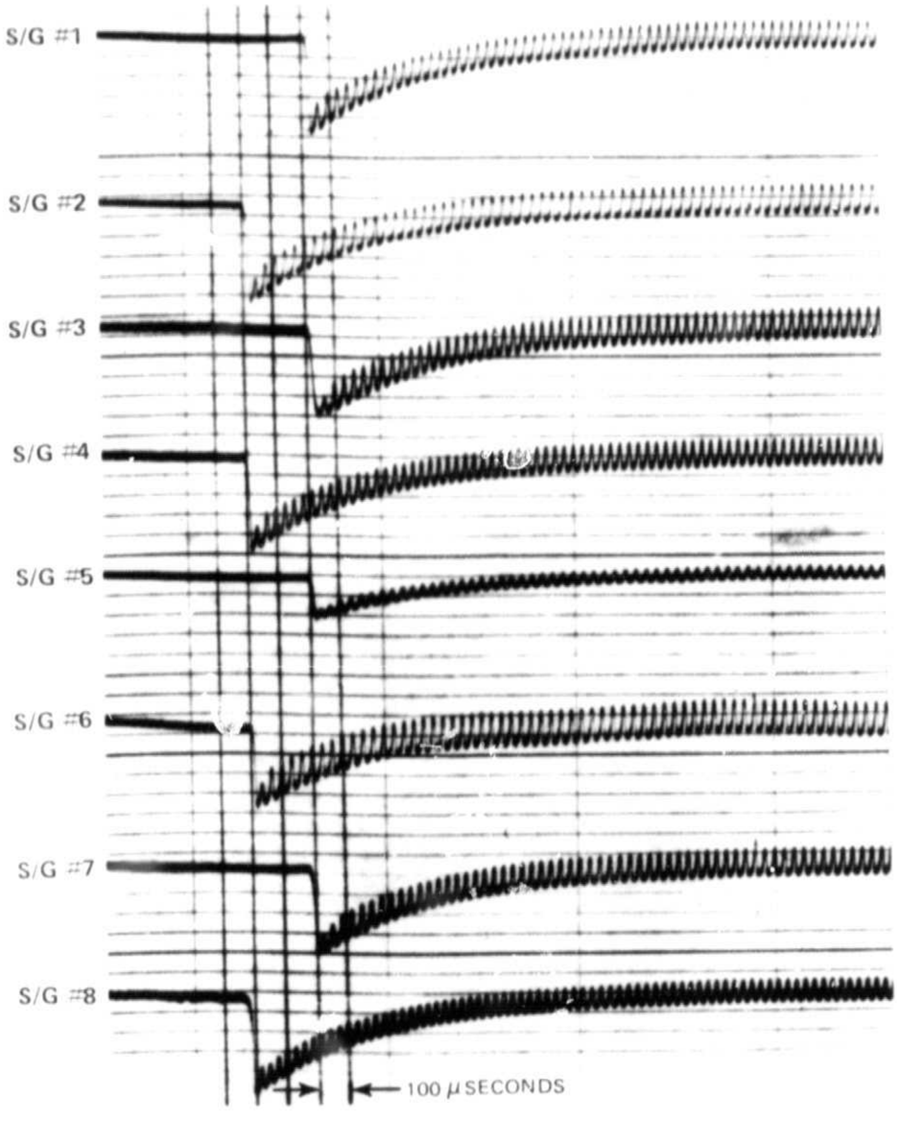



Figure 41 Magnetic Tape/Oscillograph System Time Calibration Record

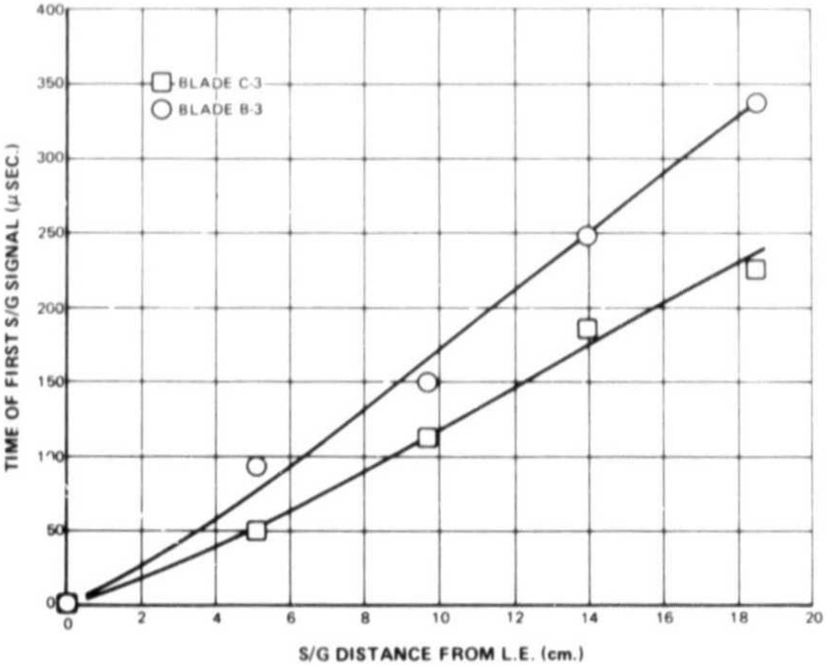



Figure 42 Strain Gage Disturbance Time at Impact Section K-K

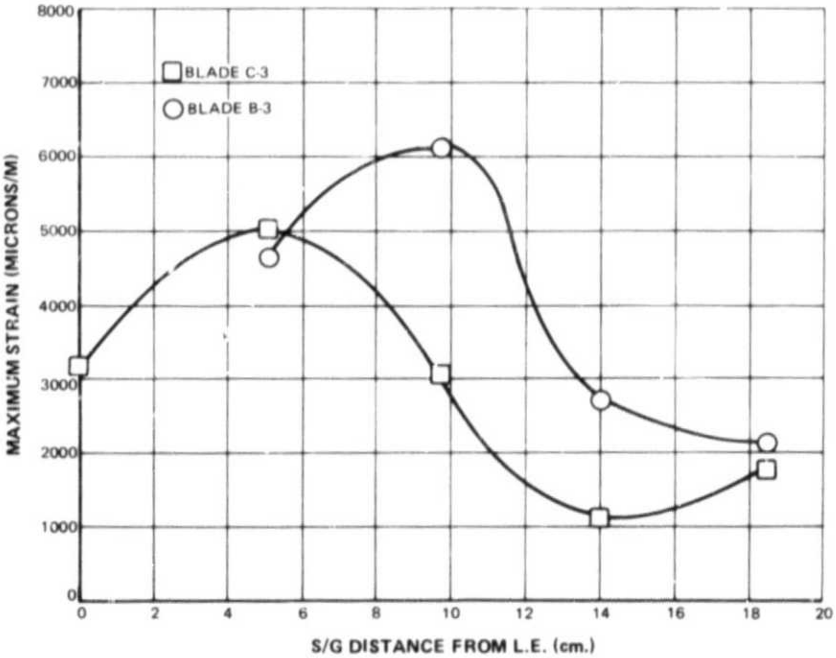



Figure 43 Maximum Strain at Impact Section K-K

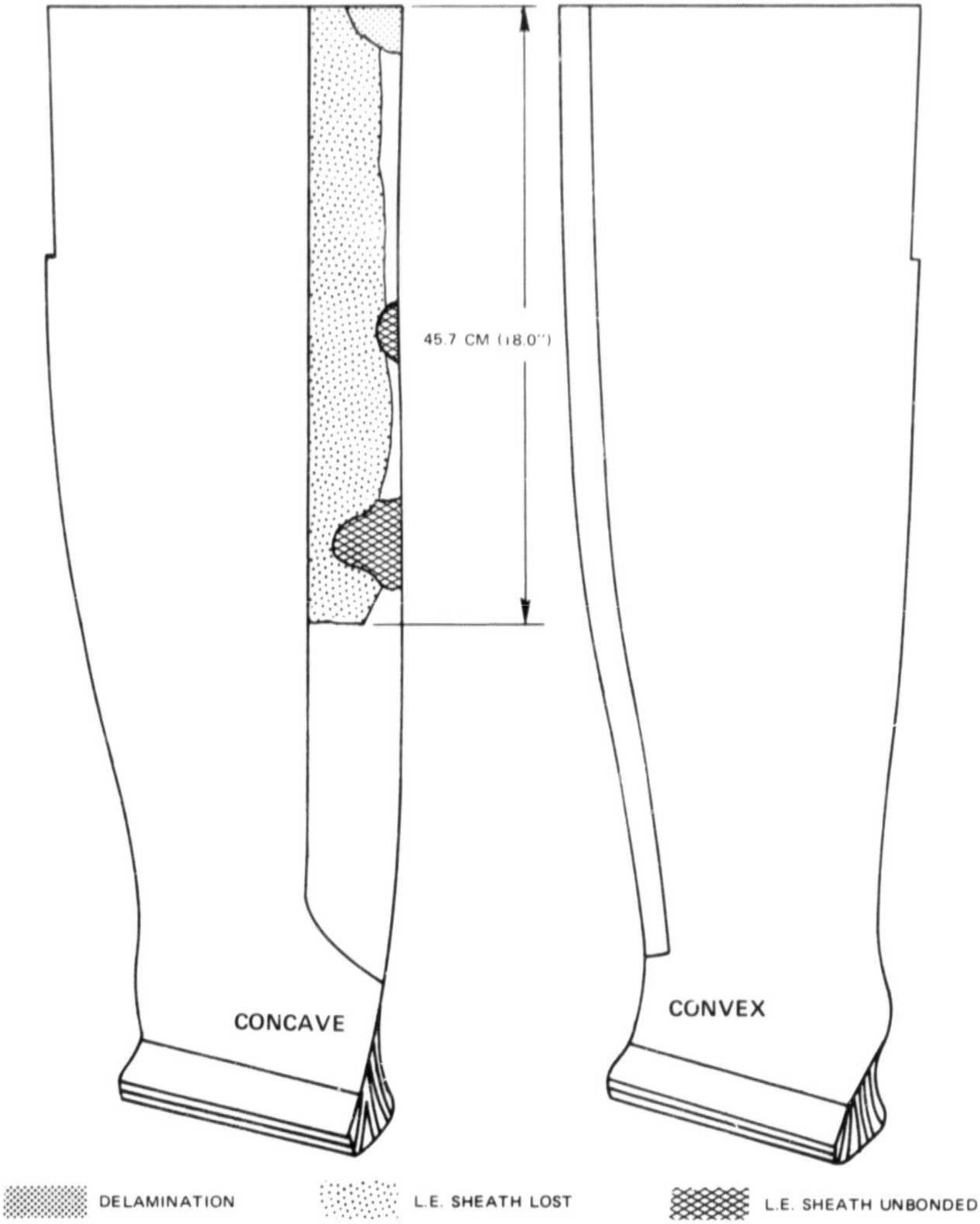



Figure 44 Visual Damage to Graphite/Epoxy Blade C-4 Following Impact with Gravel


CONVEX CONCAVE

Figure 45 Graphite/Epoxy Blade C-4 Following Impact with Gravel

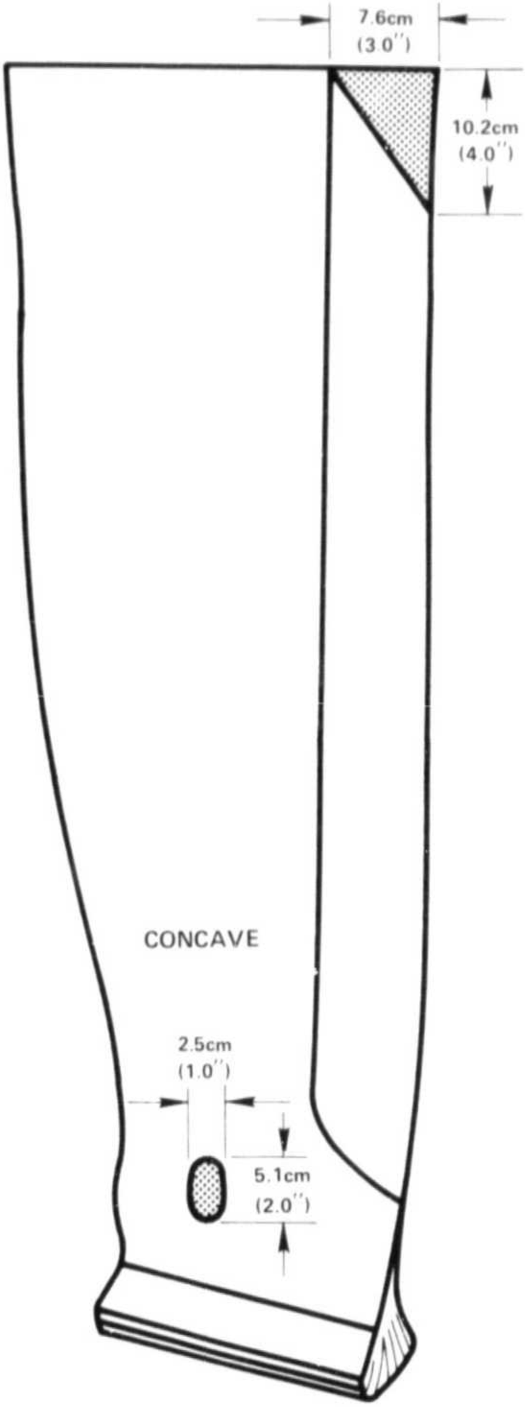



Figure 46 Post Test Ultrasonic Indications on Graphite/Epoxy Blade C-4

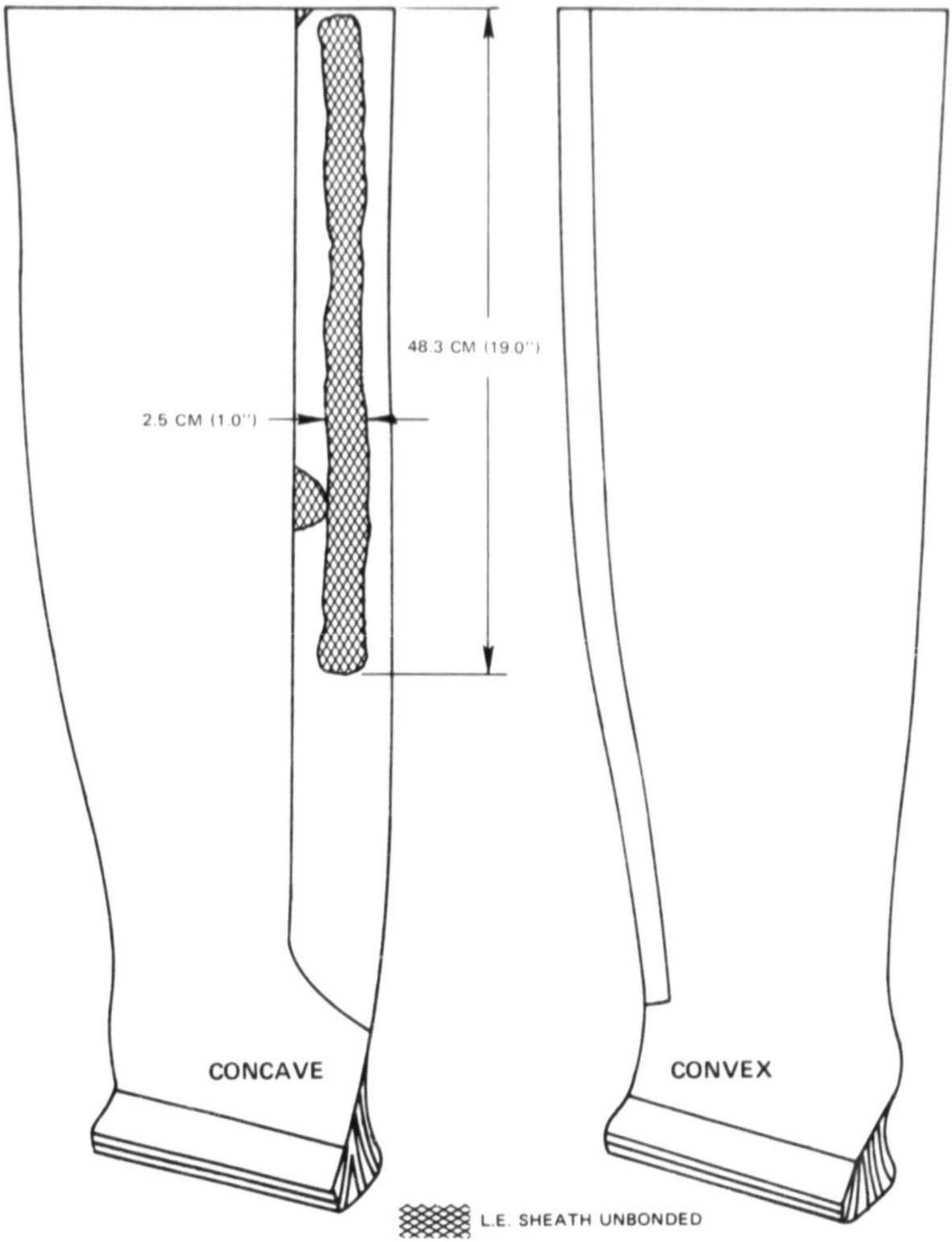
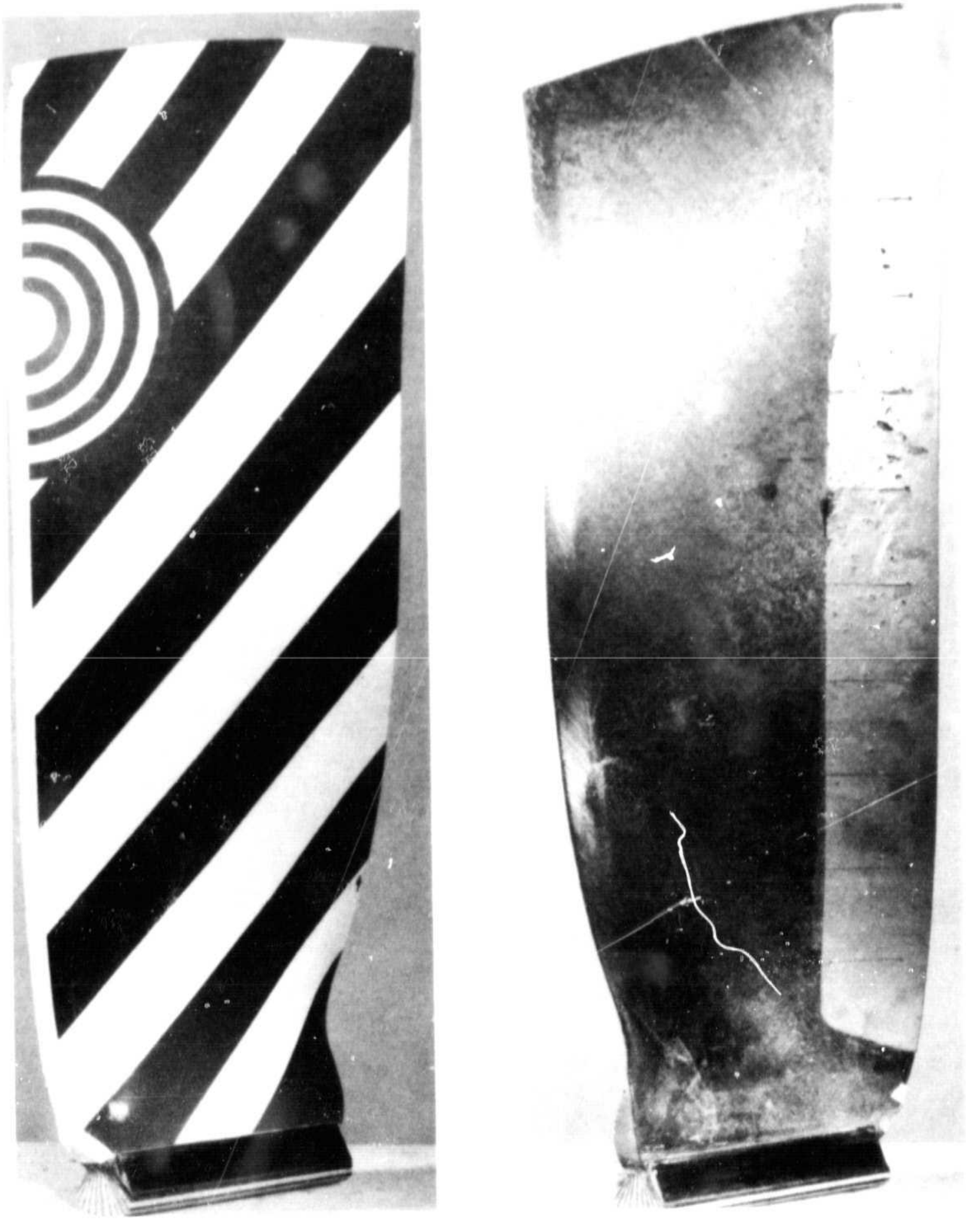



Figure 47 Visual Damage to Boron/Epoxy Blade B-4 Following Impact with Gravel



CONVEX CONCAVE

Figure 48 Boron/Epoxy Blade B-4 Following Impact with Gravel

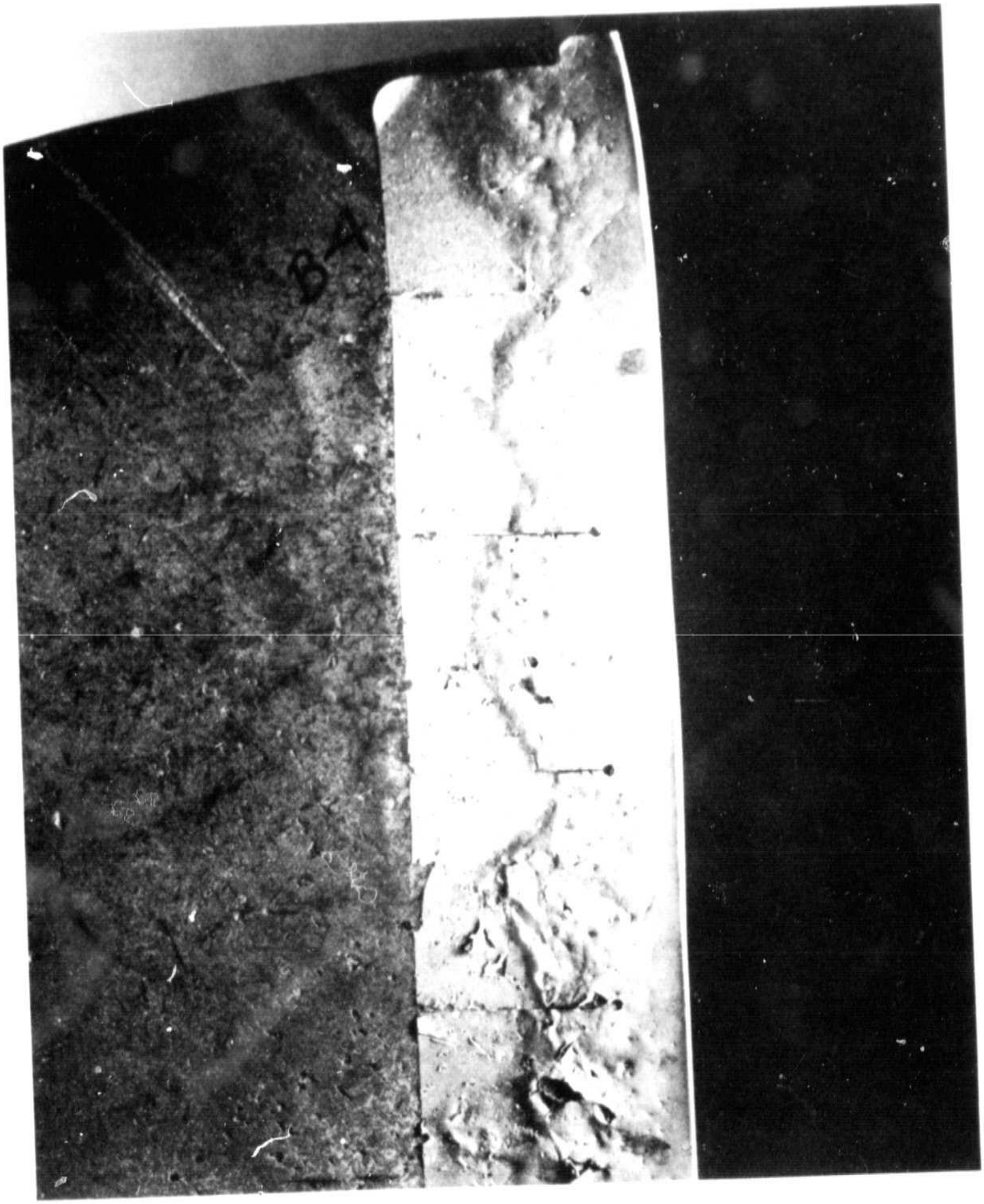
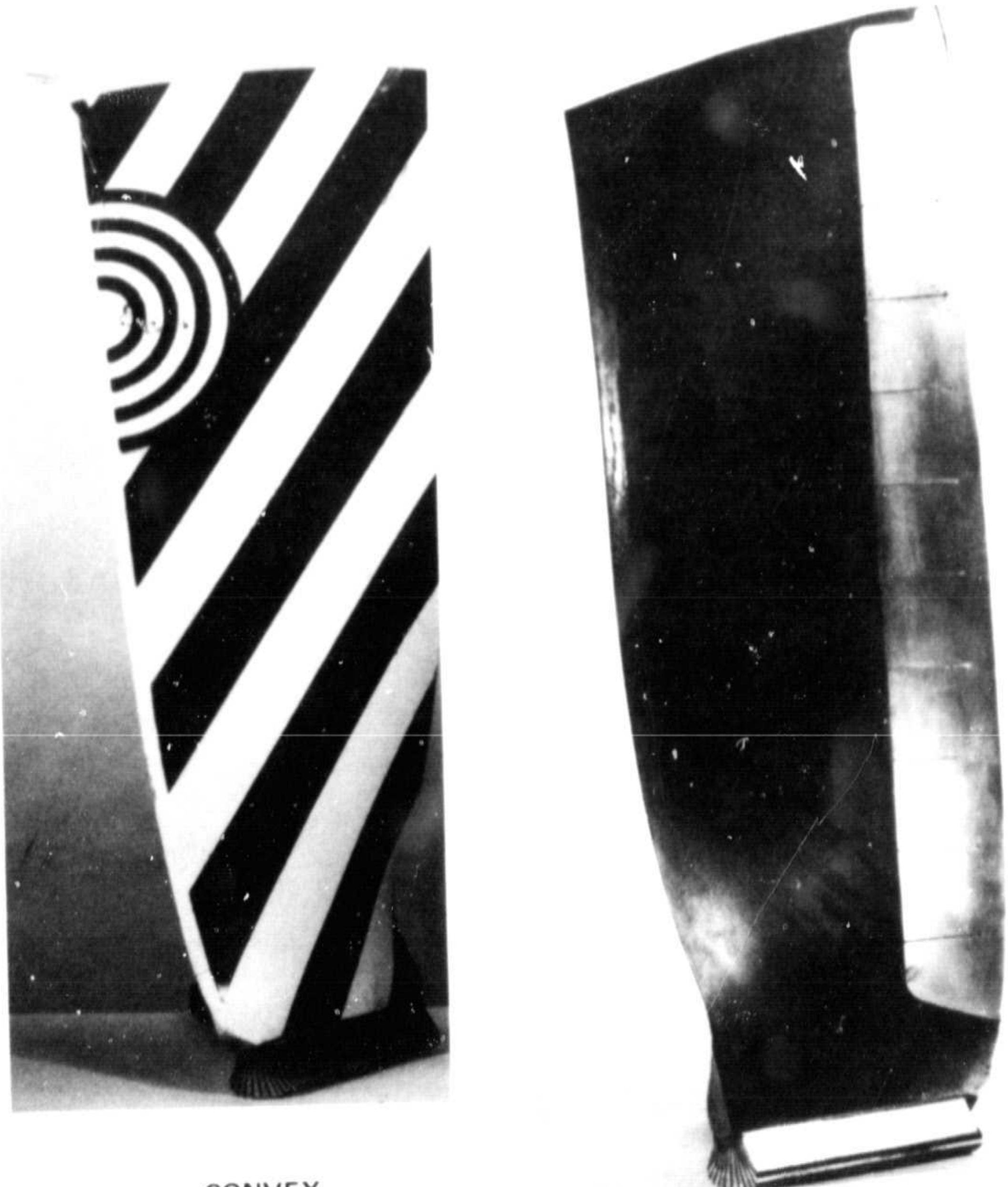



Figure 49 Boron/Epoxy Blade B-4 Following Impact with Gravel


CONVEX CONCAVE

Figure 50 Graphite/Epoxy Blade C-5 Following Impact with 75g Starling



CONVEX

CONCAVE

Figure 51 Boron/Epoxy Blade B-5 Following Impact with 80g Starling

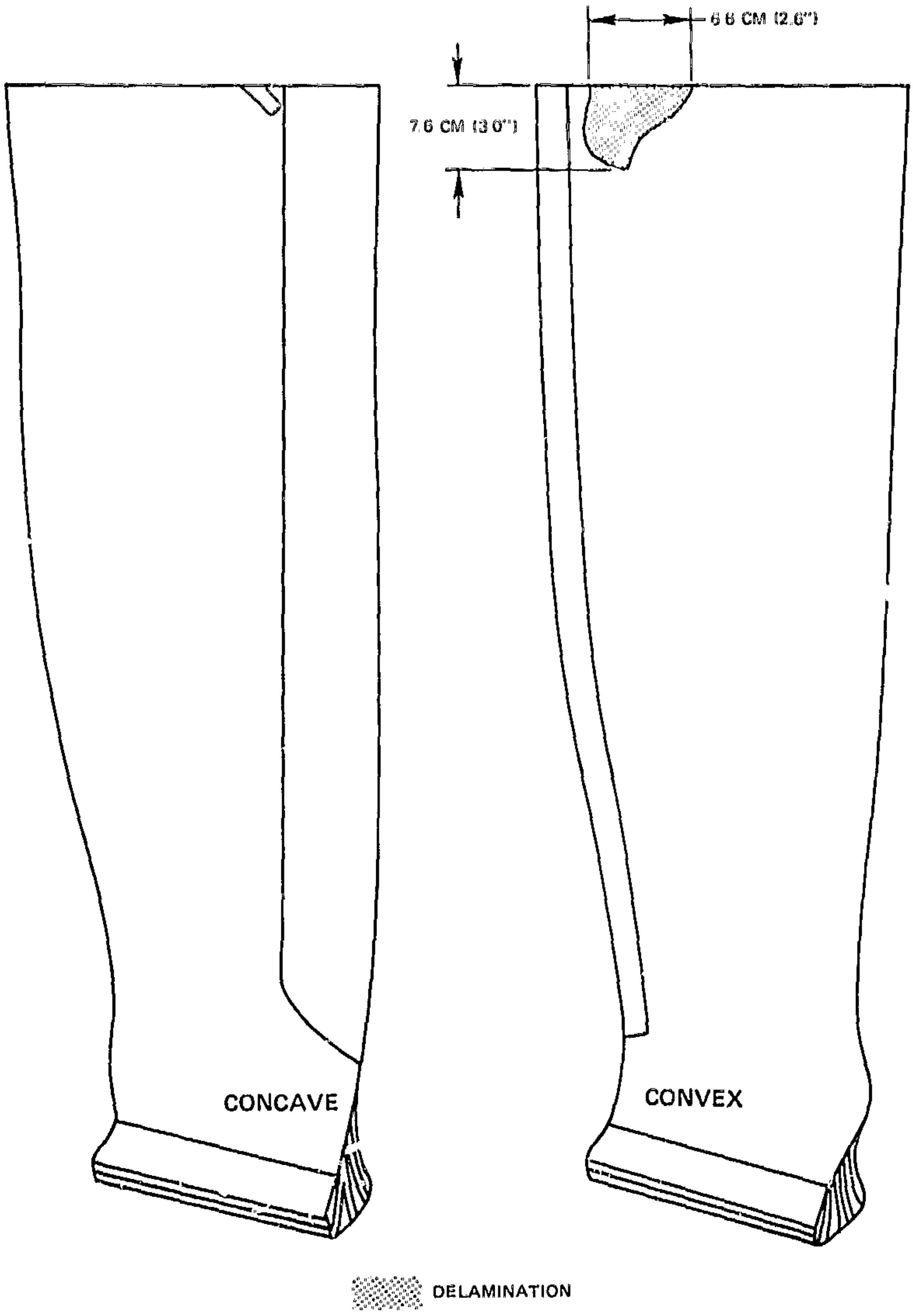



Figure 52 Visual Damage to Graphite/Epoxy Blade C-5 Following Impact with Starling

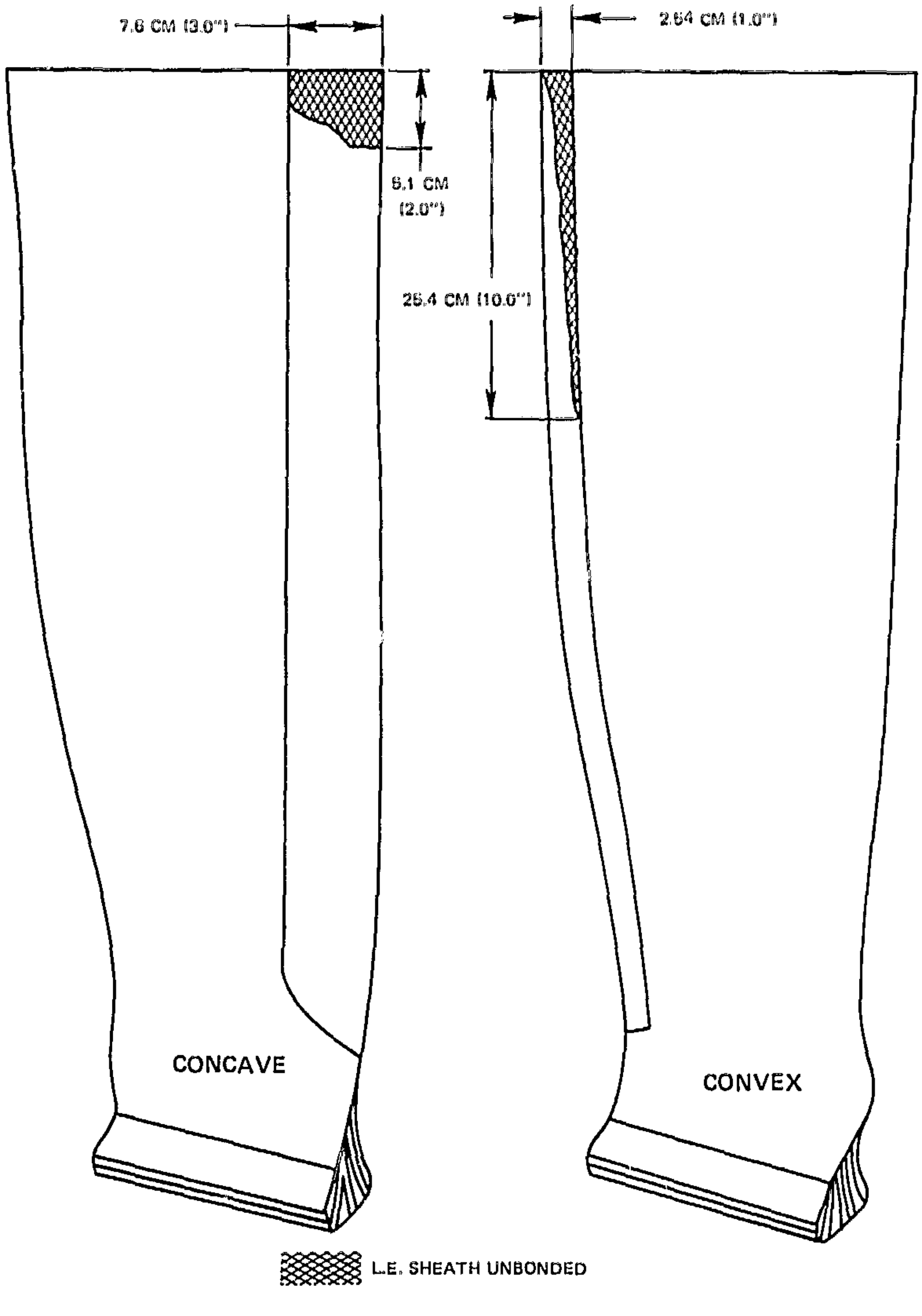



Figure 53 Visual Damage to Boron/Epoxy Blade B-5 Following Impact with Starling

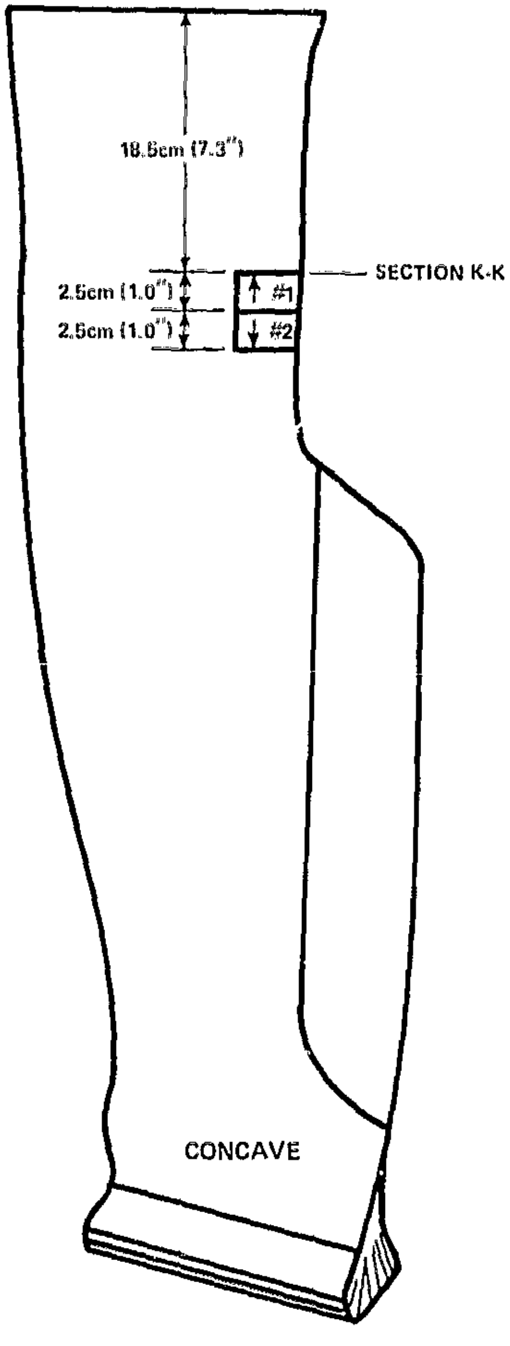



Figure 54 Metallographic Section Locations - Graphite/Epoxy Blade C-3

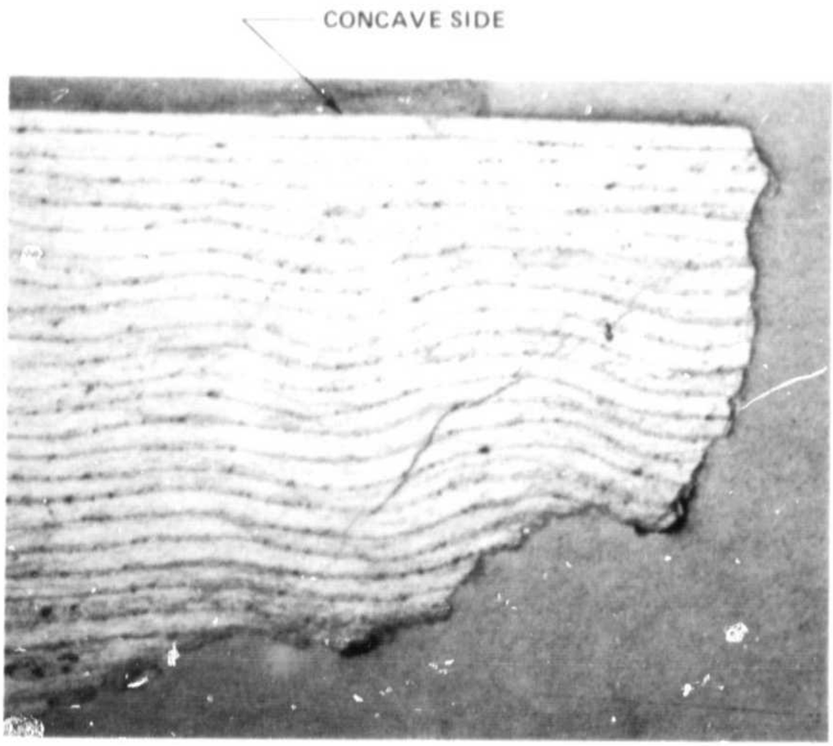



Figure 55 Photo-micrograph of Area 1, (Figure 54), of Graphite/Epoxy Blade C-3 Showing Shear Crack (15X)

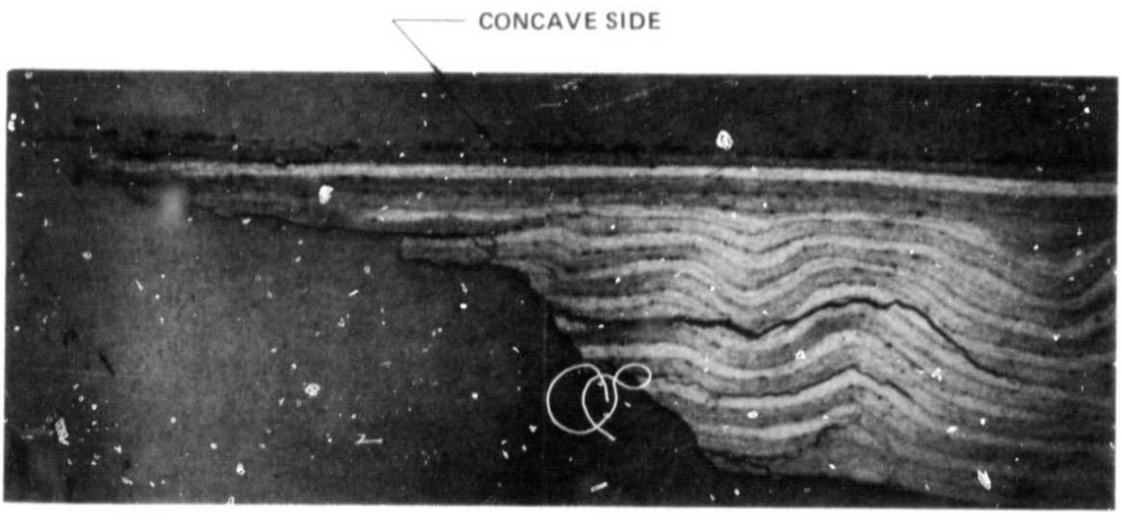



Figure 56 Photo-micrograph of Area 2, (Figure 54), Graphite/Ep[illegible] Blade C-3 Showing Interlaminar Separations (13X)

## APPENDIX A
## PREPREG TAPE QUALITY ASSURANCE TEST METHODS

Identical test techniques were utilized for both Modmor II graphite/BP-907 epoxy and Boron/BP-907 epoxy prepreg tapes except where otherwise noted. Tests run "after one week" were conducted in identical fashion to the "as received" tests, except that the prepreg tape was stored in a closed cabinet at ambient temperature, pressure, and humidity conditions for 7 days prior to testing.

### A. RESIN CONTENT

Graphite/Epoxy

1. Cut two 8 cm x 8 cm (3 in. x 3 in.) squares of prepreg from each tape to be inspected.
2. Weigh each square to 0.0001 g and record weight.
3. Digest the resin from each square for two hours in concentrated nitric acid at 339°K (150°F).
4. Wash fibers using 10 percent nitric acid in water followed by distilled water.
5. Dry 16 hours at approximately 389°K (240°F).
6. Weigh fibers to 0.0001 g.
7. Weight percent resin $= \dfrac{\text{initial prepreg weight - fiber weight}}{\text{initial prepreg weight}} \times 100\%$

Boron/Epoxy

1. Cut two 8 cm x 8 cm squares of prepreg from each tape to be inspected.
2. Weigh each square to 0.0001 g and record weight.
3. Burn out the resin for 12 hours at 645°K (700°F).
4. Weigh boron fiber and fiberglass scrim residue to 0.0001 g.
5. Weight percent resin $= \dfrac{\text{initial prepreg weight - boron and fiberglass weight}}{\text{initial prepreg weight}} \times 100\%$

### B. VOLATILE CONTENT

1. Cut two 8 cm x 8 cm squares of prepreg from non-adjacent locations in each tape to be inspected.
2. Weigh each immediately to 0.0001 g.
3. Place each square in an air circulating oven at 422°K (300°F) for ½ hour.
4. Remove and weigh to 0.0001 g.
5. Weight per cent volatiles $= \dfrac{\text{initial weight - dry weight}}{\text{initial weight}} \times 100\%$

C. RESIN FLOW

1. Prepare two flow specimens from each tape to be inspected.
2. Cut four pieces of prepreg 8 cm x 8 cm square, for each specimen, and weigh to 0.01 g.
3. Cut two 10 cm x 10 cm (4 in x 4 in) pieces of TX-1040 Teflon release fabric, four equal pieces of style 181 glass scrim bleeder cloth, and two 20 cm x 20 xm (8 in x 8 in) pieces of Mylar film.
4. Layup test specimen as follows:
   Mylar | glass | glass | Teflon | prepreg: 0° | 90° | 0° | 90° | Teflon | glass | glass | Mylar.
5. Insert layup into hot platen press at 422°K (300°F), apply 2.07 MN/m2 (300 psi) immediately, and hold for 15 minutes.
6. Remove layup from press, remove 4 ply composite panel, remove any excess resin flash from panel and reweigh to 0.01 g.
7. Weight per cent resin flow $= \dfrac{\text{initial weight - final weight}}{\text{initial weight}} \times 100\%$

D. GEL TIME

1. Prepare two gel time specimens from each tape to be inspected.
2. Cut eleven to sixteen pieces [as required to mold to .20 cm (80 mils) nominal thickness] of prepreg, 3 cm x 3 cm (1 in x 1 in) square, for each specimen.
3. Lay-up specimen with plies alternating between 0° and 90° fiber orientation.
4. Wrap specimen in aluminum foil with a notch cut in one end to allow resin squeeze-out.
5. Insert specimen in platen press between two aluminum plates .23 cm x 6.4 cm x 6.4 cm (.09 in x 2.5 in x 2.5 in) preheated to 422°K (300°F).
6. Start stop-watch and close press just enough to produce resin bead at the notch in a minimum period of time.
7. Probe resin bead with rods until long strings or threads of resin cease to form and stop stop-watch.
8. Gel time in minutes is read from stop watch.

## APPENDIX B
## COMPOSITE LAMINATE QUALITY ASSURANCE TEST METHODS

Identical test methods were employed for testing the Modmor II graphite/BP-907 epoxy and boron/BP-907 epoxy laminates unless otherwise indicated.

### A. LAMINATE MOLD CYCLE

1. Preheat press to 422°K (300°F).
2. Load prepreg into cold mold.
3. Load cold mold into hot press. Apply contact pressure.
4. Start applying additional pressure as panel reaches 408° to 422°K (275° to 300°F).
5. Close mold to stops at 422°K, hold for 2 hours.
6. Remove panel from mold.
7. Postcure panel for 2 hours at 450°K (350°F).

### B. TENSILE TESTS

Tests were conducted in accordance with ASTM Standards E8-66 and E21-66T with the following exceptions:

1. The test specimen configuration used for longitudinal, 0°, tests of unidirectional material is given in Figure B-1.
2. An alignment fixture is employed to ensure that loading is coincident with the filament direction and that bending moments are kept to a minimum.
3. A layer of compliant doubler material, such as fiberglass, is bonded to gripping surfaces of all longitudinal specimens.
4. Strain gages are mounted on both sides of the specimen in the center of the gage section at midwidth. These strain measurements are used in modulus determinations and to confirm alignment.
5. Tests are conducted at a strain rate of .005 cm/cm/min (0.005 in/in/min).

### C. SHORT BEAM INTERLAMINAR SHEAR TESTS

Tests were conducted in accordance with ASTM Proposed Standard Revision D2344-67 with the following exceptions:

1. The test specimen configuration used is shown in Figure B-2.
2. The span to thickness ratio is 4.00 ± 0.01 to 1.
3. The filament orientation is parallel to the longitudinal beam axis within 0° 30′.

## D. PANEL QUALITY INSPECTION

Density.

Panel densities were determined by weighing in air, then weighing suspended in distilled water. Panel density is then:

$$\text{density (g/cc)} = \frac{\text{dry weight}}{\text{dry weight} - \text{wet weight}}$$

Cured Ply Thickness.

Average panel thicknesses were determined using flathead micrometer readings at a minimum of 6 different locations. The cured ply thickness is determined by dividing the average thickness by the number of plies.

Volumetric Analysis (graphite/epoxy).

Determination of fiber, resin and void contents were made by a wet chemical process employing concentrated nitric acid at 339°K (150°F) to dissolve the resin fraction of the composite. The fiber weight is determined by weighing the residue after chemical leaching; the resin weight is the difference between the fiber weight and the original specimen weight. The fiber and resin volumes are determined by dividing the constituent weights by their respective densities. The initial specimen volume is determined by dividing the initial specimen weight by the laminate density. Constituent volume fractions are determined by dividing the constituent volumes by the specimen volume. The void volume fraction is then:

$$\text{Void Volume \%} = 100\% - \text{Resin Volume \%} - \text{Fiber Volume \%}.$$

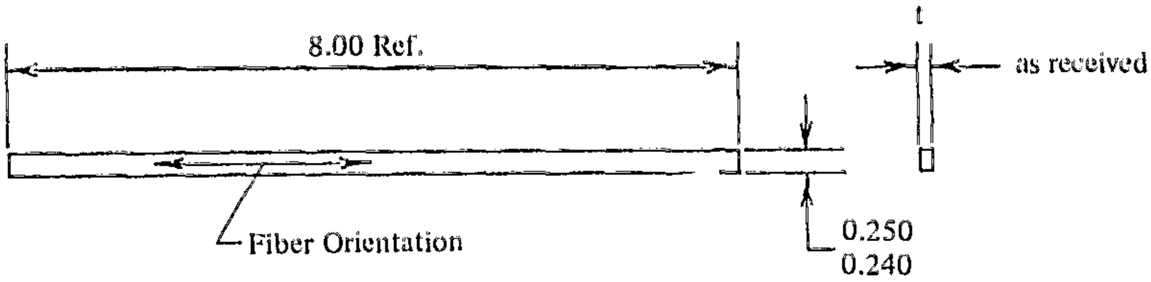
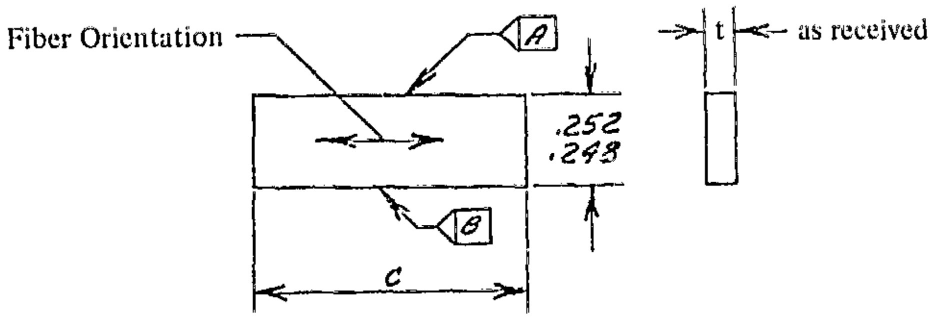



Figure B-1 Longitudinal Tensile Specimen Unidirectional Material




Surfaces A & B must be flat and parallel within 0.002 FIR

Figure B-2 Short Beam Shear Specimen Unidirectional Material