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Development of Design Allowables Data for Celion 6000/LARC-160, Graphite/Polyimide Composite Laminates

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FOREWORD

This document was prepared by Rockwell International Corporation for the National Aeronautics and Space Administration, Langley Research Center, in compliance with Contract NAS1-15183, "Design, Fabrication, and Test of Graphite/Polyimide Specimens and Structural Elements."

This report documents results of one of 20 separate tasks authorized by the contract: Task 18, "Design Allowables Tests."

The contracting officer's technical representative for the full contract was Benson Dexter, and Gregory Wichorek was the technical representative for Task 18. Rockwell performance was initially under the management of J.E. Collipriest (contract negotiation and material procurement) and subsequently under R.M. Ehret (specimen fabrication and test). Major participants in this program were P.R. Scanlan, technical planning and coordination; D.H. Wykes, specimen fabrication; J.L. Brooks and R.J. Demonet, testing; and C.D. Rosen and C.D. Brownfield, data analysis and evaluation.

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1.0 SUMMARY

A design allowables test program was conducted to characterize a graphite polyimide composite material over the temperature range of 116 K (-250°F) to 589 K (600°F). Four hundred and forty tests were conducted with Celion 6000/LARC-160 composites in fulfillment of Task 18 of NASA Contract NAS1-15183. Tests were conducted to measure tension, compression, in-plane shear, and short beam shear mechanical properties. Material environmental conditions evaluated were baseline dry, thermally aged, and moisture saturated. Tensile strength, tensile modulus, strain-to-failure and Poisson's ratio were determined for $(0)_8$, $(90)_8$, $(0/45/90/-45)_{4s}$ and $(\pm45)_{2s}$ laminates. Compression strength, compression modulus, strain-to-failure, and Poisson's ratio were determined for $(0)_{16}$, $(90)_{16}$, $(0/45/90-45)_{2s}$, and $(\pm45)_{2s}$ laminates. In-plane shear strength, modulus, and strain to failure were determined for $(90)_8$, $(0/45/90/-45)_s$ and $(\pm45)_{2s}$ laminates. Short-beam shear strength was determined for $(0)_{20}$ configureation laminates. All tests were conducted at ambient temperature, 116 K (-250°F), or 589 K (600°F).

Test results show material performance generally consistent with anticipated graphite polyimide behavior. Fiber-dominated tensile strength showed little effect of test temperature, while resin-dominated tensile strength decreased as much as 50 percent at 589 K (600°F) compared to its ambient temperature strength. Effects of moisture saturation on elevated temperature tensile strength were moderate for the quasi-isotropic $(0/45/90/-45)_{4s}$ and $(\pm45)_{2s}$ laminate in that a reduction in elevated temperature strength of nearly 17 and 25 percent, respectively, at 589 K (600°F) was observed. However, the totally resin-dominated laminate, $(90)_8$, lost nearly 70 percent of its elevated-temperature strength because of the effects of moisture saturation. Tensile modulus values for fiber-dominated laminates increased slightly with increasing temperature. As with strength, as laminates become more matrix dominated, the tensile modulus decreases with increasing temperature. The effects of moisture saturation and thermal aging on tensile modulus were slight except that the totally resin-dominated laminate showed a 40-percent reduction in elevated temperature modulus as a result of moisture saturation.

While compressive modulus was not significantly affected by the temperature extremes, compressive strengths consistently decreased with increasing temperature regardless of laminate geometry. Again, compressive strengths at 598 K (600°F), after moisture saturation, exhibited a significant reduction (nearly 50 percent for $(90)_{16}$ and quasi-isotropic laminates) compared with dry laminates tested at the same temperature. The effects of temperature on in-plane shear strength and modulus were consistent in that strengths decreased with increasing temperature, while modulus values were relatively insensitive to test temperatures. As anticipated, increasing temperature contributed to a general decrease in short beam shear strengths.

2.0 INTRODUCTION

Graphite polyimide composites have shown potential for use as a structural material at elevated temperatures on advanced aerospace vehicles. The Shuttle orbiter, for example, could conceivably save 14,000 pounds of vehicle weight by converting primary structural elements (wings, fuselage, tail, etc.) to graphite polyimide composites. Such weight saving considers the combined benefits of high specific strength/stiffness and the reduction in thermal insulation owing to the higher temperature capability of the graphite polyimide system. A series of experimental programs involving the design, fabrication, and test of graphite polyimide specimens and various structural elements was funded under NASA Contract NAS1-15183. The contract consisted of 20 separate and independent tasks. The objective of the task reported herein was to support development of mechanical properties design allowables data for Celion 6000/LARC-160 graphite polyimide composite material.

This report presents the manufacturing processes, test procedures, and test results of the Celion 6000/LARC-160 graphite polyimide design allowables test program. Tests were conducted to measure tension, compression, in-plane shear, and interlaminar shear properties. Test temperatures were 116 K (-250°F), 294 K (70°F), and 589 K (600°F). Properties were evaluated for laminates which were environmentally preconditioned by moisture saturation and thermal soak to compare with a "baseline dry" condition. Results of this study will contribute to the material properties data base required for accurate design and analysis of structural components for advanced space transportation systems and high-speed aircraft.

Results of this program cannot stand alone with respect to design allowables data, but must be combined with results of related test programs such that the data base can be evaluated statistically and the effects of lot-to-lot material variations can be considered.

3.0 MATERIALS AND SPECIMEN FABRICATION

This section describes materials, processing, and specimen fabrication procedures used for this program.

3.1 Materials

The Celion 6000/LARC-160 graphite polyimide prepreg material used for this program was from a single 53.6-pound lot (two rolls) of 12-in.-wide tape purchased from Fiberite Corporation. Prepreg acceptability for contract use was based upon supplier certifications, chemical analysis of the neat resin, and physical evaluation of two laminates fabricated from each roll of material. The prepreg material acceptability data are summarized in Table 3.1-1. The slightly low glass transition temperatures (T_g) observed for the quality control laminates were considered acceptable since minor changes in the production laminate cure and/or post-cure processes could be employed to eliminate the deficiency. All other required characteristics met specified material properties requirements. Figures 3.1-1 and 3.1-2 show the neat resin infrared (IR) spectrum and high-pressure liquid chromatogram (HPLC) respectively. Figure 3.1-3 shows the differential scanning calorimetry results for the resin.

3.2 Laminate Processing and Specimen Fabrication

Twenty-two graphite polyimide laminate panels were fabricated, from which 440 individual specimens (plus 45 spares) were obtained. The physical description and characteristics of the required types of laminates are summarized in Table 3.2-1. Fiber volume (V_f) was calculated for each laminate by four separate methods: weight loss during cure, cured panel final weight, average panel thickness, and specific gravity. These calculated V_f values, plus the measured specific gravity and glass transition temperatures (T_g) measured by thermal mechanical analysis, are also given in the table.

A two-stage processing procedure, oven imidize and autoclave cure, was utilized to fabricate all laminates. The processing procedures for the Celion 6000/LARC-160 system were developed under NASA/LaRC Contract NAS1-15371 (reported in Reference 1). The following summarizes the processing cycle.

3.2.1 Prepreg Tape Layup Procedure

The prepreg tape was stacked in the required ply orientation and numbers of plies, paper backing surface up, on a smooth tooling surface such as a metal plate covered with a nonporous Teflon-coated fabric. Edges of the prepreg tape were cut with a straight edge to the appropriate shape. A hot iron (at approximately 394 K/250°F) was employed to promote adhesion between the various plies of tape during layup.

TABLE 3.1-1. QUALITY CONTROL TEST RESULTS FOR CELION 6000/LARC-160 GRAPHITE POLYIMIDE MATERIALS

Property	Requirement*	Results			
FIBER					
Strand strength, GN/m^2 (ksi)	2.76 (400)	3.42 (496)			
Strand Modulus, GN/m^2 (msi)	230 (33)	236 (33.9)			
Fiber density, g/cc	1.77 ±0.04	1.77			
PREPREG					
Roll No.	-	1	2		
Resin solids (%)	38 ±3	36	37.4		
Volatile content (%)	12 ±3	9.0	9.0		
Gel time, minutes at 477 K (400°F)	0.5 -2.0	0.8	0.8		
Fiber areal weight (g/m^2)	155 ±5	156.9	154.6		
LAMINATES					
Roll No.	-	1	1	2	2
Panel No.	-	11	12	13	14
Orientation (16-ply)	-	$(0/90)_{4s}$	$(0/90)_{4s}$	$(0/90)_{4s}$	$(0)_{16}$
Tg, K (°F)	589 (600)	587 (585)	587 (597)	582 (588)	596 (613)
Specific gravity	1.57 ±0.03	1.580	1.597	1.588	1.583
Fiber weight (%)	69 ±2	67.4	70.3	68.6	67.9
Fiber volume (%)	60 ±2	60.8	64.2	62.2	61.4
Ply thickness (mils)	5.5 ±0.2	5.64	5.52	5.42	5.56

Materials:

Fiberite Product
No. hy-E-1678F
Fiber Lot No. HTA-7-9Y31
Resin Lot No. 34228
Prepreg Lot No. C2-105
(4-15-81)

*Minimum unless otherwise noted

SAMPLE:	LARC-160	BECKMAN 4260	
	FIBERITE, LOT NO. 34228	SPEED:	300 CM^{-1}/MIN.
DATE:	07-30-82	GAIN:	AUTO
PHASE:	FILM ON NACL	PERIOD:	2
		SLIT:	AUTO

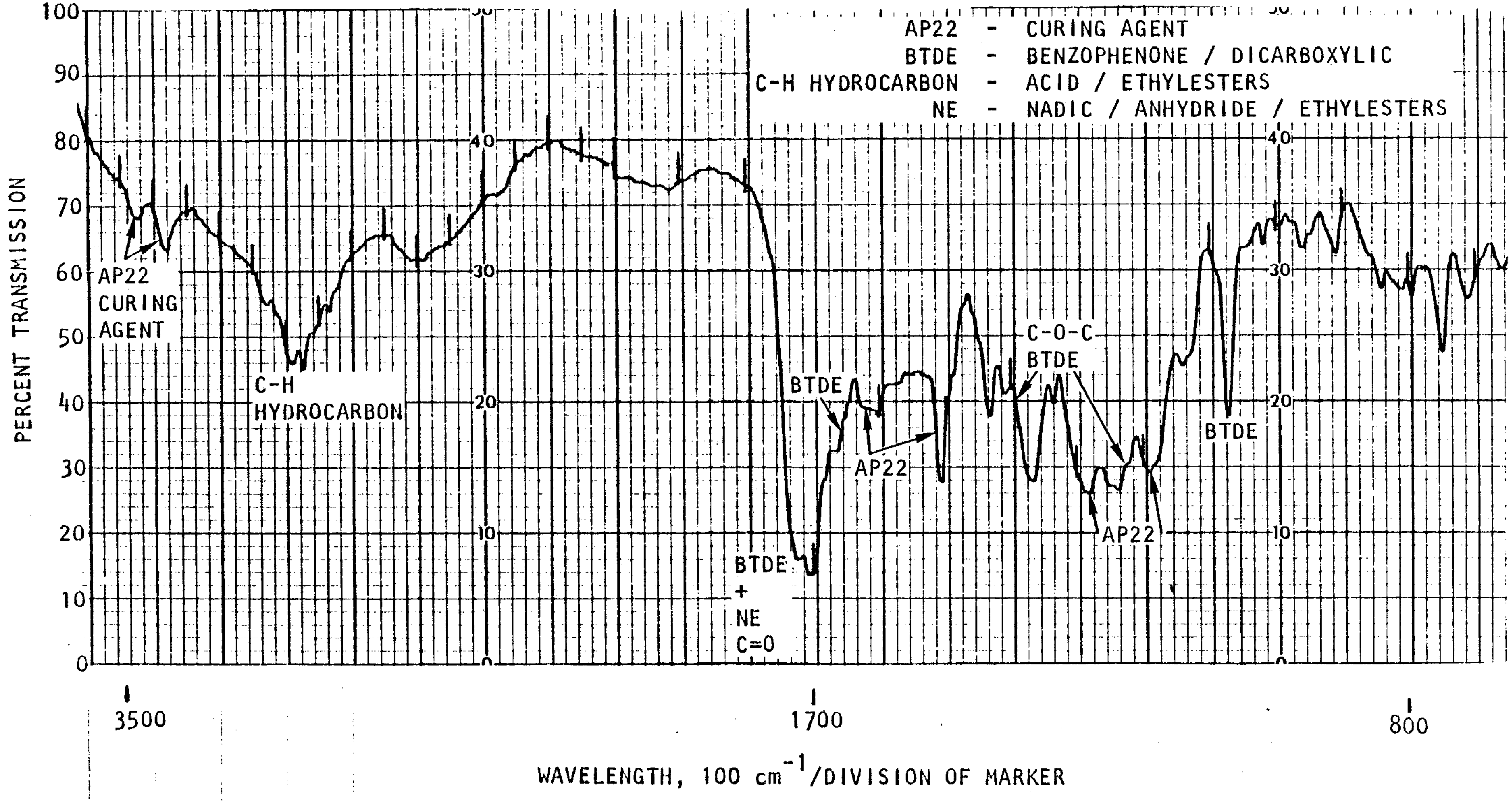

Figure 3.1-1. Neat resin IR spectrum

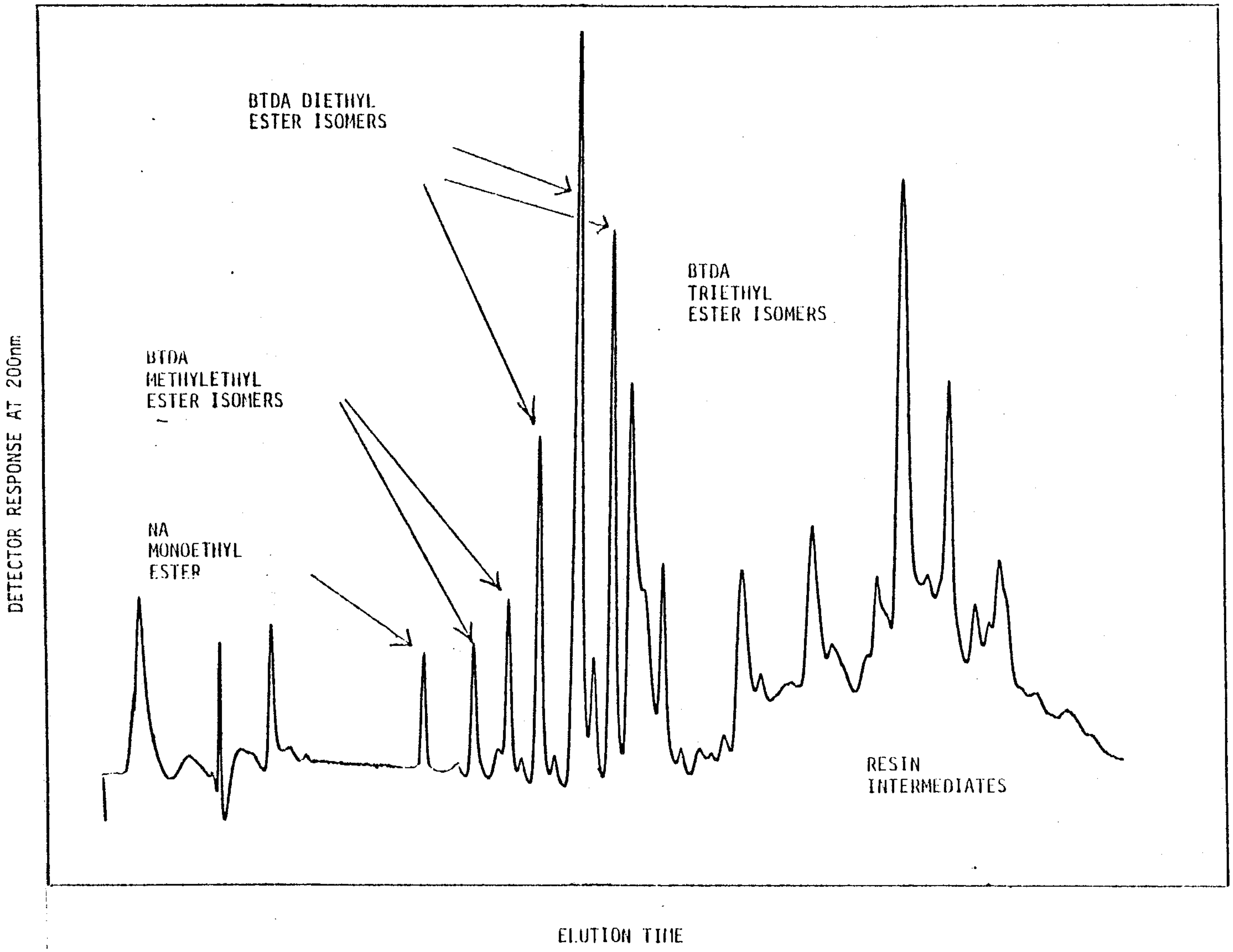

Figure 3.1-2. Neat resin HPLC chromatogram

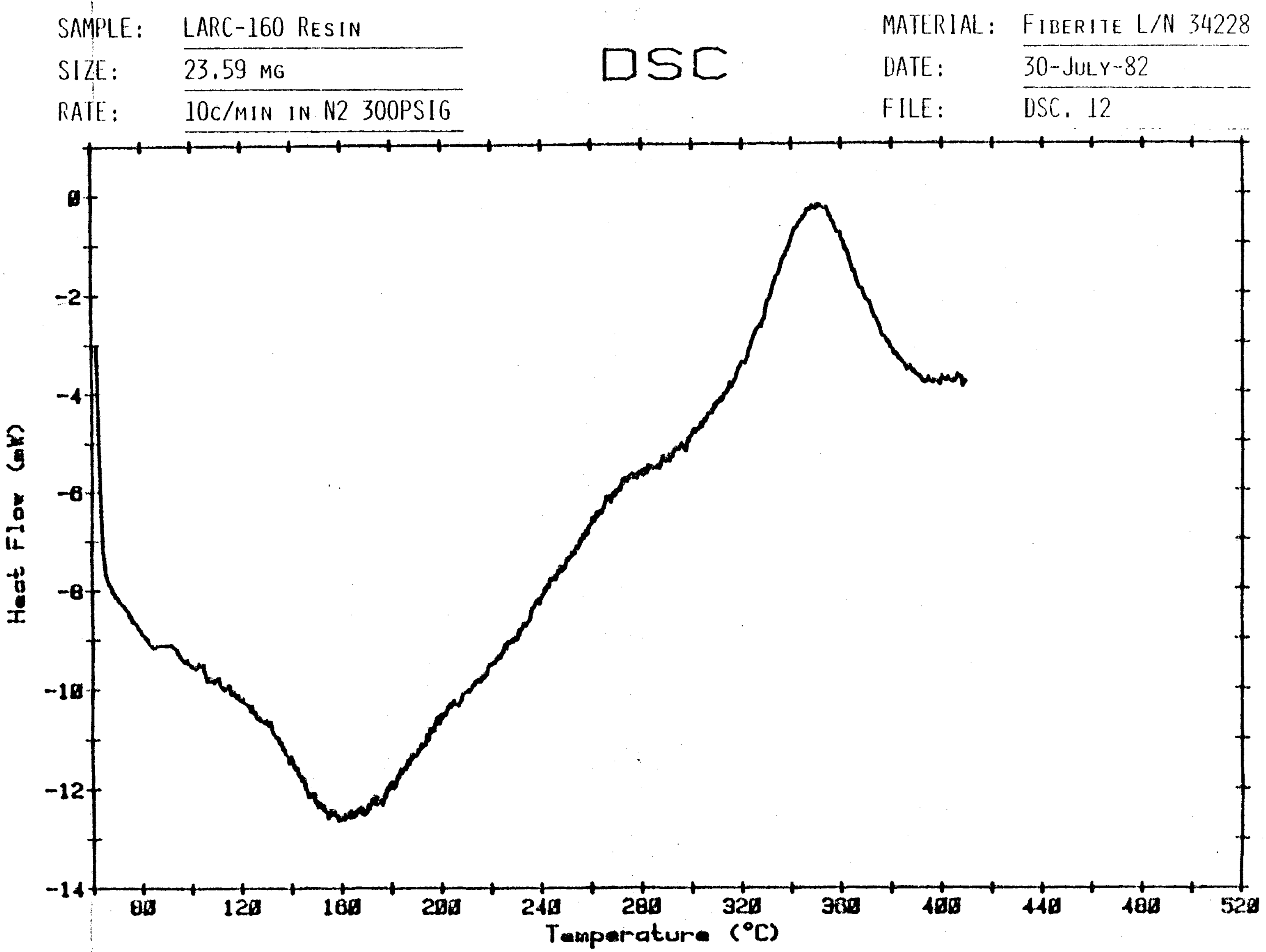

Figure 3.1-3. Differential scanning calorimetry

Care was taken to minimize gaps in the layup of tape elements. The final weight of each laminate layup was recorded. Debulking of stacked prepreg for flat laminate fabrication was not performed.

3.2.2 Imidizing Process

Principal concerns with the LARC-160 polyimide resin prepreg materials are to ensure (1) efficient, uniform removal of solvent and condensation reaction volatiles from large and/or complex surface areas and (2) resin flow control in the composite concurrent with the application of augmented pressure and vacuum during the autoclave cure cycle.

Prepreg volatile removal techniques were established with use of the tooling developed during the conduct of previous elements of this contract. A perforated steel top caul plate was used to allow uniform removal of volatiles. The plate is used for venting volatiles to the vacuum source employed during oven staging at 491-497 K (425-435°F). Perforations in the caul plate act as individual, unrestrained vacuum ports serving local surface areas.

The laminate preform is imidized on tooling shown in Figure 3.2-1. The laminate is contained in Teflon-coated porous fabric separator and Mochberg paper bleeder material. The type and amount of bleeder was determined beforehand and based upon the original resin and volatile content of each roll of prepreg and the thickness of the laminate under construction. Volatiles are reduced to less than 3 percent by this procedure. The typical imidizing cycles used for the Celion 6000/LARC-160 laminates are shown in Figure 3.2-2.

3.2.3 Cure Procedure

Imidized flat laminates were autoclave-cured on tooling shown in Figure 3.2-3. Since the laminate volatile content had been reduced to less than 3 percent during the imidizing procedure, it was treated analogous to an epoxy laminate in the cure process. Nonperforated cauls are employed with the bleeder arrangement shown in Figure 3.2-3. The autoclave cure cycle is shown in Figure 3.2-4. Autoclave pressurization rates were in the range of 5 to 15 minutes from 0 to 1378 KN/m^2 (0 to 200 psi). The pressure was applied at the start of the cycle. Resin hot melt flow was in the range of 527 to 538 K (475 to 510°F) with a final cure temperature of 589 K (600°F) minimum, typically 593 K (625°F). The time of cure was three hours (minimum) for each laminate.

3.2.4 Ultrasonic (C-scan) Evaluation of Laminates

Each laminate was submitted to the Quality Engineering Laboratory for verification of laminate quality before machining and subsequent adhesive bonding. Each laminate was inspected per an agreed-upon NASA-Langley and Rockwell ultrasonic reflector plate technique that used sensitivity "A" standards. For example, the gain and/or dB levels to be employed are established on the standard before each series of examinations and this setting is used when the part is inspected. The reflector plate technique is designed to detect distributed porosity within the graphite polyimide material, as well as the more usual types of defects associated with structural flaws.

Detergent and a soft, nonabrasive sponge were used to scrub each part clean. The setting was established as described, and the laminate was installed in the chromated water tank over the reflector plate. The transducer head was positioned over the part being examined, and a reduced plan-view C-scan recording of each laminate was then made.

The quality of the 22 laminates, as determined by ultrasonic inspection, was excellent. Minor discrepancies, usually surface irregularities, were noted on the C-scan record and used for subsequent reference during specimen cutting. Figures 3.2-5 and 3.2-6 show ultrasonic inspection records. During all phases of the fabrication and inspection cycle, no laminate was rejected or scrapped.

3.2.5 Machining/Adhesive Bonding

Copies of the applicable C-scan recording were used to lay out specimens and doubler blanks on the laminates to eliminate irregularities when present. Irregularities were either incorporated into doubler segments (for grip tabs) or eliminated completely from the panel.

Test section panels and doubler panels were machined from the large laminates. The doubler panels were then bonded to the test section panels to form subassemblies. The bonding process involved solvent cleaning the faying surfaces with MEK followed by light abrasive cleaning with Ajax cleanser and Beartex pads. The parts were then rinsed with deionized water, patted dry, and final-dried for one hour at 339 K (150°F) in a convection oven. BR-34 polyimide primer was applied, by spraying, to the cleaned faying surfaces of the test sections and grip tab doublers. The primer was air-dried for approximately one hour at ambient temperature/humidity conditions and oven-cured for 30 minutes (minimum) at 366 K (200°F). FM-34 polyimide adhesive film was then cut into appropriate shapes and applied to the applicable faying surface zones. Each subsection was assembled by using the identification coding on the detail parts, and locating pins were installed to maintain assembly configuration. The items were vacuum-bagged and autoclave-cured for two hours at 363 K (375°F) at full vacuum and 345 KN/m^2 (50 psi) augmented pressure. The subassemblies were then subjected to a free-standing oven post-cure for 6 hours at 589 K (600°F).

After the grip-tab doublers were bonded to the test sections, the subassemblies were submitted to the Quality Engineering Laboratory for additional ultrasonic (C-scan) examination to determine the quality of the adhesive bond and to reverify the integrity of the test section. Again the C-scan recordings were used to establish the final specimen cutting lay-out patterns. Typical specimen cutting diagrams are depicted in Figures 3.2-7 and 3.2-8. The specimens were machined, cleaned, checked for proper identification, and delivered to the Mechanical Properties Test Group for installation of strain gauges, environmental pretest conditioning, and testing.

TABLE 3.2-1. CELION 6000/LARC-160 GRAPHITE POLYIMIDE PANEL SUMMARY

Panel ID	Prepreg Roll No.	Ply Orientation	No. Plies	End Item Usage	Specific Gravity	% Fiber Volume $V_{(f)}$*-Target:60±2%				Glass Trans Temp, T_g (K)
						Wt Loss	Actual Wt	Thickness	Specific Gravity	
TENSION SPECIMENS (14 PANELS)										
CL8-U-18-T1	2	$[0]_8$	8	Specimens	1.589	62.5	62.3	62.5	62.5	616
CL8-U-18-T2	2	$[0]_8$	8	Tabs	1.578	62.1	62.3	62.3	60.0	614
CL8-U-18-T3	2	$[0]_8$	8	Specimens/tabs	1.586	60.3	62.3	62.5	61.8	605
CL8-90-18-T1	2	$[90]_8$	8	Specimens	1.593	62.3	61.1	60.5	63.5	616
CL8-90-18-T2	2	$[90]_8$	8	Specimens	1.582	61.4	60.9	60.9	60.9	619
CL8-90-18-T3	2	$[90]_8$	8	Tabs	1.586	60.7	60.5	60.7	61.8	615
CL8-90-18-T4	2	$[90]_8$	8	Tabs/spare	1.585	60.0	60.0	59.6	61.6	617
CL8-C-18-T1	2	$[0/+45/90/-45]_s$	8	Specimens	1.587	61.1	62.1	61.1	62.1	615
CL8-C-18-T2	2	$[0/+45/90/-45]_s$	8	Specimens/tabs	1.584	60.9	61.1	62.3	61.4	604
CL8-C-18-T3	2	$[0/+45/90/-45]_s$	8	Tabs/spare	1.584	60.3	60.7	61.6	61.4	613
CL8-45-18-T1	2	$[\pm 45]_{2s}$	8	Specimens/tabs	1.584	60.0	60.5	59.2	61.4	613
CL8-45-18-T2	1	$[\pm 45]_{2s}$	8	Specimens/tabs	1.594	62.4	64.9	62.8	63.7	614
CL8-45-18-T3	1	$[\pm 45]_{2s}$	8	Specimens/tabs	1.594	61.7	64.5	62.3	63.7	613
CL8-45-18-T4	1	$[\pm 45]_{2s}$	8	Specimens/tabs	1.586	61.2	63.5	60.3	61.9	615
COMPRESSION SPECIMENS (4 PANELS)										
CL16-U-18-C1	1	$[0]_{16}$	16	Specimens/tabs	1.587	57.9	60.8	58.9	62.1	607
CL16-90-18-C1	1	$[90]_{16}$	16	Specimens/tabs	1.578	58.4	60.2	59.0	59.9	604
CL16-C-18-C1	1	$[0/+45/90/-45]_{2s}$	16	Specimens/tabs	1.594	58.7	59.8	58.9	63.7	605
CL16-45-18-C1	1	$[\pm 45]_{4s}$	16	Specimens/tabs	1.576	58.9	59.8	59.1	59.5	587
IN-PLANE SHEAR SPECIMENS (3 PANELS)										
CL8-90-18-1PS1	1	$[90]_8$	8	Specimens	1.601	62.0	63.8	60.4	65.4	615
CL8-C-18-1PS1	1	$[0/+45/90/-45]_s$	8	Specimens	1.600	63.4	63.6	62.2	65.2	616
CL8-45-18-1PS1	1	$[\pm 45]_{2s}$	8	Specimens	1.597	61.8	62.4	61.9	64.5	616
INTERLAMINAR SHEAR SPECIMENS (1 PANEL)										
CL20-U-18-1LS1	1	$[0]_{20}$	20	Specimens	1.577	59.0	60.0	61.2	59.7	615

*Fiber volume determined by four methods shown

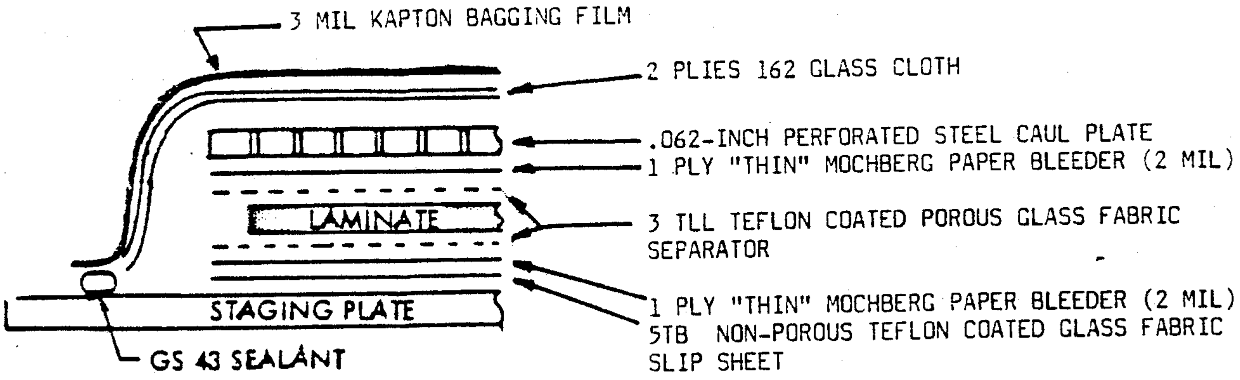

Figure 3.2-1. Tooling for imidizing Celion 6000/LARC 160 laminates

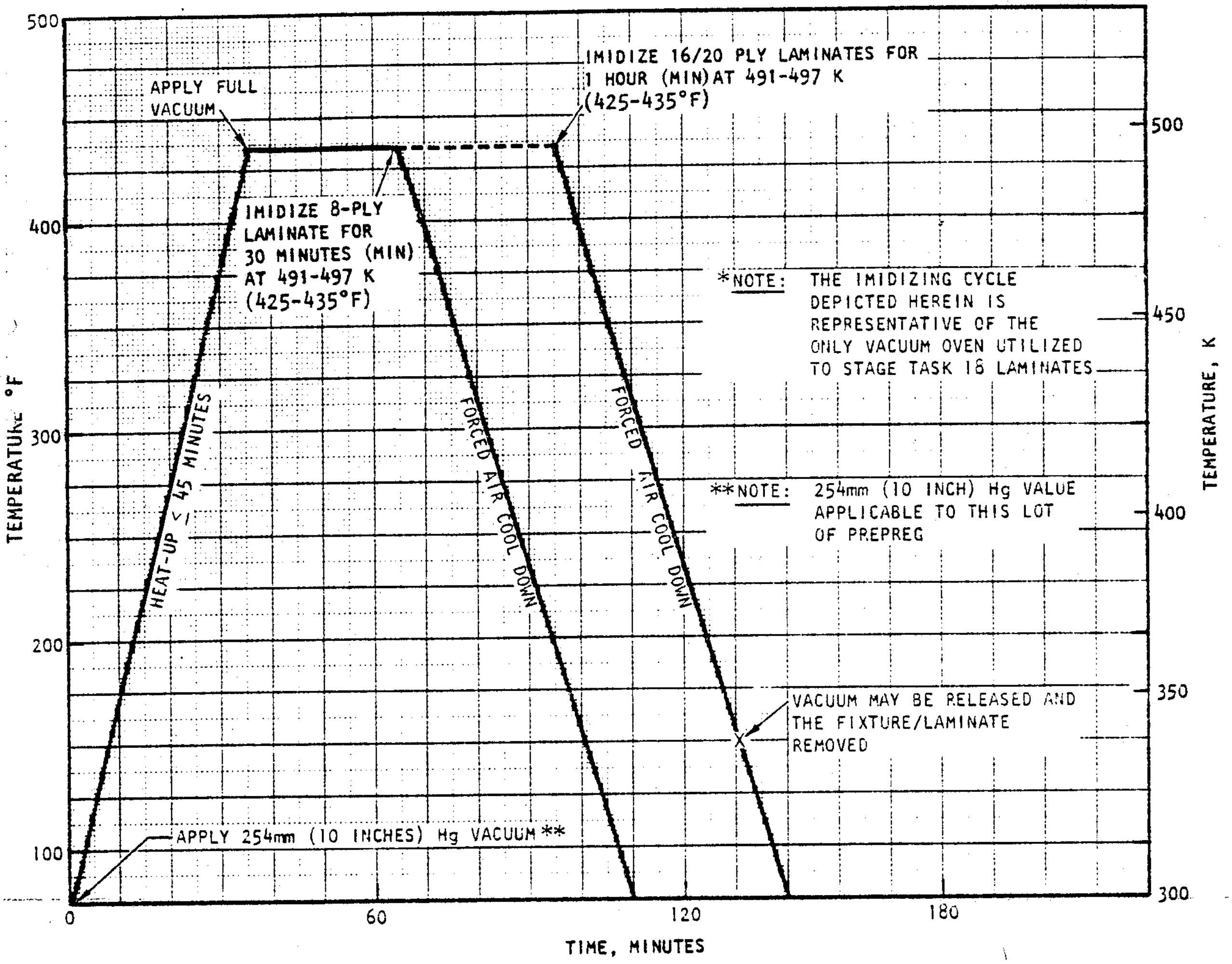

Figure 3.2-2. Typical imidizing (staging) cycle - Celion 6000/LARC-160

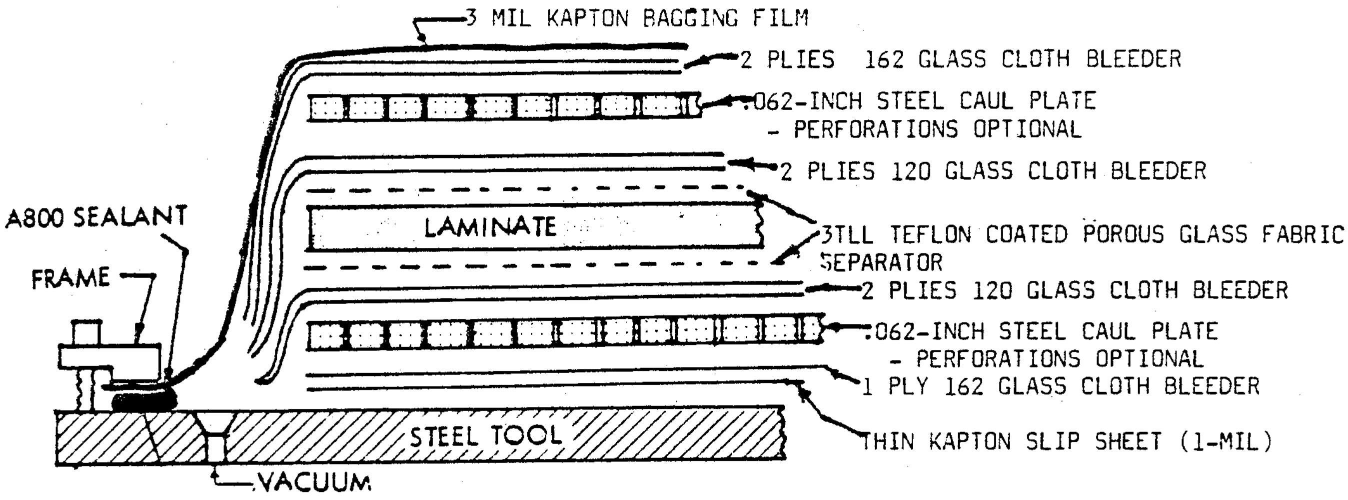

Figure 3.2-3. Tooling for curing Celion 6000/LARC-160 laminates

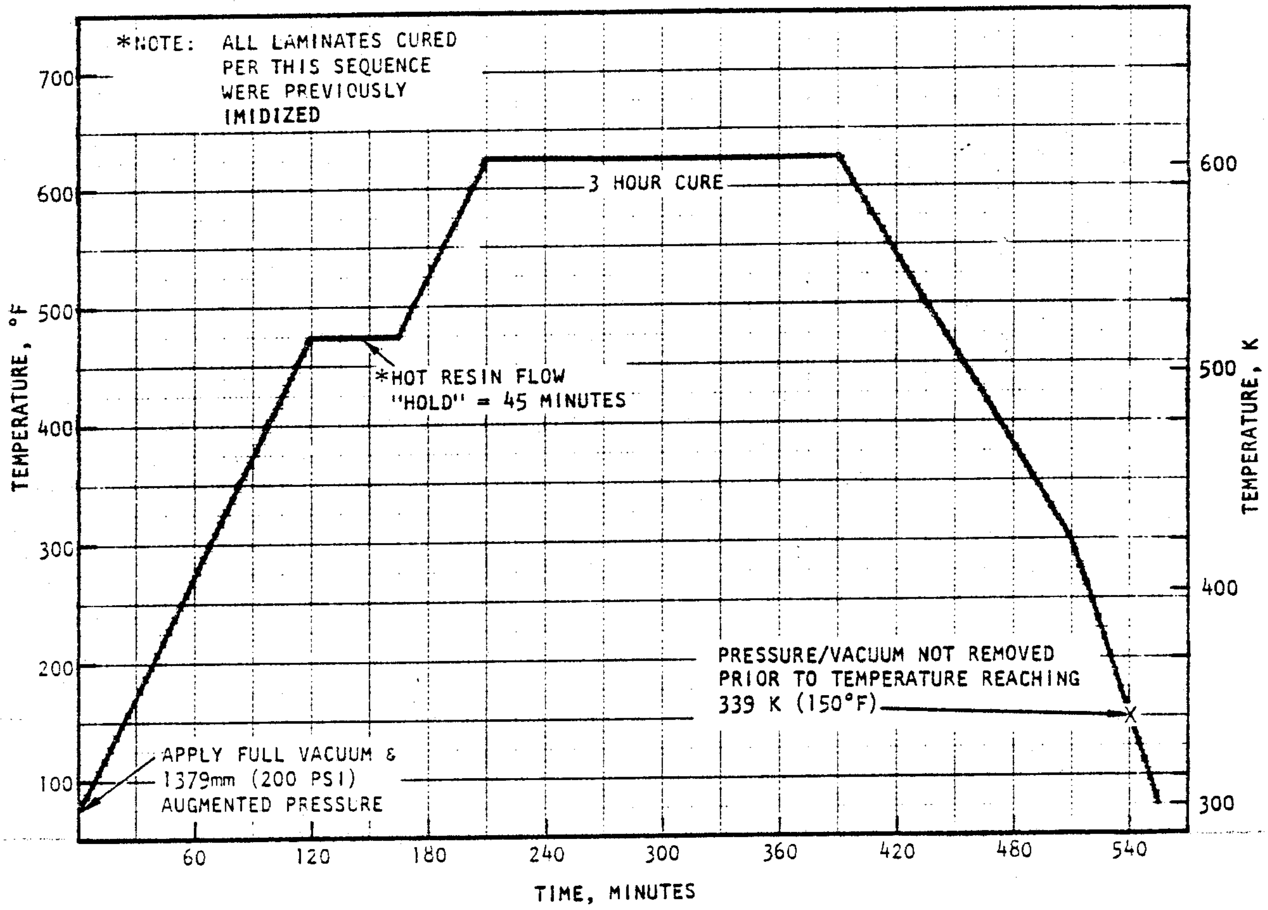

Figure 3.2-4. Typical autoclave cure cycle - Celion 6000/LARC-160

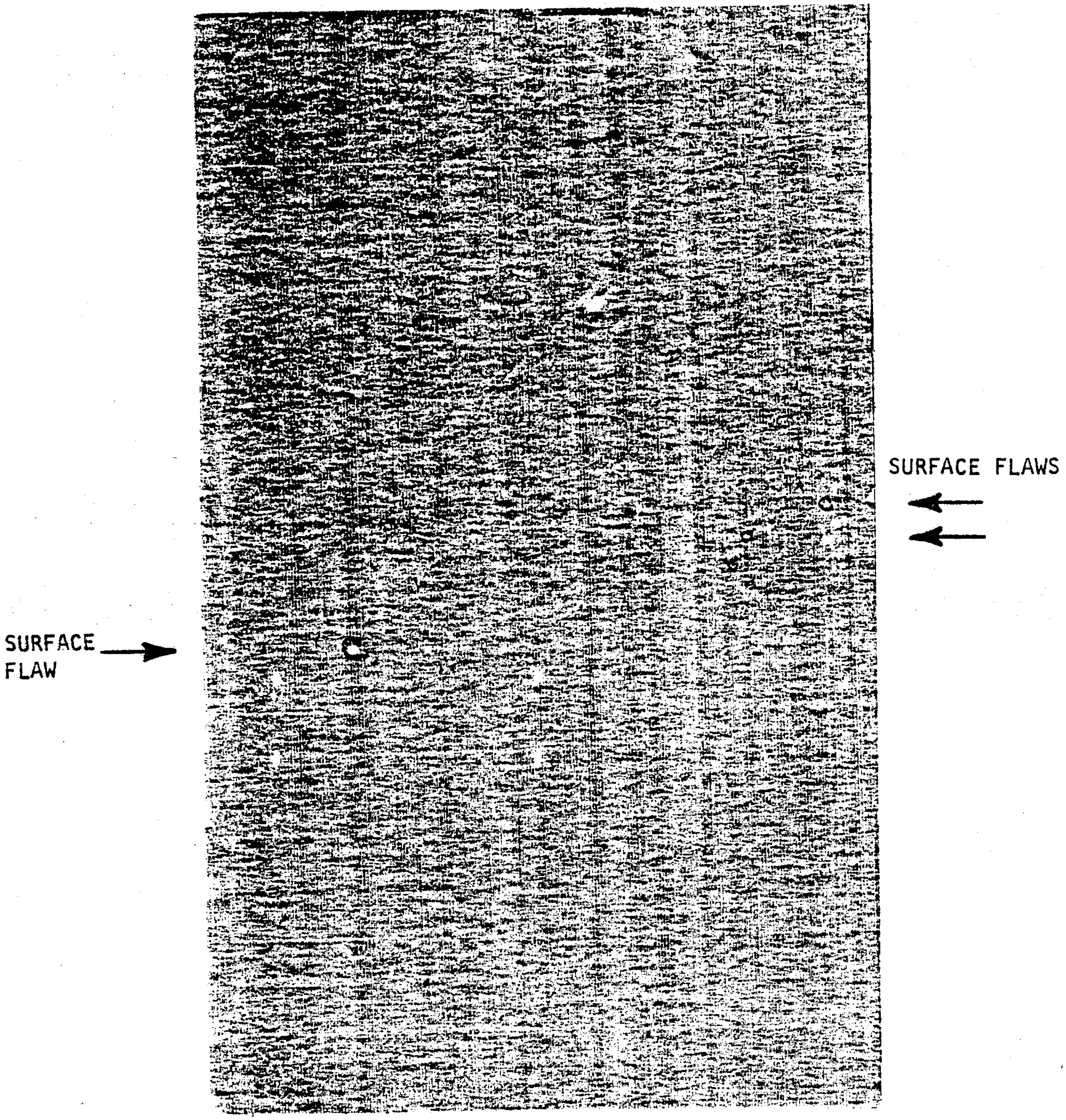

Figure 3.2-5. C-Scan for Laminate CL8-45-18-T1, $(\pm45)_{2s}$

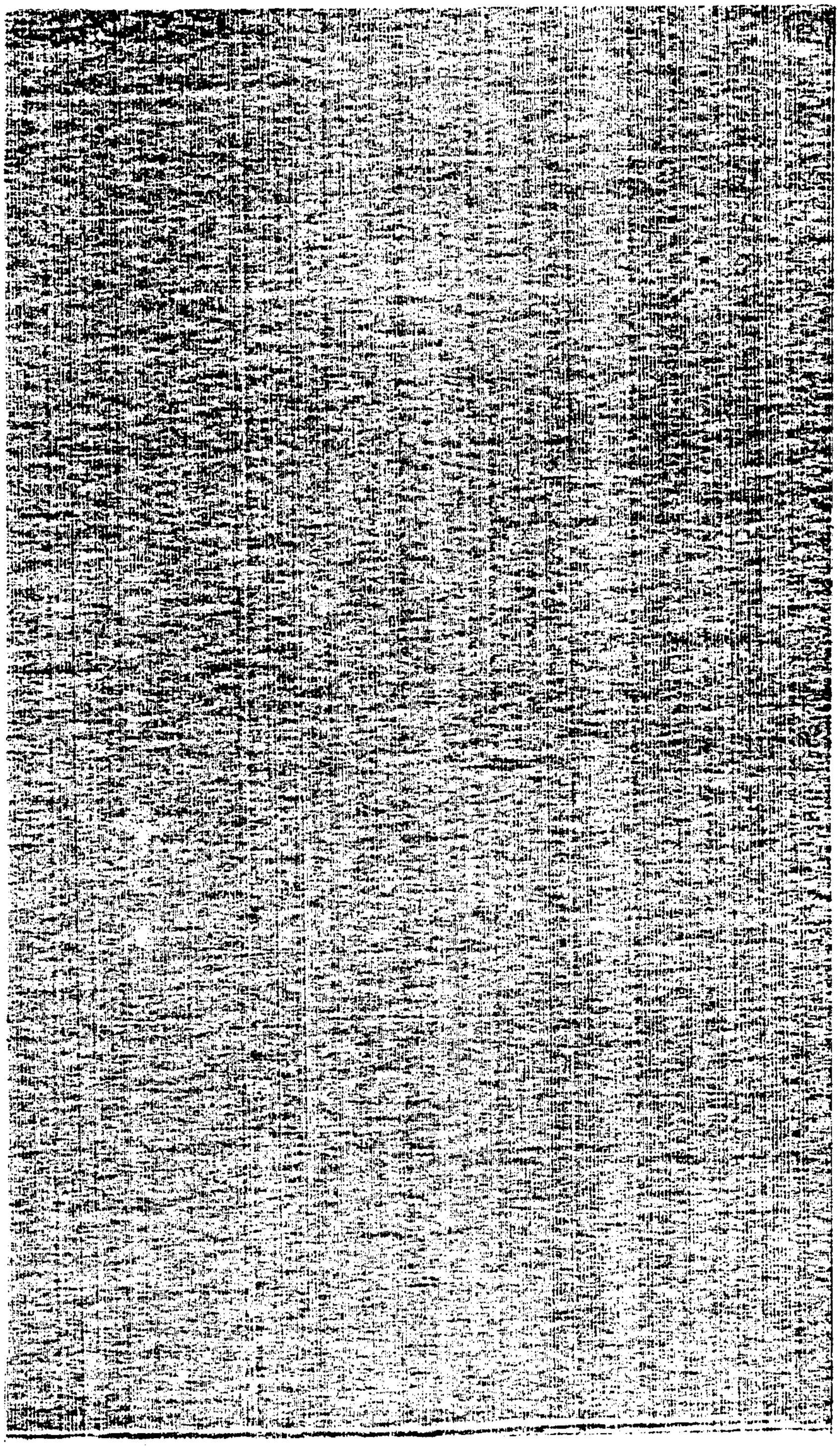

Figure 3.2-6. C-Scan for Laminate CL8-90-18-T1, $(90)_8$

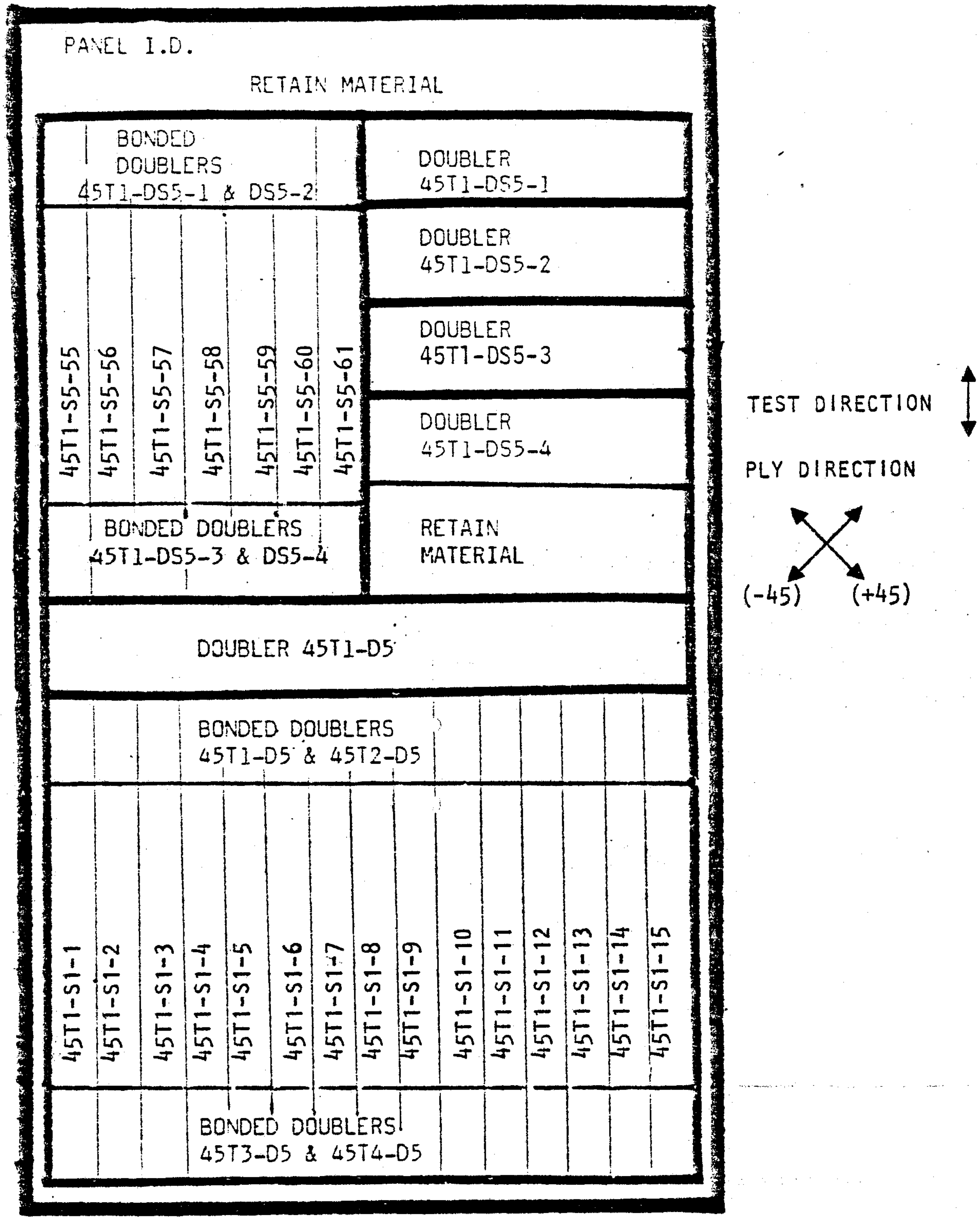

Figure 3.2-7. Cutting diagram for laminate CL8-45-18-T1

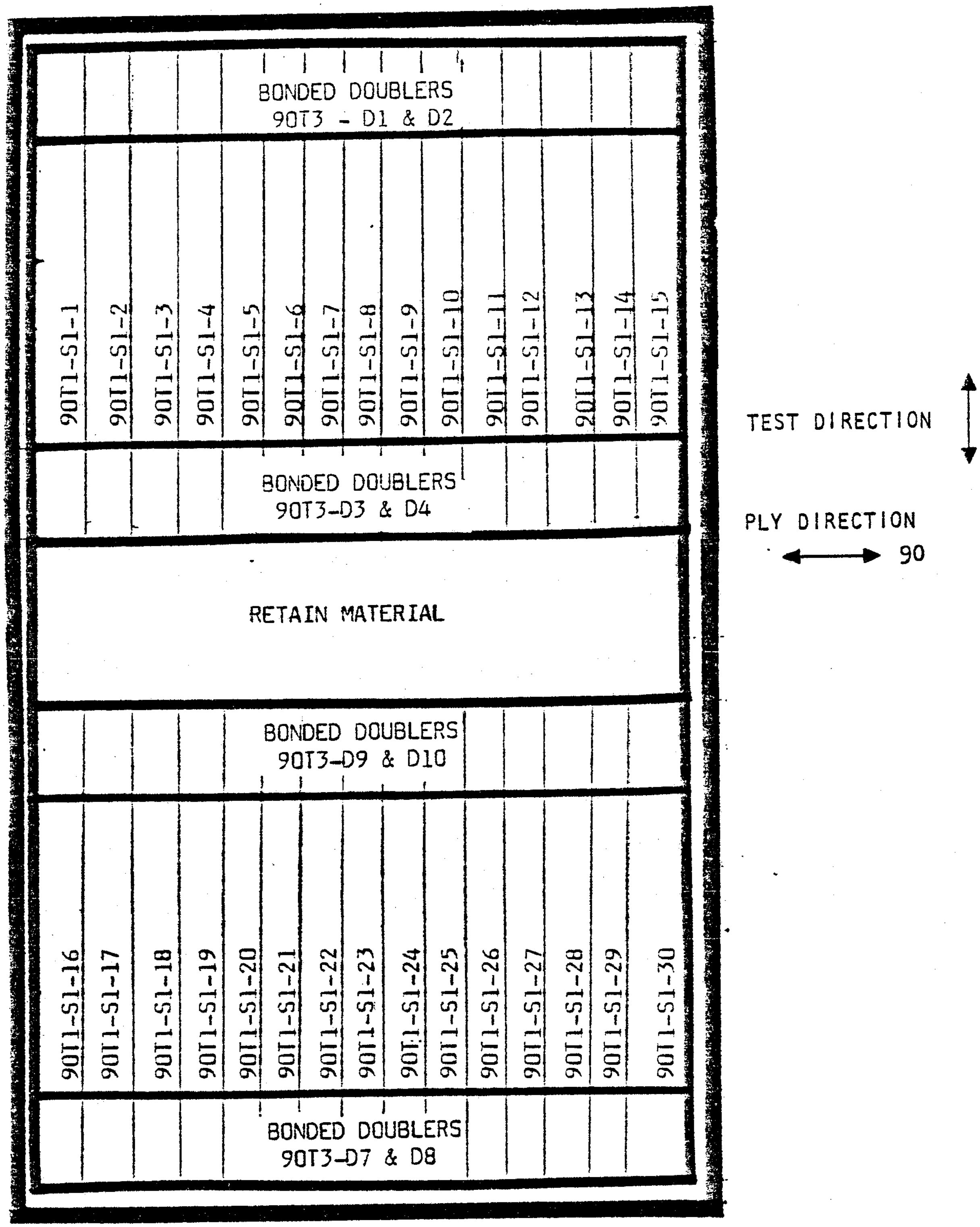

Figure 3.2-8. Cutting Diagram for Laminate CL8-90-18-T1

4.0 MECHANICAL PROPERTY TESTING

This section presents the test matrix, specimen configurations, test procedures, and test results for all testing of Celion 6000/LARC-160 graphite polyimide laminates.

4.1 Testing Summary

Graphite polyimide mechanical properties were determined in accordance with the test matrix (Table 4.1-1). After appropriate preconditioning, the tension, compression, in-plane shear, and short beam shear tests were conducted at ambient temperature, 116 K (-250°F) or 589 K (600°F). The majority of specimens (78 percent) were dried in a vacuum furnace prior to testing for baseline properties. The remaining specimens were preconditioned by moisture saturation in a suitable chamber or 125 hours of thermal soak at 589 K (600°F). One-half of all baseline-dry specimens (except short beam shears) were instrumented with bonded strain gauges. Remaining tests were monitored with available extensometry equipment as applicable for the particular test. Environmental conditioning for strain-gauged specimens was performed after gauge installation but prior to lead wire installation.

Tension, compression, and in-plane shear testing was conducted with a 10,000-kg-capacity (22,000-pound) closed-loop electro-hydraulic test machine (Figure 4.1-1) operating in load control. All load and strain values for strain-gauged specimens were monitored through automatic data acquisition systems which provided results in digital and graphic form and performed appropriate data reduction calculations. Riehle test equipment was used for interlaminar (short beam) shear testing.

4.2 Strain Gauge Installation

All strain gauges installed on design allowable specimens were applied in accordance with standard laboratory procedures. This involved using AE10 adhesives to apply gauges to room-temperature and cryogenic test specimens. The gauges were applied to elevated-temperature specimens with M-Bond 610 adhesive, which required an oven cure for two hours. In all instances the appropriate surface zone of each specimen was lightly abraded, followed by solvent wiping and cleaning prior to gauge installation.

After the exposure to environmental conditioning, lead wires were installed to each gauge. Standard 60/40 tin/lead solder was used to attach the wires to the room-temperature and cryogenic gauges; silver braze was used on the wires for the elevated temperature gauges.

Biaxial back-to-back strain gauges were installed on applicable tension and compression specimens. Back-to-back rosette strain gauges were installed on in-plane (rail) shear specimens.

TABLE 4.1-1. PROGRAM TEST MATRIX

Test Type	Ply Orientation	Number of Tests									Total Tests
		Baseline Dry			Moisture Saturated			Thermal Soaked			
		Test Temperature									
		116 K (-250°F)	RT	589 K (600°F)	116 K (-250°F)	RT	589 K (600°F)	116 K (-250°F)	RT	589 K (600°F)	
Tension	$[0]_8$	10	10	10							30
	$[90]_8$	10	10	10		5	5				40
	$[0/45/90/-45]_s$	10	10	10		5	5				40
	$[\pm45]_{2s}$	10	10	10		5	5	5	5	5	55
Compression	$[0]_{16}$	10	10	10							30
	$[90]_{16}$	10	10	10		5	5				40
	$[0/45/90/-45]_{2s}$	10	10	10		5	5				40
	$[\pm45]_{4s}$	10	10	10							30
In-plane Shear	$[90]_8$	10	10	10							30
	$[0/45/90/-45]_s$	10	10	10							30
	$[\pm45]_{2s}$	10	10	10							30
Short Beam Shear	$[0]_{20}$	5	5	5	5	5	5	5	5	5	45
Totals		115	115	115	5	30	30	10	10	10	440

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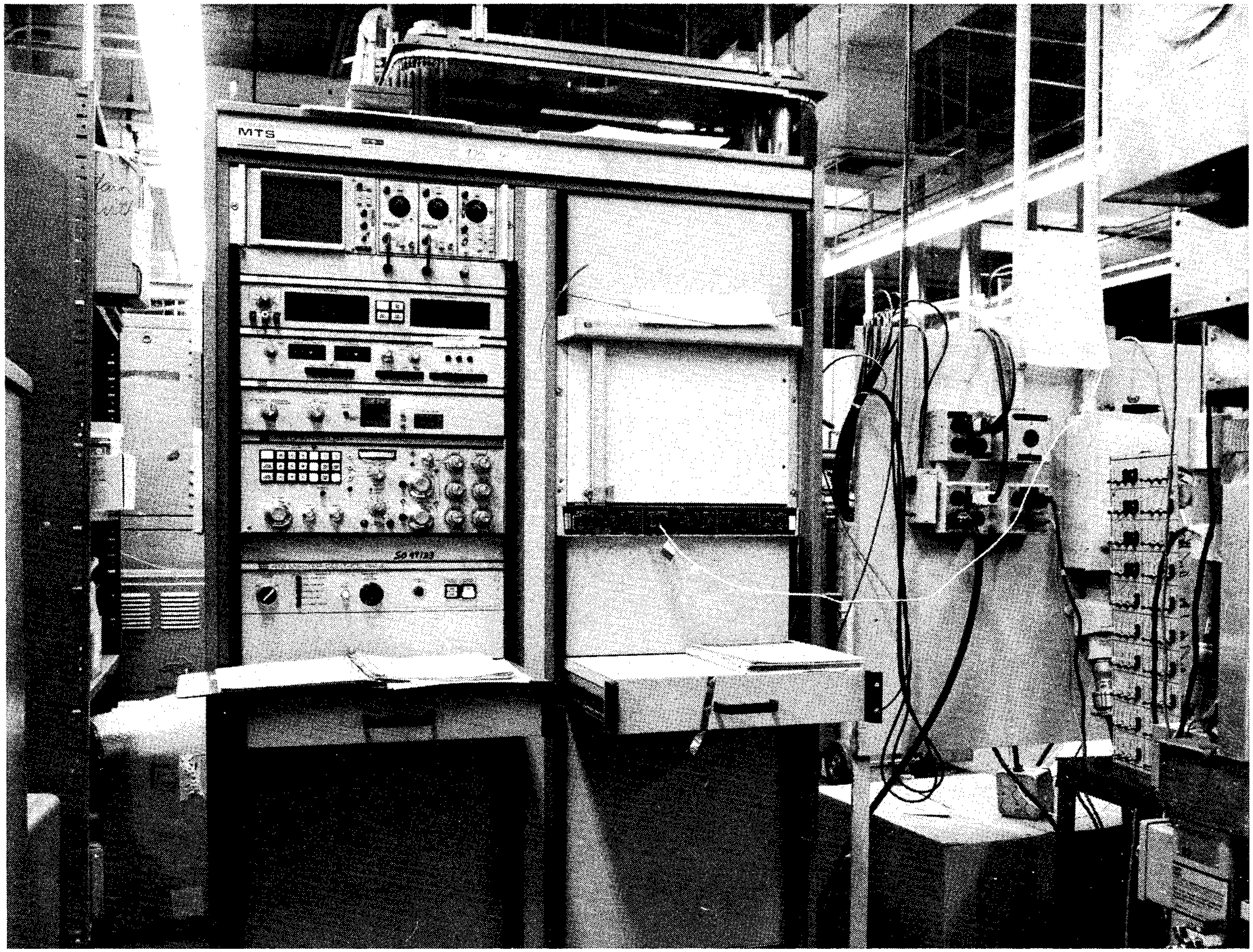

Figure 4.1-1. 22,000-pound capacity MTS electro-hydraulic test machine console

4.3 Conditioning - Procedure and Controls

4.3.1 Baseline Dry Condition

Specimens were placed in a vacuum chamber at a reduced pressure not greater than 500 Pa (3.8 mm Hg) absolute and a temperature of 366 K (200 ±5°F) and dried to a baseline level before testing. Approximately 345 specimens plus 35 spares were conditioned per the following parameters:

At least two specimens of each laminate were accurately weighed (nearest 0.1 milligram). The weights were recorded before the start of conditioning and at one week intervals thereafter to determine weight loss. The specimens were considered dry and ready for test when weight loss did not change more than 0.1 percent after three consecutive weekly measurements.

After the baseline-dry condition was established, the specimens were retained in the chamber at the temperature and pressure conditions defined until tests were performed. The specimens were removed in groups that could be tested within any 8-hour shift and stored in desiccators or sealed nylon plastic bags (strain-gauged specimens) between chamber removal and final mechanical testing.

4.3.2 Moisture Saturation Condition

Specimens were placed in a humidity chamber with a relative humidity of 95 ±5 percent, temperature of 333 K (140 ±5°F), and ambient pressure and then conditioned to a constant moisture level.

Moisture saturation was determined in the same manner as the baseline-dry conditioning except that the specimens were considered to be saturated when measured weights did not increase by more than 0.1 percent from the previous weight after three consecutive weight measurements made at one-week intervals. After a saturated condition was established, the specimens remained in the chamber at the conditions indicated until the mechanical tests were performed.

4.3.3 Thermal Soak Condition

Specimens were exposed in an air-circulating oven at 589 K (600 ±10°F) and atmospheric pressure for a period of 125 hours. After completion of the thermal soak conditioning, the specimens were stored in a baseline-dry vacuum chamber until the mechanical tests were performed.

4.3.4 Test Temperatures

Test temperatures for the Celion 6000/LARC-160 tests were controlled as follows:

Room temperature tests were conducted in an air-conditioned laboratory maintained at a nominal 294 K (70°F) and 40-percent relative humidity.

For the elevated temperature tests, specimens were placed in a circulating hot-air test chamber that was electrically heated with use of resistance heating elements. Air temperature was controlled from a thermocouple located next to the specimen and connected to the temperature controller. Specimen temperature was maintained at 589 ±6 K (600 ±10°F) and continuously monitored through a second thermocouple placed on the specimen and connected to a Leeds and Northrup temperature potentiometer.

For the 116 K (-250°F) tests, specimens were placed in a circulating-air test chamber that was cooled by evaporating liquid nitrogen. Temperatures were controlled in the same manner as for elevated temperature tests, with specimen temperatures controlled to ±6 K (±10°F).

All specimens were brought to temperature and then soaked for 30 ±10 minutes prior to test.

4.4 Computer Data Acquisition System Procedure

A laboratory program was developed for the Hewlett-Packard 9845B desk top computer. The objective of the computer program was to enable real time data acquisition and plotting of stress and strain by monitoring the system load cell and the strain gauges attached to each specimen. The computer scan routine was triggered by a specified percentage change in the load cell feedback signal. This percentage change was either 2 percent or 1 percent of full scale, depending on the load range being used at the time. The computer converted the load cell and strain gauge feedback signals to stress and micro-strain respectively. These data were stored in the computer memory in addition to being plotted as stress versus strain. At test completion, the load, stress, strain, specimen parameters, and strain gauge parameters were printed in formatted and tabular form in addition to being stored by the system mass memory unit. A photograph and schematic of the data acquisition system are shown in Figures 4.4-1 and 4.4-2. Samples of typical computer-generated data tables and plots are shown in Figures 4.4-3 and 4.4-4.

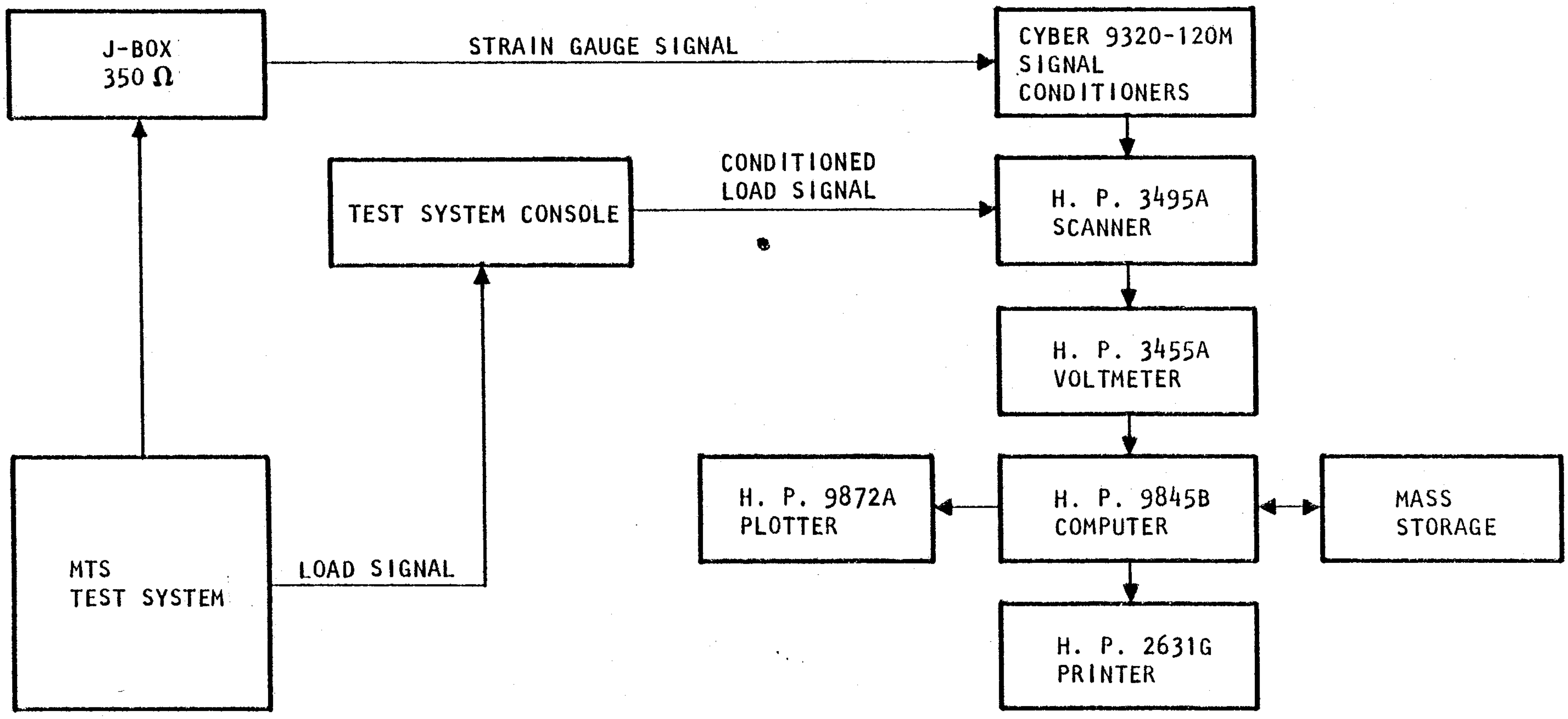

Figure 4.4-1. Schematic of the data acquisition and test systems

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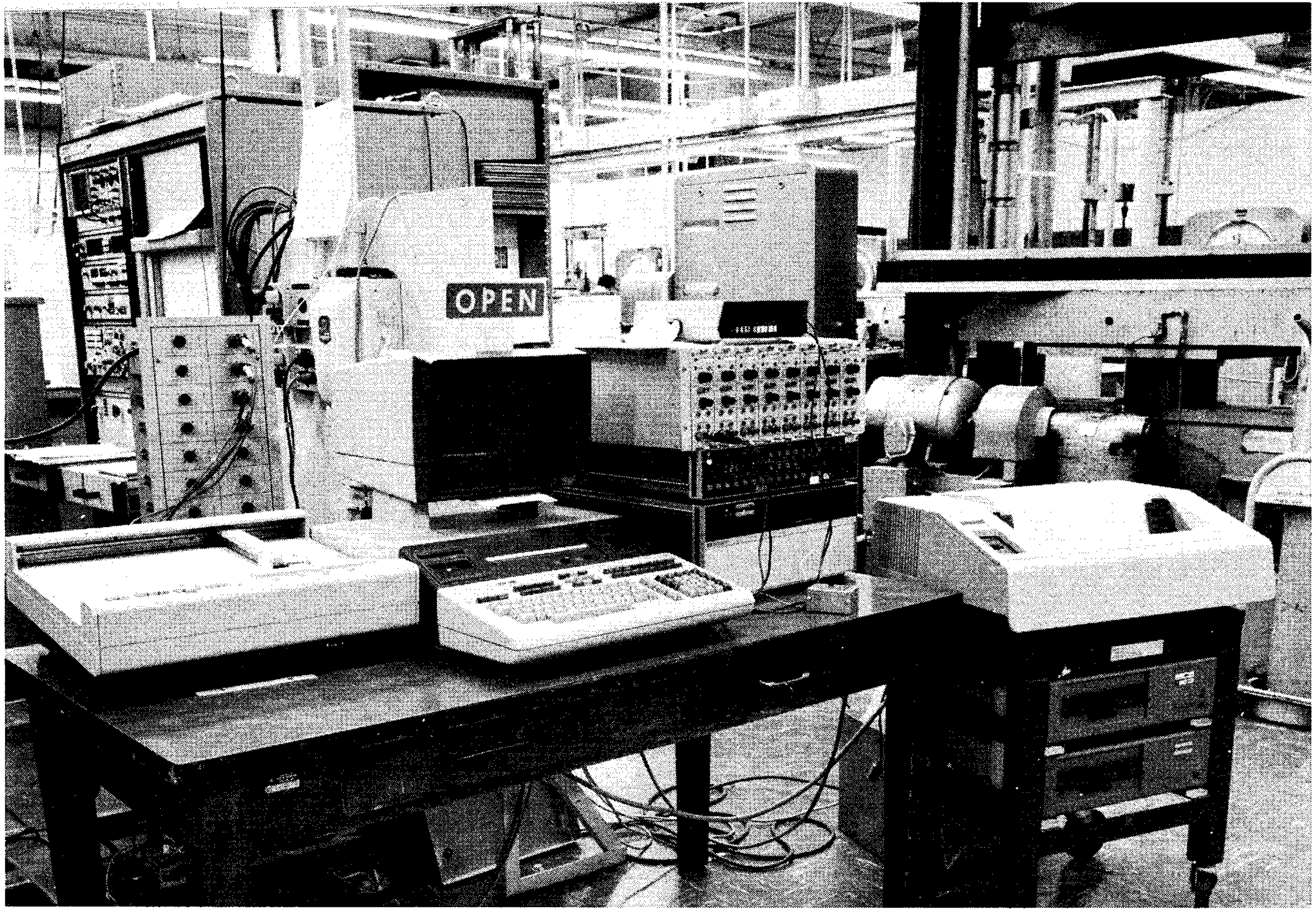

Figure 4.4-2. Computer-controlled data acquisition system

```
**********************************
* LARC 160-CELION PROPERTIES     *
*                                *
* LR 3349    SPECIMEN CT1-S1-4   *
* SWA 81-028 FEB. 16, 1982       *
**********************************

--------------------------------------------------------------------------------

SPECIMEN  PARAMETERS: T= .047      W=1.005      AREA= .047
          MODULUS (msi) 6.40          POISSON RATIO    .263
          Ftu (KSI)= 79.04            ULT. STRAIN (u-STRAIN)= 12650

   GAGE NO. 1      Gf= 2.070       Gr=351.400         Rc= 21700
   GAGE NO. 2      Gf= 2.070       Gr=351.500         Rc= 21700
   GAGE NO. 3      Gf= 2.070       Gr=351.300         Rc= 21700
   GAGE NO. 4      Gf= 2.070       Gr=351.200         Rc= 21700

--------------------------------------------------------------------------------

  LOAD       STRESS        G1          G2            G3            G4
  (LBS)       (PSI)       ***********MICRO-INCHES******************

     1.1         22          0           0             0             0
   116.8       2473        -61        -138           281           468
   213.5       4520       -127        -238           558           787
   316.1       6692       -201        -338           857          1117
   420.9       8910       -280        -439          1163          1449
   525.6      11126       -361        -537          1472          1779
   629.7      13330       -449        -631          1781          2110
   737.1      15605       -533        -731          2095          2446
   843.0      17846       -617        -832          2410          2780
   950.9      20130       -706        -931          2728          3118
  1059.3      22426       -796       -1030          3046          3456
  1160.0      24558       -879       -1124          3344          3770
  1260.9      26693       -964       -1218          3644          4090
  1362.9      28854      -1050       -1314          3990          4427
  1465.5      31025      -1134       -1416          4303          4770
  1568.3      33201      -1220       -1513          4650          5112
  1672.4      35405      -1336       -1600          5057          5522
  1777.2      37624      -1394       -1713          5433          5898
  1882.2      39848      -1479       -1827          5786          6259
  1987.6      42079      -1574       -1942          6191          6704
  2095.0      44353      -1670       -2036          6649          7218
  2202.3      46624      -1771       -2131          7011          7607
  2310.2      48908      -1897       -2230          7397          8009
  2411.2      51047      -2000       -2301          7757          8365
  2510.8      53155      -2123       -2364          8093          8711
  2613.4      55328      -2199       -2473          8427          9069
  2715.9      57497      -2297       -2562          8749          9423
  2818.2      59663      -2345       -2687          9082          9806
  2921.3      61846      -2442       -2794          9436         10165
  3025.2      64046      -2557       -2902          9840         10605
  3130.9      66283      -2655       -2998         10190         10969
  3237.5      68539      -2782       -3092         10555         11350
  3344.5      70804      -2900       -3200         10915         11726
  3451.9      73078      -3029       -3298         11274         12110
  3551.5      75188      -3150       -3383         11613         12456
  3651.8      77310      -3263       -3474         11949         12803

FAILURE AT 3715#
```

Figure 4.4-3. Typical computer-generated data table for design allowables testing

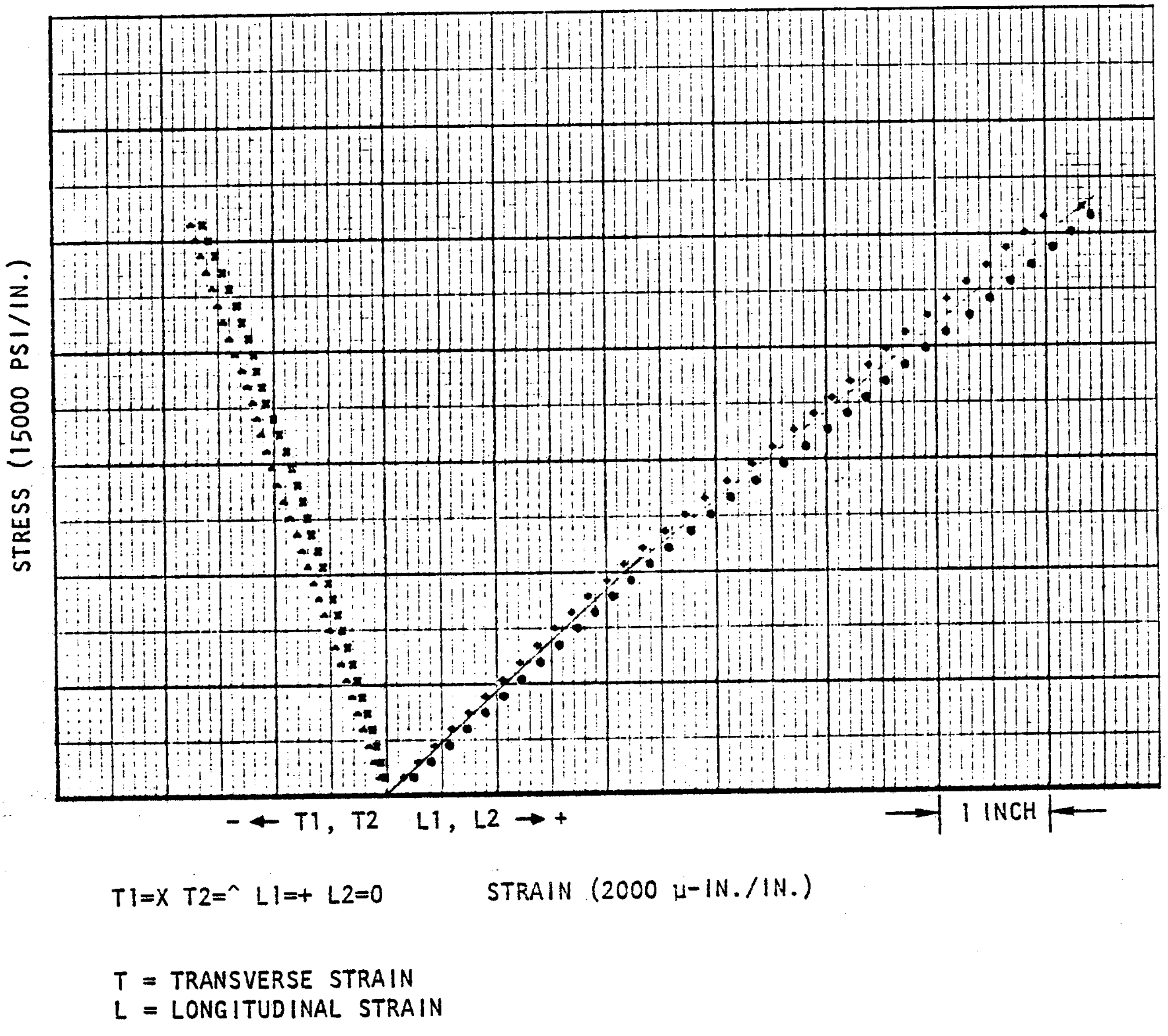

Figure 4.4-4. Typical computer generated plot of design allowables test data

4.5 Calibration and Checkout

Before the data acquisition system was used for tension-compression testing, the computer program was checked by comparing modulus values obtained from titanium and aluminum tensile specimens with values from conventional test methods. The modulus of the two specimens was first obtained by utilizing an extensometer, attached over the strain-gauged area, and applying load with a Riehle universal test machine while autographically recording load versus strain. Modulus values of 117.2 and 7.0 GN/m^2 (17.0 and 10.3 MSI) were obtained from the titanium and aluminum specimens respectively. The specimens were then installed in a MTS electro-hydraulic test system, and the load cell and two longitudinal back-to-back specimen strain gauges were monitored by the computer. Two runs were completed for each specimen. Modulus values of 117.2 and 117.9 GN/m^2 (17.0 and 17.1 MSI) were obtained for the titanium specimen. For the aluminum specimen modulus values of 71.0 and 71.7 GN/m^2 (10.3 and 10.4 MSI) were obtained.

A calibration procedure was also completed before the rail shear specimens were tested. A rail shear specimen of 50.8 by 76.2 by 1.27 mm (2.0 by 3.0 by 0.050 in.) was fabricated from 6061-T6 aluminum alloy sheet. The configuration of the specimen was the same as that of the composite specimens to be tested and was strain-gauged in the same manner, i.e., back-to-back rosette gauges. The aluminum specimen was used to check out the computer system for real time data acquisition and plotting of shear stress versus maximum shear strain. The computer logic was the same as described except that the load cell feedback signal was converted to shear load and the feedback signals from the back-to-back rosette strain gauges were averaged and converted to maximum shear strain.

The published shear modulus for 6061-T6 is G = 3.8 (Reference 2). During the checkout phase of the rail shear program, consistent values of G = 3.76 were obtained by the data acquisition system from the aluminum specimen.

4.6 Tension Tests

This section presents the procedures and test results for tension tests of $(0)_8$, $(0/45/90/-45)_s$, $(\pm 45)_{2s}$ and $(90)_8$ Celion 6000/LARC-160 graphite polyimide laminates.

4.6.1 Test Procedures

Tensile tests were performed in general accordance with ASTM D-3039 (Reference 3). Straight-sided tensile coupons were used to determine strength, modulus, strain to failure, and Poisson's ratio. Specimen design, fixtures, and test setup are shown in Figures 4.6-1 and 4.6-2. To optimize the quantity of data recorded, the rate of loading was set to reach the anticipated failure load of the specimen at approximately five minutes after testing began. Data were obtained autographically from biaxial strain gauges mounted back-to-back on five of the ten baseline-dry specimens in each test group. The remaining specimens in each group were instrumented with clip-on hang-down extensometers as were all the moisture-saturated and thermal-soaked specimens.

4.6.2 Tension Test Results

Results of the tension tests are presented in Tables 4.6-1 through 4.6-4. Typical failed tension specimens are shown in Figures 4.6-3 through 4.6-6.

Laminate strengths are plotted as functions of temperature and specimen conditioning in Figure 4.6-7. For the baseline-dry condition, the $(0)_8$, $(0/45/90/-45)_s$ and $(\pm 45)_{2s}$ laminates were not significantly affected by temperature. However, the $(90)_8$ laminate retained only 50 percent of its room-temperature strength when tested at 589 K (600°F).

The effects of thermal soak on tensile strength, determined for $(\pm 45)_{2s}$ laminates, were evidenced as a small loss in strength at each test temperature when compared with baseline-dry strengths.

The effects of moisture saturation on elevated-temperature tensile strengths were moderate for the quasi-isotropic and $(\pm 45)_{2s}$ laminates in that a reduction in elevated temperature strength of nearly 17 and 25 percent respectively at 589 K (600°F) was observed. However, the totally resin-dominated laminate, $(90)_8$, lost nearly 70 percent of its baseline-dry elevated temperature strength because of the effects of moisture saturation.

Tensile modulus results are plotted in Figure 4.6-8. Modulus values for fiber-dominated laminates increased slightly with increasing temperature. As with strength, as laminates become more resin dominated, the tensile modulus decreases with increasing temperature.

The effects of thermal soak on tensile modulus for $(\pm 45)_{2s}$ laminates (the only configuration tested) were minimal at each test temperature.

Compared with the baseline-dry condition, the effect of moisture saturation on tensile modulus was minimal for the quasi-isotropic and $(\pm 45)_{2s}$ laminates. However, the totally resin-dominated laminate, $(90)_8$, showed a reduction in elevated temperature modulus of nearly 40 percent as the result of moisture saturation.

As anticipated, moisture saturation does not significantly affect tension strength and modulus when tested at room temperature except that for the $(\pm 45)_{2s}$ configuration, a 17-percent increase in modulus was recorded. The mechanism of matrix degradation at elevated temperatures for moisture-saturated laminates was not investigated. Blistering as a result of vaporization of entrapped moisture has been postulated as the probable mechanism leading to similar results for Celion 3000/PMR-15 graphite polyimide (Reference 4). However, no obvious physical evidence of blistering was observed in the failed specimens.

Poisson's ratio and failure strains were measured for all strain-gauged specimens. Poisson's ratio was computed from the ratio of the slopes of the linear portion of the stress-strain data. Failure strains were taken from the last longitudinal strain gauge reading prior to specimen failure. For $(\pm 45)_{2s}$ laminates, the failure strains often exceeded the capability of the instrumentation. Significant scatter in $(90)_8$ Poisson's ratio data was observed.

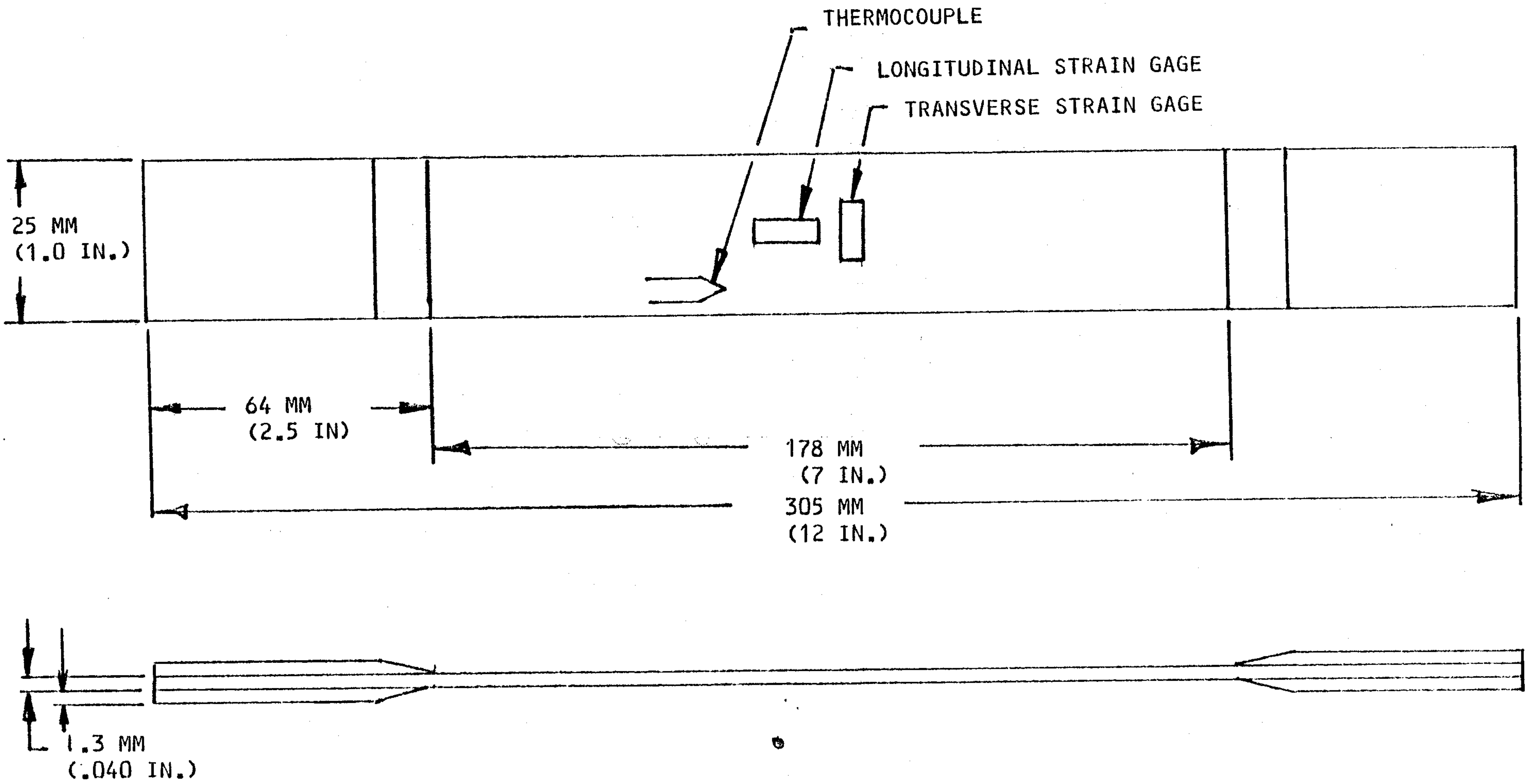

Figure 4.6-1. Tension specimen configuration

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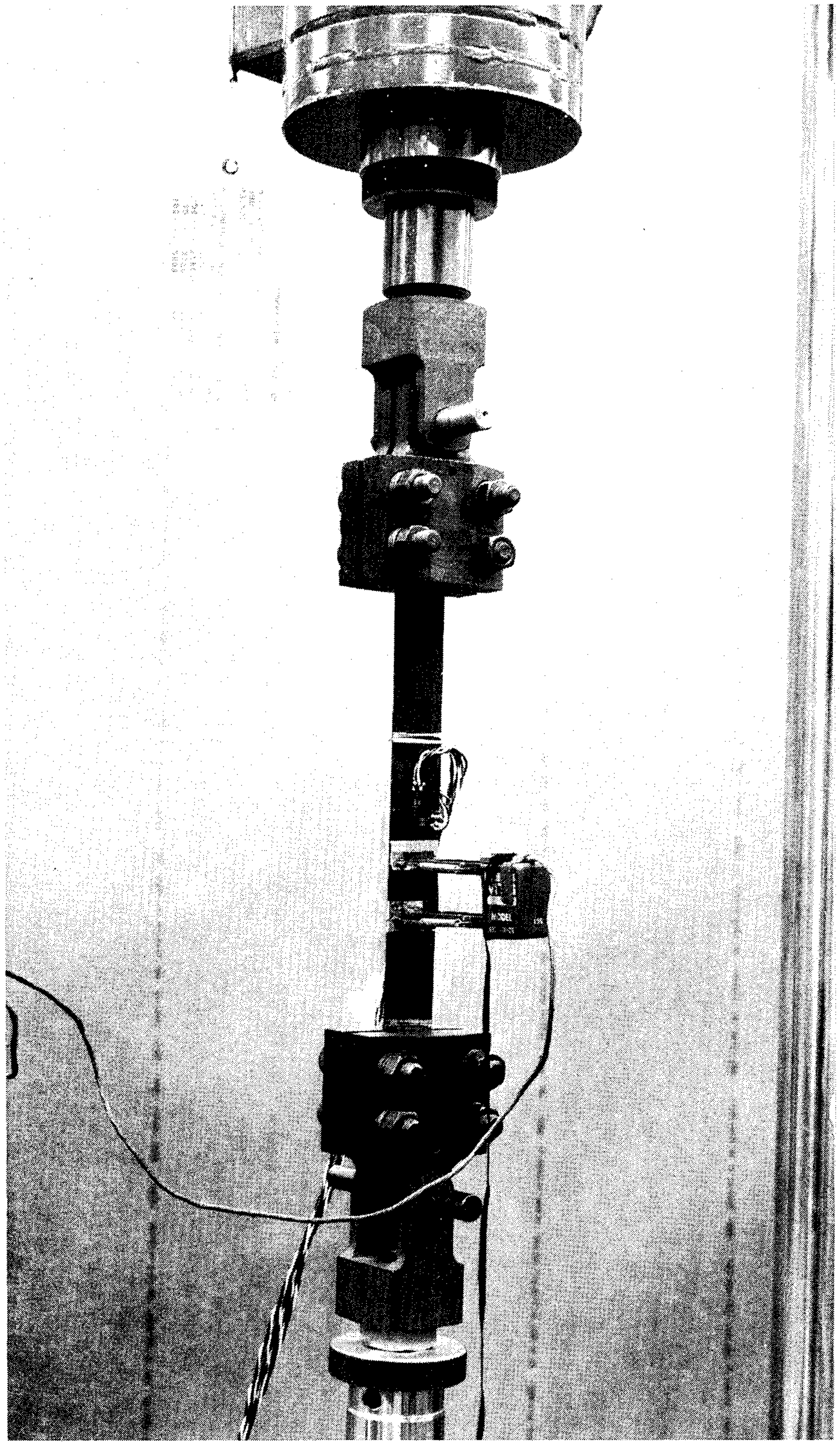

Figure 4.6-2. Test fixture and setup for tension tests

TABLE 4.6-1. TENSILE PROPERTIES OF CELION 6000/LARC-160 LAMINATES WITH $(0)_8$ FIBER ORIENTATION (BASELINE DRY)

Room Temperature							116 K (-250°F)							589 K (600°F)						
	F_{tu}		E_t		ε ult (%)	ν		F_{tu}		E_t		ε ult (%)	ν		F_{tu}		E_t		ε ult (%)	ν
ID	MN/m^2	KSI	GN/m^2	MSI			ID	MN/m^2	KSI	GN/m^2	MSI			ID	MN/m^2	KSI	GN/m^2	MSI		
UT1							UT1							UT1						
S1-2	1655	240	141	20.50	1.11	0.333	S1-12	1469	213	138	20.06	0.97	0.311	S2-22	1738	252	166	24.04	1.44	0.278
S1-3	1634	237	138	20.02	1.14	0.323	S1-13	1745	253	142	20.55	1.14	0.246	S2-23	1793	260	171	24.81	1.03	0.292
S1-4	1752	254	136	19.75	1.22	0.319	S1-14	1697	246	143	20.69	1.15	0.259	S2-24	1579	229	157	22.76	0.97	0.304
S1-5	1731	251	135	19.56	1.24	0.318	S1-15	1379	200	147	21.24	0.99	0.354	S2-25	*	*	159	23.04	*	0.294
S1-6	1738	252	137	19.91	1.19	0.323	S2-16	1690	245	142	20.58	1.18	0.351	S2-26	1772	257	172	25.00	1.10	0.292
S1-7	1841	263	161	23.31	1.03		S2-17	1572	228	145	21.05	0.99		S2-27	1724	250	153	22.13	1.05	-
S1-8	1765	256	146	21.10	1.13		S2-18	1703	247	148	21.43	1.05		S2-28	1869	271	172	25.00	1.10	-
S1-9	1724	250	145	21.00	1.08		S2-19	1676	243	136	19.67	1.12		S2-29	1634	237	162	23.54	1.00	-
S1-10	1710	248	142	20.58	1.18		S2-20	1752	254	140	20.27	1.21		UT3						
S1-11	1779	258	136	19.75	1.20		S2-21	1690	245	138	20.00	1.10		S3-31	*	*	161	23.35	*	-
														S3-32	1745	253	172	25.00	1.06	-
Avg	1731	251	142	20.55	1.15	0.323		1634	237	142	20.55	1.09	0.304		1731	251	165	23.87	1.09	0.292

*Result not reported due to testing error or irregularity

TABLE 4.6-2. TENSILE PROPERTIES OF CELION 6000/LARC-160 LAMINATES WITH $(90)_8$ FIBER ORIENTATION

Room Temperature							116 K (-250°F)							589 K (600°F)						
ID	F_{tu}		E_t		ε ult (%)	ν	ID	F_{tu}		E_t		ε ult (%)	ν	ID	F_{tu}		E_t		ε ult (%)	ν
	MN/m^2	KSI	GN/m^2	MSI				MN/m^2	KSI	GN/m^2	MSI				MN/m^2	KSI	GN/m^2	MSI		
BASELINE DRY																				
90T1							90T1							90T1						
S1-1	27.2	3.94	9.6	1.40	0.32	0.023	S1-11	51.9	7.53	1[illegible].8	2.00	0.49	0.021	S2-23	10.3	1.49	7.45	1.08	0.12	0.001
S1-2	33.8	4.90	9.5	1.38	0.40	0.024	S1-12	49.6	7.20	10.9	1.58	0.47	0.023	S2-24	25.7	3.73	7.59	1.10	0.34	0.001
S1-3	43.3	6.28	9.6	1.39	0.50	0.024	S1-13	54.3	7.88	11.8	1.71	0.50	0.009	S2-25	24.8	3.59	7.10	1.03	0.37	0.049
S1-4	40.4	5.86	9.9	1.43	0.44	0.023	S1-14	36.6	5.31	10.8	1.56	0.32	0.003	S2-26	22.4	3.25	7.93	1.15	0.29	0.019
S1-5	31.0	4.49	9.7	1.41	0.35	0.025	S1-15	37.2	5.39	11.8	1.71	0.33	0.050	S2-27	21.0	3.04	7.66	1.11	0.28	0.001
S1-6	37.6	5.44	9.8	1.42	0.36	-	90T1							S2-28	*	*	6.76	0.98	*	-
S1-7	36.1	5.23	10.9	1.58	0.40	-	S4-46	56.3	8.17	10.3	1.49	0.54	-	S2-29	17.4	2.52	5.59	0.81	0.30	-
S1-8	43.6	6.32	10.9	1.58	0.38	-	S4-47	47.1	6.83	11.2	1.62	0.48	-	90T2						
S1-9	34.5	5.00	10.9	1.58	0.31	-	S4-48	52.8	7.65	11.2	1.62	0.53	-	S3-31	*	*	*	*	*	-
S1-10	39.2	5.68	10.5	1.52	0.35	-	S4-49	45.6	6.61	12.0	1.74	0.34	-	S3-32	11.5	1.67	5.86	0.85	0.20	-
							S4-50	44.8	6.50	11.7	1.70	0.41	-	S3-33	15.0	2.17	5.38	0.78	0.25	-
Avg	36.6	5.31	10.1	1.47	0.38	0.024		47.6	6.91	11.5	1.67	0.44	-		18.5	2.68	6.82	0.99	0.27	-
MOISTURE SATURATED																				
90T2														90T2						
S3-35	30.2	4.38	9.4	1.36	0.32	-								S3-40	5.5	0.80	3.86	0.56	0.15	
S3-36	35.1	5.09	9.6	1.39	0.36	-								S3-41	5.2	0.76	4.62	0.67	0.12	
S3-37	34.1	4.94	9.5	1.37	0.36	-								S3-42	4.8	0.69	3.38	0.49	0.24	
S3-38	34.1	4.94	9.5	1.37	0.36	-								S3-43	5.7	0.83	4.97	0.72	0.10	
S3-39	34.1	4.94	8.5	1.24	0.39	-								S3-45	5.7	0.83	4.21	0.61	0.12	
Avg	33.5	4.86	9.3	1.35	0.36	-									5.4	0.78	4.20	0.61	0.15	

*Results not reported due to testing error or irregularity.

TABLE 4.6-3. TENSILE PROPERTIES OF CELION 6000/LARC-160 LAMINATES WITH $(0/45/90/-45)_s$ FIBER ORIENTATION

Room Temperature							116 K (-250°F)							589 K (600°F)						
ID	F_{tu}		E_t		ε ult (%)	ν	ID	F_{tu}		E_t		ε ult (%)	ν	ID	F_{tu}		E_t		ε ult (%)	ν
	MN/m²	KSI	GN/m²	MSI				MN/m²	KSI	GN/m²	MSI				MN/m²	KSI	GN/m²	MSI		
BASELINE DRY																				
CT1							CT1							CT1						
S1-1	503	72.9	50.3	7.30	1.08	0.297	S1-11	502	72.8	44.5	6.46	1.13	0.293	S2-21	621	90.0	62.0	8.99	1.04	0.356
S1-2	596	86.4	51.6	7.49	1.26	0.301	S1-12	550	79.8	49.3	7.15	0.90	0.317	S2-22	559	81.0	56.6	8.21	0.95	0.318
S1-3	535	77.6	51.4	7.45	1.13	0.307	S1-13	554	80.4	55.3	8.02	1.05	0.348	S2-23	603	87.4	62.0	8.99	0.99	0.363
S1-4	545	79.0	44.1	6.40	1.27	0.263	S1-14	528	76.6	53.5	7.76	1.05	0.338	S2-24	616	89.4	62.8	9.11	0.95	0.344
S1-5	617	89.5	53.9	7.82	1.27	0.290	S1-15	502	72.8	52.8	7.65	1.10	0.351	S2-25	547	79.3	56.4	8.18	0.97	0.312
S1-6	566	82.1	54.5	7.90	1.15	-	CT1							S2-26	572	82.9	48.3	7.00	1.15	-
S1-7	505	73.3	54.5	7.90	1.15	-	S2-16	517	75.0	49.0	7.10	1.03	-	S2-28	583	84.6	52.1	7.56	1.20	-
S1-8	535	77.6	51.1	7.41	1.17	-	S2-17	544	78.9	48.3	7.00	1.13	-	S2-29	487	70.6	48.3	7.01	1.20	-
S1-9	600	87.0	55.9	8.10	1.19	-	S2-18	521	75.6	45.5	6.60	1.17	-	CT2						
S1-10	575	83.3	47.7	6.92	1.15	-	S2-19	534	77.5	44.8	6.50	1.20	-	S3-30	448	65.0	42.3	6.13	1.14	-
							S2-20	593	86.0	50.1	7.27	1.10	-	S3-42	461	81.4	51.3	7.42	1.17	-
Avg	557	80.9	51.5	7.47	1.18	0.292		534	77.5	49.3	7.15	1.09	0.329		559	81.2	54.2	7.86	1.08	0.339
MOISTURE SATURATED																				
CT2														CT2						
S3-31	549	79.6	65.9	9.56	0.80	-								S3-36	459	66.5	45.5	6.60	1.02	-
S3-32	552	80.0	54.5	7.90	1.00	-								S3-37	480	69.6	51.7	7.50	1.01	-
S3-33	600	87.0	52.1	7.56	1.20	-								S3-38	459	66.6	50.3	7.30	0.96	-
S3-34	601	87.2	57.1	8.28	1.05	-								S3-39	489	70.9	54.5	7.90	0.98	-
S3-35	600	87.0	60.0	8.70	1.02	-								S3-40	442	64.1	53.1	7.70	0.86	-
Avg	580	84.2	57.9	8.40	1.01	-									465	67.5	51.0	7.40	0.97	-

TABLE 4.6-4. TENSILE PROPERTIES OF CELION 6000/LARC-160 LAMINATES WITH $(\pm 45)_{2s}$ FIBER ORIENTATION

Room Temperature							116 K (-250°F)							589 K (600°F)						
ID	F_{tu}		E_t		ε ult (%)	ν	ID	F_{tu}		E_t		ε ult (%)	ν	ID	F_{tu}		E_t		ε ult (%)	ν
	MN/m^2	KSI	GN/m^2	MSI				MN/m^2	KSI	GN/m^2	MSI				MN/m^2	KSI	GN/m^2	MSI		
BASELINE DRY																				
45T1							45T1							45T2						
S1-2	128.6	18.39	16.5	2.39	1.10	0.724	S1-12	140.5	20.38	21.2	3.08	0.80+	0.822	S2-23	130.1	18.87	16.7	2.42	1.08+	0.786
S1-3	138.5	20.09	18.4	2.67	1.14	0.792	S1-13	132.8	19.25	19.9	2.89	0.84+	0.744	S2-24	133.2	19.31	17.9	2.59	1.05+	0.900
S1-4	140.6	20.39	18.5	2.69	1.03	0.798	S1-14	132.6	19.23	19.3	2.80	0.87+	0.685	S2-25	120.9	17.53	15.0	2.18	1.05+	0.759
S1-5	145.4	21.09	19.3	2.80	1.01	0.820	45T2							S2-26	125.9	18.25	14.4	2.09	1.08+	0.714
S1-6	143.9	20.87	16.4	2.38	1.46	0.747	S2-16	140.2	20.33	23.2	3.37	0.74+	0.756	S2-27	137.9	20.00	15.2	2.21	1.10+	0.884
S1-7	134.9	19.56	19.5	2.83	1.33	-	S2-17	143.6	20.83	23.0	3.33	0.77+	0.773	S2-28	136.3	19.76	12.8	1.85	5.24+	-
S1-8	129.2	18.74	23.3	3.38	1.03	-	S2-18	135.6	19.66	20.9	3.03	1.18	-	45T3						
S1-9	135.4	19.64	19.2	2.78	1.18	-	S2-19	138.5	20.09	21.4	3.10	1.18	-	S3-30	83.9	12.17	11.9	1.73	3.49	-
S1-10	142.6	20.68	19.3	2.80	1.35	-	S2-20	142.8	20.70	21.4	3.10	1.30	-	S3-31	125.0	18.13	11.9	1.73	5.36+	-
S1-11	141.6	20.53	20.1	3.04	1.30	-	S2-21	136.7	19.82	21.6	3.13	1.08	-	S3-32	113.9	16.51	13.4	1.95	5.42+	-
							S2-22	141.1	20.46	20.7	3.00	1.38	-	S3-33	103.0	14.93	13.6	1.97	4.10	-
Avg	137.9	20.00	19.2	2.78	1.19	0.776		138.4	20.07	21.2	3.08	1.22	0.756		121.0	17.55	14.3	2.07	-	0.808
MOISTURE SATURATED																				
45T3														45T3						
S3-34	155.5	22.55	23.0	3.34	1.38	-								S3-39	94.7	13.74	13.1	1.90	5.40+	-
S3-35	150.2	21.78	22.9	3.32	1.23	-								S3-40	103.7	15.05	11.0	1.60	5.40+	-
S3-36	155.1	22.50	25.1	3.64	1.35	-								S3-41	96.9	14.05	11.7	1.70	7.05+	-
S3-37	156.7	22.73	20.0	2.91	1.90	-								45T4						
S3-38	163.4	23.69	20.1	3.02	2.03	-								S4-43	83.2	12.07	17.2	2.50	11.10+	-
														S4-44	83.1	12.05	16.5	2.40	11.40+	-
Avg	156.2	22.65	22.4	3.25	1.58	-									92.3	13.39	13.9	2.02	-	-
THERMAL SOAKED																				
45T4							45T4							45T4						
S4-45	118.1	17.12	19.7	2.86	1.20	-	S4-50	130.1	18.86	18.6	2.70	1.55	-	S5-56	93.5	13.56	10.5	1.52	2.70	-
S4-46	112.2	16.27	23.0	3.32	1.50	-	S4-51	134.5	19.51	19.8	2.87	1.93	-	S5-57	119.6	17.35	11.0	1.60	3.00	-
S4-47	115.4	16.74	19.7	2.86	0.95	-	S4-52	129.9	18.83	17.9	2.60	2.15	-	S5-58	127.4	18.48	11.0	1.60	5.39+	-
S4-48	119.3	17.30	21.0	3.05	1.15	-	S4-53	124.8	18.10	17.7	2.57	1.58	-	S5-59	105.6	15.32	10.4	1.51	5.42+	-
S4-49	118.7	17.21	21.0	3.05	1.21	-	45T1							S5-60	119.9	17.39	12.9	1.87	5.54+	-
							S5-55	118.7	17.21	15.6	2.27	1.70	-							
Avg	116.7	16.93	20.9	3.03	1.20	-		127.5	18.50	17.9	2.60	1.78	-		113.2	16.42	11.2	1.62	-	-

+Actual strain to failure exceeded capability of instrumentation; final reading shown for information only.

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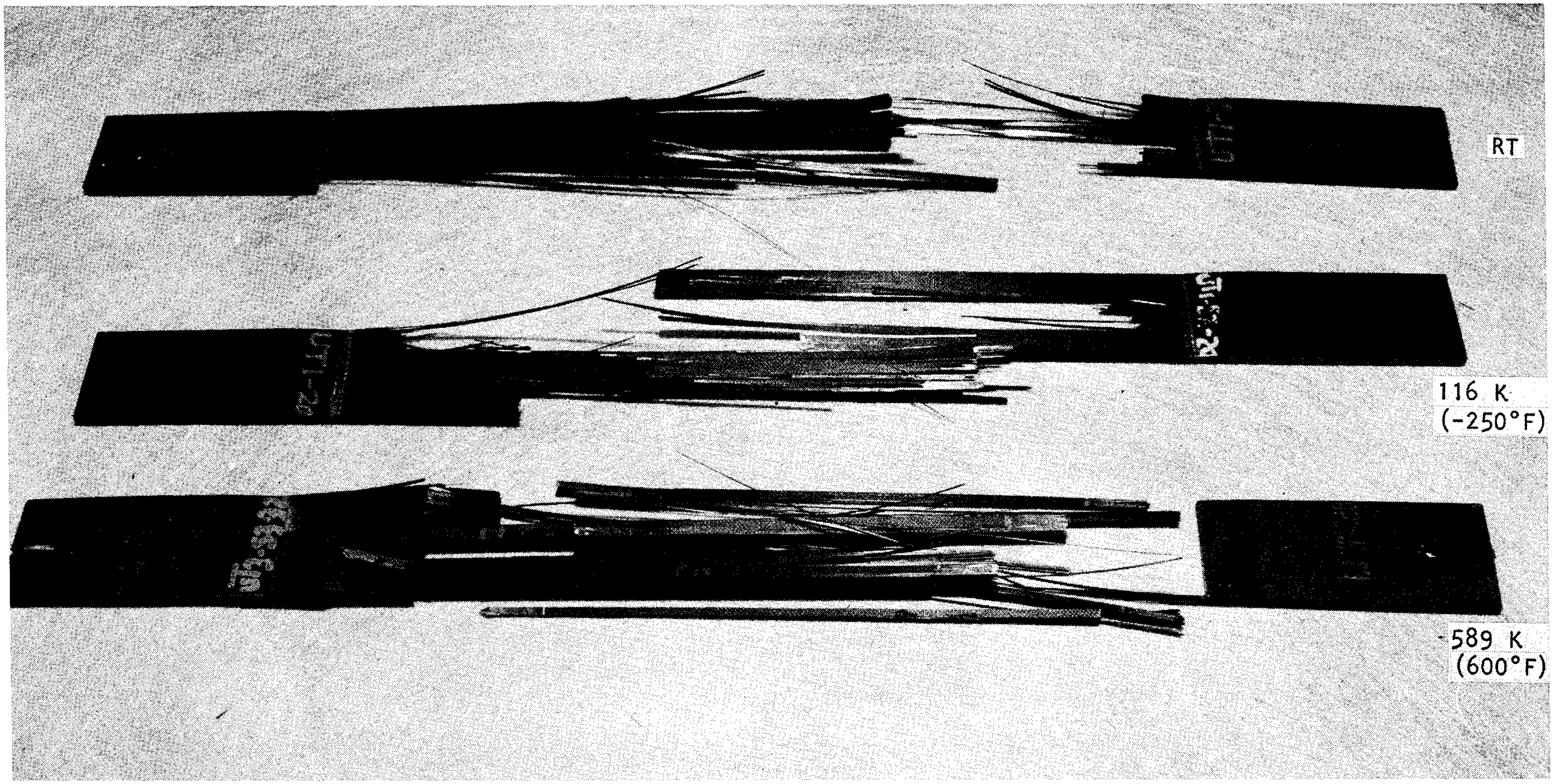

Figure 4.6-3. Typical tensile failures for $(0)_8$ laminates

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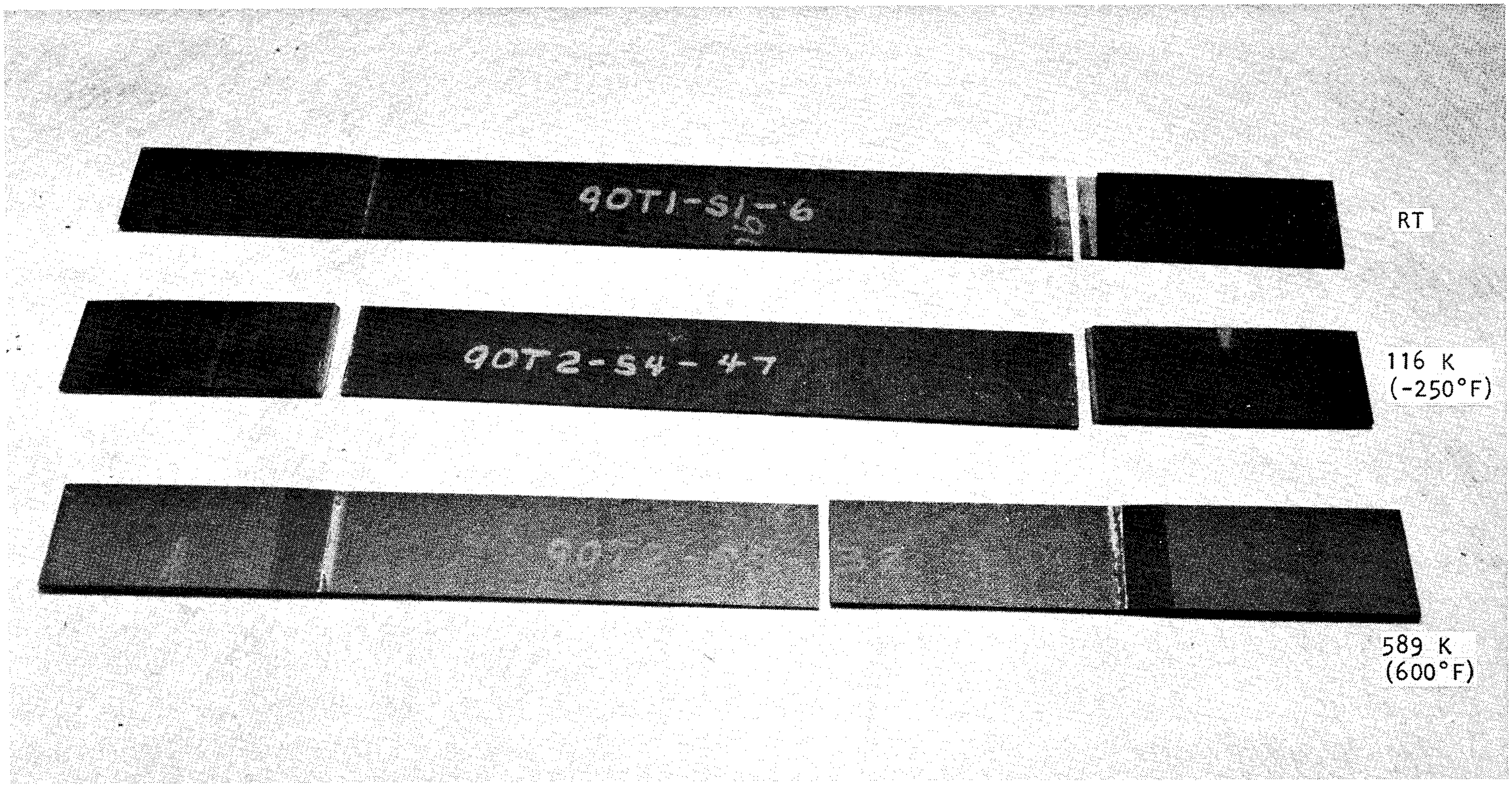

Figure 4.6-4. Typical tensile failures for $(90)_8$ laminates

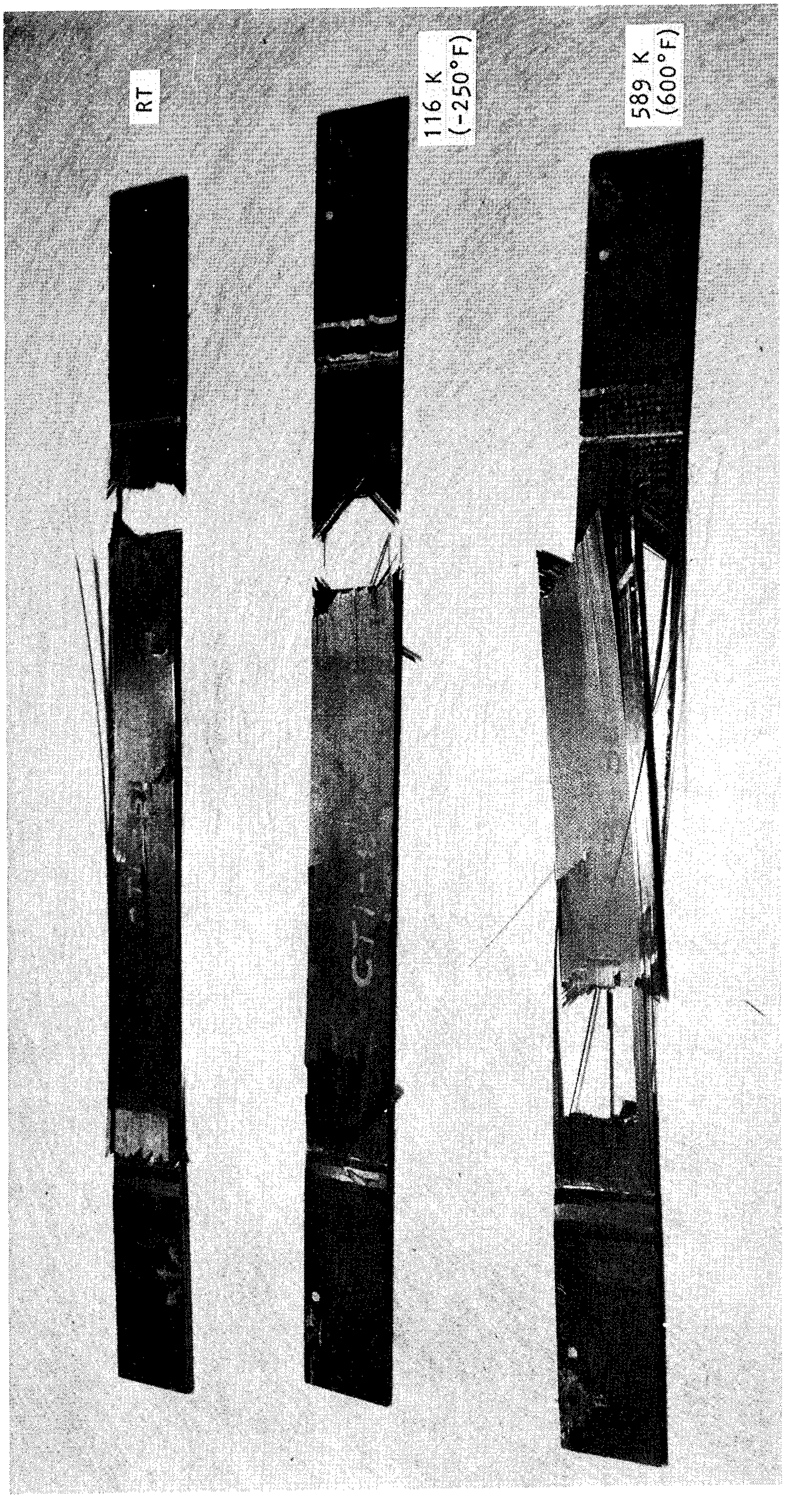

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Figure 4.6-5. Typical tensile failures for $(0/45/90/-45)_s$ laminates

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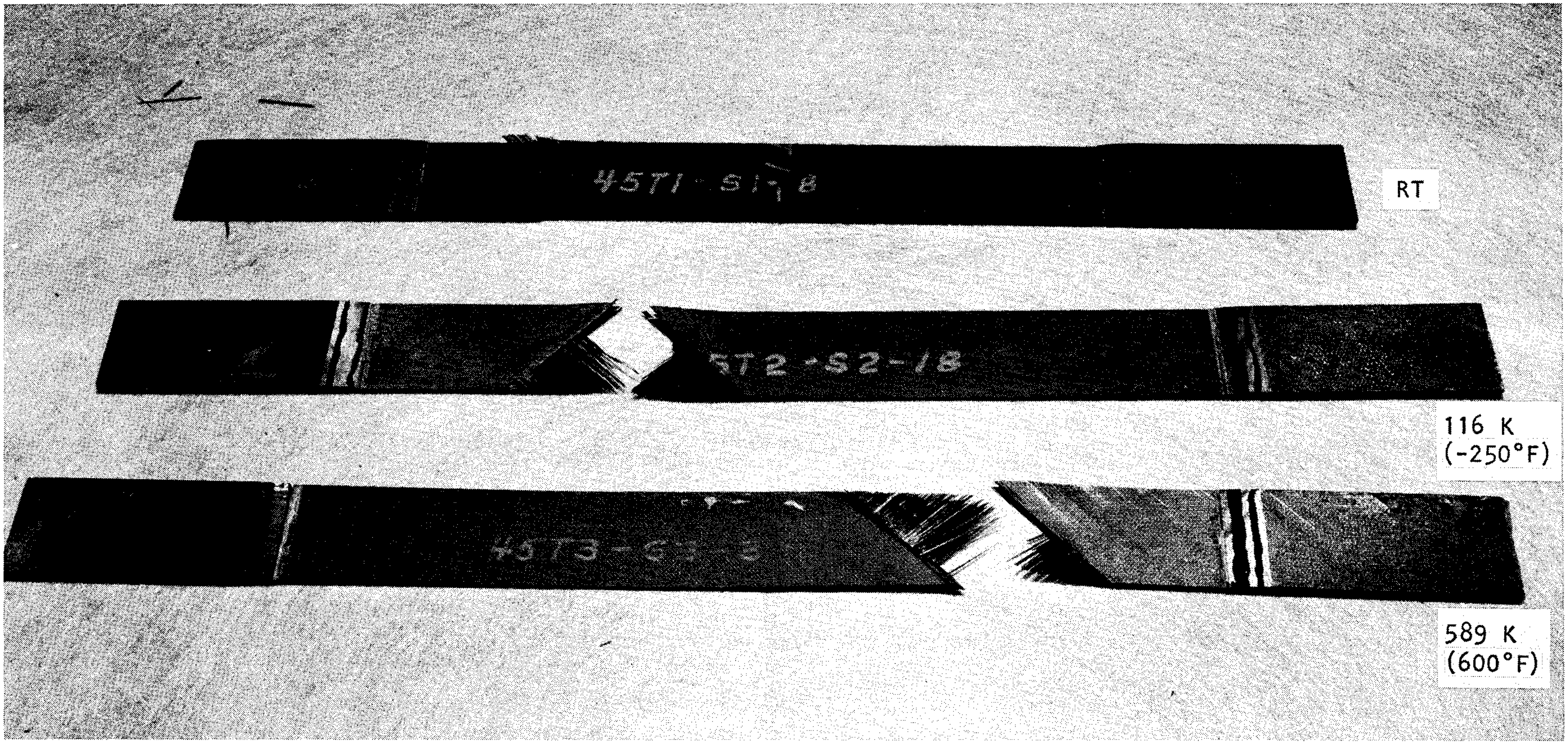

Figure 4.6-6. Typical tensile failures for $(\pm 45)_{2s}$ laminates

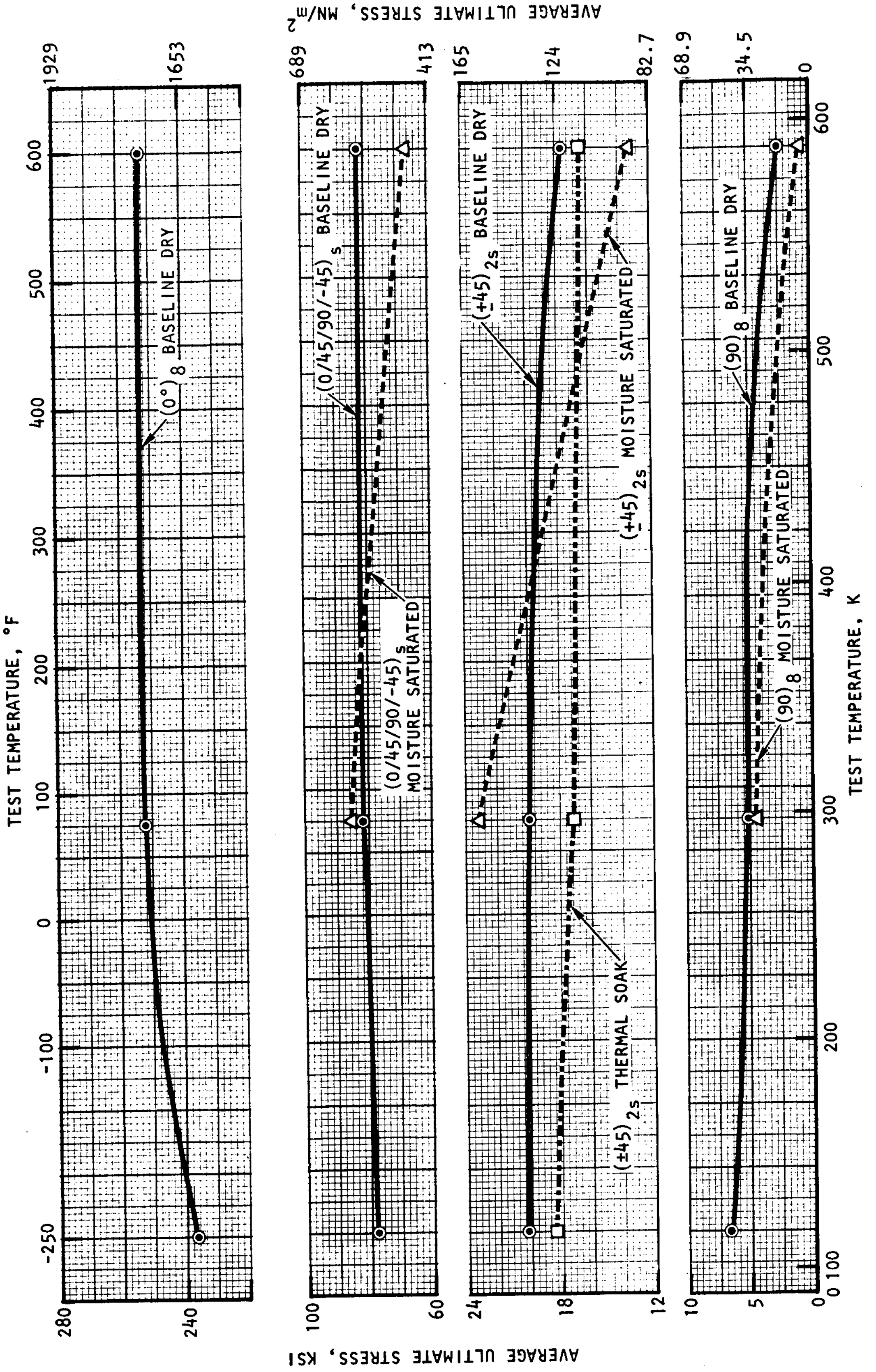

Figure 4.6-7. Tensile strength properties of Celion 6000/LARC-160 laminates

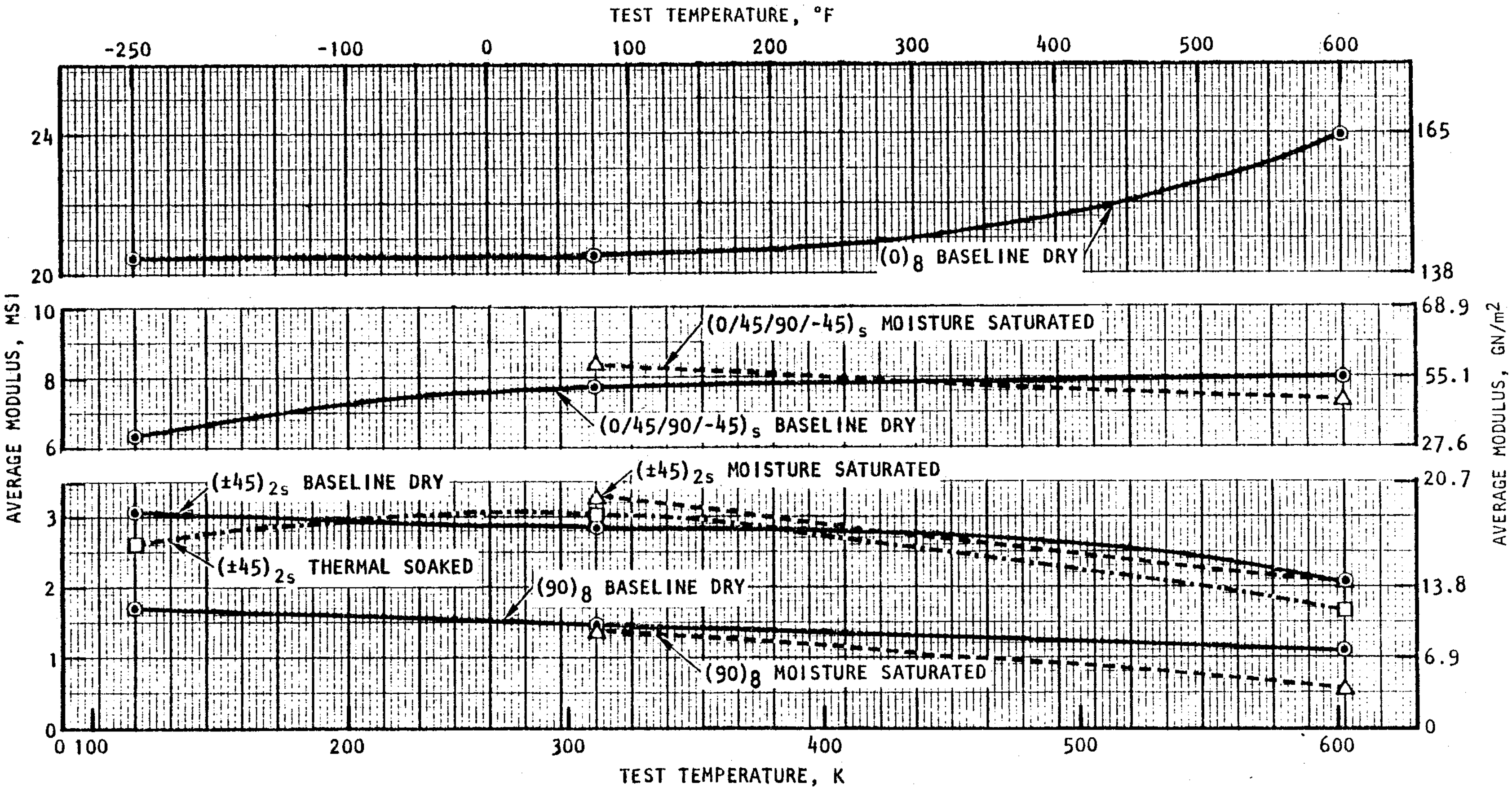

Figure 4.6-8. Tensile modulus properties of Celion 6000/LARC-160 laminates

4.7 Compression Tests

This section presents the procedures and test results for compression tests of $(0)_{16}$, $(0/45/90/-45)_{2s}$, $(\pm 45)_{4s}$ and $(90)_{16}$ Celion 6000/LARC-160 graphite/polyimide laminates. As defined by the program test matrix (Table 4.1-1), only the baseline-dry and moisture-saturated conditions were evaluated.

4.7.1 Compression Test Procedure

An IITRI* fixture (furnished by NASA LaRC) was used in performing the compression tests in accordance with the procedures and methods described in Reference 5. Compressive strength, compressive modulus, strain to failure, and Poisson's ratio measurements were determined. The specimen configuration and test fixture are shown in Figures 4.7-1 and 4.7-2 respectively.

Load rates and stabilization of the test temperature were established in the same manner as the tensile specimens'. Load strain data were obtained autographically from biaxial strain gauges mounted back to back on five of the ten baseline-dry specimens in each test group. The short compression specimen gauge length, less than 12.7 mm (0.5 inch), precluded attaching a standard mechanical extensometer directly onto the specimen. An attempt was made to measure strain by attaching a mechanical extensometer to the collets which held the specimen. However, these strain data proved to be biased and of no value because of specimen-collet deformation, slippage, and bending. An attempt was also made to correlate test machine ram travel (stroke) with specimen strain. These data also proved to be of no analytical value. As a result, the only mechanical property measured using the non-strain-gauged specimens was ultimate strength. The effect of bonding tabs on these specimens in such proximity to the test section was not evaluated.

4.7.2 Compression Test Results

Results of the compression tests are presented in Tables 4.7-1 through 4.7-4. Typical failed compression specimens are shown in Figures 4.7-3 and 4.7-4.

Compressive strengths are plotted as functions of temperature and specimen conditioning in Figure 4.7-5. Compressive strengths consistently decreased with increasing temperature regardless of laminate geometry. This could be anticipated since compressive stability is usually controlled by the resin matrix. Compressive strengths at 598 K (600°F), following moisture saturation, exhibited a significant reduction (nearly 50 percent for $(90)_{16}$ and the quasi-isotropic laminates) when compared with dry laminates tested at the same temperature.

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*Illinois Institute of Technology Research Institute

Compressive modulus results are plotted in Figures 4.7-6 and exhibit little change as a function of test temperature. Elastic modulus was not determined for moisture-saturated specimens. Poisson's ratio and failure strains were measured for all strain-gauged specimens. Poisson's ratio was computed from the ratio of the slopes of the linear portion of the stress-strain data. Failure strains were taken from the last longitudinal strain gauge reading prior to failure. Again, for $(\pm45)_{2s}$ laminates, the failure strains often exceeded the capability of the instrumentation. For the $(90)_{16}$ laminates, observed changes in Poisson's ratio as a function of test temperature could not be explained.

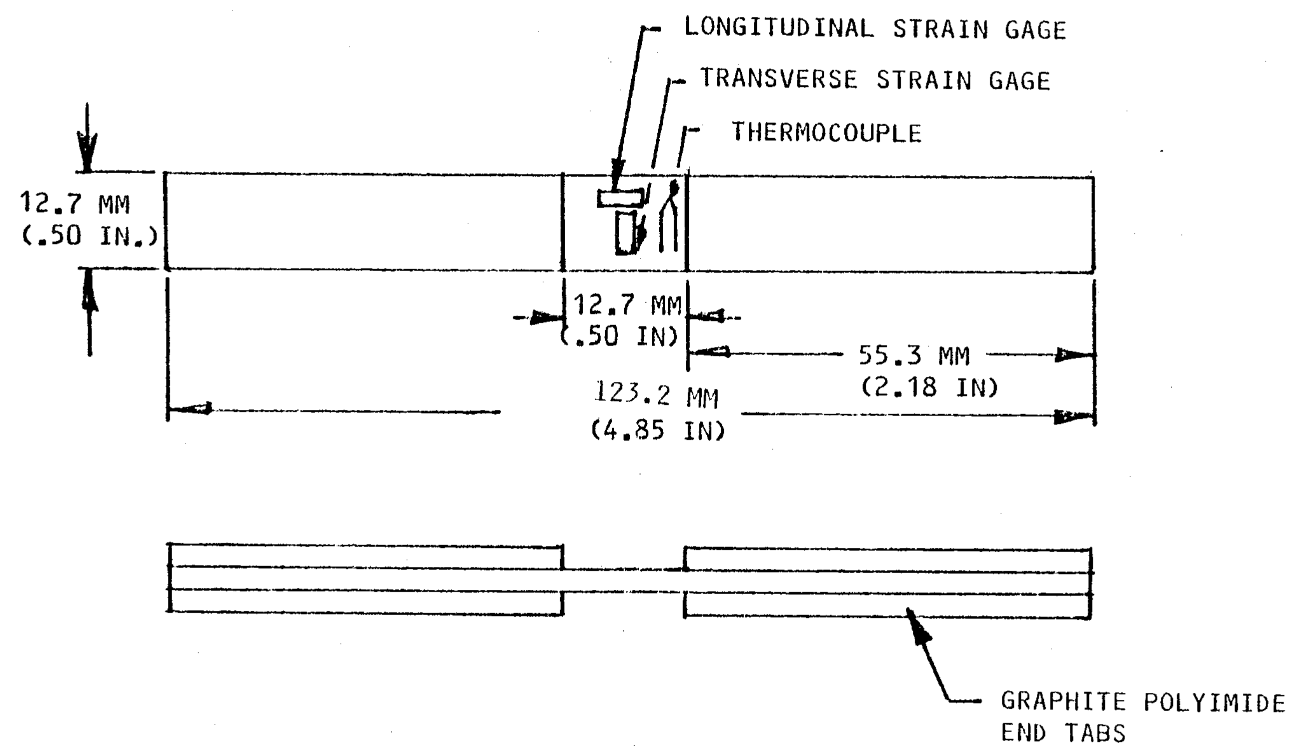

Figure 4.7-1. IITRI compression specimen

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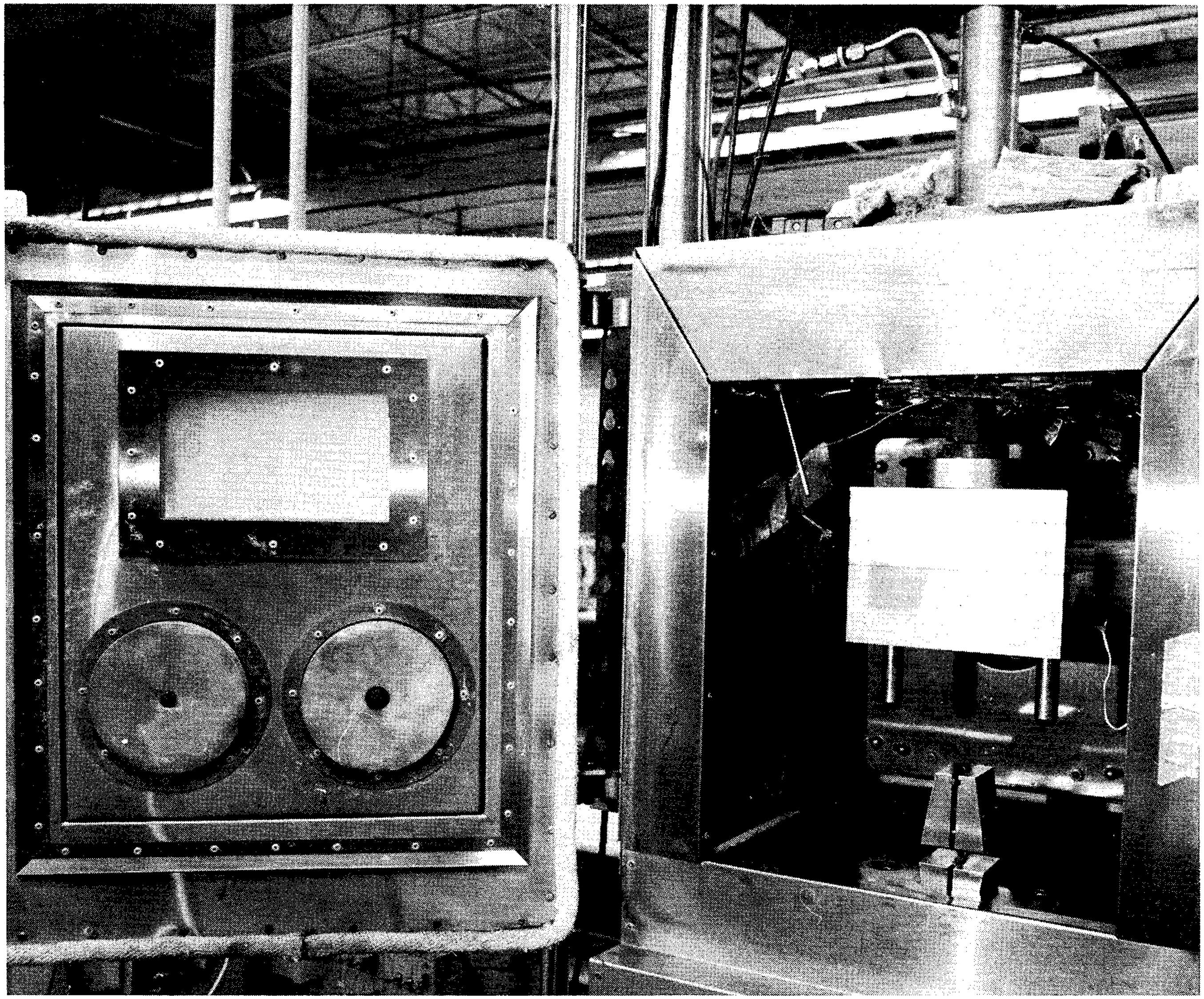

Figure 4.7-2. IITRI compression fixture installed in oven

TABLE 4.7-1. COMPRESSION PROPERTIES OF CELION 6000/LARC-160 LAMINATES WITH $(0)_{16}$ FIBER ORIENTATION (BASELINE DRY)

Room Temperature							116 K (-250°F)							589 K (600°F)						
	F_{cu}		E_c		ε ult (%)	ν		F_{cu}		E_c		ε ult (%)	ν		F_{cu}		E_c		ε ult (%)	ν
ID	MN/m^2	KSI	GN/m^2	MSI			ID	MN/m^2	KSI	GN/m^2	MSI			ID	MN/m^2	KSI	GN/m^2	MSI		
UC1							UC1							UC1						
S1-1	959	139	118	17.10	0.82	0.368	S1-11	1676	243	119	17.31	1.84	0.329	S1-21	855	124	131	18.99	0.72	0.316
S1-2	1083	157	129	18.75	0.96	0.426	S1-12	1717	249	119	17.25	2.72	0.340	S1-22	910	132	136	19.74	0.81	0.345
S1-3	924	134	112	16.28	0.85	0.327	S1-13	1821	264	115	16.67	2.07	0.333	S1-23	786	114	133	19.22	0.60	0.322
S1-4	1214	176	122	17.75	1.12	0.331	S1-14	1697	246	115	16.67	1.71	0.444	S1-24	876	127	135	19.65	0.66	0.320
S1-5	1324	192	119	17.30	1.40	0.359	S1-15	1703	247	112	16.22	2.03	0.352	S1-25	999	145	129	18.75	0.96	0.344
S1-6	1269	184	-	-	-	-	S1-17	1752	254	-	-	-	-	S1-26	938	136	-	-	-	-
S1-7	1421	206	-	-	-	-	S1-20	1876	272	-	-	-	-	S1-27	890	129	-	-	-	-
S1-8	1407	204	-	-	-	-	S1-32	1807	262	-	-	-	-	S1-28	821	119	-	-	-	-
S1-9	1359	197	-	-	-	-								S1-29	890	129	-	-	-	-
S1-10	1469	213	-	-	-	-								S1-30	828	120	-	-	-	-
														S1-19	834	121	-	-	-	-
Avg	1241	180	120	17.44	1.03	0.362		1757	255	116	16.82	2.08	0.360		875	127	133	19.27	0.750	0.329

TABLE 4.7-2. COMPRESSION PROPERTIES OF CELION 6000/LARC-160 LAMINATES WITH $(90)_{16}$ FIBER ORIENTATION

Room Temperature							116 K (-250°F)							589 K (600°F)						
ID	F_{cu}		E_c		ε ult (%)	ν	ID	F_{cu}		E_c		ε ult (%)	ν	ID	F_{cu}		E_c		ε ult (%)	ν
	MN/m^2	KSI	GN/m^2	MSI				MN/m^2	KSI	GN/m^2	MSI				MN/m^2	KSI	GN/m^2	MSI		
BASELINE DRY																				
90C1							90C1							90C1						
S1-1	161	23.34	9.2	1.34	1.86	0.011	S1-31	199	28.87	11.5	1.67	2.18	0.060	S1-21	96.0	13.92	7.5	1.09	1.42	0.039
S1-2	*	*	*	*	*	*	S1-32	176	25.57	10.9	1.58	2.24	0.060	S1-22	98.5	14.29	6.5	0.95	*	0.034
S1-3	*	*	*	*	*	*	S1-13	173	25.15	10.8	1.56	1.98	0.062	S1-23	82.9	13.47	7.9	1.14	1.43	0.023
S1-4	175	25.45	9.8	1.42	2.21	0.015	S1-14	177	25.71	10.1	1.47	2.09	0.059	S1-24	102.5	14.86	7.6	1.10	1.36	0.026
S1-5	154	22.30	9.9	1.43	1.68	0.022	S1-15	226	32.72	10.8	1.56	2.76	0.062	S1-25	98.5	14.29	7.2	1.05	1.46	0.031
S1-6	155	22.47	-	-	-	-	S1-16	163	23.59	-	-	-	-	S1-26	99.1	14.37	-	-	-	
S1-7	148	21.40	-	-	-	-	S1-17	169	24.49	-	-	-	-	S1-27	107.0	15.51	-	-	-	
S1-8	173	25.11	-	-	-	-	S1-18	204	29.60	-	-	-	-	S1-28	96.8	14.04	-	-	-	
S1-9	174	25.19	-	-	-	-	S1-19	207	30.00	-	-	-	-	S1-29	*	*	-	-	-	
S1-10	176	25.53	-	-	-	-	S1-20	160	23.20	-	-	-	-	S1-30	104.7	15.18	-	-	-	
							S1-33	189	27.39	-	-	-	-				-			
Avg	164	23.85	9.6	1.40	1.92	-		186	26.90	10.8	1.57	2.25	0.061		99.5	14.44	7.4	1.07	1.42	0.031
MOISTURE SATURATED																				
90C1														90C1						
S1-34	168	24.38	-	-	-	-								S1-40	61.0	8.85	-	-	-	-
S1-35	168	24.33	-	-	-	-								S1-41	39.6	5.75	-	-	-	-
S1-36	168	24.33	-	-	-	-								S1-42	57.8	8.38	-	-	-	-
S1-37	162	23.54	-	-	-	-								S1-43	59.6	8.64	-	-	-	-
S1-38	159	23.08	-	-	-	-								S1-44	74.8	10.85	-	-	-	-
Avg	165	23.93	-	-	-	-									58.5	8.49	-	-	-	-

*Result not reported due to testing error or irregularity.

TABLE 4.7-3. COMPRESSION PROPERTIES OF CELION 6000/LARC-160 LAMINATES WITH $(0/45/90/-45)_{2s}$ FIBER ORIENTATION

Room Temperature							116 K (-250°F)							589 K (600°F)						
ID	F_{cu}		E_c		ε ult (%)	ν	ID	F_{cu}		E_c		ε ult (%)	ν	ID	F_{cu}		E_c		ε ult (%)	ν
	MN/m^2	KSI	GN/m^2	MSI				MN/m^2	KSI	GN/m^2	MSI				MN/m^2	KSI	GN/m^2	MSI		
BASELINE DRY																				
CC1							CC1							CC1						
S1-1	544	78.94	49.7	7.21	1.34	0.272	S1-11	596	86.38	48.1	6.98	1.50	0.297	S1-21	490	71.06	49.2	7.14	1.15	0.295
S1-2	561	81.30	47.5	6.89	1.38	0.275	S1-12	594	86.17	49.9	7.23	1.43	0.306	S1-22	509	73.83	51.7	7.50	0.82	0.290
S1-3	613	88.96	45.4	6.59	1.60	0.278	S1-13	590	85.56	64.7	9.38	1.43	0.344	S1-23	472	68.51	51.7	7.50	0.79	0.300
S1-4	581	84.27	40.7	5.90	1.37	0.315	S1-14	490	71.09	47.5	6.88	1.30	0.321	S1-24	481	69.79	49.2	7.14	1.22	0.330
S1-5	490	71.06	47.0	6.82	1.05	0.301	S1-15	636	92.22	54.4	7.89	1.54	0.368	S1-25	493	71.46	52.9	7.67	0.66	0.324
S1-6	579	83.96	-	-	-	-	S1-16	560	81.25	-	-	-	-	S1-26	425	61.67	-	-	-	-
S1-7	629	91.15	-	-	-	-	S1-17	578	83.75	-	-	-	-	S1-27	497	72.08	-	-	-	-
S1-8	500	72.50	-	-	-	-	S1-18	560	81.25	-	-	-	-	S1-28	511	74.17	-	-	-	-
S1-9	595	86.25	-	-	-	-	S1-19	592	85.83	-	-	-	-	S1-32	460	66.67	-	-	-	-
S1-10	596	86.46	-	-	-	-	S1-20	547	79.38	-	-	-	-	S1-33	477	69.11	-	-	-	-
Avg	568	82.49	46.0	6.68	1.35	0.288		574	83.29	52.9	7.67	1.44	0.327		481	69.84	51.0	7.39	0.93	0.318
MOISTURE SATURATED																				
CC1														CC1						
S1-34	521	75.52	-	-	-	-								S1-39	240	34.87	-	-	-	-
S1-35	478	69.27	-	-	-	-								S1-40	200	28.94	-	-	-	-
S1-36	544	78.96	-	-	-	-								S1-41	293	42.55	-	-	-	-
S1-37	590	85.52	-	-	-	-								S1-42	255	37.02	-	-	-	-
S1-38	643	93.26	-	-	-	-								S1-43	200	28.94	-	-	-	-
Avg	555	80.51	-	-	-	-									238	34.46	-	-	-	-

TABLE 4.7-4. COMPRESSION PROPERTIES OF CELION 6000/LARC-160 LAMINATES WITH $(\pm 45)_{4s}$ FIBER ORIENTATION (BASELINE DRY)

Room Temperature							116 K							589 K						
ID	F_{cu}		E_c		ε ult (%)	ν	ID	F_{cu}		E_c		ε ult (%)	ν	ID	F_{cu}		E_c		ε ult (%)	ν
	MN/m^2	KSI	GN/m^2	MSI				MN/m^2	KSI	GN/m^2	MSI				MN/m^2	KSI	GN/m^2	MSI		
45C1							45C1							45C1						
S1-1	188	27.34	14.3	2.08	2.07	0.708	S1-11	189	27.42	19.2	2.78	1.66	0.761	S1-21	112	16.26	10.8	1.56	1.57+	0.750
S1-2	166	24.00	16.2	2.35	1.90	0.749	S1-12	225	32.63	20.3	2.94	1.79	0.682	S1-22	116	16.75	13.0	1.89	1.08+	0.788
S1-3	169	24.48	16.5	2.40	2.50	0.718	S1-13	205	29.78	15.6	2.27	1.88	0.636	S1-23	108	15.71	13.0	1.88	1.65+	0.788
S1-4	169	24.50	15.7	2.28	1.82	0.737	S1-14	197	28.61	19.6	2.84	1.69	0.717	S1-24	110	15.88	11.0	1.60	1.30+	0.820
S1-5	166	24.02	16.9	2.45	1.66	0.780	S1-15	204	29.63	18.1	2.63	1.57	0.737	S1-25	110	15.96	10.9	1.58	1.02+	0.886
S1-6	180	26.09	-	-	-	-	S1-16	184	26.63	-	-	-	-	S1-26	119	17.21	-	-	-	-
S1-7	167	24.19	-	-	-	-	S1-17	194	28.16	-	-	-	-	S1-27	117	17.00	-	-	-	-
S1-8	173	25.04	-	-	-	-	S1-18	191	27.71	-	-	-	-	S1-28	118	17.15	-	-	-	-
S1-9	171	24.78	-	-	-	-	S1-19	191	27.71	-	-	-	-	S1-29	117	17.02	-	-	-	-
S1-10	167	24.22	-	-	-	-	S1-20	167	24.25	-	-	-	-	S1-30	119	17.19	-	-	-	-
Avg	171	24.87	15.9	2.31	1.99	0.738		195	28.25	18.5	2.69	1.72	0.707		114	16.61	11.7	1.70	-	0.806

+Actual strain to failure exceeded capability of instrumentation; final reading shown for information only

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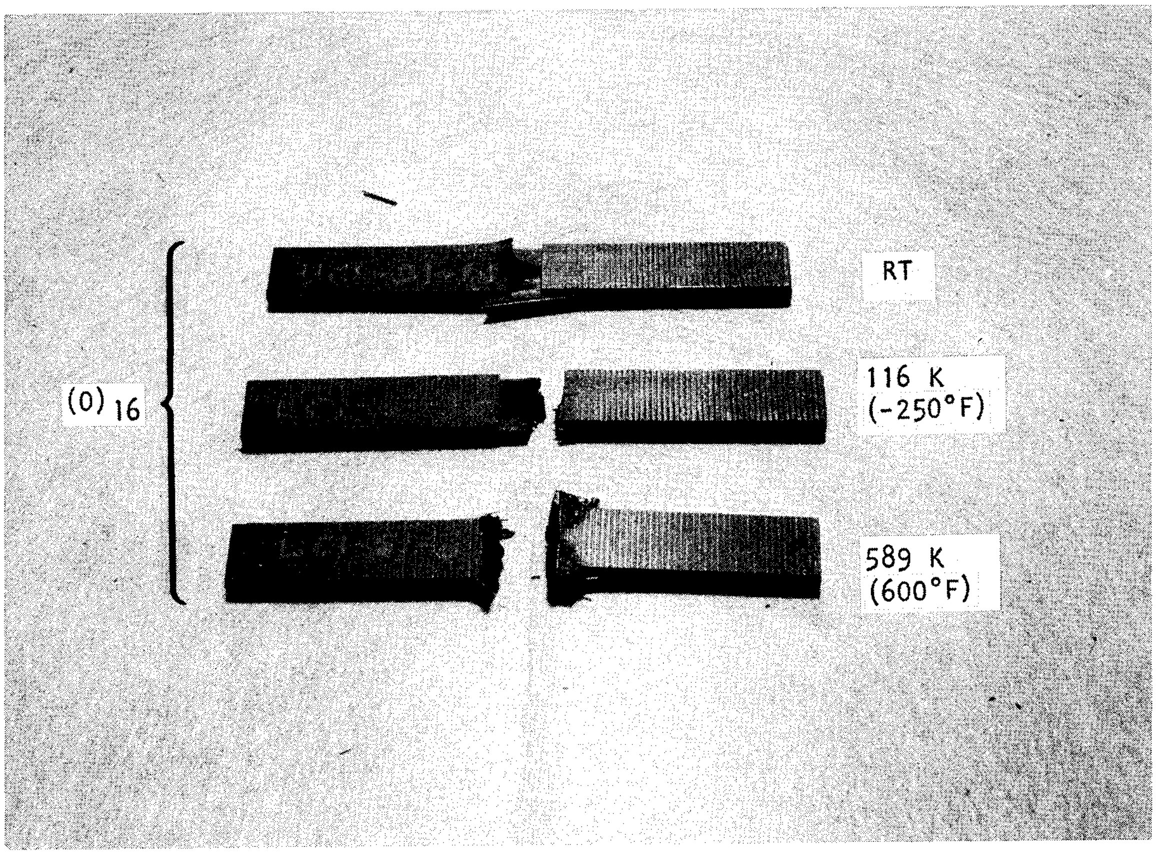

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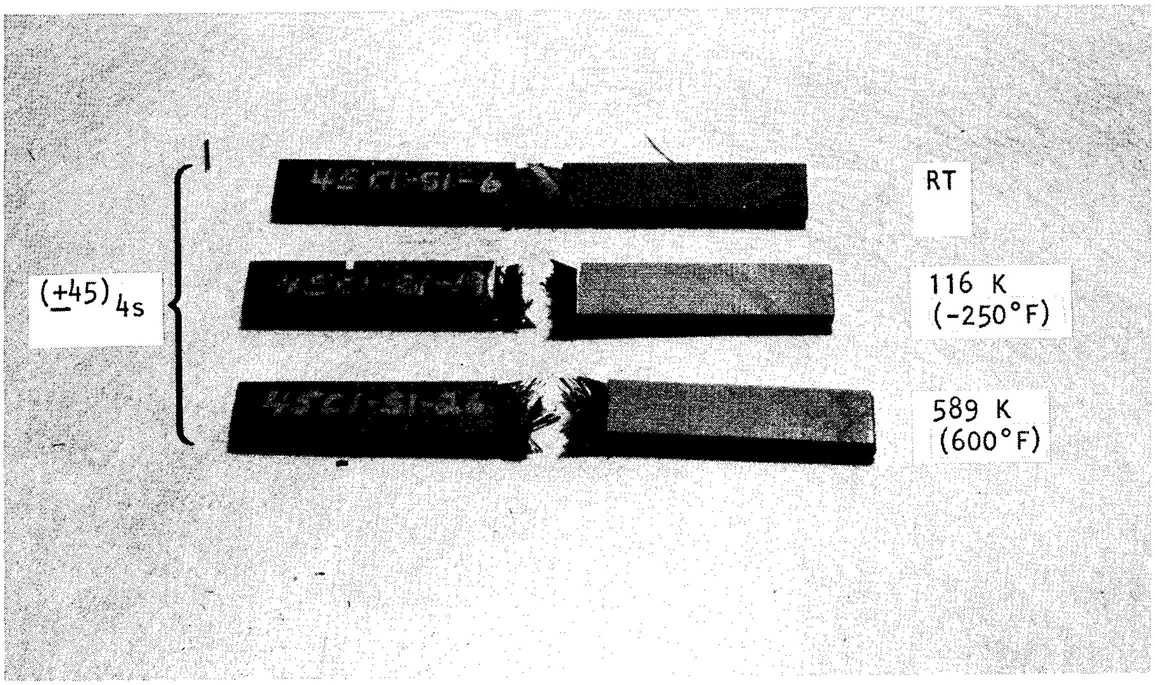

Figure 4.7-3. Typical compression failures for baseline dry laminates

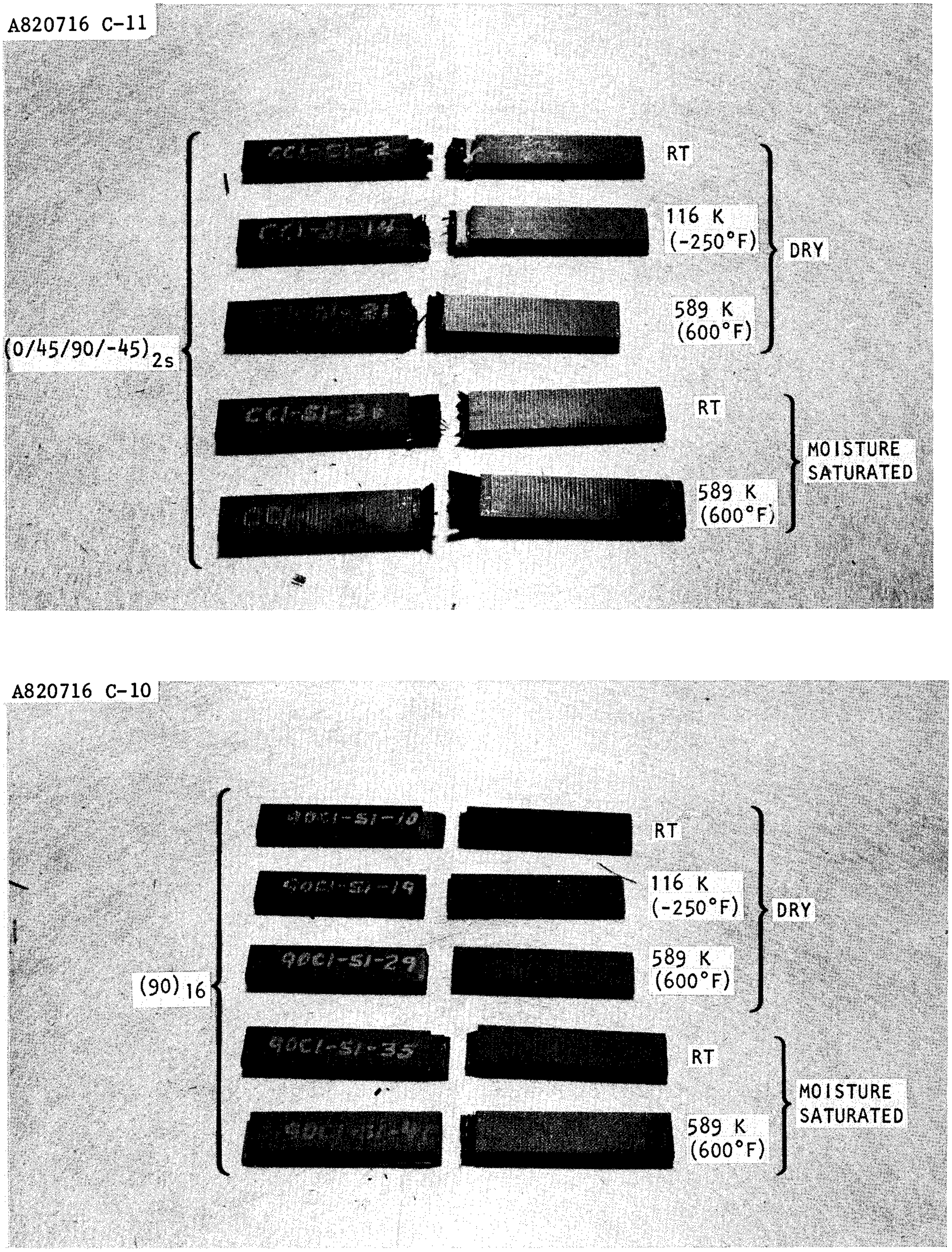

Figure 4.7-4. Typical compression failures for baseline dry and moisture-saturated laminates

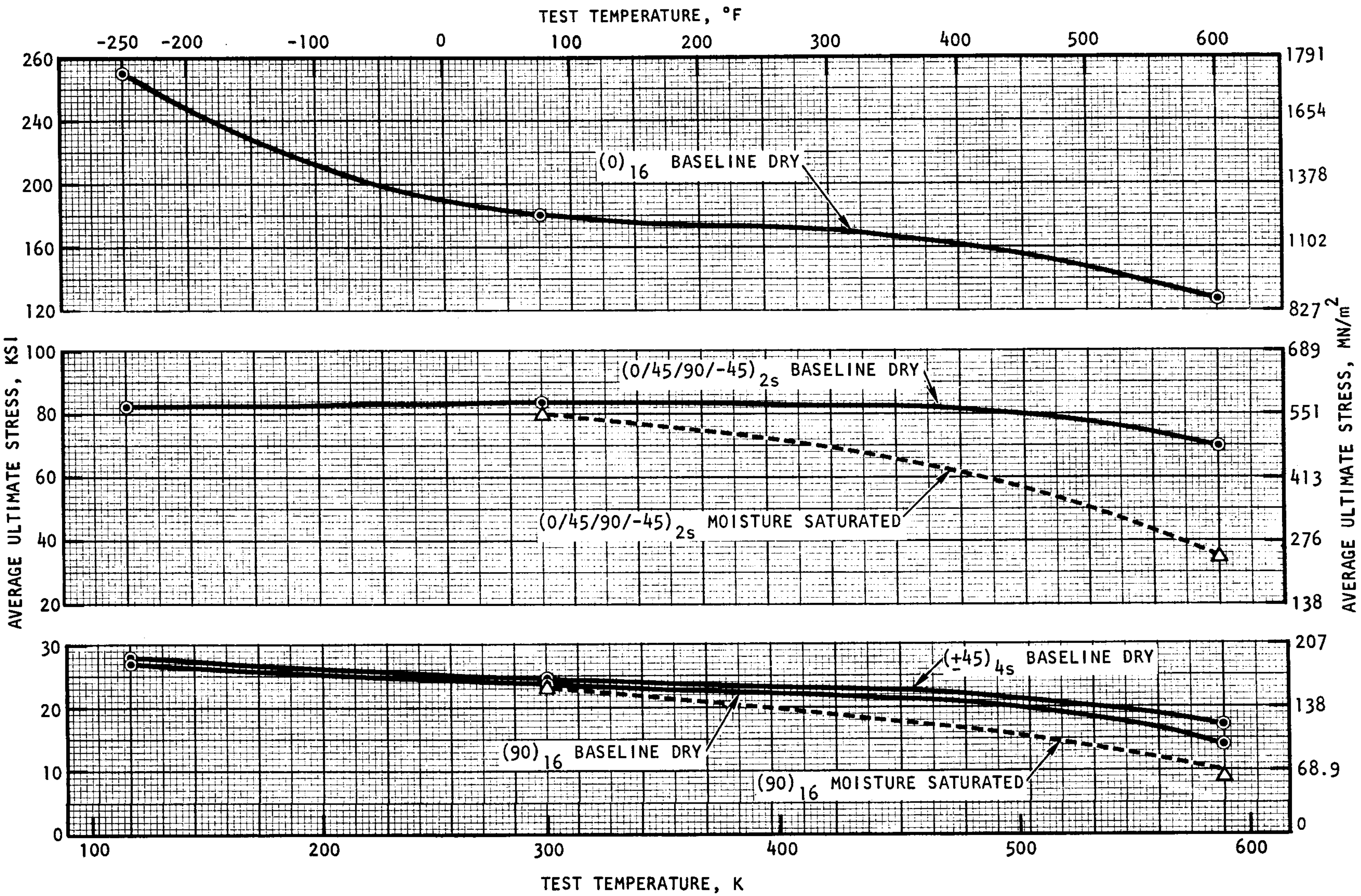

Figure 4.7-5. Compression strength properties of Celion 6000/LARC-160 laminates

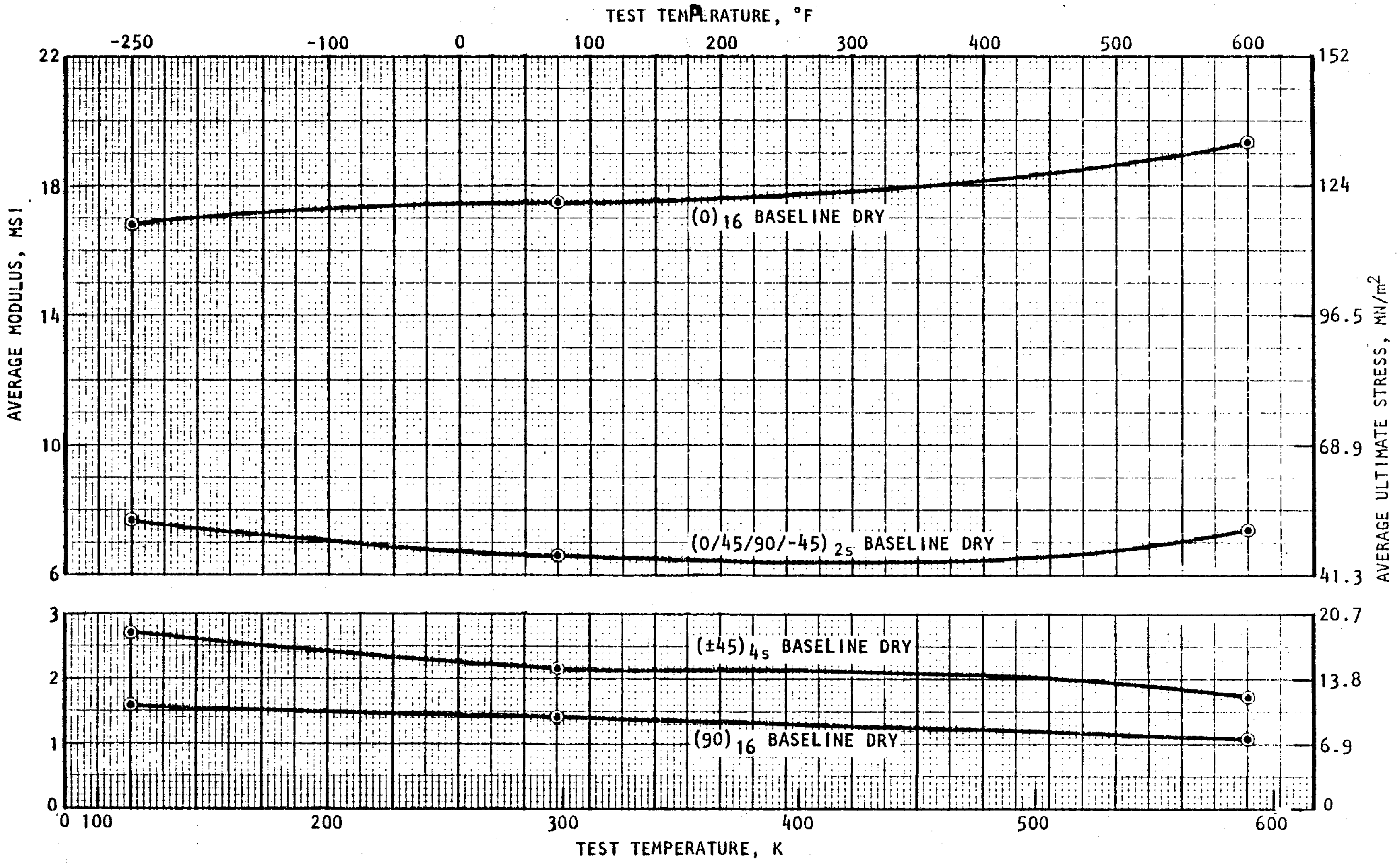

Figure 4.7-6. Compression modulus properties of Celion 6000/LARC-160 laminates

4.8 In-Plane Shear (Rail) Coupon Tests

This section presents the procedures and results for in-plane shear tests of $(0/45/90/-45)_s$, $(\pm45)_{2s}$ and $(90)_8$ Celion 6000/LARC-160 graphite/polyimide laminates. As defined by the program test matrix (Table 4.1-1) only the baseline-dry condition was evaluated.

4.8.1 Test Procedures

The bolted rail shear tests configuration described in Reference 6 was used in the in-plane shear tests.

A test section aspect ratio (length/width) of 6 was used (as opposed to 10, which was used in the reference) and should, according to the finite element analysis results of the reference, optimize the uniformity of the shear stress distribution along the centerline of the test section. The recommended rail grid pattern was not used because of its potential for damage to the thin test specimens. During testing at temperature extremes, specimen slippage was prevented by re-torquing the bolts which clamp the rails together after the specimens reached test temperature, thereby minimizing the effects of differential thermal expansion. Again, load was applied at a constant rate to reach the anticipated failure load in approximately five minutes. Shear properties determined include ultimate shear strength, ultimate shear strain, and shear modulus. The test specimen configuration and setup for rail shear testing are shown in Figures 4.8-1 and -2 respectively. Data were obtained autographically from back-to-back rosette strain gauges on 5 of the 10 baseline-dry specimens tested in each group. Attempts to instrument the test fixture with extensometers attached to the load rails gave a nonlinear and nonsymmetrical response. Therefore, deflection measurements for the non-strain-gauged specimens were monitored by machine ram travel.

4.8.2 In-Plane (Rail) Shear Test Results

Results of the rail shear tests are presented in Tables 4.8-1 through 4.8-3. Typical failed test coupons are shown in Figures 4.8-3 through -5. Effects of test temperature on composite rail shear strength and modulus properties are presented in Figures 4.8-6 and -7, respectively.

The equation used to calculate maximum shear strain was

$$\gamma_{MAX} = \sqrt{2}\sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2}$$

where

ε_1 = transverse strain
ε_2 = 45° strain
ε_3 = longitudinal strain

The shear strengths for the $(\pm45)_{2s}$ laminates were considerably lower than anticipated. This is attributed to a stress riser effect associated with rail shear tests of composites having a Poisson's ratio approaching unity (Reference 7). Strength is significantly reduced while modulus is not affected. The $(\pm45)_{2s}$ strength results, therefore, are presented for information only.

Because of an apparent inconsistency in the room-temperature results for the quasi-isotropic laminates (see Table 4.8-2) where all strain-gauged specimens failed at lower loads than nongauged specimens, an additional set of six instrumented specimens was tested. Results of these tests confirm that all results are within the same data scatter band, and no testing irregularity was identified.

The effects of test temperature on shear strength and modulus were consistent with anticipated results in that strength decreased with increasing temperature and modulus was much less affected by temperature.

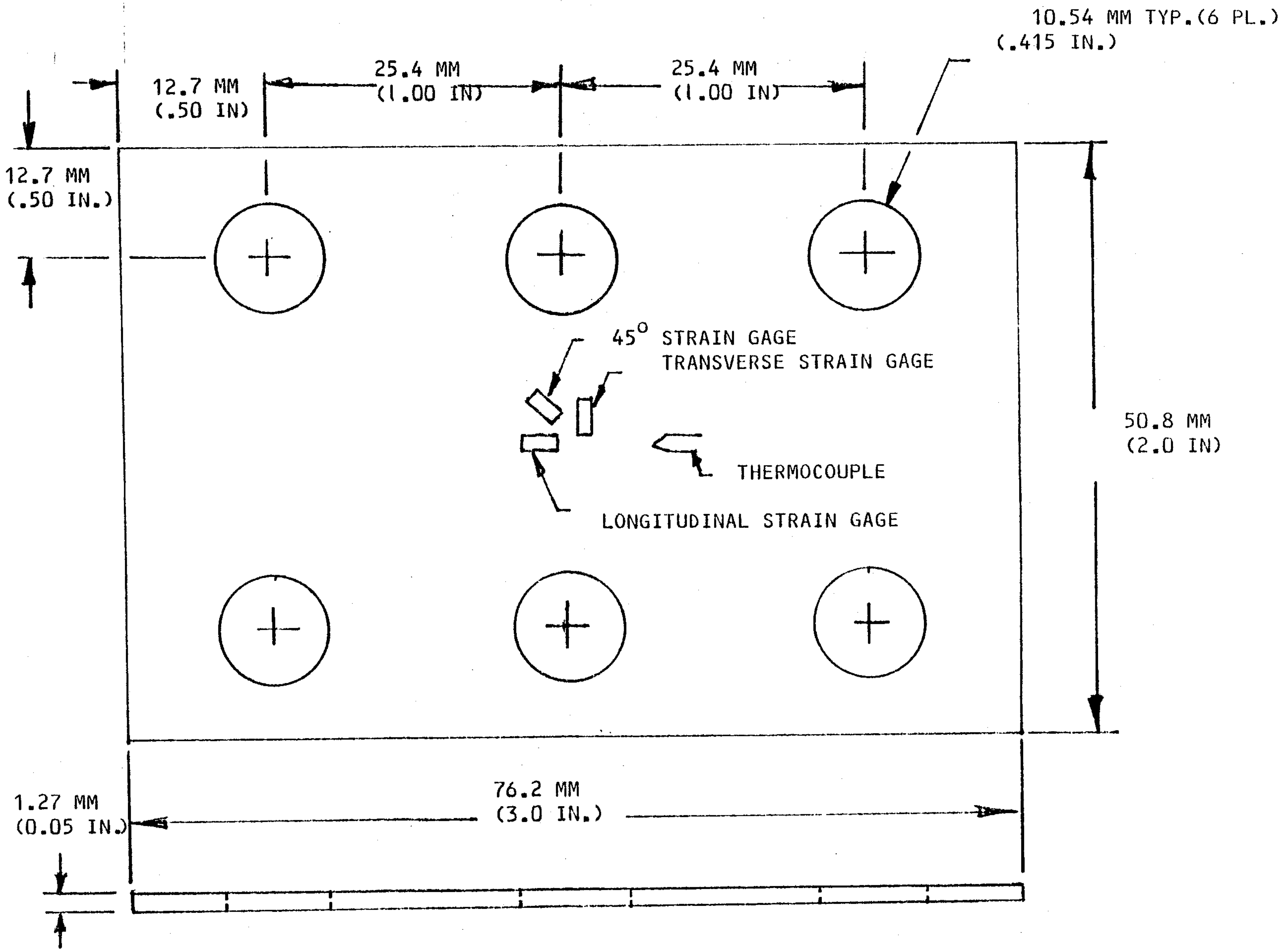

Figure 4.8-1. In-plane (rail) shear specimen

A820721 C-31C

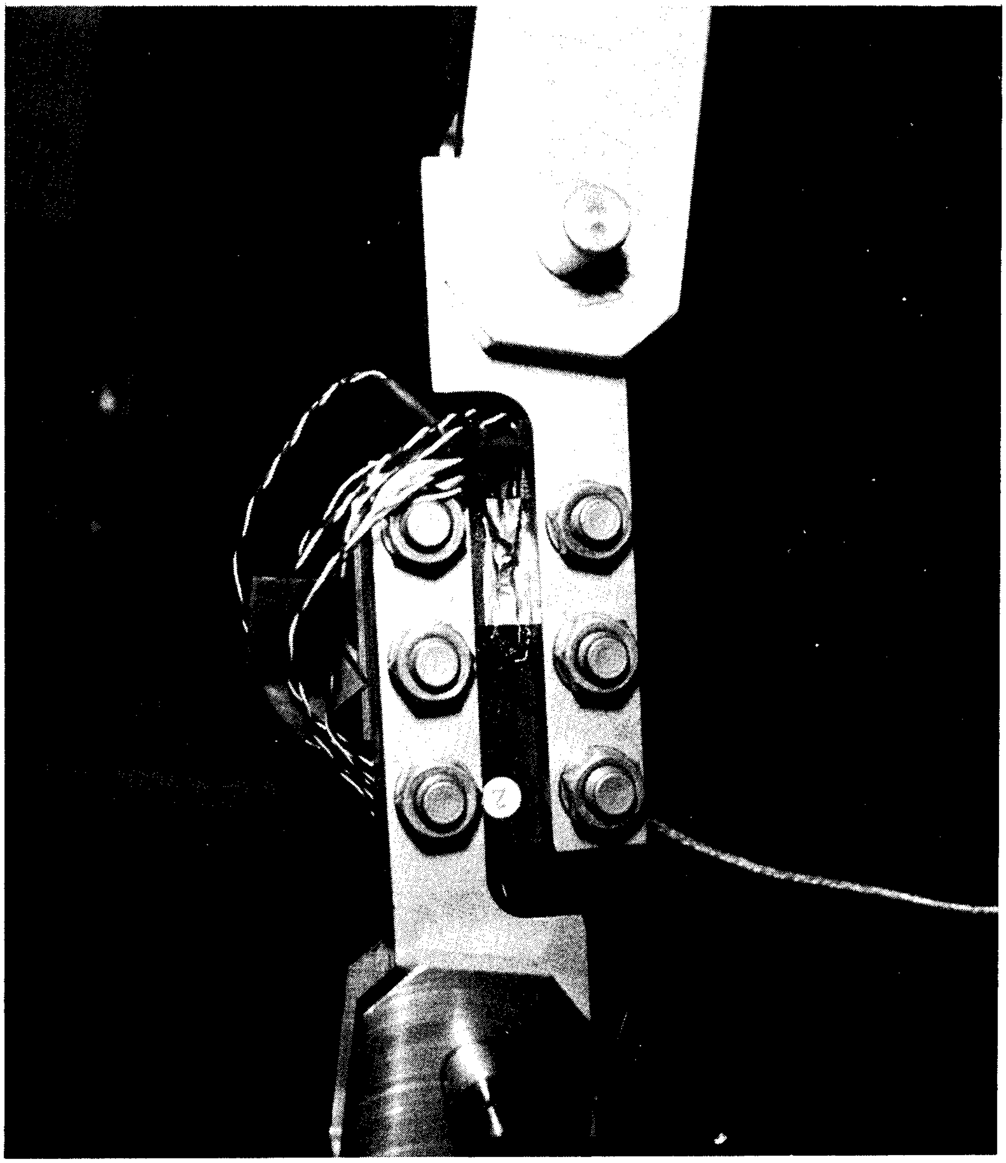

Figure 4.8-2. Test fixture and setup for rail shear tests

TABLE 4.8-1. IN-PLAND (RAIL) SHEAR PROPERTIES OF CELION 6000/LARC-160 LAMINATES WITH $(90)_8$ FIBER ORIENTATION

Room Temperature						116 K (-250°F)						589 K (600°F)					
ID	F_{su}		G		ε ult (%)	ID	F_{su}		G		ε ult (%)	ID	F_{su}		G		ε ult (%)
	MN/m^2	KSI	GN/m^2	MSI			MN/m^2	KSI	GN/m^2	MSI			MN/m^2	KSI	GN/m^2	MSI	
90IPS						90IPS						90IPS					
-1	79.6	11.54	6.00	0.87	2.39	-6	105	15.17	6.14	0.89	1.9+						
-2	81.4	11.81	6.14	0.89	1.20+	-7	96	13.88	6.41	0.93	2.06	-13	48.7	7.06	4.90	0.71	2.20+
-3	74.0	10.73	5.72	0.83	2.20+							-14	49.1	7.12	4.14	0.60	1.80+
-4	71.4	10.36	5.79	0.84	1.60+							-15	45.4	6.58	3.79	0.55	1.40+
-5	79.6	11.54	6.14	0.89	1.20+	-11	97	14.08	6.07	0.88	1.7+	-16	44.8	6.50	3.52	0.51	1.70+
-17	79.4	11.51	-	-	-	-21	108	15.64	-	-	-	-26	51.1	7.41	-	-	-
-18	85.2	12.36	-	-	-	-22	104	15.04	-	-	-	-27	55.8	8.09	-	-	-
-19	76.3	11.07	-	-	-	-23	104	15.02	-	-	-	-28	48.4	7.02	-	-	-
-20	84.9	12.31	-	-	-	-24	104	15.08	-	-	-	-29	56.2	8.15	-	-	-
-31	69.0	10.01	-	-	-	-25	99	14.33	-	-	-	-30	50.5	7.32	-	-	-
Avg	78.1	11.32	5.96	0.86	-		102	14.78	6.21	0.90	-		50.0	7.25	4.09	0.59	-

+Strain gauge disbond near 90 percent of maximum load; final readings shown for information only

Table 4.8-2. In-Plane (Rail) Shear Properties of Celion 6000/LARC-160 Laminates With $(0/45/90/-45)_s$ Fiber Orientation

Room Temperature						116 K (-250°F)						589 K (600°F)					
ID	F_{su}		G		ε ult (%)	ID	F_{su}		G		ε ult (%)	ID	F_{su}		G		ε ult (%)
	MN/m^2	KSI	GN/m^2	MSI			MN/m^2	KSI	GN/m^2	MSI			MN/m^2	KSI	GN/m^2	MSI	
CPIS						CPIS						CPIS					
						-6	277	40.12	19.7	2.85	1.90	-12	241	34.90	20.34	2.95	1.73
-2	201	29.13	18.2	2.64	2.05	-7	355	51.42	19.8	2.87	2.80	-13	179	25.98	21.65	3.14	0.84
-3	200	29.05	18.1	2.63	1.91	-8	326	47.28	20.5	2.98	2.50	-14	239	34.64	21.86	3.17	1.37
-4	185	26.77	18.6	2.70	1.66	-9	307	44.47	19.9	2.88	2.30	-15	213	30.91	20.34	2.95	1.58
-5	192	27.91	18.5	2.69	2.28	-10	322	46.72	20.1	2.92	2.40	-16	214	31.09	21.24	3.08	1.37
-11	245	35.5	-	-	-	-21	367	53.28	-	-	-	-26	163	23.60	-	-	-
-17	259	37.6	-	-	-	-22	351	50.85	-	-	-	-27	189	27.35	-	-	-
-18	268	38.9	-	-	-	-23	397	57.54	-	-	-	-28	181	26.30	-	-	-
-19	280	40.6	-	-	-	-24	399	57.92	-	-	-	-29	204	29.60	-	-	-
-20	281	40.7	-	-	-	-25	377	54.73	-	-	-	-30	204	29.60	-	-	-
-31	261	37.9	-	-	-												
-32	217	31.5	-	-	-												
-33	203	29.4	-	-	-												
-34	194	28.2	-	-	-												
-35	199	28.8	-	-	-												
-36	188	27.3	-	-	-												
Avg	225	32.60	18.4	2.67	1.98		348	50.43	20.0	2.90	2.40		203	29.43	21.1	3.06	1.38

TABLE 4.8-3. IN-PLANE (RAIL) SHEAR PROPERTIES OF CELION 6000/LARC-160 LAMINATES WITH $(\pm 45)_{2s}$ FIBER ORIENTATION

Room Temperature						116 K (-250°F)						589 K (600°F)					
	F_{su}*		G				F_{su}*		G				F_{su}*		G		
ID	MN/m^2	KSI	GN/m^2	MSI	ε ult (%)	ID	MN/m^2	KSI	GN/m^2	MSI	ε ult (%)	ID	MN/m^2	KSI	GN/m^2	MSI	ε ult (%)
45IPS						45IPS						45IPS					
-1	284	41.22	31.9	4.62	2.06	-6	289	41.92	29.6	4.29	1.40	-12	158	22.79	34.2	4.96	2.94
-2	280	40.60	29.9	4.34	1.82	-7	360	52.23	28.6	4.15	1.59	-13	175	25.43	32.5	4.71	2.41
-3	175	25.35	31.0	4.50	0.67	-8	303	43.96	28.5	4.14	1.55	-14	144	20.95	33.9	4.92	3.15
-4	223	32.36	28.0	4.06	1.20	-9	324	47.00	30.3	4.39	1.20	-15	164	23.75	35.3	5.12	3.64
-5	239	34.64	28.5	4.14	1.35	-10	248	36.02	30.8	4.46	1.00	-16	178	25.79	33.9	4.92	1.67
-11	219	31.76	-	-	-	-21	312	45.23	-	-	-	-26	200	29.07	-	-	-
-17	240	34.87	-	-	-	-22	325	47.20	-	-	-	-27	176	25.48	-	-	-
-18	210	30.40	-	-	-	-23	264	38.33	-	-	-	-28	203	29.44	-	-	-
-19	221	32.10	-	-	-	-24	359	52.05	-	-	-	-29	204	29.59	-	-	-
-20	225	32.60	-	-	-	-25	227	32.96	-	-	-	-30	162	23.45	-	-	-
Avg	232	33.59	29.9	4.33	1.42		301	43.69	29.6	4.29	1.35		176	25.58	34.0	4.93	2.76

*Shear strengths are presented for information only; refer to text.

A820913 C-3C

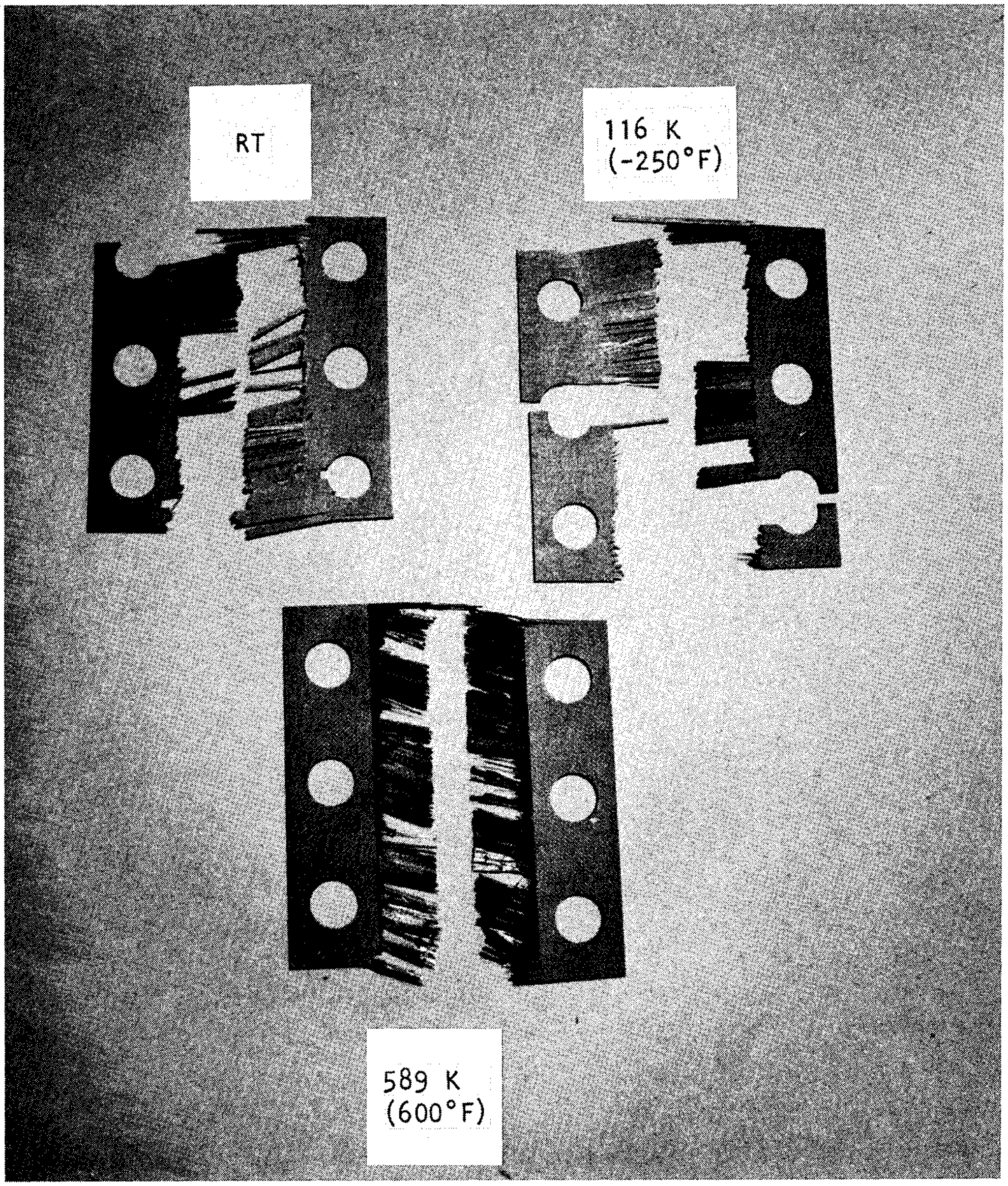

Figure 4.8-3. Typical rail shear failures for baseline dry $(90)_8$ laminates

A829013 C-1C

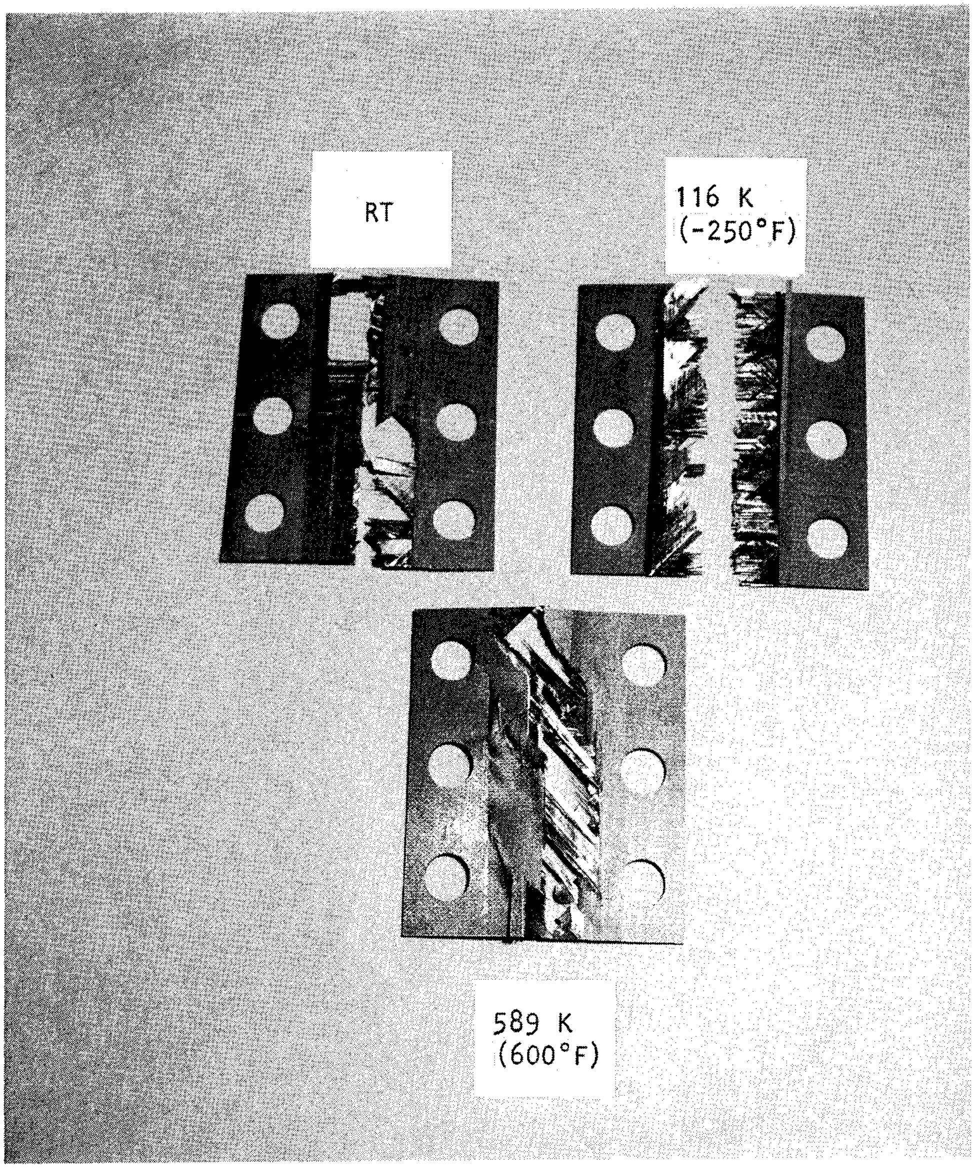

Figure 4.8-4. Typical rail shear failures for baseline dry $(0/45/90/-45)_s$ laminates

A820913 C-2C

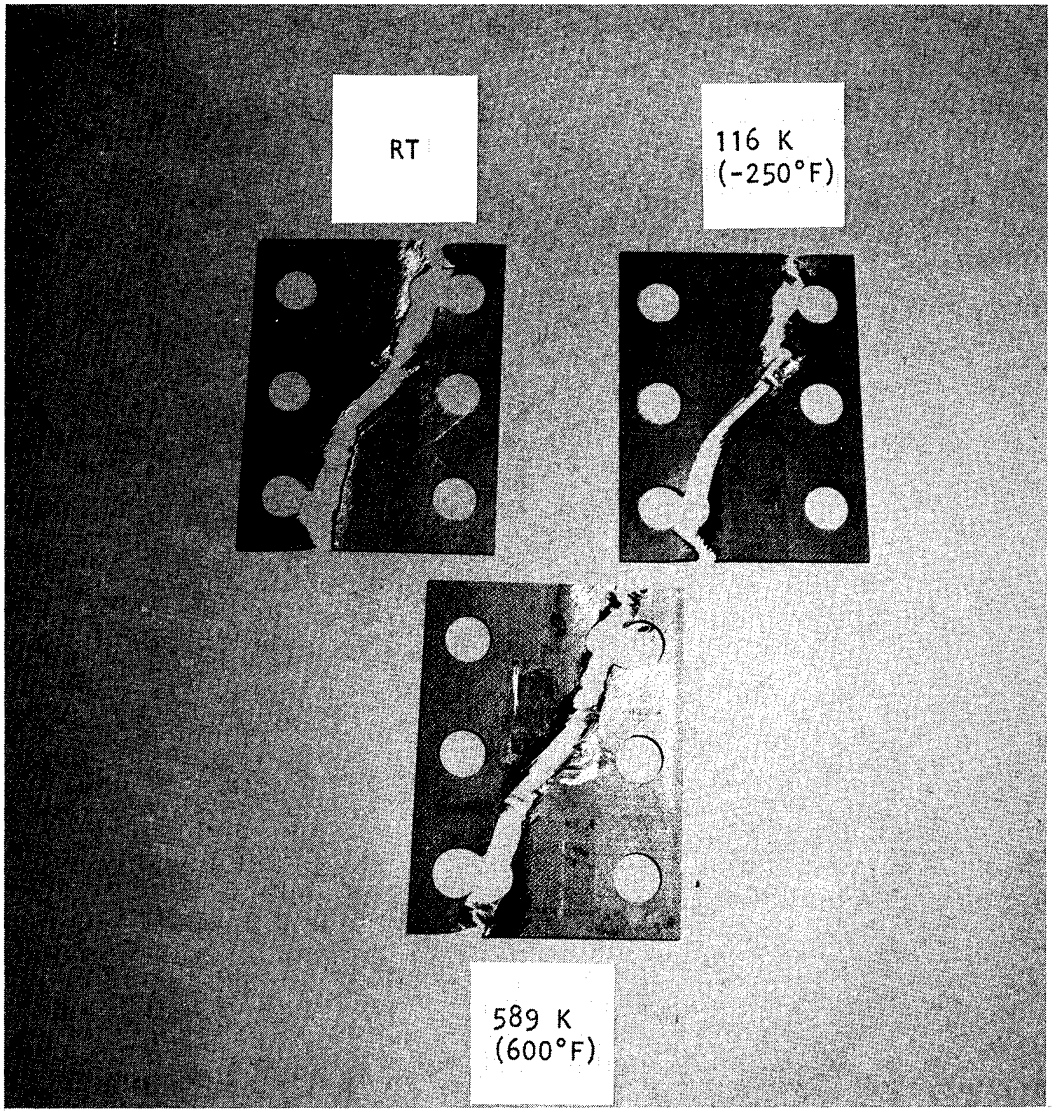

Figure 4.8-5. -Typical rail shear failures for baseline dry $(\pm45)_{2s}$ laminates

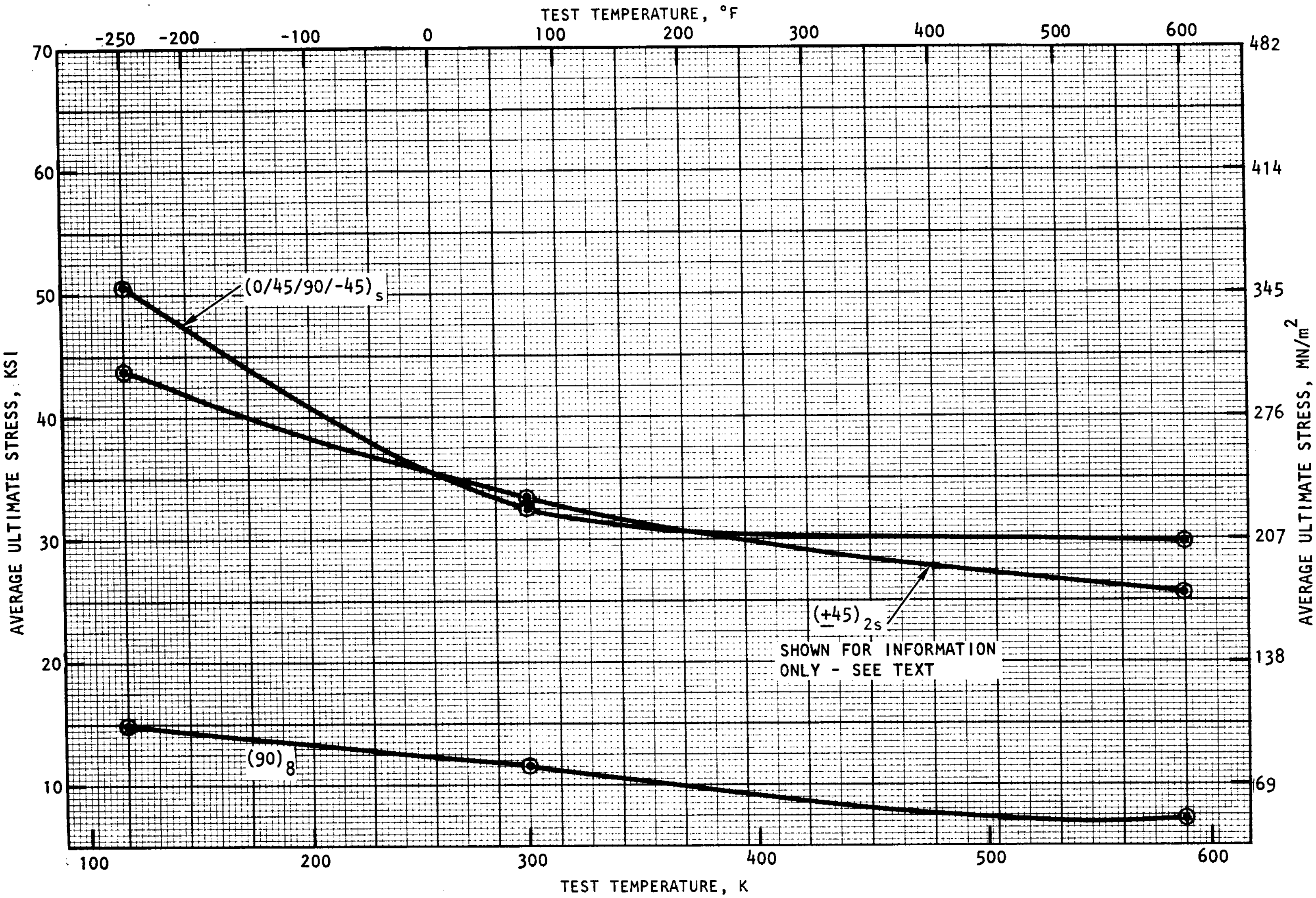

Figure 4.8-6. In-plane (rail) shear strength properties of Celion 6000/LARC-160 laminates

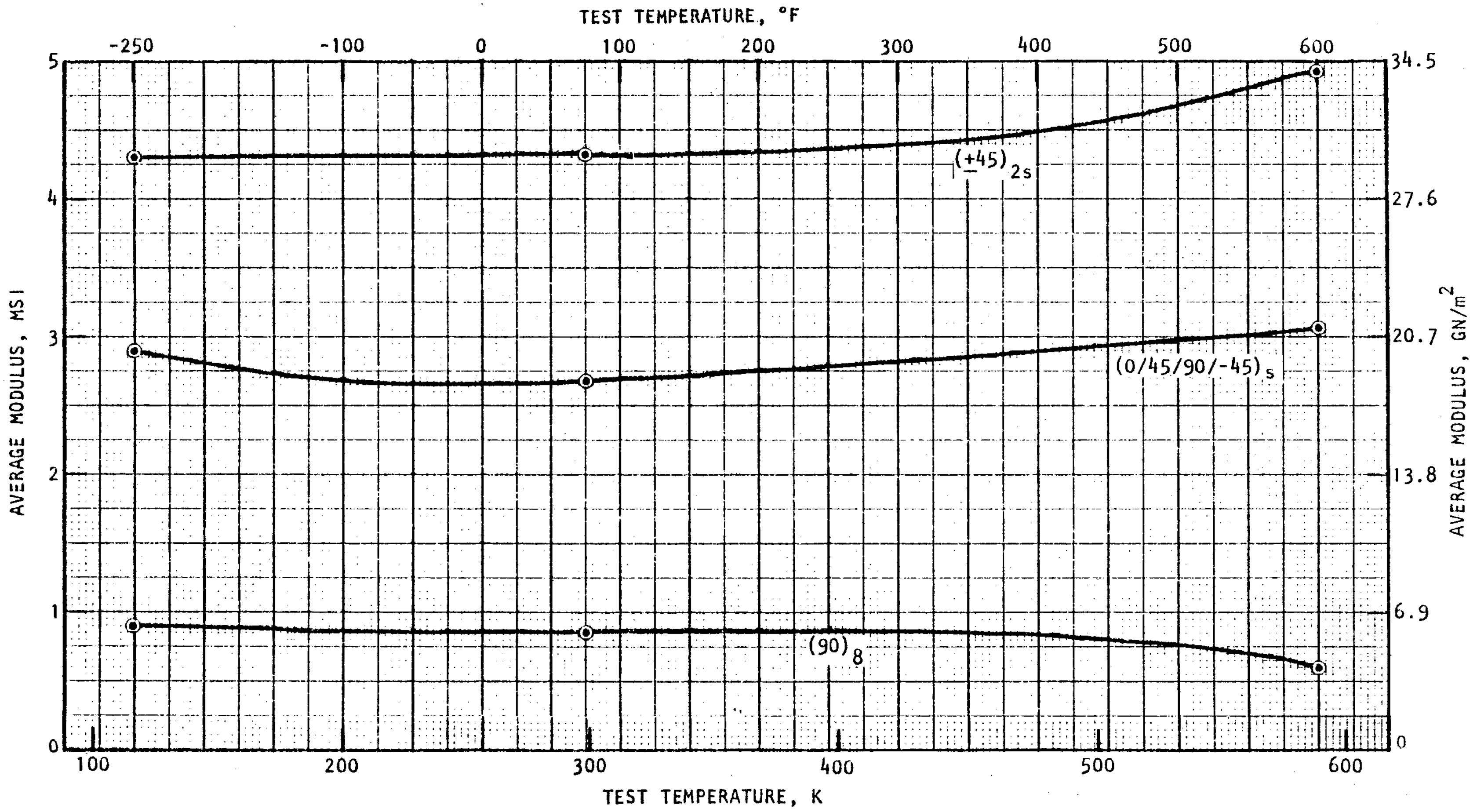

Figure 4.8-7. In-plane (rail) shear modulus properties of Celion 6000/LARC 160 laminates

4.9 Short Beam Shear Specimen Test Procedure

This section presents the procedures and results for short beam shear tests of $(0)_{20}$ Celion 600/LARC-160 graphite polyimide laminates. As defined by the program test matrix (Table 4.1-1), tests were conducted on baseline-dry, moisture-saturated and thermally aged laminates.

4.9.1 Test Procedures

The short beam shear test specimen configuration shown in Figure 4.9-1 was in accordance with ASTM D2344 (Reference 8) with a span-to-thickness ratio of 4:1. Deflection measurements were made autographically during each test with an isolated deflectometer positioned at the specimen midpoint. Load-deflection curves were obtained for all tests and were used to give a positive indication of when actual specimen failure occurred. Specimens were loaded at a head travel of 1.27 mm (0.05 in.)/minute after being stabilized at the test temperature for 30 ±10 minutes. For these tests only, Riehle test equipment was used in lieu of MTS test equipment. The test fixture and setup used for this test procedure are shown in Figures 4.9-2 and 4.9-3.

4.9.2 Short Beam Shear Test Results

The short beam, or interlaminar, shear test results are provided in Table 4.9-1. The room temperature baseline dry values are comparable to the current minimum typical specification values of 103.4 MN/m^2 (15 ksi). The effects of temperature, moisture saturation, and thermal exposure are tabulated in Table 4.9-1 and are plotted in Figure 4.9-4. As anticipated, temperature contributed to a general decrease in interlaminar shear strength. Thermal aging appears to slightly decrease room temperature and 116 K (-250°F) strengths while improving the 589 K (600°F) strengths. When compared with baseline-dry interlaminar shear strengths, the moisture saturated properties were higher at 116 K (-250°F) and lower at room temperature and 589 K (600°F).

TABLE 4.9-1. SHORT BEAM SHEAR STRENGTH OF CELION 6000/LARC-160 LAMINATES WITH $(0)_{20}$ FIBER ORIENTATION

Environmental Conditioning	Room Temperature			116 K (-250°F)			589 K (600°F)		
	ID	SBSS*		ID	SBSS*		ID	SBSS*	
		MN/m^2	KSI		MN/m^2	KSI		MN/m^2	KSI
Baseline dry	1	105	15.3	7	112	16.3	3	51.0	7.4
	6	99	14.4	8	111	16.1	4	55.9	8.1
	12	107	15.5	10	120	17.4	5	49.0	7.1
	14	114	16.5	11	119	17.3	9	52.4	7.6
	15	106	15.4	B	155	22.4	II	51.7	7.5
	50	111	16.1						
	Avg.	107	15.5		123	17.9		52.4	7.6
Moisture saturation 333 K (95-100%) relative humidity	16	89	12.9	21	139	20.1	26	52.4	7.6
	17	95.9	13.9	22	151	21.9	27	52.4	7.6
	18	102.1	14.8	23	134	19.5	28	53.1	7.7
	19	100.7	14.6	24	129	18.7	29	54.5	7.9
	20	95.9	13.9	25	151	21.9	30	55.2	8.0
	Avg.	96.5	14.0		141	20.4		53.8	7.8
Thermal soak 125 hours at 589 K (600°F)	1S	91.0	13.2	31	104	15.1	6S	57.2	8.3
	2S	92.4	13.4	32	110	16.0	7S	60.7	8.8
	3S	75.2	10.9	33	105	15.2	8S	60.0	8.7
	4S	85.5	12.4	34	97	14.1	9S	58.6	8.5
	5S	76.6	11.1	35	103	15.0	10S	59.3	8.6
	Avg.	84.1	12.2		104	15.1		59.3	8.6

*Short beam shear strength

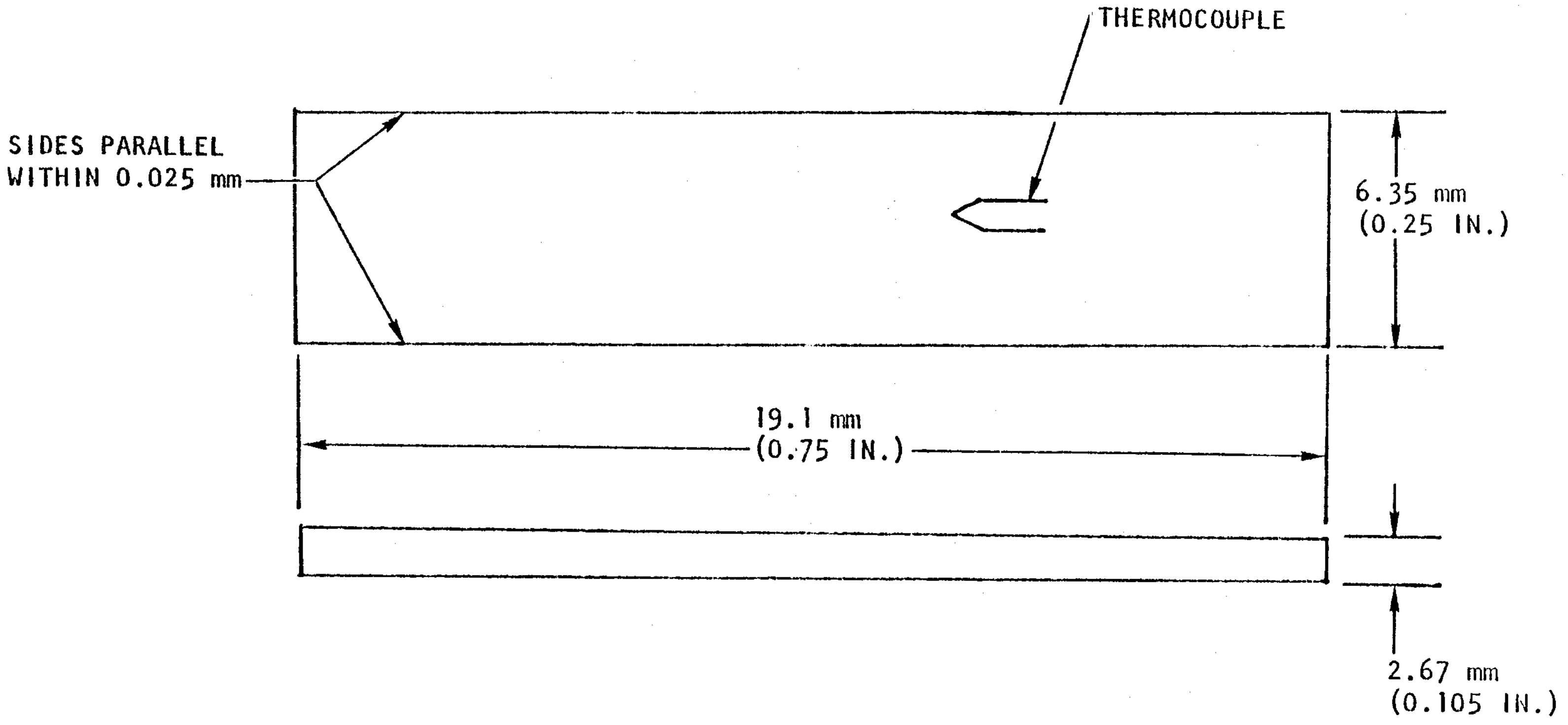

Figure 4.9-1. Short-beam shear specimen

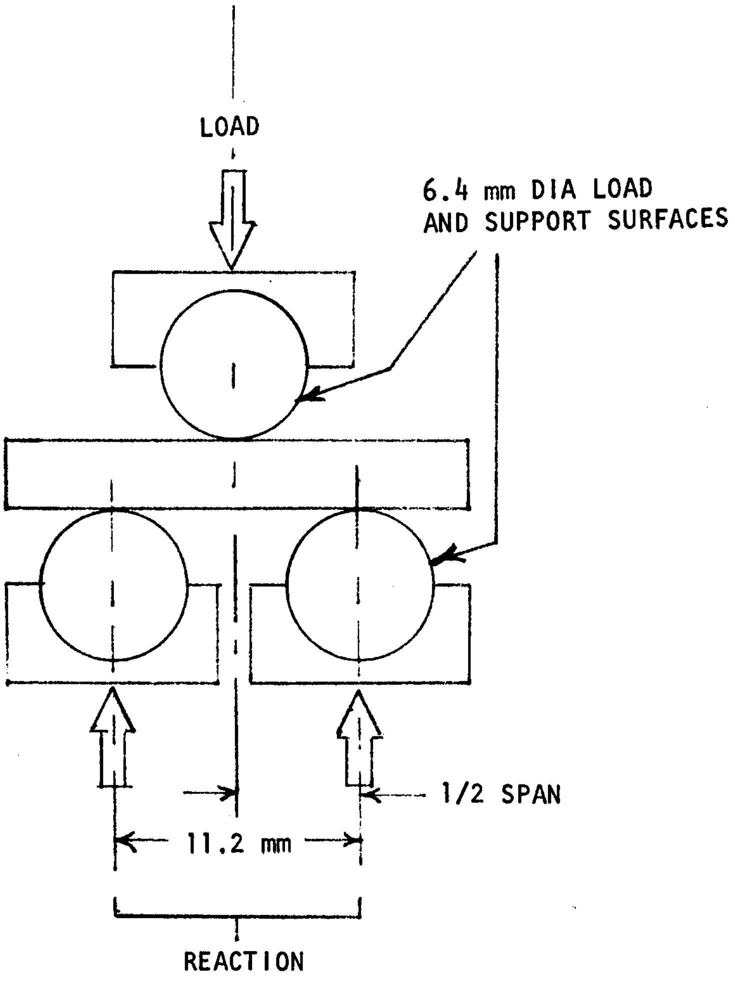

Figure 4.9-2. Short-beam shear test fixture

A820716 C-40C

Figure 4.9-3. Test fixture and setup for short beam shear tests

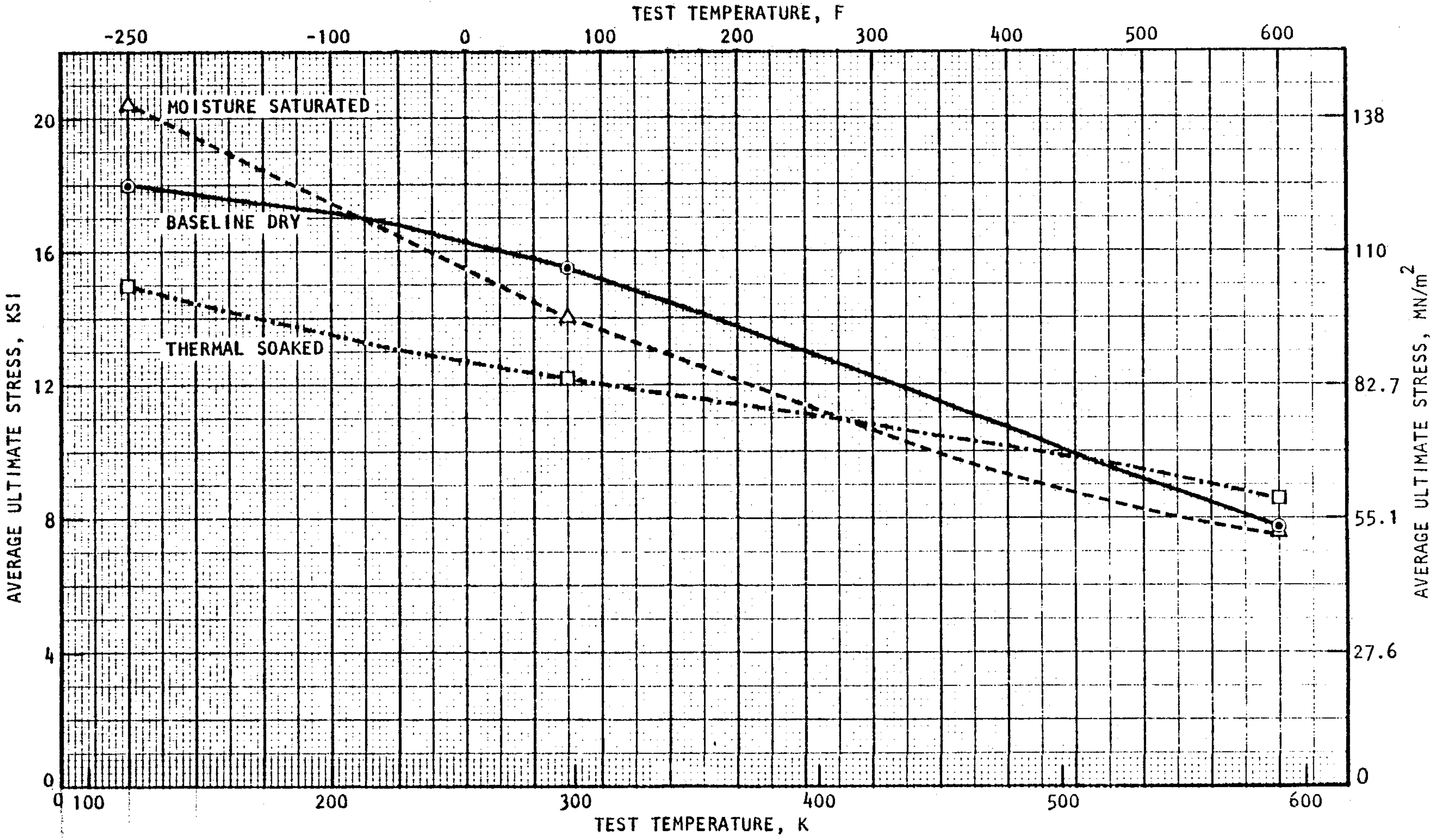

Figure 4.9-4. Short beam shear properties of Celion 6000/LARC-160 laminates

4.10 Data Summary

All Celion 6000/LARC-160 test results are summarized in Table 4.10-1. Where applicable, average values of strength, modulus, strain to failure, and Poisson's ratio are given for each laminate configuration, test temperature, and preconditioning environment.

TABLE 4.10-1. SUMMARY OF CELION 6000/LARC-160 GRAPHITE POLYIMIDE TENSILE, COMPRESSION, IN-PLANE SHEAR, AND SHORT BEAM SHEAR AVERAGE PROPERTIES

		Tension							
		Baseline Dry			Moisture Saturated		Thermal Soaked		
Fiber Orientation	Tensile Property	116 K (-250°F)	RT	589 K (600°F)	RT	589 K (600°F)	116 K (-250°F)	RT	589 K (600°F)
$(0)_8$	F_{tu} MN/m^2	1634	1731	1731					
	(ksi)	(237)	(251)	(251)					
	E_t GN/m^2	142	142	165					
	(msi)	(20.55)	(20.55)	(23.87)					
	ε ult %	1.09	1.15	1.09					
	ν	0.304	0.323	0.292					
$(90)_8$	F_{tu} MN/m^2	47.6	36.6	18.5	33.5	5.4			
	(ksi)	(6.91)	(5.31)	(2.68)	(4.86)	(0.78)			
	E_t GN/m^2	11.5	10.1	6.82	9.3	4.20			
	(msi)	(1.67)	(1.47)	(0.99)	(1.35)	(0.61)			
	ε ult %	0.44	0.38	0.27	0.36	0.15			
	ν	-	0.024	-	-	-			
$(\pm 45)_{2s}$	F_{tu} MN/m^2	138.4	137.9	121.0	156.2	92.3	127.5	116.7	113.2
	(ksi)	(20.07)	(20.0)	(17.55)	(22.65)	(13.39)	(18.50)	(16.93)	(16.42)
	E_t GN/m^2	21.2	19.2	14.3	22.4	13.9	17.9	20.9	11.2
	(msi)	(3.08)	(2.78)	(2.07)	(3.25)	(2.02)	(2.60)	(3.03)	(1.62)
	ε ult %	1.22	1.19	-	-	-	1.78	1.20	-
	ν	0.756	0.776	0.808	-	-	-	-	-
$(0/45/90/-45)_s$	F_{tu} MN/m^2	534	557	559	580	465			
	(ksi)	(77.5)	(80.9)	(81.2)	(84.2)	(67.5)			
	E_t GN/m^2	49.3	51.5	54.2	57.9	51.0			
	(msi)	(7.15)	(7.47)	(7.86)	(8.40)	(7.40)			
	ε ult %	1.09	1.18	1.08	1.01	0.97			
	ν	0.329	0.292	0.339	-	-			

		Compression				
		Baseline Dry			Moisture Saturated	
Fiber Orientation	Compression Property	116 K (-250°F)	RT	589 K (600°F)	RT	589 K (600°F)
$(0)_{16}$	F_{cu} MN/m^2	1757	1241	875		
	(ksi)	(255)	(180)	(127)		
	E_c GN/m^2	116	120	133		
	(msi)	(16.82)	(17.44)	(19.27)		
	ε ult %	2.08	1.03	0.75		
	ν	0.360	0.362	0.329		
$(90)_{16}$	F_{cu} MN/m^2	186	164	99.5	165	58.5
	(ksi)	(26.90)	(23.85)	(14.44)	(23.93)	(8.49)
	E_c GN/m^2	10.8	9.6	7.4		
	(msi)	(1.57)	(1.40)	(1.07)		
	ε ult %	2.25	1.92	1.42		
	ν	0.061	-	0.031		
$(\pm 45)_{4s}$	F_{cu} MN/m^2	195	171	114		
	(ksi)	(28.25)	(24.87)	(16.61)		
	E_c GN/m^2	18.5	15.9	11.7		
	(msi)	(2.69)	(2.31)	(1.70)		
	ε ult %	1.72	1.99	-		
	ν	0.707	0.738	0.806		
$(0/45/90/-45)_{2s}$	F_{cu} MN/m^2	574	568	481	555	238
	(ksi)	(83.29)	(82.49)	(69.84)	(80.51)	(34.46)
	E_c GN/m^2	52.9	46.0	51.0		
	(msi)	(7.67)	(6.68)	(7.39)		
	ε ult %	1.44	1.35	0.93		
	ν	0.327	0.288	0.318		

	In-Plane (Rail) Shear								
Fiber Orientation	$(90)_8$			$(\pm 45)_{2s}$			$(0/45/90/-45)_s$		
Test Temperature	116 K (-250°F)	RT	589 K (600°F)	116 K (-250°F)	RT	589 K (600°F)	116 K (-250°F)	RT	589 K (600°F)
F_{su} MN/m^2	102	78.1	50.0	301	232	176	348	225	203
(ksi)	(14.78)	(11.32)	(7.25)	(43.69)	(33.59)	(25.58)	(50.43)	(32.60)	(29.43)
G GN/m^2	6.21	5.96	4.09	29.6	29.87	34.0	20.0	18.4	21.1
(ksi)	(0.90)	(0.86)	(0.59)	(4.29)	(4.33)	(4.93)	(2.90)	(2.67)	(3.06)
ε ult %	-	-	-	1.35	1.42	2.76	2.40	1.98	1.38

	Short Beam Shear MN/m^2 (ksi)								
	Baseline Dry			Moisture Saturated			Thermal Soaked		
Fiber Orientation	116 K (-250°F)	RT	589 K (600°F)	116 K (-250°F)	RT	589 K (600°F)	116 K (-250°F)	RT	589 K (600°F)
$(0)_{20}$	123 (17.9)	107 (15.5)	52.4 (7.6)	141 (20.4)	96.5 (14.0)	53.8 (7.8)	104 (15.1)	84.1 (12.2)	59.3 (8.6)

5.0 DATA ANALYSIS

The results of this program cannot stand alone with respect to design allowable data, but must be combined with results of related test programs such that the data base can be evaluated statistically and the effects of lot-to-lot material variations can be considered. However, in legitimate preliminary structural design evaluations and/or sophisticated analytical studies in support of advanced designs, materials properties more closely representing design allowables should be used as opposed to simply using strength data averages. Since no single procedure is accepted for preparing preliminary design allowables from a small data sample, this task could not be performed.

Shear modulus values for unidirectional laminates were calculated from the elastic property results of the (±45) tension tests. The relationship used for this calculation was derived from Reference 9 and reads as follows:

$$G_{12} = \frac{E_X}{2(1 + \mu_{xy})}$$

where

G_{12} = longitudinal shear modulus of unidirectional laminates

E_X = average tension and compression elastic modulus of (±45) laminates

μ_{xy} - in-plane Poisson's ratio of (±45) laminates

The calculations yield the following tabulated results:

Test Temperature	Shear Modulus
116 K (-250°F)	5.70 GN/m^2 (0.82 msi)
Room temperature	4.90 GN/m^2 (0.71 msi)
589 K (600°F)	3.50 GN/m^2 (0.51 msi)

The results compare favorably with measured properties for (90) laminates.

6.0 CONCLUSIONS

Results of this program support the following conclusions:

1. Celion 6000/LARC-160 graphite/polyimide is a viable material system for structural applications from 116 K (-250°F) to 589 K (600°F).

2. With state-of-the-art manufacturing and process controls, high quality, flat laminates can be produced.

3. Rail shear strengths of (±45) laminates of graphite/polyimide should not be used for analysis because of the stress riser effects associated with the particular laminate configuration and test method.

4. Moisture saturation results in a significant reduction in elevated temperature strength, elastic modulus and in-plane shear properties for resin dominated laminates.

5. Additional material properties data are required before preliminary design allowables can be established and primary structural applications seriously considered for this material system.

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16. Abstract

A design allowables test program was conducted on Celion 6000/LARC-160 graphite polyimide composite to establish material performance over a 116 K (-250°F) to 589 K (600°F) temperature range.

Tension, compression, in-plane shear and short beam shear properties were determined for uniaxial, quasi-isotropic and ±45° laminates. Effects of thermal aging and moisture saturation on mechanical properties were also evaluated.

Celion 6000/LARC-160 graphite/polyimide can be considered an acceptable material system for structural applications to 589 K (600°F).

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