AD-A133 305 RUBBER-MODIFIED EPOXY AND GLASS LAMINATES FOR APPLICATION TO NAVAL SHIP STRUCTURES(U) DAVID W TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER BET.. 1/1

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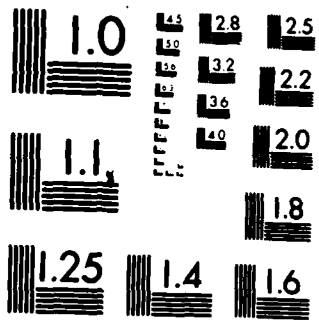

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: DTNSRDC-83/048
2. GOVT ACCESSION NO.: AD-A133305
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): RUBBER-MODIFIED EPOXY AND GLASS LAMINATES FOR APPLICATION TO NAVAL SHIP STRUCTURES
5. TYPE OF REPORT & PERIOD COVERED: Final
6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s):
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8. CONTRACT OR GRANT NUMBER(s):
9. PERFORMING ORGANIZATION NAME AND ADDRESS:
David W. Taylor Naval Ship Research and Development Center
Bethesda, Maryland 20084
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: (See reverse side)
11. CONTROLLING OFFICE NAME AND ADDRESS: Naval Sea Systems Command, Washington, D.C. 20362
12. REPORT DATE: September 1983
13. NUMBER OF PAGES: 40
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):
15. SECURITY CLASS. (of this report): UNCLASSIFIED
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:
16. DISTRIBUTION STATEMENT (of this Report):

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):
18. SUPPLEMENTARY NOTES:

Presented at: 28th National Sampe Symposium, 12-14 April 1983, Anaheim, California

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Naval ship structures, composites, glass-reinforced plastics, rubber-toughened laminates

20 ABSTRACT (Continue on reverse side if necessary and identify by block number)

Because the decks and other structural elements of naval combatants are exposed to extreme handling and wear loads during construction, and operational and overhaul periods, a rubber-modified epoxy resin is being evaluated for application to naval ship structures. Preliminary results indicate that the rubber-modified resin performs substantially better in

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

(Block 10)

Program Element 62761N
Task Area SF 615 415 01
Work Unit 1730-635

(Block 20 continued)

impact-resistance tests than do laminates of standard brittle glass-reinforced plastic (GRP). Drop-ball impact tests are performed on 6.5-in. diameter, 0.25-in. thick disks. Currently very little is known about the mechanics of this phenomena, its long-term behavior in a marine environment, and its characteristics when incorporated into a complex structure. A series of tests have been conducted on specimens, joints, panels, and structural components in an attempt to gain more information. Two generic carboxy terminated butadiene acrylonitrile (CTBN)-modified epoxy/glass cloth material systems have been characterized, exposed to fatigue and long-term immersion loading, and evaluated when incorporated into several different structural configurations. The results of all these tests indicate that this material can withstand the harsh environmental and in-service loading conditions experienced by naval combatants.

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ABSTRACT

Because the decks and other structural elements of naval combatants are exposed to extreme handling and wear loads during construction, and operational and overhaul periods, a rubber-modified epoxy resin is being evaluated for application to naval ship structures. Preliminary results indicate that the rubber-modified resin performs substantially better in impact-resistance tests than do laminates of standard brittle glass-reinforced plastic (GRP). Drop-ball impact tests are performed on 6.5-in. diameter, 0.25-in. thick disks. Currently, very little is known about the mechanics of this phenomena, its long-term behavior in a marine environment, and its characteristics when incorporated into a complex structure. A series of tests have been conducted on specimens, joints, panels, and structural components in an attempt to gain more information. Two generic carboxy terminated butadiene acrylonitrile (CTBN)-modified epoxy/glass cloth material systems have been characterized, exposed to fatigue and long-term immersion loading, and evaluated when incorporated into several different structural configurations. The results of all these tests indicate that this material can withstand the harsh environmental and inservice loading conditions experienced by naval combatants.

ADMINISTRATIVE INFORMATION

The work described herein was performed by the Surface Ship Division, Code 173, of the Structures Department and the Fabrication Technology Division, Code 2822, of the Ship Materials Engineering Department. The work was sponsored by the Naval Sea Systems Command, NAVSEA PMS 396 under the SSBN Subsystem Technology Program, by NAVSEA 05M3 under OPN funding, and by NAVSEA 05R25 under Project Number SF 615 415 01.

INTRODUCTION

The David W. Taylor Naval Ship Research and Development Center (DTNSRDC) conducted a program to evaluate various composite ship structures (such as superstructures, fairwaters, and sonar domes) incorporating a rubber-modified epoxy to improve the impact and wear resistance of the standard epoxy glass-reinforced plastic (GRP) laminates. In the past, submarine and surface ship GRP structures were fabricated using standard brittle epoxy and polyester resins to save weight and/or reduce maintenance costs as compared with fabricating them from conventional shipbuilding materials, such as steel. But these gains in weight and cost savings were somewhat offset by the fact that brittle resins tend to crack, craze and wear under the harsh environmental and inservice loading conditions experienced by naval combatants. If the toughness of these resins could be substantially improved with the addition of small amounts of carboxy terminated butadiene acrylonitrile (CTBN) rubber, the advantages of applying fibrous composites to naval ships would justify a modest research and development effort to quantitatively evaluate their potential. This report gives the results of such an evaluation, as well as the test results to determine their structural behavior under fatigue and long-term immersion.

PHYSICAL AND MECHANICAL PROPERTIES

Table 1 gives the results of several tests conducted to obtain (1) the physical and mechanical properties of the CTBN-toughened epoxy/style 181 glass cloth laminate, and (2) the minimum specified properties of a standard epoxy/style 181 glass cloth laminate for application to the Deep Submergence Rescue Vehicle (DSRV) outer fairing. Although the compressive strength does not quite meet the required strength of 60 ksi in each instance, it can be seen that the small amount of rubber added to the epoxy resin has a generally insignificant effect on the physical and mechanical properties of the laminates.

IMPACT AND WEAR RESISTANCE

The potential for substantial improvement in impact resistance of glass/epoxy laminates was first observed as a result of comparative drop-ball impact tests on 6.5-in. diameter, 0.25-in. thick disks fabricated from several combinations of glass fibers and either epoxy or polyester resins. (See the results of E724 epoxy laminate (CTBN modified) listed in Table 2.) Subsequent tests were conducted on three similar disks (U.S. Polymeric 7781-Z6040/E719 GRP laminate) in which an average of nine drops at 113 ft-lb was required to produce a through crack. These results were so promising that this material, or its generic equivalent (Hexcel 7781-Z6040/F155) was chosen as the primary contender for application to a submarine fairwater and is being considered for application to submarine and surface ship sonar domes.

The next series of tests was conducted to determine the strength retention of the rubber-toughened laminate after impact, and to compare the degradation in properties of the rubber-toughened system with a standard epoxy system. In-plane

TABLE 1 - RESULTS OF RUBBER-MODIFIED EPOXY/GLASS CLOTH PROPERTY CHARACTERISTICS

Physical and Mechanical Properties	Glass-Finish/Resin System					
	DSRV Spec. for Standard Epoxy	7781/ E724*	7781-Z6040/ E719*	7781-Z6040/ E719**	7781-Z6040/ F155***	7781-Z6040/ E719***
Specific Gravity	1.88 ± 0.06	1.83	1.86	1.88		
Resin Content	33 ± 4	38.6	36.4	35.2		
Void Content	1.5 max	--	0	0		
Tensile Strength (ksi)	40.5 min	59.0	45.3	51.3	61.3	62.9
Tensile Modulus (msi)	3.2 min	3.57	3.5	3.86		
Compressive Strength (ksi)	60 min	53.3	65.5	58.5	75.8	70.9
Compressive Modulus (msi)	3.2 min	3.45	4.13	3.91		
Flexural Strength (ksi)	50 min	76.8	65.1	--	91.1	89.7
Flexural Modulus (msi)		2.88	3.33	--		
Interlaminar Shear (ksi)	2.7 min		6.6	--	6.3	6.4

*Tested by DTNSRDC, Code 2823.

**Tested by HITCO.

***Tested by IIT Research Institute.

TABLE 2 - COMPARISON OF IMPACT RESISTANCE OF EPOXY AND POLYESTER RESIN GRP LAMINATES

Material System	Energy Required to Produce a Through Crack--Drop-Ball Test (ft-lb)
Hexcel F148 DAP Polyester/ 7781 Glass Cloth	11.4
U.S. Polymeric E724 Epoxy/ 7781 Glass Cloth	33.6*
3M 1009-26C Epoxy/ Unidirectional Glass Tape	6.3
Synres Chem Synolite 5559T Polyester/ 1 oz. MAT(1), 24 oz. WR(8)	6.8
Synres Chem Synolite 5559T Polyester/ 1 oz. MAT(5), 24 oz. WR(8)	10.1

*Since a through crack could not be produced with a single drop at the maximum energy level available for this test (113 ft-lb), this energy level was that required to produce an area of delamination equal to that shown by ultrasonics on the other four materials when a through crack, approximately 1 in. in diameter, was produced.

tensile strength and normal-to-plane tensile peel strength tests were performed on the 7781-Z6040/F155 laminate to establish initial strength data. (See Figures 1 and 2 for specimen geometry and Tables 3 and 4 for test results.) A drop-ball machine with an adjustable height drop distance was used for impact performance. Tests were conducted on laminate disks measuring 6.5 in. in diameter and 0.25 in. in thickness. These were positioned in a fixture such that the circumference was rigidly supported; the unsupported diameter was 5.5 in. A steel ball measuring 4.5 in. in diameter and weighing 13.658 lb was used in all tests. Impact data were initially generated at energy levels of 26.6, 49.3, and 98.7 ft-lb. In-plane tensile specimens were cut from the impacted laminate disks and tested for residual tensile strength. Figure 3 shows the results of residual in-plane tensile strength as a function of normal impact energy. This graph was used to estimate the amount of energy required to cause a 50 percent reduction in in-plane tensile strength; the safety factor for this material is two. An additional test was conducted with an impact energy of 110.6 ft-lb in order to aid in the extrapolation of an energy level at which there would be a 50 percent reduction in in-plane tensile strength; an energy level of 103 ft-lb was found to give a 50 percent strength retention and was used to impact four more specimens. Peel samples were then cut from the impacted region, bonded to the load blocks, and tested as shown in Figure 2; see Table 5 for results. The authors concluded that, at an energy level of 103 ft-lb, there was a 50 percent retention in in-plane tensile strength and a 25 percent retention in the peel or normal-to-plane tensile strength.

In a similar manner, the above tests were repeated using 6.5-in. diameter by 0.25-in. thick disks laminated with 3M Scotchply 1009-26C unidirectional tape laid in a pattern of three longitudinal (0 deg) and one transverse (90 deg). Energy levels of 8.4 to 154.5 ft-lb were used to impact six disks; however, as can be seen in Table 6, there was no trend of reduced residual in-plane tensile strength in the 0-deg direction with an increase in impact energy. Two additional disks were impacted, and residual in-plane tensile stresses were measured in the 90-deg direction; see Table 7 for results. Likewise, there was no trend of reduced in-plane tensile strength in the 90-deg direction with an increase in impact energy.

Next, residual normal tensile peel strength tests after impact were conducted. Table 8 shows the same lack of proportionality between impact energy and residual strength. Three additional residual strength tests were run after impact; one in

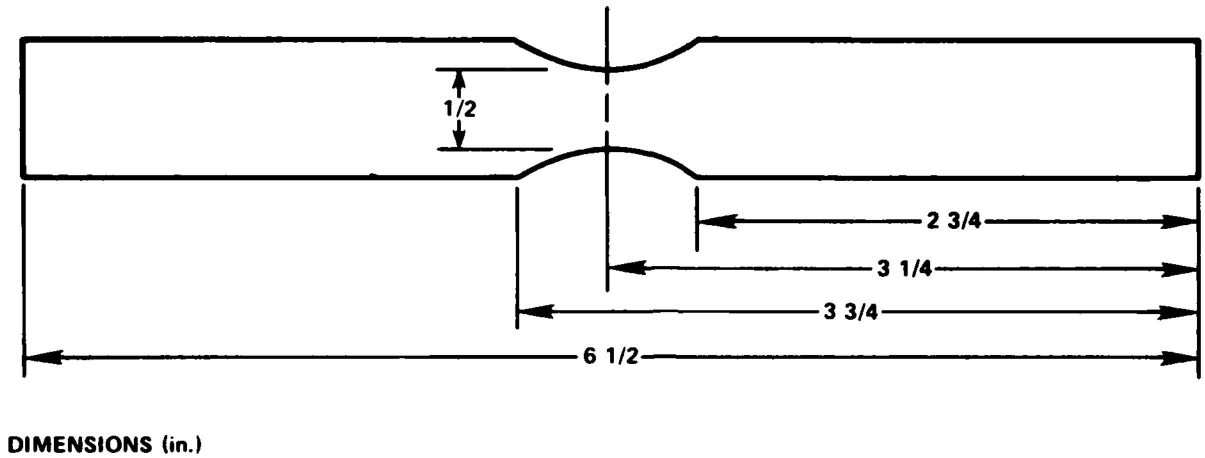


Figure 1 - Modified ASTM D-638 In-Plane Tensile Specimen

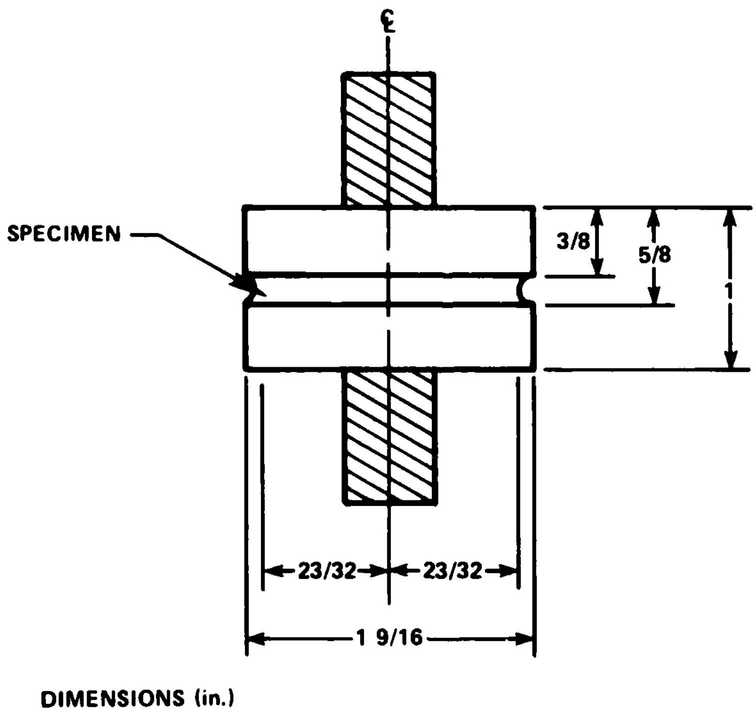


Figure 2 - Normal Tensile Peel Strength Specimen

TABLE 3 - IN-PLANE TENSILE STRENGTH OF 7781-Z6040/F155

Specimen	Width (in.)	Thickness (in.)	Strain Rate (in./min.)	Load (lb)	Ultimate Strength (psi)
1	0.515	0.242	0.05	5270	42,285
2	0.511	0.242	0.05	4940	39,948
3	0.525	0.242	0.05	5510	43,369
4	0.482	0.242	0.2	5050	43,294
5	0.510	0.242	0.2	5260	42,619
6	0.492	0.242	0.2	4940	42,490
Avg.					42,168

TABLE 4 - NORMAL TENSILE PEEL STRENGTH OF 7781-Z6040/F155

Specimen	Diameter (in.)	Load (lb)	Ultimate Strength (psi)
1	1.488	8610	4951
2	1.510	8430	4707
3	1.492	8660	4954
4	1.470	8240	4855
5	1.480	8580	4987
Avg.			4891

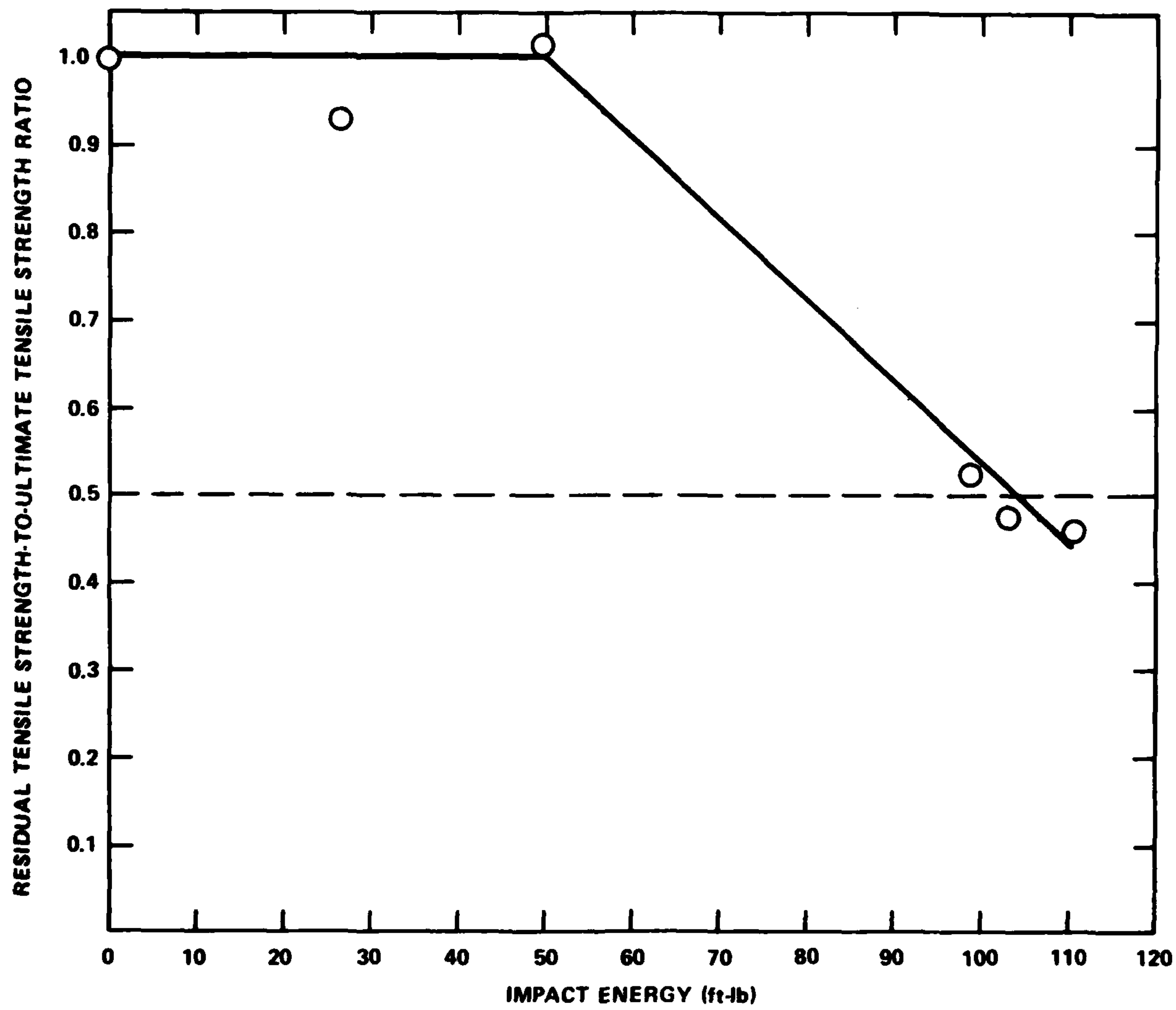


Figure 3 - Residual In-Plane Tensile Strength versus Normal Impact Energy of 7781-Z6040/F155

TABLE 5 - RESIDUAL NORMAL TENSILE PEEL STRENGTH AFTER IMPACT OF 7781-Z6040/F155

Specimen	Diameter (in.)	Load (lb)	Strength (psi)	Failure Mode
1	1.600	2760	1373	Laminate
2	1.592	2240	1125	Laminate
3	1.590	370	186	Adhesive
3R	1.590	1430	720	Laminate
Avg.			1249	

TABLE 6 - RESIDUAL IN-PLANE 0 DEGREE TENSILE STRENGTH AFTER IMPACT OF 1009-26C

Specimen	Impact Energy (ft-lb)	Width (in.)	Thickness (in.)	Load (lb)	Strength (psi)	Percent Ultimate
1	8.40	0.753	0.227	13,090	76,580	83.7
2	26.86	0.753	0.227	12,550	73,421	80.2
3	26.86	0.754	0.226	11,830	69,423	75.8
4	53.71	0.751	0.227	12,970	76,080	83.1
5	100.70	0.756	0.226	12,640	73,980	80.8
6	154.50	0.756	0.226	12,610	74,395	81.3

Note: The ultimate tensile strength of virgin material used for the calculation of percent ultimate is 91,547 psi.

TABLE 7 - RESIDUAL IN-PLANE 90 DEGREES TENSILE STRENGTH AFTER IMPACT OF 1009-26C

Specimen	Impact Energy (ft-lb)	Width (in.)	Thickness (in.)	Load (lb)	Strength (psi)	Percent Ultimate
1	50.3	0.751	0.227	6,630	38,891	75.6
2	100.7	0.753	0.227	6,820	39,889	77.6

Note: The ultimate tensile strength of virgin material used for the calculation of percent ultimate is 51,415 psi.

TABLE 8 - RESIDUAL NORMAL TENSILE PEEL STRENGTH AFTER IMPACT OF 1009-26C

Specimen	Impact Energy (ft-lb)	Diameter (in.)	Thickness (in.)	Load (lb)	Strength (psi)	Percent Ultimate
1a	8.4	1.585	0.227	637	323	9 (cleavage)
1b	8.4	1.585	0.227	659	333	10 (cleavage)
2a	26.86	1.590	0.227	2761	1391	40
2b	26.86	1.590	0.227	932	469	13
3a	26.86	1.595	0.226	1589	795	23
3b	26.86	1.595	0.226	851	426	12
4a	53.71	1.595	0.227	533	266	8
9	4.99	1.580	0.226	786	400	11
10	1.18	1.580	0.226	857	437	12 (cleavage)

Note: Specimens 1-4 were cut from impact panels of residual in-plane tensile strength, adjacent to the actual impact site. The ultimate normal tensile peel strength of virgin material used for the calculation of percent ultimate is 3499 psi.

interlaminar shear and two in four-point bending (see Tables 9 and 10 for results). The percent of ultimate strengths in normal tension, interlaminar shear, and four-point bending is much lower than for the residual in-plane (0 deg and 90 deg) tensile strengths. Still, the conclusion from this series of tests is that one single mode of failure (in this case, tension) cannot be used to evaluate the effect of impact damage on the strength degradation of real structures. Unfortunately, there was neither additional time, money, nor material to continue this investigation.

One additional series of tests was run on two sets of 18-in. square by 0.25-in. thick GRP panels. One set was laid up with Newport Adhesives 7781-Z6040/1107 prepreg (a generic equivalent of the 7781-Z6040/E719 and 7781-Z6040/F155 CTBN-modified GRP laminates) and the other set with the 1009-26C. The panels were impacted as specified in Table 11, and then tested in the 24-in. water tunnel to evaluate the effect of impact damage on the tendency for loose fibers to peel off when exposed to high-speed (15 knots) water flow; this phenomenon has been referred to as "hydropeel." (Although funding levels did not allow for residual strength tests in order to compare the effects of impact on these panels, an evaluation of Figures 4 through 7 shows that the CTBN-modified epoxy panel sustained less visual delamination than the standard epoxy panel following 60 impacts at 206 ft-lb. Likewise, an evaluation of two ultrasonic C-Scans (Figures 8 and 9) shows the same trend after one impact at 206 ft-lb. Finally, an evaluation of Figures 10 and 11 shows the same trend after 36 impacts against jointed panels at 206 ft-lb.)

Significant hydropeel occurred for only one test condition, i.e., the 1009-26C panel with butt joints in which the loose fibers were directly exposed to the water flow. All the nonjointed panels had a groove machined across the area of impact damage following the first series of hydropeel tests, but in no case did hydropeel begin either before or after the grooves were made. The jointed CTBN-modified epoxy panel sustained enough damage after 36 impacts at 206 ft-lb that a small area of broken fibers was exposed to the water flow, but only one small piece (1 sq in.) peeled back and broke off after exposure to high-speed water flow. A comparison of Figures 12 and 13 shows the relative extent of hydropeel for the two material systems.

Three conclusions can be reached from this series of tests. First, the standard epoxy appears to sustain a larger area of delamination than the CTBN-modified epoxy for the same impact loads. Second, a significant amount of damage must exist whereby

TABLE 9 - RESIDUAL INTERLAMINAR SHEAR STRENGTH AT 0 DEGREE AFTER IMPACT OF 1009-26C

Specimen	Impact Energy (ft-lb)	Width (in.)	Thickness (in.)	Load (lb)	Strength (psi)	Percent Ultimate
1	100.7	0.439	0.226	407	3077	49

Note: The ultimate interlaminar shear strength of virgin material used for the calculation of percent ultimate is 6269 psi.

TABLE 10 - RESIDUAL FOUR-POINT BENDING STRENGTH AT 0 DEGREE AFTER IMPACT OF 1009-26C

Specimen	Impact Energy (ft-lb)	Width (in.)	Thickness (in.)	Load (lb)	Strength (psi)	Percent Ultimate
1	100.7	0.478	0.227	69	3664	9
2	53.7	0.550	0.226	86	4072	10

Note: The ultimate four-point bending strength of virgin material used for the calculation of percent ultimate is 42,130 psi.

TABLE 11 - SUMMARY OF "HYDROPEEL" TEST CONDITIONS

Specimen	Material I.D.	Joints	Test	Grooved	Impact Energy (ft-lb)	Number of Drops	Time at Max. Flow (hr)
1	1009-26C	No	1	No	206	1	2
			3	Yes	206	1	2
2	1009-26C	No	2	No	206	60	2
			4	Yes	206	60	1.75
3	1009-26C	Yes	5	No	206	36	2
			6	Yes	206	36	0.5
			7	No*	206	36	4
4	7781-Z6040 / 1107	Yes	8	No*	206	36	3

*Broken fibers exposed to flow.

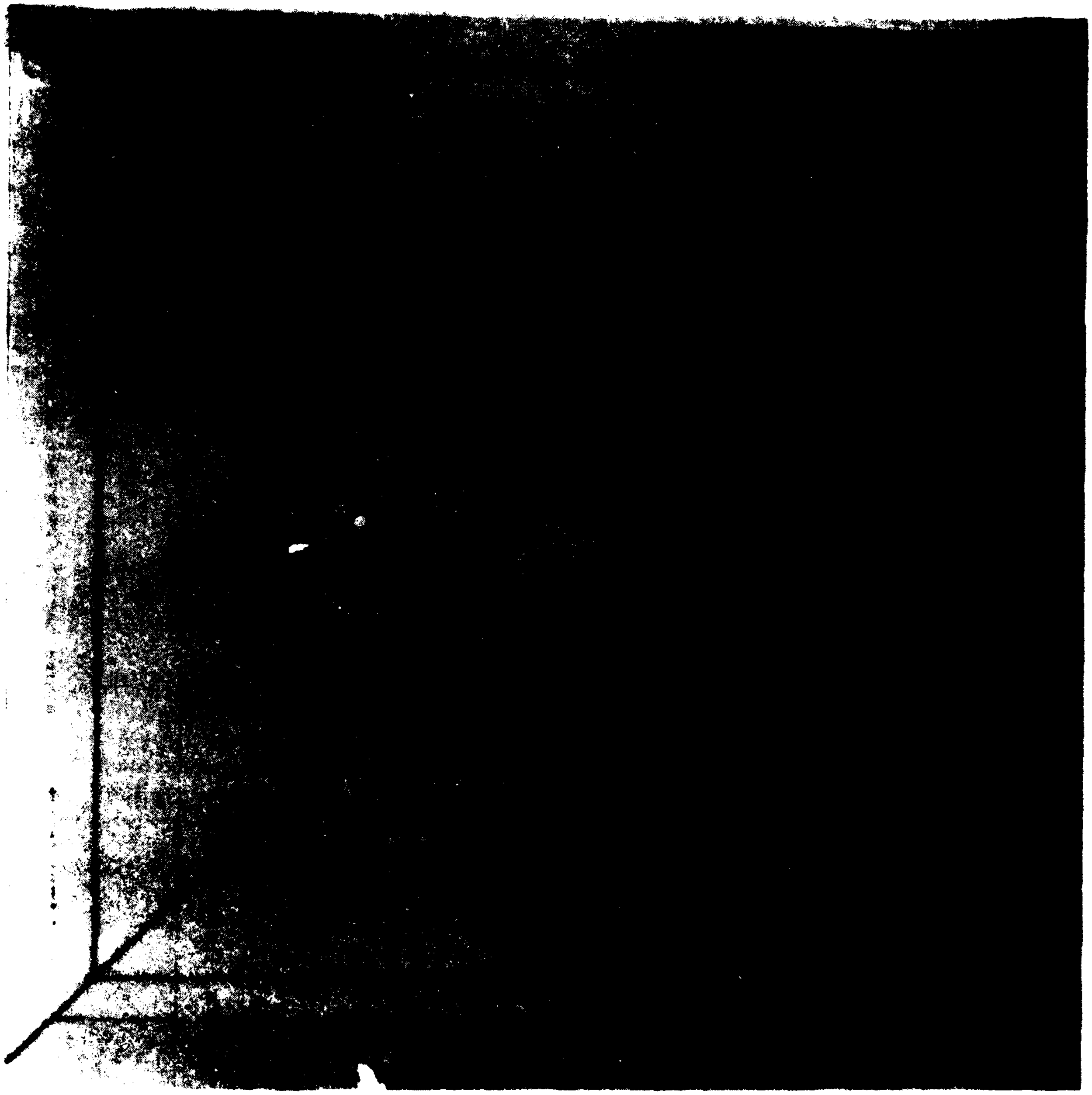


Figure 4 - Front Surface of CTBN-Modified Epoxy GRP Panel
After 60 Impacts at 206 Foot-Pounds

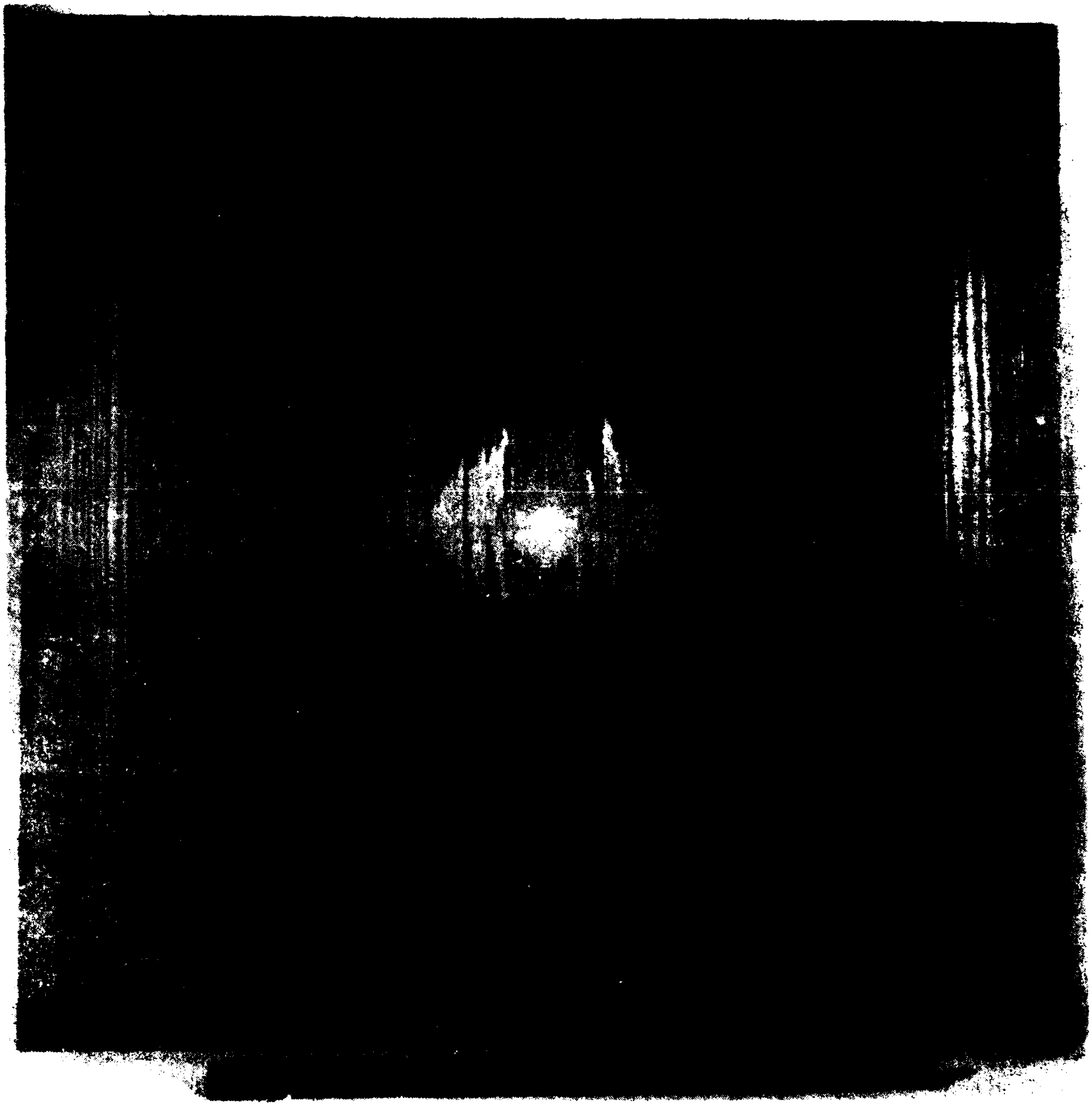


Figure 5 - Front Surface of Standard Epoxy GRP Panel After 60 Impacts at 206 Foot-Pounds

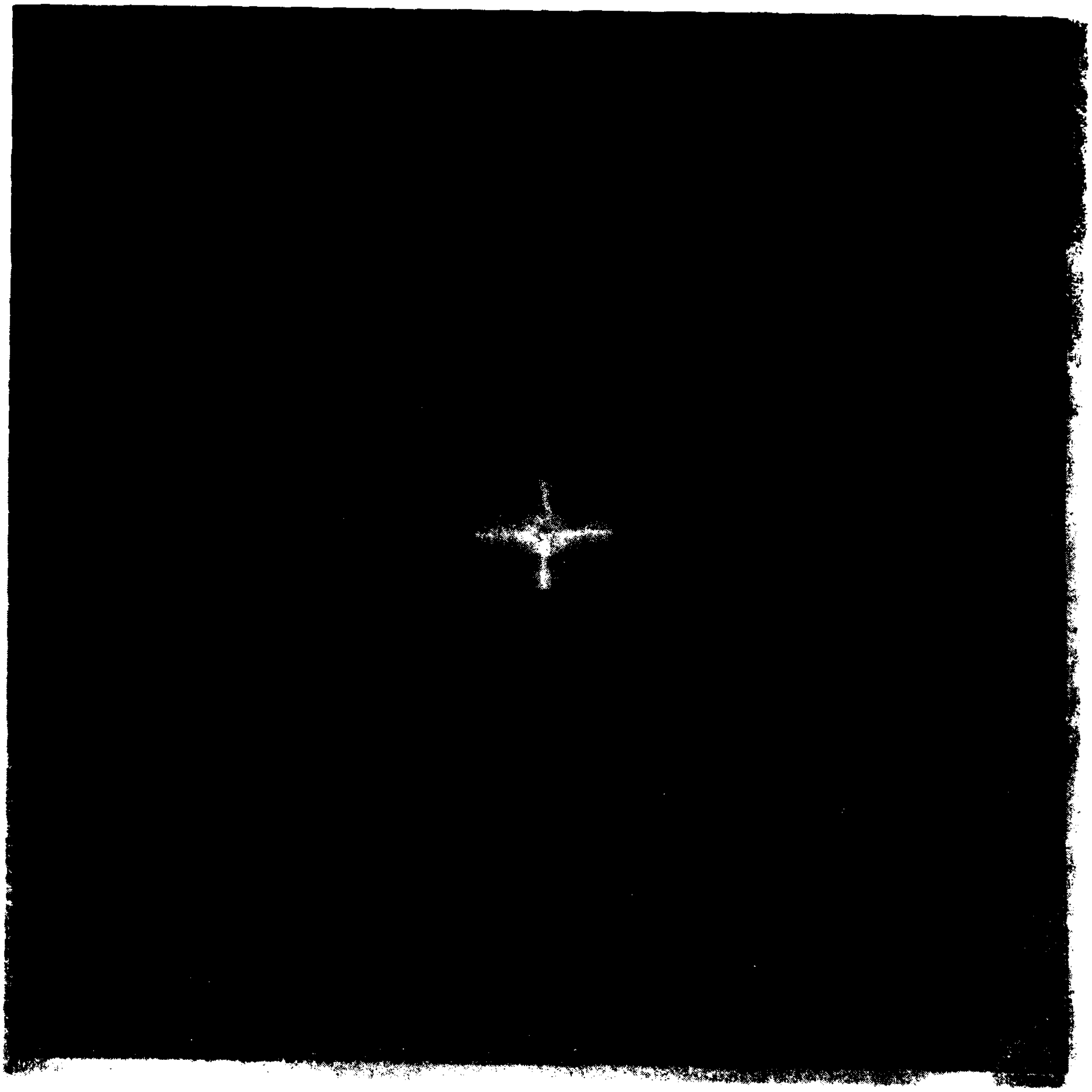


Figure 6 - Back Surface of CTBN-Modified Epoxy GRP Panel After 60 Impacts at 206 Foot-Pounds

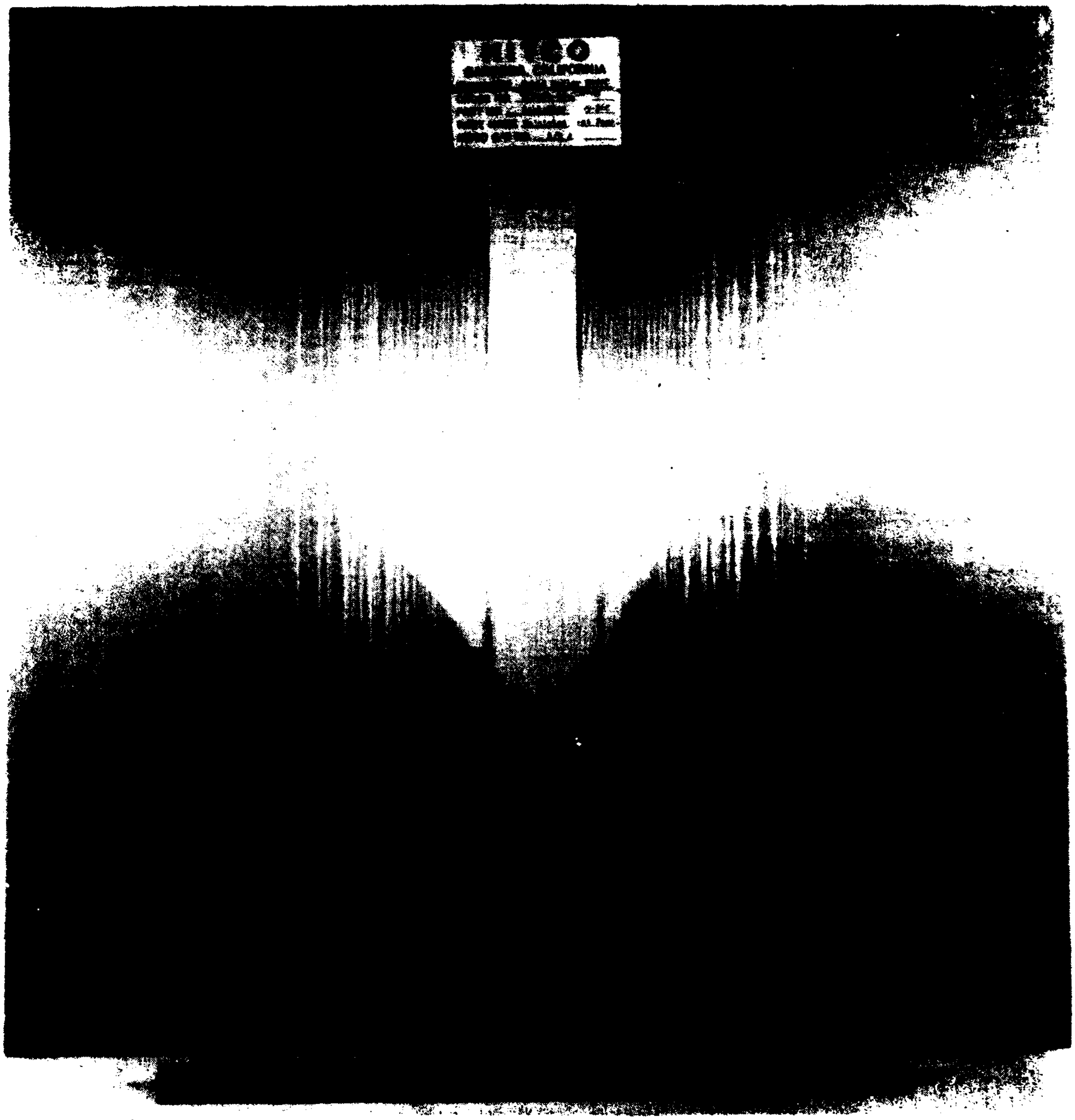


Figure 7 - Back Surface of Standard Epoxy GRP Panel After 60 Impacts at 206 Foot-Pounds

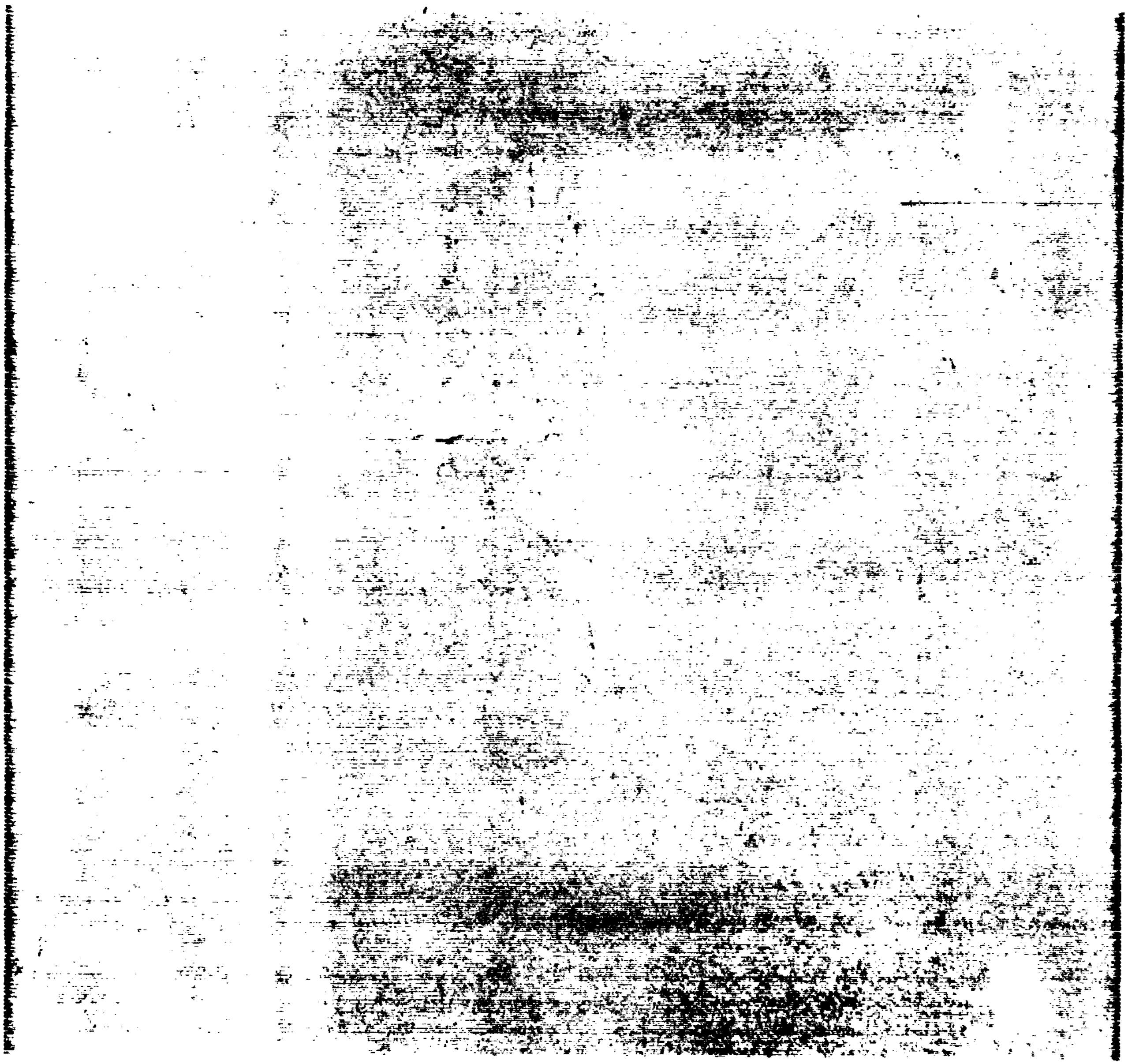


Figure 8 - Ultrasonic C-Scan of CTBN-Modified Epoxy GRP Panel After One Impact at 206 Foot-Pounds

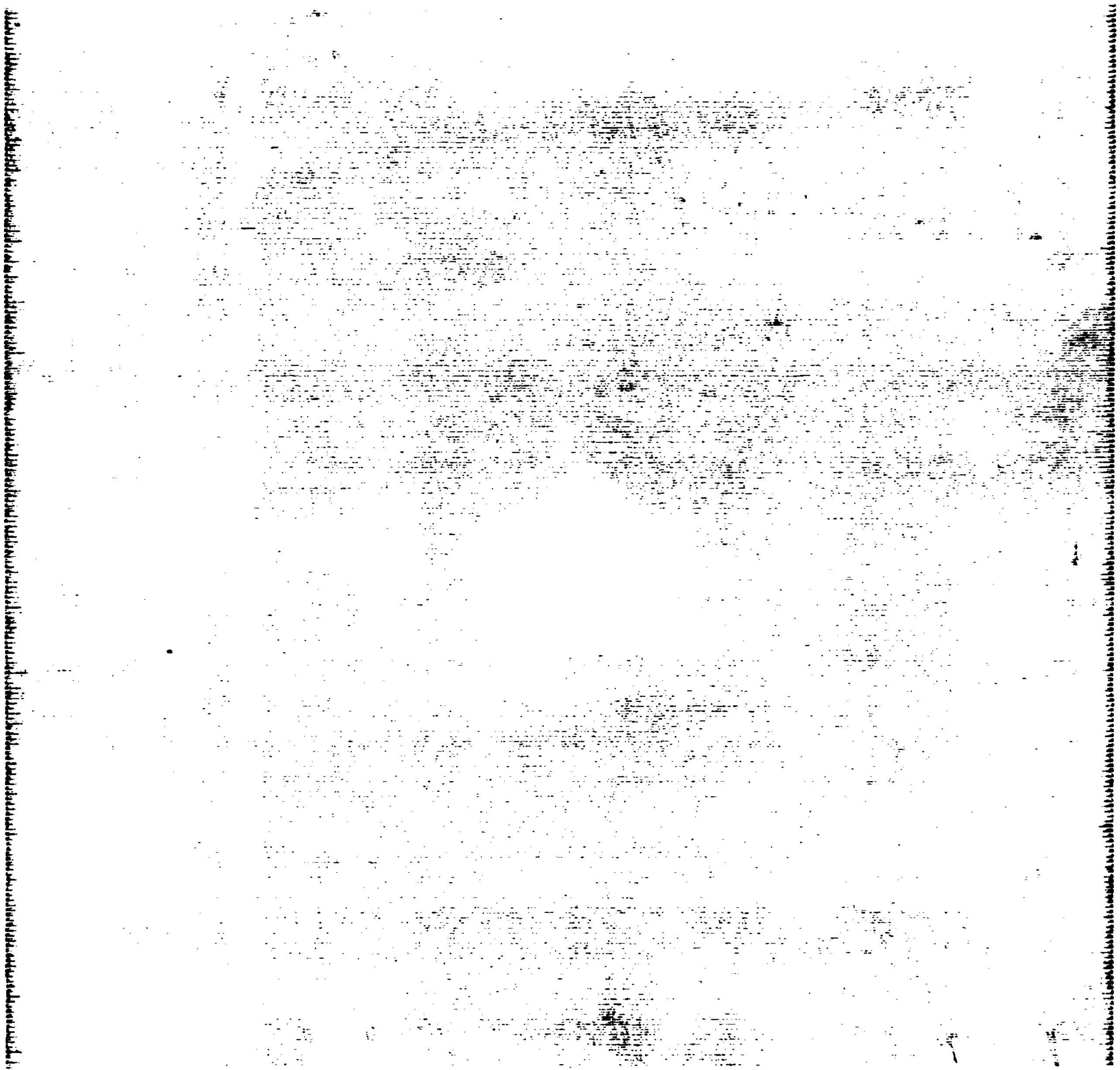


Figure 9 - Ultrasonic C-Scan of Standard Epoxy GRP Panel After One Impact at 206 Foot-Pounds

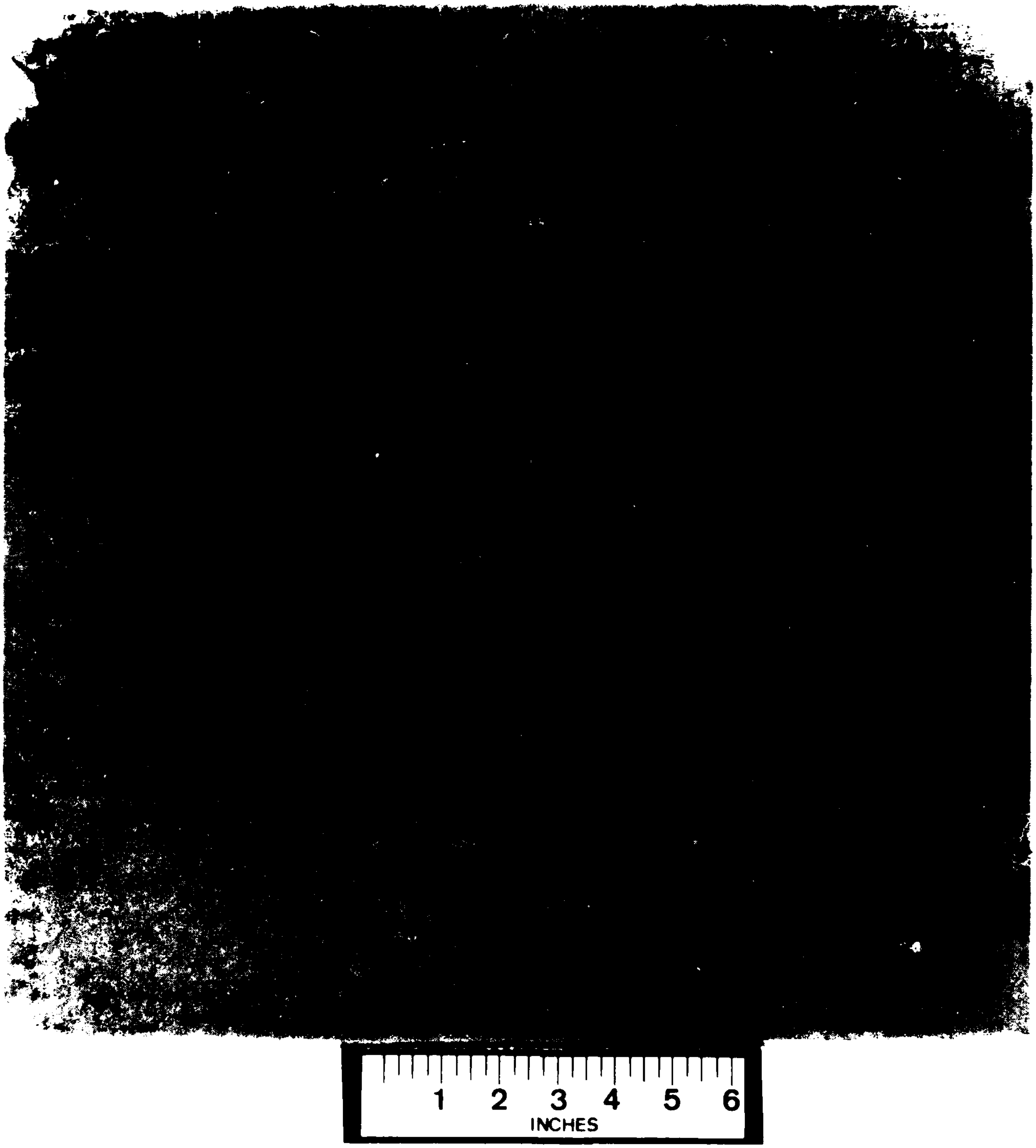


Figure [illegible] - Front Surface of Jointed CTBN-Modified Epoxy RP Panel After [illegible] Impacts at 206 Foot-Pounds

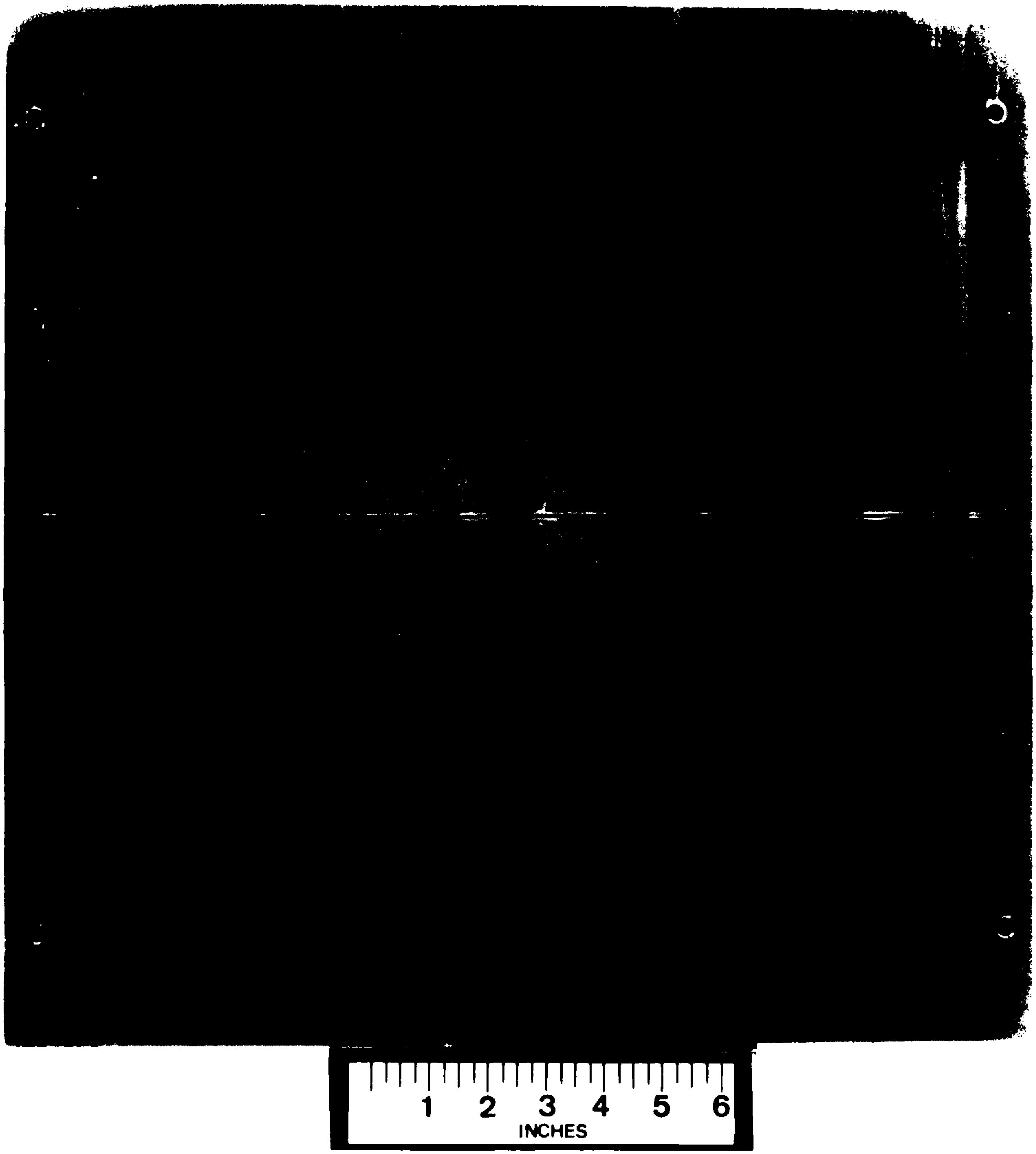


Figure 11 - Front Surface of Jointed Standard Epoxy GRP Panel After 36 Impacts at 206 Foot-Pounds

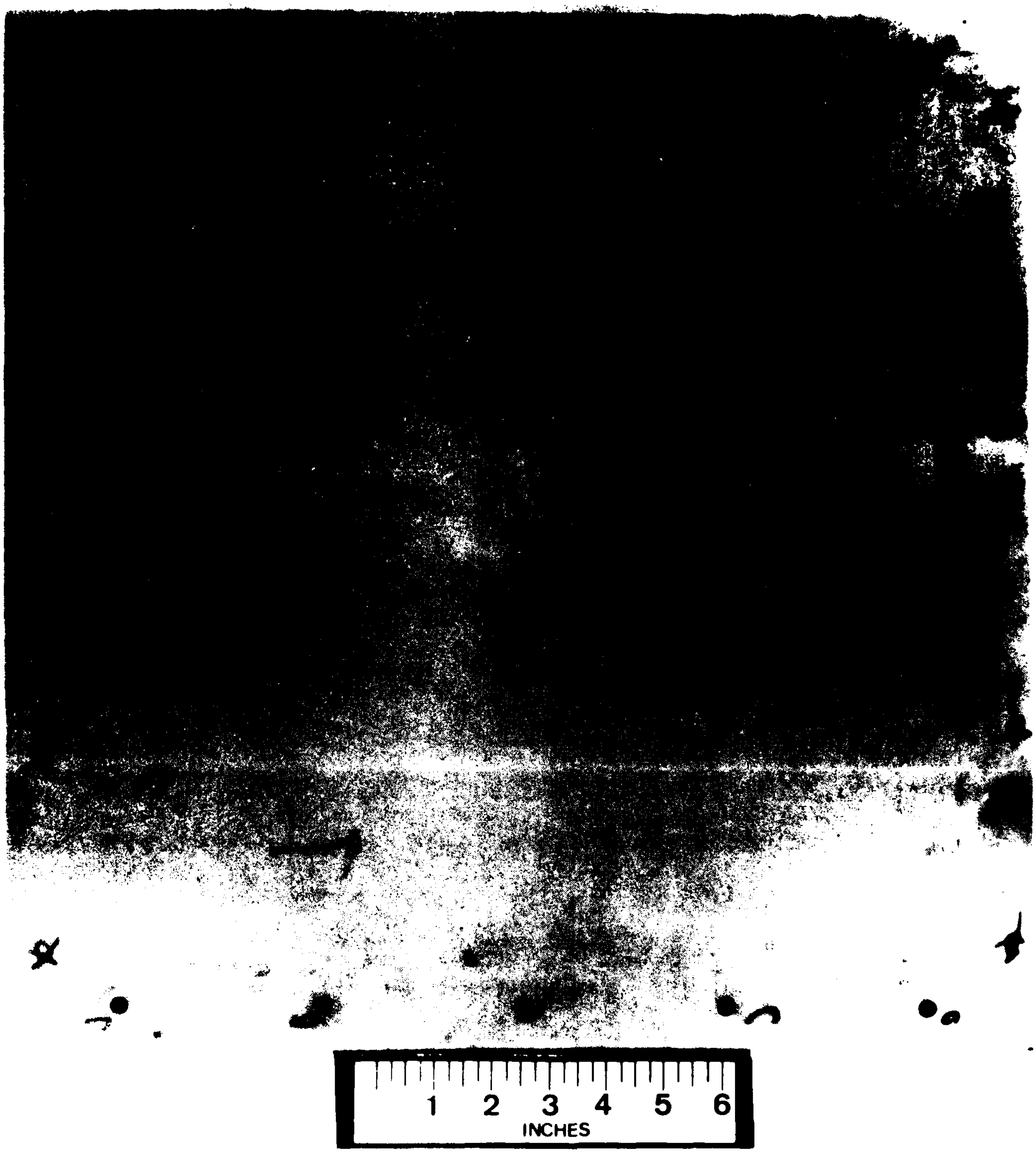


Figure 12 - Back Surface of Painted CTBN-Modified Epoxy GRP Panel After 36 Impacts at 206 Foot-pounds and 3 Hours at Maximum Water Flow

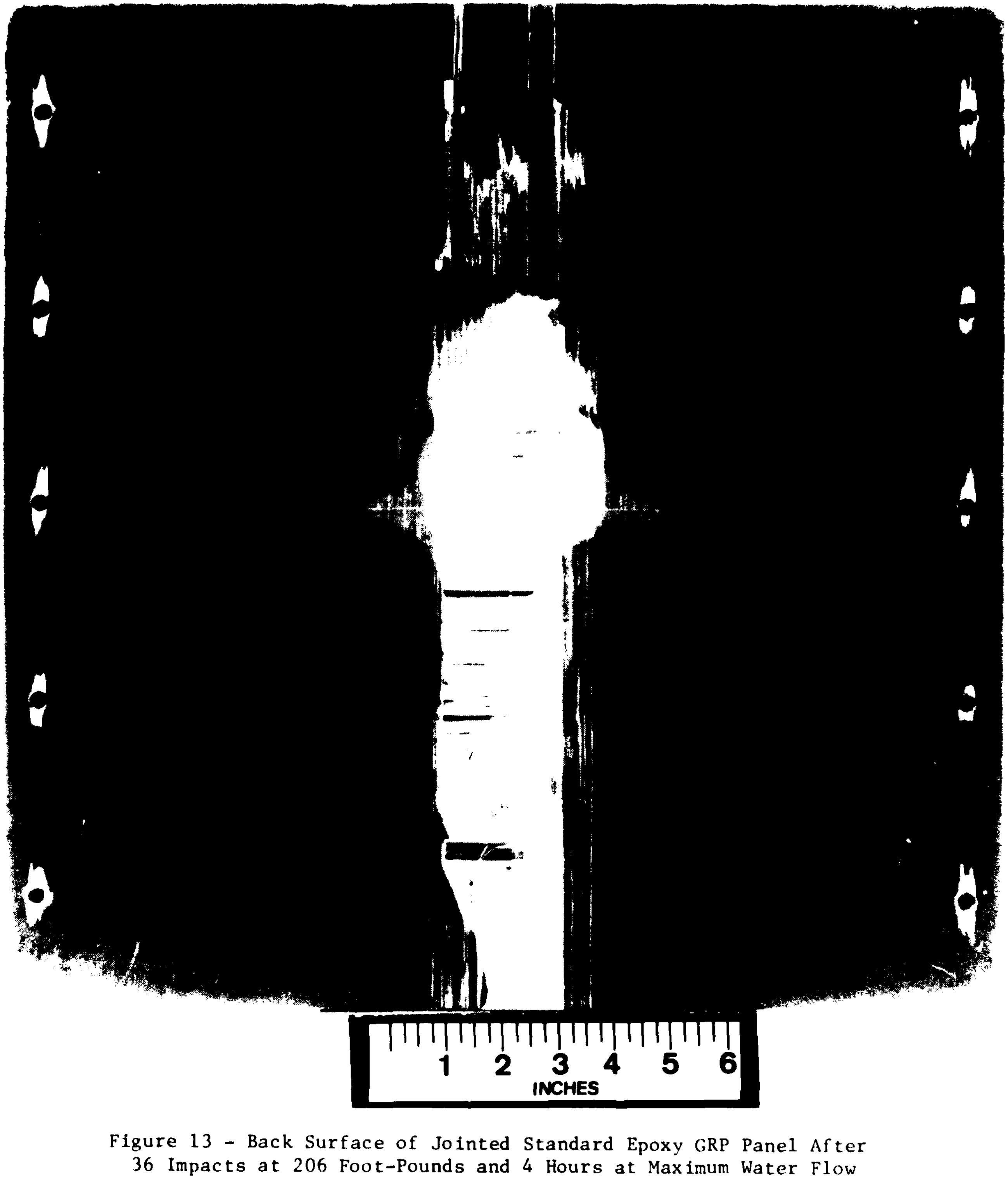


Figure 13 - Back Surface of Jointed Standard Epoxy GRP Panel After 36 Impacts at 206 Foot-Pounds and 4 Hours at Maximum Water Flow

a large area of broken fibers is exposed to the direct force of flowing water in order for hydropeel to occur. And third, it appears that the 1009-26C material system with a standard "brittle" epoxy and unidirectional fibers has a much greater propensity for hydropeel than the rubber-toughened epoxy/glass cloth laminate.

FATIGUE AND LONG-TERM IMMERSION

Once the initial impact tests indicated the potential value in applying rubber-toughened GRP laminate to ship structures, preliminary water absorption and fatigue tests were conducted; see Tables 12 and 13 for results. Because the results of these tests looked promising, a more comprehensive test program was planned. Strength versus number of cycles (S/N) curves were developed for tension-tension, tension-compression, compression-compression and interlaminar shear; the data are presented in Tables 14 through 17. In addition, a 72-hr water boil test and tests of immersions of specimens in water at atmospheric and 600 psi pressures for three years are being performed. Specimens were removed from the immersed conditions at different time intervals and tested for residual strength; see Figures 14 and 15 for plots of residual strength versus time of immersion.

These tests led the authors to conclude that there does not appear to be any unusual degradation in the strength properties of a CTBN-toughened GRP laminate due to fatigue or long-term immersion in the marine environment.

STRUCTURAL BEHAVIOR

During the course of the preliminary design study for a GRP submarine fairwater, a series of unstiffened and stiffened panel and structural component tests were conducted. These panels and components were laid up using the 7781/Z6040/E719 rubber-toughened epoxy/glass cloth material system. All tests involved the measurement of deflections and strains, as well as a comparison of experimental values with the theory used to design each structure.

The authors concluded from this series of tests that (1) the addition of the rubber modifier had no effect on the elastic behavior of the structures, (2) the rubber modifier appeared to decrease the tendency for GRP brittle failures, and (3) the addition of the rubber modifier improved the machinability and durability of the laminates; see Figure 16.

TABLE 12 - WATER ABSORPTION CHARACTERISTICS OF 7781-Z6040/E719

Duration of Immersion* (hr)	Percent Increase in Weight	
	Atmospheric Pressure	600 psi Pressure
24	0.030	0.030
96	0.069	0.065
120	0.070	0.072
144	0.073	0.076
168	0.080	0.083
192	0.087	0.088
264	0.100	0.100

*Tap water.

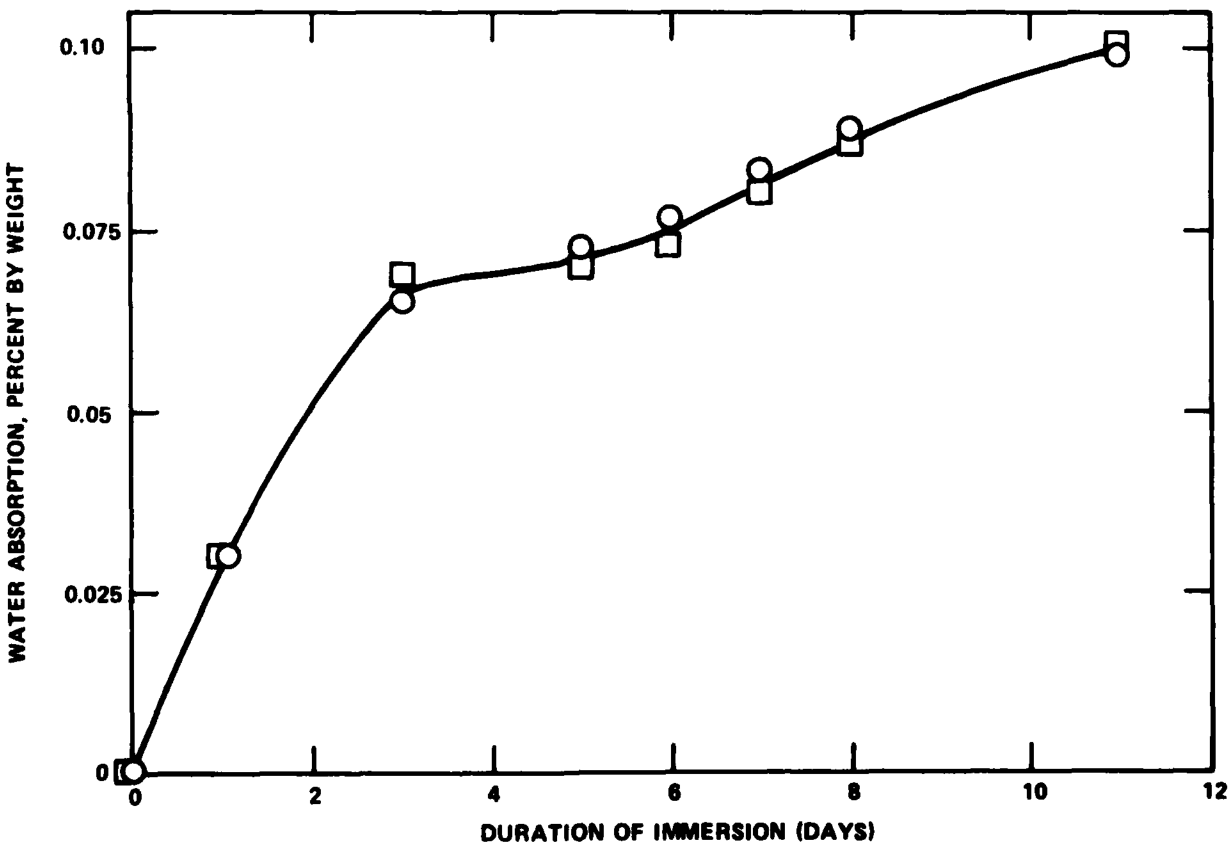


TABLE 13 - EFFECT OF SHORT-TERM IMMERSION ON FLEXURAL FATIGUE STRENGTH OF 7781-Z6040/E719

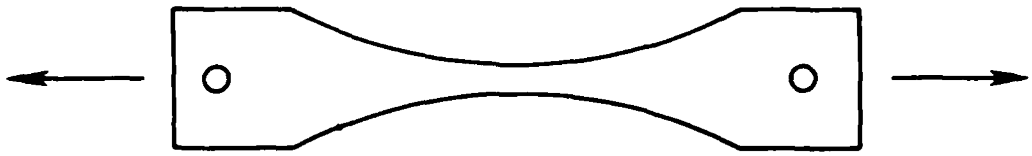
Cyclic Rate (cycles/min)	Method of Cooling	Number of Cycles	Type of Failure	Number of Hours at 600 psi Immersion	Residual Strength (ksi)	Strength Retention (percent)	Residual Modulus ($psi \times 10^6$)	Modulus Retention (percent)
900	Fan	54,700	Cyclic	0	0	0	0	0
325	None	24,000	Cyclic	0	0	0	0	0
325	Fan	205,000	Static	0	46.6	72	2.85	86
225	Fan	233,000	Static	0	59.2	91	3.14	94
227	Fan	200,100	Static	64	59.1	91	2.94	88
222	Fan	200,000	Static	64	54.9	84	2.99	90

Notes:

1. All specimens were cycled from 0 to 32.55 ksi using a Krause flexural-fatigue test machine.
2. For the two specimens with 64 hours immersion, the test was conducted in four steps; each consisting of 50,000 cycles followed by 16 hours immersion in tap water.

TABLE 14 - AXIAL FATIGUE TEST IN TENSION-TENSION OF 7781-Z6040/E719

Stress Ratio: +0.05
Test Temperature: 75°F
Test Speed: 900 cycles/min



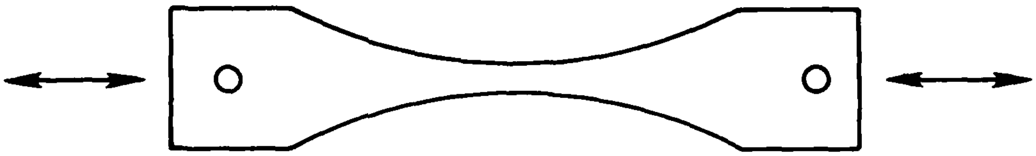
Specimen I.D.	Specimen Dimensions (in.)	Stressed Area (in.^{2})	Max. Load (lb)	Min. Load (lb)	Max. Stress (psi)	Cycles to Failure
50 Percent of Ultimate						
A1	0.255/0.263	0.06707	1,680	84	25,050	823,500
A2	0.254/0.264	0.06731	1,686	84	25,050	873,800
A3	0.254/0.262	0.06655	1,667	83	25,050	936,800
80 Percent of Ultimate						
A4	0.257/0.265	0.06811	2,730	136	40,080	1,500
A5	0.255/0.263	0.06707	2,690	134	40,080	1,600
A6	0.258/0.263	0.06785	2,720	136	40,080	1,400
65 Percent of Ultimate						
A7	0.259/0.262	0.06786	2,210	110	32,565	77,400
A8	0.257/0.262	0.06733	2,190	110	32,565	58,800
A9	0.253/0.263	0.06654	2,170	108	32,565	39,200

Notes:

1. Axial tension-tension specimens.
2. Average ultimate tensile strength is 50,100 psi.

TABLE 15 - AXIAL FATIGUE TEST IN TENSION-COMPRESSION OF 7781-Z6040/E719

Stress Ratio: -1
Test Temperature: 75°F
Test Speed: 900 cycles/min



Specimen I.D.	Specimen Dimensions (in.)	Stressed Area ($in.^2$)	Max. Load (lb)	Min. Load (lb)	Max. Stress (psi)	Cycles to Failure
50 Percent of Ultimate						
D 1	0.255/0.264	0.06731	+1,690	-1,690	25,050	1,300
D 2	0.258/0.264	0.06811	+1,710	-1,710	25,050	1,100
D 3	0.255/0.262	0.06681	+1,670	-1,670	25,050	2,200
30 Percent of Ultimate						
D 4	0.253/0.262	0.06629	+ 996	- 996	15,030	1,000,000*
D 5	0.248/0.263	0.06522	+ 980	- 980	15,030	1,420,000*
D 6	0.253/0.262	0.06629	+ 996	- 996	15,030	1,460,000*
40 Percent of Ultimate						
D 7	0.250/0.263	0.06575	+1,320	-1,320	20,040	3,500
D 8	0.249/0.262	0.06524	+1,310	-1,310	20,040	1,194,500
D 9	0.252/0.262	0.06678	+1,340	-1,340	20,040	1,114,000*
D10	0.255/0.263	0.06706	+1,340	-1,340	20,040	909,500
45 Percent of Ultimate						
D11	0.253/0.261	0.06603	+1,490	-1,490	22,550	183,600
D12	0.255/0.262	0.06681	+1,510	-1,510	22,550	154,400

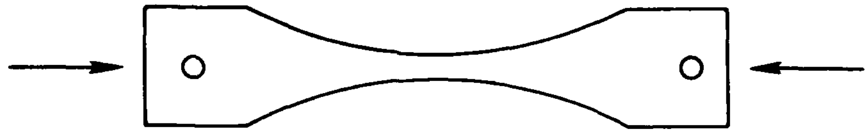
Notes:

1. Axial tension-compression specimens.
2. Average ultimate tensile strength is 50,100 psi.

*No failure--test discontinued.

TABLE 16 - AXIAL FATIGUE TEST IN COMPRESSION-COMPRESSION OF 7781-Z6040/E719

Stress Ratio: +0.05 (compression-compression)
Test Temperature: 75°F
Test Speed: 900 cycles/min



Specimen I.D.	Specimen Dimensions (in.)	Stressed Area (in.^{2})	Max. Load (lb)	Min. Load (lb)	Max. Stress (psi)	Cycles to Failure
50 Percent of Ultimate						
B 1	0.254/0.262	0.06655	-1,946	- 97	29,250	14,700
B 2	0.260/0.265	0.06890	-2,015	-101	29,250	32,300
B 3	0.252/0.264	0.06653	-1,950	- 97	29,250	11,500
35 Percent of Ultimate						
B 4	0.255/0.262	0.06681	-1,370	- 68	20,500	1,240,000*
B 5	0.255/0.262	0.06681	-1,370	- 68	20,500	1,000,000*
B 6	0.257/0.263	0.06759	-1,384	- 69	20,500	1,380,000*
42.5 Percent of Ultimate						
B 7	0.257/0.263	0.06759	-1,680	- 84	24,860	1,000,000*
B 8	0.251/0.262	0.06576	-1,635	- 82	24,860	32,800
B 9	0.256/0.262	0.06707	-1,670	- 83	24,860	1,420,000*
45 Percent of Ultimate						
B10	0.249/0.262	0.06524	-1,720	- 86	26,300	1,000,000*
55 Percent of Ultimate						
B12	0.255/0.262	0.06681	-2,150	-107	32,200	377,900
B13	0.255/0.262	0.06881	-2,150	-107	32,200	1,000,000*
75 Percent of Ultimate						
B11	0.252/0.262	0.06602	-2,900	-145	43,900	1,900
B14	0.253/0.262	0.06629	-2,190	-145	43,900	400

Notes:

1. Axial compression specimens.
2. Average ultimate compression strength is 58,500 psi.

*No failure--test discontinued.

TABLE 17 - AXIAL FATIGUE TEST IN SHEAR OF 7781-Z6040/E719

Stress Ratio: +0.05
Test Temperature: 75°F
Test Speed: 900 cycles/min

Specimen I.D.	Specimen Dimensions (in.)	Stressed Area ($in.^2$)	Max. Load (lb)	Min. Load (lb)	Max. Stress (psi)	Cycles to Failure
50 Percent of Ultimate						
1	0.528/0.997	0.5264	1,105	55	2,100	2,800
2	0.524/0.997	0.5224	1,097	55	2,100	2,600
3	0.528/0.999	0.5275	1,108	55	2,100	1,100
30 Percent of Ultimate						
4	0.528/0.999	0.5275	665	33	1,260	52,200
5	0.530/1.000	0.5300	668	33	1,260	40,500
6	0.529/1.000	0.5290	667	33	1,260	47,600
15 Percent of Ultimate						
7	0.526/1.001	0.5265	332	17	630	1,000,000*
8	0.526/0.999	0.5255	331	17	630	1,000,000*
9	0.528/0.999	0.5275	332	17	630	1,000,000*
20 Percent of Ultimate						
10	0.530/1.005	0.5326	447	22	840	1,000,000*
11	0.532/1.006	0.5352	450	22	840	1,000,000*
12	0.532/1.002	0.5331	448	22	840	1,000,000*

Notes:

1. Double notched shear specimens.
2. Average ultimate shear strength is 4,200 psi.

*No failure--test discontinued.

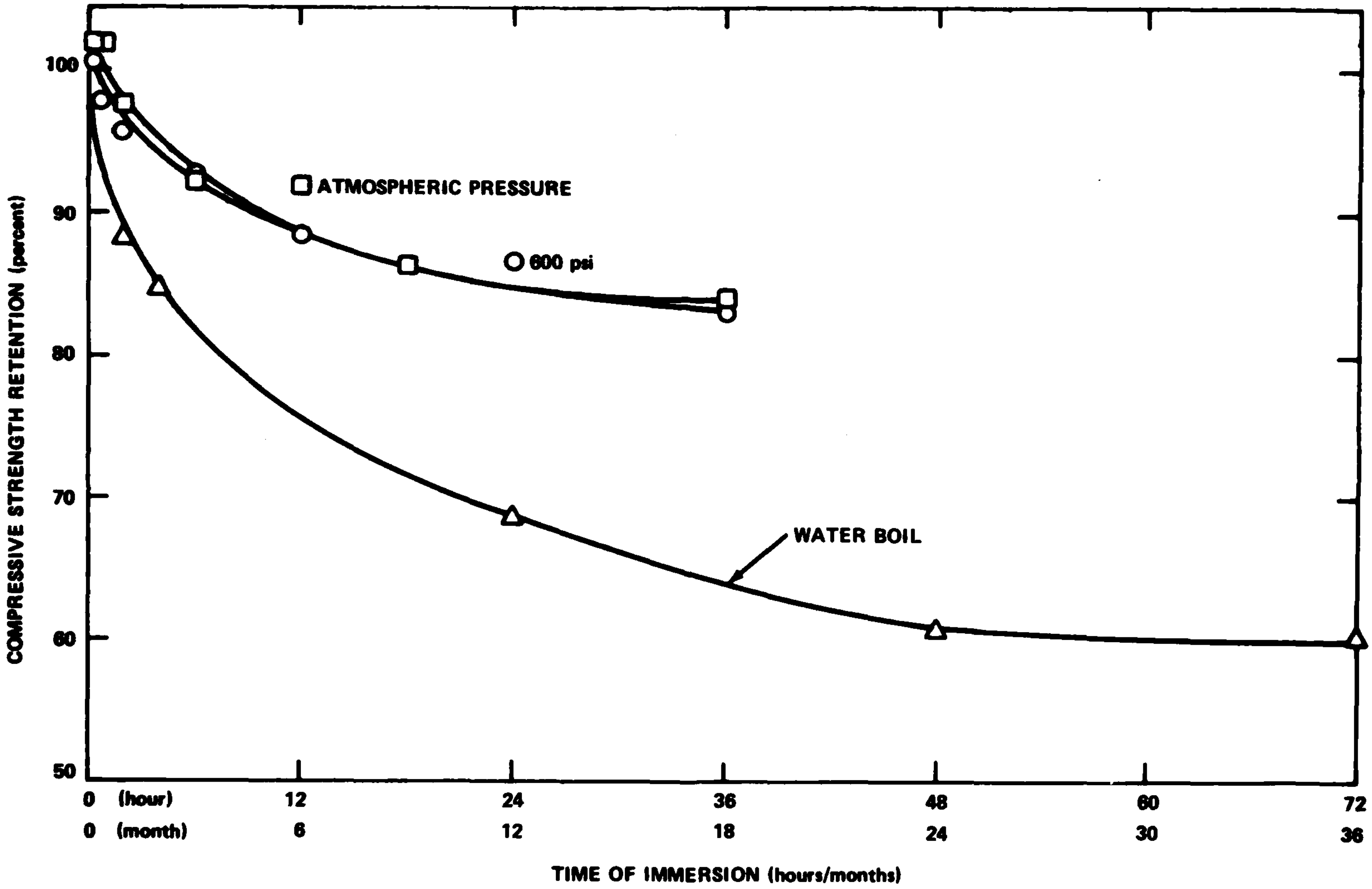


Figure 14 - Compressive Strength Retention for 7781-Z6040/F155

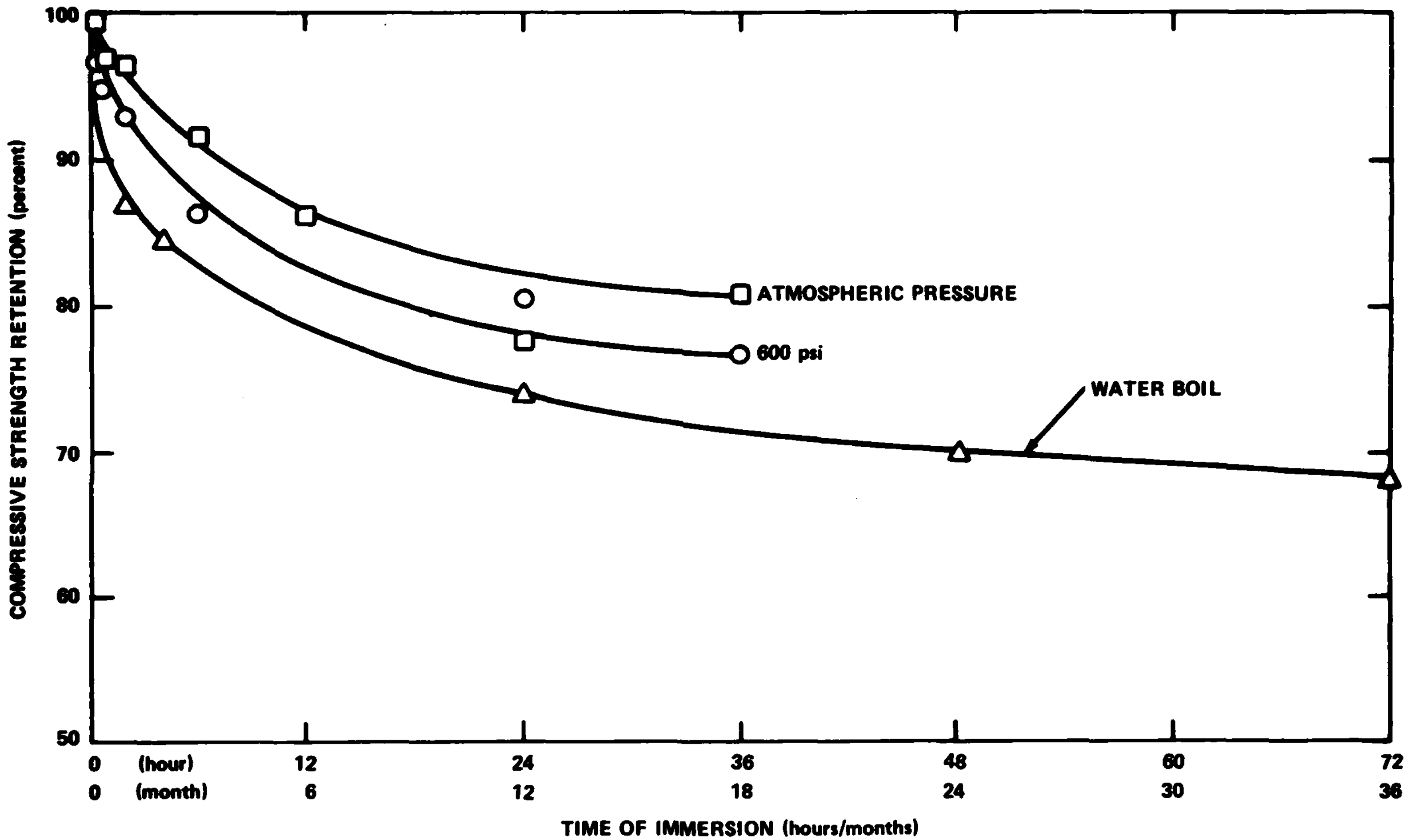


Figure 15 - Compressive Strength Retention for 7781-Z6040/E719

Figure 16 - Demonstration of Durability of CTBN-Modified Epoxy GRP Laminate

CONCLUSIONS

1. The small amount of CTBN rubber (5-10 percent) required to substantially increase the impact-resistance and durability of standard "brittle" epoxy laminates has little or no effect on the physical and mechanical properties.

2. Although it is difficult to quantify the impact-resistant benefits of the rubber-toughened epoxy because of different results for different failure modes, the energy required to cause a through-crack in a 6.5-in. diameter, 0.25-in. thick disk was much greater for the toughened epoxies than for the standard "brittle" epoxies and polyesters.

3. It appears that the standard epoxy/unidirectional glass tape materials have a much greater propensity for hydropeel than do the rubber-toughened epoxy/glass cloth laminates.

4. There does not appear to be any unusually high degradation in the strength properties of a rubber-toughened GRP laminate due to either fatigue or long-term immersion in the marine environment.

5. The addition of the CTBN rubber modifier had no effect on the ability to predict the elastic behavior of composite structures; the rubber modifier appeared to decrease the tendency for GRP brittle failures, and the addition of the rubber modifier improved the machining and handling characteristics of the laminate.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to the following persons for their interest, support and guidance throughout this project: Bernie Fink, George Lee, and Norb Nyers of HITCO; Kenneth Hofer and Gregory Skaper of IIT Research Institute; Jeffrey Beach, Philip Granum, and Norman Tideswell of DTNSRDC; Irv Wolock of NRL; and Daniel Nichols, Peter Jouannet, and Thomas White of NAVSEA.

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