NASA Technical Paper 1496

Elevated-Temperature Application of the IITRI Compression Test Fixture for Graphite/Polyimide Filamentary Composites

B. Basava Raju, Charles J. Camarda,
and Paul A. Cooper

SEPTEMBER 1979

NASA

NASA Technical Paper 1496

Elevated-Temperature Application of the IITRI Compression Test Fixture for Graphite/Polyimide Filamentary Composites

B. Basava Raju, Charles J. Camarda,
and Paul A. Cooper
Langley Research Center
Hampton, Virginia

National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

1979

SUMMARY

Seventy-nine advanced composite compression specimens, fabricated from HTS-1/PMR-15 and HTS-2/PMR-15 graphite/polyimide material, were tested to investigate experimentally the IITRI test method for determining compressive properties of composite materials at room and elevated temperatures (589 K (600° F)).

Minor modifications were made to the standard IITRI fixture and a high degree of precision was maintained in specimen fabrication and load alignment. Specimens included four symmetric laminate orientations designated as [0], $[0,\pm45,90]_{2S}$, [90], and $[\pm45]_{5S}$. Specimens 0.635, 1.27, 1.91, and 2.54 cm (0.25, 0.5, 0.75, and 1.0 in.) wide were tested to evaluate the effect of width on measured modulus and strength. In most cases three specimens of each width were tested at room and elevated temperature and a polynomial regression analysis was used to reduce the data. Tangent modulus, Poisson's ratio, and compressive ultimate strengths and strains were determined for $[0]_{15}$, $[0]_{16}$, $[90]_{20}$, $[0,\pm45,90]_{2S}$, and $[\pm45]_{5S}$ graphite/polyimide laminates. A statistical analysis of the data is presented to evaluate test scatter and property variation with respect to load, temperature, and specimen geometry.

Scatter of replicate tests and back-to-back strain variations were low, and no specimens failed by instability. Variation of specimen width had a negligible effect on the measured ultimate strengths and initial moduli of the specimens. Measured compressive strength and stiffness values were sufficiently high for the material to be considered a usable structural material at temperatures as high as 589 K (600° F).

INTRODUCTION

The benefits of structural-mass savings with the use of filamentary composite materials in the design of subsonic aircraft are well established. The potential economic gain from structural-mass savings in the design of reentry spacecraft with thermally insulated surfaces and of high-speed aircraft is even greater due to the increased operating costs and weight sensitivity of such vehicles. Graphite/polyimide composite materials have attractive properties for use in elevated-temperature applications and can have reasonable load carrying ability up to 589 K (600° F) (ref. 1), but have yet to be characterized at elevated temperatures sufficiently. The designer, in order to use a material system properly, must have a reliable experimental characterization of the response of the material to various loadings; however, the characterization of composite materials is considerably more complex than of metals because of the heterogeneous and anisotropic nature of composite lamina.

The experimental determination of compressive properties of composites presents unusually severe problems especially at elevated temperatures where fixture/specimen interaction can cause complex stress distributions. A properly designed test procedure for determining compressive allowables should be configured so that compressive loads are introduced without causing specimen end failures and the specimen should be aligned to avoid producing extraneous bending stresses. Instability failure must be avoided without resorting, if possible, to direct support of the test area. Specimens must have practical thicknesses, be inexpensive, and the test results must be repeatable with a minimum of scatter. Furthermore, premature failure due to stress concentrations at end-tab/specimen interfaces must be avoided, and the specimem must be large enough so that the test area is sufficiently removed from the load-introduction region in order that stress gradients be negligible.

There have been numerous attempts to develop a reliable compressive test technique to determine moduli and allowable stresses of composite materials, some of which are merely adaptations of methods used for metallic specimens. A good historical account of compressive test techniques for composites and their associated problems is presented in references 2 to 4. Various specific test techniques ranging from block compression tests of composites to fully supported laminate tests are given in references 5 to 11. Each of these techniques exhibits deficiencies in meeting one or more of the above criteria for acceptable compression allowables testing or are not readily adaptable to elevated-temperature application. The most successful compression technique to date has been the sandwich-beam-flexure method. However, sandwich-beam-flexure specimens are relatively large and expensive and require a large amount of composite material for fabrication. Also, the low adhesive shear strengths at elevated temperature of bonding agents used to join the laminates to the sandwich core often cause premature specimen failure outside the test region. The standard IITRI[1] test fixture (refs. 2 and 3) requires an inexpensive test specimen and has the potential to meet the above criteria for a successful compression allowables test.

The purpose of the present paper is to investigate the application of the IITRI compressive test fixture at elevated temperature (589 K (600° F)) and to present compressive moduli and ultimate strains of HTS/PMR-15 graphite/polyimide material. Considerable care was taken in specimen fabrication to minimize back-to-back strain variations due to specimen bending. The effects of specimen width and temperature were studied for various laminate orientations.

Tangent modulus, Poisson's ratio, and compressive ultimate strengths and strains were determined for $[0]_{15}$, $[0]_{16}$, $[90]_{20}$, $[0,\pm45,90]_{2S}$, and $[\pm45]_{5S}$ graphite/polyimide laminates at both room and elevated temperatures (589 K (600° F)). The effect of specimen width on the material property characterization was studied and a statistical analysis of the data is presented to evaluate test scatter and property variation with respect to load, temperature, and specimen geometry.

Identification of commercial products in this report is used to describe adequately the test materials and instrumentation. The identification of these commercial products does not constitute official endorsement, expressed or implied, of such products by the National Aeronautics and Space Administration.

---

[1] IITRI: Illinois Institute of Technology (IIT) Research Institute.

SYMBOLS

Values are given in both SI and U.S. Customary Units. Measurements and calculations were made in U.S. Customary Units.

$C_0, C_1, C_2, \ldots$	coefficients used in regression analysis (see eq. (1))
E	modulus
e	eccentricity, $e_1 - e_2$ (see fig. 1)
e_1, e_2	see figure 1
n	total number of experimental operations of replicate tests
$S_{\sigma/\varepsilon}$	standard error of estimate
w	width
$\Delta\varepsilon$	incremental strain used to calculate $E_{T,I}$
ε	compressive strain
ε_{ult}	ultimate compressive strain
ν	Poisson's ratio
σ	compressive stress
σ_{ult}	ultimate compressive stress

Subscripts:

I	initial
i	summation index
T	tangent

TEST SPECIMENS, APPARATUS, AND PROCEDURE

Test Specimens

To insure proper load alignment and friction-free elevated-temperature testing, and to qualify the test technique at elevated temperature, five titanium-alloy (Ti-6Al-4V annealed) specimens 0.635 cm (0.25 in.) wide were fabricated with overall and test-region dimensions as shown in figure 1. End tabs were $[0,90]_S$ laminates of 7576/CPI-2237 glass/polyimide[2] material and were bonded to the specimens using FM-34 film adhesive.[3]

Seventy-nine composite specimens were fabricated using four different laminate orientations and two graphite/polyimide (Gr/PI) materials. The test matrix is given in table I. The $[0]_{15}$, $[0]_{16}$, and $[0,\pm45,90]_{2S}$ laminates were made from HTS-1/PMR-15 material and the $[90]_{20}$ and $[\pm45]_{5S}$ laminates were made from HTS-2/PMR-15 material. Specimen blanks 12.3 cm (4.85 in.) long by 8.89 cm (3.5 in.) wide were fabricated (as shown in fig. 1) by bonding end tabs to the GR/PI laminates using FM-34 film adhesive. The end tabs were $[0,90]_S$ laminates of 7576/CPI-2237 glass/polyimide material. Specimens of various widths (0.635, 1.27, 1.91, and 2.54 cm (0.25, 0.5, 0.75, and 1.0 in.)) were cut from the blanks. Preliminary tests indicated that better results were obtained if close tolerances were held on certain specimen dimensions. Thus the parallel end-tab surfaces were ground to within ±0.005 cm (±0.002 in.). The eccentricity e, where $e = e_1 - e_2$ (fig. 1), was maintained to within ±0.008 cm (±0.003 in.), and the parallel ends of the specimen were ground to within ±0.008 cm (±0.003 in.). Cure cycles used to manufacture the Gr/PI specimens and glass/polyimide end tabs are given in the appendix along with the specimen bonding procedures.

Test Apparatus

The test fixture (see fig. 2) consisted of two massive end blocks and two trapezoidal wedge collets which fit in slots machined in the end blocks. The collets grip the specimens and, with the aid of two hardened steel alignment pins, the specimens are aligned with respect to the end blocks. The entire test fixture and the specimen assembly were inserted inside an environmental chamber to prevent thermal gradients throughout the specimen length which could occur using the thin wafer-type heaters suggested in reference 3. Strip heaters (fig. 2) were used to accelerate heating the massive end blocks and thus reduce test time. To minimize thermal deformations, all the components of the compression fixture with the exception of the alignment pins were fabricated from 17-4 PH stainless steel heat-treated to H 1150. The alignment pins were made from AISI C-1060 steel hardened to Rockwell 60C. The trapezoidal wedge collets were modified (fig. 3) to accommodate various width specimens and spacers were used to assure alignment. The wedge collets were bolted together and a support pin was included in each collet (fig. 3) to prevent slippage of the specimen during the load cycle and to support the specimen if the end tabs should shear off or slip at elevated temperatures. Friction-free lateral alignment of the fixture was assured by a guidance system of two parallel roller bushings in the upper half of the fixture into which fit the two hardened alignment pins of the lower half of the fixture (fig. 2). Considerable effort was required to align the fixtures to prevent out-of-plane bending strains. With the faces of the end blocks aligned parallel to within 0.008 cm

---

[2]7576/CPI-2237 glass/polyimide: Manufactured by Ferro Corporation, Composites Division.

[3]FM-34 film adhesive: Manufactured by American Cyanamid Company, Bloomingdale Division.

(0.003 in.), average back-to-back strains of all tests differed by less than 10 percent. Once proper alignment was accomplished, consistent results were obtained from test to test without requiring realignment.

Test Procedure

Checkout tests were performed using the titanium-alloy specimens to develop a test procedure that would insure proper alignment and minimize extraneous frictional forces at both room and elevated temperatures. Also several tests were made at elevated temperature without a specimen installed to assure that the alignment pins, coated with a high-temperature lubricant, did not produce appreciable frictional forces which would cause erroneous measured moduli and ultimate stresses. In most cases, three replicate tests were made for each composite configuration to evaluate the repeatability of the test procedure.

For room-temperature tests the specimen was fixed to the wedge collets by means of clamping screws and alignment was assured by the collet alignment pins. The end support pins were used to prevent slippage and the test specimen was aligned with respect to these pins so that uniform contact was maintained. The clamping screws were tightened with a torque wrench to a uniform clamping pressure of 45.8 MPa (6640 psi) at each end tab. The collets were then placed into the end blocks and an initial load of 222 N (50 lbf) was applied by a 245-kN (55 000-lbf) universal testing machine operating in a displacement control mode at a crosshead speed of 0.117 cm/min (0.046 in/min); strain readings at this load were zeroed out.

For elevated-temperature testing the test fixture was located in an environmental chamber. The specimens were clamped into the wedge collets as described above and were placed in the bottom end block as shown in figure 2, and the specimen test section was allowed to expand freely as the temperature increased. The strip heaters and oven were controlled individually to maintain a uniform temperature for the fixture and specimen. Once the desired temperature was reached and a steady-state condition obtained, the top end block was positioned, an initial load applied, and the apparent thermal strains were zeroed out as before. The remaining procedure was identical to the room-temperature procedure.

INSTRUMENTATION AND DATA ACQUISITION

At least one specimen of each series of replicate tests had a self-temperature-compensating high-temperature strain rosette gage, WK-06-030WR-120 (0.076 cm (0.03 in.) in length), manufactured by Micro-Measurements Division of Vishay Intertechnology, Inc., on one face to obtain Poisson's ratio and a single gage, WK-06-62AP-350 (0.16 cm (0.062 in.) in length) on the opposite face to monitor out-of-plane bending strains during testing to define proper load alignment. All other specimens had back-to-back single strain gages. No attempts were made to quantify either the strain variation across the width of a specimen or how such variation may be affected by specimen dimensions. However, specimens instrumented with rosette gages indicated that shear strains were negligible. Each elevated-temperature specimen had a chromel/alumel thermocouple bonded in the test region of the specimen. This test-region thermocouple, and thermocouples bonded to the collets (fig. 3) and grips (fig. 2), together with a temperature sensor were used to measure the uniformity of temperature during heating and determine when a steady-state thermal environment was reached. Both the strain gages and thermocouples were bonded using a polyimide adhesive (either M-Bond 610 or PLD-700 available from Micro-Measurements and BLH Electronics, respectively).

A data handling system consisting of a 40-channel scanner, digital voltmeter, plotter, printer, clock, and calculator was used to record and reduce data. Load signals from the load cell were connected to one channel of the scanner. Strain signals from the self-temperature-compensating gages were initially balanced by a Wheatstone bridge balance and during the test were input to selected scanner channels. Thermocouples mounted on the collets and specimen were monitored on a strip chart recorder and were connected to the scanner through a 273 K (32° F) cold-junction reference.

Strains, temperatures, and load were scanned and recorded every 1 to 3 sec and a stress/strain curve was plotted in real time. Quantities were stored in volts and engineering units on magnetic tape and printed during each test. After each series of replicate tests was completed, a data reduction program averaged the longitudinal strains in the back-to-back gages of individual tests and used a regression analysis to determine the coefficients of a best fit for all tests in the series in the least-squares sense of a third-order polynomial relating stress and strain according to the equation:

$$\sigma = C_0 + C_1\varepsilon + C_2\varepsilon^2 + C_3\varepsilon^3 \qquad (1)$$

The third-order curve in most cases produced a good fit of data. Two methods were used to calculate the tangent modulus:

Method 1: The polynomial was differentiated.

Method 2: An incremental strain ($\Delta\varepsilon$) region was chosen over which average results of the tests were fitted by means of least-squares using a straight-line fit. The tangent modulus in each $\Delta\varepsilon$ region was the slope of each particular straight line. Higher order polynomial curve-fit equations were investigated but, in general, produced oscillatory curves of tangent modulus plotted against strain upon differentiation.

The coefficients of the regression equation are found by solution of the following matrix equations:

$$\begin{bmatrix} \sum_i \sigma_i \\ \sum_i \varepsilon_i\sigma_i \\ \sum_i \varepsilon_i{}^2\sigma_i \\ \sum_i \varepsilon_i{}^3\sigma_i \end{bmatrix} = \begin{bmatrix} n & \sum_i \varepsilon_i & \sum_i \varepsilon_i{}^2 & \sum_i \varepsilon_i{}^3 \\ \sum_i \varepsilon_i & \sum_i \varepsilon_i{}^2 & \sum_i \varepsilon_i{}^3 & \sum_i \varepsilon_i{}^4 \\ \sum_i \varepsilon_i{}^2 & \sum_i \varepsilon_i{}^3 & \sum_i \varepsilon_i{}^4 & \sum_i \varepsilon_i{}^5 \\ \sum_i \varepsilon_i{}^3 & \sum_i \varepsilon_i{}^4 & \sum_i \varepsilon_i{}^5 & \sum_i \varepsilon_i{}^6 \end{bmatrix} \begin{bmatrix} C_0 \\ C_1 \\ C_2 \\ C_3 \end{bmatrix} \tag{2}$$

where the symbol $\sum_i$ implies summation from 1 to n and n is the total number of points recorded during a series of replicate tests for a given test configuration.

To assess the magnitude of scatter of experimental points about the regression equation, the standard error of estimate $S_{\sigma/\varepsilon}$, which is a measure of the mean deviation of the sample points from the regression line, is determined as follows:

$$S_{\sigma/\varepsilon} = \left(\frac{\sum_i \sigma_i{}^2 - C_0 \sum_i \sigma_i - C_1 \sum_i \varepsilon_i\sigma_i - C_2 \sum_i \varepsilon_i{}^2\sigma_i - C_3 \sum_i \varepsilon_i{}^3\sigma_i}{n - 4} \right)^{1/2} \tag{3}$$

RESULTS AND DISCUSSION

Reproducibility of Test Method

Results of five preliminary checkout tests at room and elevated temperatures using titanium-alloy specimens are presented in table II. Room-temperature values of modulus agree well with those of reference 12, and the elevated-temperature values differ from those of reference 12 by only 10 percent. This indicates that extraneous frictional loads at elevated temperature were minimal. Back-to-back strain variations were below 10 percent indicating proper alignment and minimal out-of-plane specimen bending.

The reproducibility, minimal bending, and agreement with published material data (ref. 12) established confidence in the application of the test method for testing to 589 K (600° F). However, the possibility of free-edge effects in composite specimens, end-tab effects, and end constraints could affect the nature of stress distributions in the test section and could lead to conservative values for ultimate compressive stresses.

Stress and tangent modulus as functions of strain for the various composite laminations are presented in figures 4 to 12. Table III lists the coefficients of the regression equation used in the reduction of the experimental data and the standard error of estimate $S_{\sigma/\epsilon}$. The description of the geometry and test conditions of the individual specimens and tabulated results of ultimate stress and strain, Poisson's ratio, and modulus at 0.2-percent strain for individual tests are presented in tables IV to VII. The dots in the stress plots of figures 6 to 12 represent experimental data points of all replicate tests; the solid line is the best fit third-order polynomial obtained from the regression analysis. The tangent-modulus curves of figures 5 to 12 were plotted using method 1 and the X-symbols in those figures are results obtained by method 2.

The Gr/PI specimens exhibited good alignment as shown by the low variation in back-to-back strain readings in figure 4. At 0.2-percent strain, tables IV to VII indicate an average variation in back-to-back strains of 8 percent for all tests. The precise methods used in fabricating the specimens and aligning the test fixture minimized specimen bending and variation in back-to-back strain values for even the lowest-modulus specimens tested. The highest values of $S_{\sigma/\epsilon}$ in table III were for the 0.635-cm (0.25-in.) width [0] laminates. Results of three individual 1.27-cm (0.5-in.) wide [0] specimens and average values of back-to-back strains shown in figure 5 indicate the high degree of repeatability of test data and validity of presenting average curves for replicate tests using method 1. The two methods used for predicting tangent modulus/strain results were in good agreement as shown in figures 5 to 12.

Effect of Specimen Width

The effects of variation in specimen width on the measured ultimate compressive strength and initial tangent modulus are shown in figures 13 to 16. Specimen width had only a small effect on measured average material properties; variation in the measured ultimate strength for the various specimen widths was of the same order as the magnitude of scatter of replicate tests. The measured ultimate strength of all specimens wider than 0.635 cm (0.25 in.), with the exception of the $[\pm 45]_{5S}$ specimens, tends to decrease slightly as width increases; the $[\pm 45]_{5S}$ laminate shows the opposite tendency. Specimen widths greater than 2.54 cm (1.0 in.) wide give a test-section aspect ratio greater than 2 and thus are probably not practical since plate effects across the specimen are likely to dominate the specimen behavior.

Material Behavior

The Gr/PI material showed consistent behavior throughout the test program. Measured compressive strengths and stiffnesses were sufficiently high for the material to be considered usable in compression at temperatures as high as 589 K (600° F). Some changes in failure modes were noted between the tests at room and elevated temperature but changes in specimen width did not affect the failure modes of any of the laminations tested.

The unidirectional laminate orientation.- An interesting feature of unidirectional HTS-1/PMR-15 material (fig. 13) is that measured average modulus values at 0.2-percent strain of approximately 134 GPa (19.5×10^6 psi) at 589 K (600° F) were 15 percent higher than room-temperature values. Although this increase in stiffness at elevated temperatures is unexpected, it was not caused by extraneous frictional loads and was repeatable. Also, the room-temperature results agree closely with those obtained in reference 4 using the sandwich-beam-flexure test method. Additional tests at elevated temperature using the sandwich beam would be helpful in verifying this phenomenon. Although the tangent modulus increased, the ultimate compressive strengths decreased by approximately 45 percent with increase in temperature. The room-temperature ultimate compressive stresses obtained in the present study are approximately 30 percent lower than those obtained in reference 4. Average ultimate strains for the [0] laminate were 0.0094 at room temperature and were similar to those of reference 4. The strain to failure decreased considerably at elevated temperature.

The unidirectional specimens exhibited a nonlinear behavior at room temperature (as was stated in ref. 4) as shown by the tangent-modulus curve in figure 5. The tangent modulus decreases by over 30 percent before failure occurs. However, at elevated temperatures the tangent modulus decreased by less than 15 percent before failure (fig. 6). Because of the nonlinear material behavior of the composite, design compression moduli should be based on operating stress or strain levels and not on initial values.

Most of the [0] specimens failed in the unsupported test region near the tab. The fractured surface in the majority of cases was almost at right angles to the direction of load as shown in figure 17(a) indicating shear failure through the fibers and matrix as described in reference 13. In some cases, however, the fractured surface was inclined at an angle as shown in figure 17(b). Both types of failures were noted in reference 11.

The $[0,\pm45,90]_{2S}$ laminate orientation.- Results of the quasi-isotropic specimens are presented in figures 7, 8, and 14 and in table V. Curves of tangent modulus plotted against strain (figs. 7 and 8) indicate nonlinear behavior in the stress/strain relationship and an average $E_{\epsilon=0.002}$ of approximately 45 GPa (6.5×10^6 psi) at room temperature and 41 GPa (6×10^6 psi) at the elevated temperature. Measured ultimate strengths at elevated temperature decreased approximately 20 percent from room-temperature values of 0.38 GPa (0.055×10^6 psi). Average ultimate room-temperature strains were 0.0093 and were reduced 24 percent at the elevated temperature.

Specimens of this lamination failed in the center at both room and elevated temperatures as shown in figure 18. It appears that some delamination occurs in the middle of the specimen and the lamina fail at various angles along the fiber direction by matrix cracking.

The $[\pm45]_{5S}$ laminate orientation.- The notable feature of the $[\pm45]_{5S}$ laminate is that it exhibits highly nonlinear properties as evidenced by the stress and tangent-modulus curves of figures 9 and 10. An approximate room-temperature tangent modulus at 0.2-percent strain is 15 GPa (2.2×10^6 psi) but approaches zero at a strain of 0.018. Values of ultimate stress and strain and Poisson's ratio are listed in table VI. The initial modulus and strength at 589 K (600° F) are lower than room-temperature values by 57 and 53 percent, respectively, as shown in figure 16.

Most of the room-temperature test specimens failed near the tab region by delamination in the upper two layers as shown in figure 19(a). Elevated-temperature test specimens failed by cracks which extended from the center of the specimen to a region near the tabs as shown in figure 19(b). Each of the plies failed along the fiber length by matrix cracking similar to the $[0,\pm45,90]_{2S}$ laminate.

The [90] laminate orientation.- Compressive properties of the [90] laminate are shown in figures 11, 12, and 15 and listed in table VII. Initial-modulus values were low (8.3 GPa (1.2×10^6 psi)) and dropped to 5.2 GPa (0.75×10^6 psi) at 589 K (600° F). Ultimate strengths of this laminate were higher than those of the $[\pm45]_{5S}$ laminate and dropped from 193 MPa (0.028×10^6 psi) at room temperature to 69 MPa (0.01×10^6 psi) at 589 K (600° F). Results of stress and tangent modulus as functious of strain indicate that the [90] laminate, although matrix controlled, did not exhibit a behavior as nonlinear as the $[\pm45]_{5S}$ laminate. As expected the [90] laminate exhibited the highest strain to failure, approximately 0.029 at room temperature.

As shown in figure 20, failures were near the center of the test specimen inclined at an angle to the plane of the specimen through the thickness. Failure surfaces angled from the center of the specimen toward the tabs.

CONCLUDING REMARKS

A total of 79 graphite/polyimide composite and 5 titanium compression coupon specimens were tested to investigate the application of the IITRI test method to determine at room and elevated temperatures (589 K (600° F)) the compressive properties of high-strength filamentary composite material. The tests were also used to assess the stiffness and ultimate strength of high-temperature graphite/polyimide (HTS/PMR-15) laminates at room and elevated temperatures. Titanium-alloy (Ti-6Al-4V annealed) specimens were used to check testing procedures. Various filament and matrix-controlled laminates with specimen widths ranging from 0.635 to 2.54 cm (0.25 to 1.0 in.) were tested to evaluate laminate behavior and effect of width and temperature on measured ultimate strength and modulus.

The IITRI test fixture was modified to allow specimen width variations and to prevent specimen slippage. To eliminate thermal gradients in the specimen, elevated-temperature tests were conducted in an environmental chamber and strip heaters were used to accelerate heating of the test fixtures. A high degree of precision in specimen fabrication and load alignment prevented instability failures and minimized out-of-plane specimen bending of even the lowest-modulus laminates tested, as evidenced by an average variation in longitudinal back-to-back strain readings of only 8 percent. Close tolerances maintained in specimen fabrication and in the test fixture set-up resulted in low scatter in experimental data.

Variation in specimen width had a negligible effect on the measured ultimate strengths and initial moduli of specimens. Variation in the measured ultimate strength for various specimen widths was of the same order as the magnitude of scatter of replicate tests. Specimen strengths of all laminations decreased with temperature, as did modulus, with the exception of the unidirectional laminate which experienced an increase in modulus of approximately 15 percent at elevated temperatures.

Measured compressive static strength and stiffness values were sufficiently high for the material to be considered as a usable structural material at temperatures as high as 589 K (600° F).

The IITRI test method appears to be a viable means for obtaining modulus and Poisson's ratio data of composite materials up to 589 K (600° F); however, the possibility of free-edge effects, tab effects, and end constraints could introduce stress concentrations in the test section leading to conservative values for ultimate compressive stresses.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
July 30, 1979

APPENDIX

FABRICATION PROCEDURES

Laminate Fabrication and Cure Cycle

Laminates of HTS-1/PMR-15 and HTS-2/PMR-15 material were B-staged by pulling a vacuum of 34 kPa (10 in. of Hg) and holding a temperature of 483 K (410° F) for 2 hr. The vacuum pressure was maintained and the laminate was cooled to 339 K (150° F) after which the vacuum was released and the laminate allowed to cool to room temperature. Following B-staging the laminates were vacuum bagged and subjected to a vacuum of 105.2 kPa (28 in. of Hg) which was maintained throughout the cure cycle. An initial external pressure of 1.03 MPa (150 psi) was applied to the bagged laminate during which the temperature was raised to 522 K (480° F) at a rate of 1.7 K/min (3° F/min). The external pressure was then increased to 1.72 MPa (250 psi) and held for 30 min. After 30 min the temperature was raised to 603 K (625° F) and held for 3 hr. The laminate was cooled, under combined vacuum and pressure, at a rate of 2.8 K/min (5° F/min) to 339 K (150° F). The vacuum and pressure were released and the laminate allowed to cool to room temperature. All HTS-1/PMR-15 laminates were fabricated in an autoclave and all HTS-2/PMR-15 laminates were fabricated in a press. The 7576/CPI-2237 glass/polyimide end tabs were fabricated in an autoclave using the same procedure described above. All test panels were ultrasonically scanned for defects after fabrication. Typical results of a $[\pm 45]_{5S}$ Gr/PI laminate at 20 and 15 Hz are shown in figure 21. For quality assurance all laminates were scanned at frequencies from 80 to 20 Hz. Below 20 Hz cross-ply laminations become visible as shown in figure 21.

Specimen Fabrication

Specimen blanks 12.3 cm (4.85 in.) long and 8.89 cm (3.5 in.) wide and end tabs were primed and assembled with FM-34 film adhesive in a bonding fixture and enclosed in a vacuum bag. The assembly was positioned on the press platen which contained heating elements, a vacuum (105.2 kPa (28 in. of Hg)) was drawn, and the press was closed to contact the specimen with minimal pressure to allow uniform heating. The specimen was heated to 405 K (270° F) at which point a pressure of 0.689 MPa (100 psi) was applied. The temperature was then raised to 450 K (350° F) and was held under pressure for 2 hr. The temperature was then increased to 589 K (600° F) at the same pressure and held for 2 hr and then the specimen was allowed to cool for 2 hr in the platens. The platens were water cooled until the specimen reached room temperature at which point the pressure was released.

REFERENCES

1. Davis, John G., Jr.: Composites for Advanced Space Transportation Systems - CASTS. NASA TM-80038, 1978.

2. Hofer, K. E., Jr.; and Rao, P. N.: A New Static Compression Fixture for Advanced Composite Materials. J. Test. & Eval., vol. 5, no. 4, July 1977, pp. 278-283.

3. Hofer, Kenneth E.; Rao, P. N.; and Humphrey, V. E.: Development of Engineering Data on the Mechanical and Physical Properties of Advanced Composites Materials. AFML-TR-72-205, Part I, U.S. Air Force, Sept. 1972. (Available from NTIS as AD 757 524.)

4. Shuart, Mark J.; and Herakovich, Carl T.: An Evaluation of the Sandwich Beam in Four-Point Bending as a Compressive Test Method for Composites. NASA TM-78783, 1978.

5. Verette, R. M.: Temperature/Humidity Effects on the Strength of Graphite/ Epoxy Laminates. AIAA Paper No. 75-1011, Aug. 1975.

6. Ho, Tzu-Li: A Compressive Test Method for Composites. Materials Review '75, Volume 7 of the National SAMPE Technical Conference Series, Soc. Advance. Mater. & Process Eng., 1975, pp. 295-305.

7. Ewins, P. D.: A Compressive Test Specimen for Unidirectional Carbon Fibre Reinforced Plastics. C.P. No. 1132, British A.R.C., 1970.

8. Purslow, D.; and Collings, T. A.: A Test Specimen for the Compressive Strength and Modulus of Unidirectional Carbon Fibre Reinforced Plastic Laminates. British R.A.E., Tech. Rep. 72096, June 1972.

9. Collings, T. A.: Transverse Compressive Behaviour of Unidirectional Carbon Fibre Reinforced Plastics. British R.A.E., Tech. Rep. 72237, Feb. 1973.

10. Collings, T. A.: Transverse Compressive Behaviour of Unidirectional Carbon Fibre Reinforced Plastics. Composites, vol. 5, no. 3, May 1974, pp. 108-116.

11. Ryder, J. T.; and Black, E. D.: Compression Testing of Large Gage Length Composite Coupons. Composite Materials: Testing and Design (Fourth Conf.), ASTM STP 617, 1977, pp. 170-189.

12. Metallic Materials and Elements for Aerospace Vehicle Structures. MIL-HDBK-5A, U.S. Dep. Def., Feb. 8, 1966. (Supersedes MIL-HDBK-5.)

13. Ewins, R. D.; and Ham, A. C.: The Nature of Compressive Failure in Unidirectional Carbon Fibre Reinforced Plastics. Tech. Rep. 73057, British R.A.E., 1973.

TABLE I.- TEST MATRIX

Temperature	Lamination (a)	Number of specimens at width of -			
		0.635 cm (0.25 in.)	1.27 cm (0.5 in.)	1.91 cm (0.75 in.)	2.54 cm (1.0 in.)
Room	$[0]_{15}$	4	4	---	---
589 K (600° F)		4	3	---	---
Room	$[0]_{16}$			3	3
589 K (600° F)		---	---	1	3
Room	$[0,\pm45,90]_{2S}$	3	3	3	3
589 K (600° F)		---	4	2	3
Room	$[\pm45]_{5S}$	3	3	3	3
589 K (600° F)		1	2	1	3
Room	$[90]_{20}$	---	2	3	3
589 K (600° F)		---	---	3	3

[a]The $[0]_{15}$, $[0]_{16}$, and $[0,\pm45,90]_{2S}$ laminates are HTS-1/PMR-15 material and the $[\pm45]_{5S}$ and $[90]_{20}$ laminates are HTS-2/PMR-15 material.

TABLE II.- COMPRESSIVE MODULUS OF TITANIUM-ALLOY (Ti-6Al-4V ANNEALED) SPECIMENS

Test specimen	Thickness, cm (in.)	Width, cm (in.)	Temperature, K (°F)	$E_{\varepsilon=0.002}$, GPa (psi)	Average $E_{\varepsilon=0.002}$, GPa (psi)	$\left(\frac{\Delta\varepsilon}{\varepsilon}\right)_{\varepsilon=0.002}$	E, GPa (psi) (ref. 12)
1	0.206 (0.081)	1.25 (0.50)	299 (78.5)	119 (17.3×10^6)	119 (17.3×10^6)	0.08	113 (16.4×10^6)
2	.206 (.081)	1.25 (.50)	299 (78.5)	119 (17.3×10^6)		.09	
3	.206 (.081)	1.25 (.50)	299 (78.5)	119 (17.3×10^6)		.06	
4	0.206 (0.081)	1.25 (0.50)	600 (620.3)	105 (15.2×10^6)	104 (15.1×10^6)	0.03	93 (13.5×10^6)
5	.206 (.081)	1.25 (.50)	600 (620.3)	103 (19.9×10^6)		.03	

TABLE III.- COEFFICIENTS OF POLYNOMIALS USED TO CURVE-FIT DATA

$$[\sigma = c_0 + c_1\varepsilon + c_2\varepsilon^2 + c_3\varepsilon^3]$$

Test	c_0	c_1	c_2	c_3	$S_{\sigma/\varepsilon}$	
					MPa	psi
6 to 9	-4.281963E+2	1.738076E+7	-4.307440E+8	3.484513E+9	17.09	2478
10 to 13	-1.752013E+1	1.945599E+7	5.537667E+8	-2.177505E+11	14.95	2169
14 to 17	-3.311728E+2	1.795999E+7	-2.910428E+8	-7.275017E+9	3.52	510
18, 19	1.068052E+2	2.088699E+7	2.909110E+8	-1.023671E+11	5.56	807
21 to 23	-6.929880E+2	1.832626E+7	-3.274367E+8	-4.228268E+8	14.31	2075
24	-1.519817E+1	1.770148E+7	1.886626E+8	-5.963078E+10	2.50	362
25 to 27	-1.541524E+2	1.904401E+7	-3.219846E+8	-1.227038E+10	2.79	405
28 to 30	-5.417422E+1	1.803240E+7	7.826432E+8	-2.082399E+11	5.71	828
31 to 33	-3.883396E+2	7.165562E+6	-1.573699E+8	-1.058449E+8	3.13	454
34 to 36	-7.529958E+1	6.830120E+6	-7.166822E+7	-6.308054E+9	7.05	1022
37 to 40	-2.400372E+1	5.980138E+6	8.474296E+7	-2.332710E+10	5.52	801
41 to 43	-1.173011E+2	6.937188E+6	4.146706E+7	-1.217526E+10	6.02	873
44, 45	3.256175E+1	5.981659E+6	4.090571E+8	-6.954411E+10	10.45	1516
46 to 48	7.657509E+1	5.440791E+6	2.653141E+8	-3.373712E+10	10.51	1524
49 to 51	1.869539E+1	6.658674E+6	8.039340E+7	-2.217091E+10	3.56	517
52, 53	-8.473282E+1	1.320650E+6	-9.564260E+6	-2.867886E+7	2.75	399
54 to 56	-1.392896E+2	1.344902E+6	-1.778584E+7	2.212936E+8	.59	86
57 to 59	-1.526878E+2	9.158846E+5	-2.003001E+7	-1.094170E+8	3.30	479
60 to 62	-1.674997E+2	1.363774E+6	-1.744204E+7	1.545318E+8	1.92	279
63 to 65	-1.667344E+2	1.029645E+6	-2.689743E+7	1.268461E+8	2.34	339
66 to 68	-2.993084E+2	2.963036E+6	-1.563618E+8	2.432429E+9	4.02	583
69 to 71	-3.493869E+2	2.726213E+6	-1.321916E+8	2.098299E+9	1.83	265
72 to 74	-2.106709E+2	2.554613E+6	-1.045894E+8	1.425384E+9	2.60	377
75 to 77	-3.088755E+2	2.925618E+6	-1.185348E+8	1.598303E+9	1.79	259
78	-1.107024E+2	8.224594E+5	-4.555997E+7	1.047674E+9	1.02	148
79, 80	4.268581E+1	1.076469E+6	-4.711192E+7	5.061644E+8	5.13	744
81	-1.362988E+1	8.776588E+5	-5.313026E+7	1.396668E+9	.42	61
82 to 84	1.363565E+2	1.398009E+6	-8.907387E+7	2.135569E+9	8.46	1227

TABLE IV.- COMPRESSIVE PROPERTIES OF UNIDIRECTIONAL HTS-1/PMR-15 SPECIMENS

(a) SI Units

Test	Number of plies	Laminate thickness, cm	Width, cm	Temperature, K	σ_{ult}, MPa	Average σ_{ult}, MPa	ε_{ult}	Average ε_{ult}	$E_{\varepsilon=0.002}$, GPa	Average $E_{\varepsilon=0.002}$, GPa	$\left(\frac{\Delta\varepsilon}{\varepsilon}\right)_{\varepsilon=0.002}$	ν_I
6	15	0.282	0.635	292	981		0.0118		107.3		0.03	
7	15	.282	.635	292	1086	951	.0125	0.0106	108	109.3	.03	
8	15	.282	.635	282	809		.0082		112.6		.16	
9	15	.287	.635	291	927		.00991					0.346
10	15	.279	.635	589	485		.00363		133.5		.15	
11	15	.279	.635	589	361	413	.0028	.00286	118	137.6	0	
12	15	.279	.635	589	403		.00258		145		.18	.33
13	15	.279	.635	589	403		.00243		154		.13	
14	15	.272	1.27	291	961		.00971		117		.03	
15	15	.282	1.27	291	1037	972	.01067	.00991	119	116	.01	.521
16	15	.282	1.27	291	951		.01003		113		.07	.368
17	15	.279	1.27	291	940		.00923		115		0	
18	15	.282	1.27	589	603		.00427		151		.03	
19	15	.279	1.27	589	603	611	.00434	.00455	139	142	.09	
20	15	.279	1.27	589	627		.00505		135		.02	.315
21	16	.287	1.91	292	958		.009256		122		.09	
22	16	.287	1.91	292	923	880	.008544	.008355	123	120	.06	
23	16	.287	1.91	292	758		.007265		116		.08	.371
24	16	.287	1.91	589	492		.00398		122	122	.06	
25	16	.287	2.54	292	896		.00848		123		.12	
26	16	.287	2.54	292	792	818	.007897	.00795	119	121	.02	
27	16	.287	2.54	292	765		.007485		121		0	.345
28	16	.287	2.54	589	500		.003933		125		.11	
29	16	.287	2.54	589	497	468	.004133	.0027	124	127	.09	
30	16	.287	2.54	589	408		.0032		131		.07	

TABLE IV.- Concluded

(b) U.S. Customary Units

Test	Number of plies	Laminate thickness, in.	Width, in.	Temperature, °F	σ_{ult}, psi	Average σ_{ult}, psi	ϵ_{ult}	Average ϵ_{ult}	$E_{\epsilon=0.002}$, psi	Average $E_{\epsilon=0.002}$, psi	$\left(\frac{\Delta\epsilon}{\epsilon}\right)_{\epsilon=0.002}$	ν_I
6	15	0.111	0.25	66	0.1423 × 10^6		0.0118		15.6 × 10^6		0.03	
7	15	.111	.25	66	.1575	0.1379 × 10^6	.0125	0.0106	15.7	15.9 × 10^6	.03	
8	15	.111	.25	48	.1173		.0082		16.3		.16	
9	15	.113	.25	64	.1344		.00991					0.346
10	15	.110	.25	600	.0703		.00363		19.4		.15	
11	15	.110	.25	600	.0524	.0599	.0028	.00286	17.1	20.0	0	
12	15	.110	.25	600	.0584		.00258		21.0		.18	.33
13	15	.110	.25	600	.0584		.00243		22.3		.13	
14	15	.107	.50	64	.1394		.00971		17.0		.03	
15	15	.111	.50	64	.1504	.1410	.01067	.00991	17.2	16.8	.01	.521
16	15	.111	.50	64	.1379		.01003		16.4		.07	.368
17	15	.110	.50	64	.1363		.00923		16.7		0	
18	15	.111	.50	600	.0875		.00427		21.9		.03	
19	15	.110	.50	600	.0875	.0886	.00434	.00455	20.1	20.6	.09	
20	15	.110	.50	600	.0909		.00505		19.6		.02	.315
21	16	.113	.50	66	.1389		.009256		17.7		.09	
22	16	.113	.75	66	.1339	.1276	.008544	.008355	17.8	17.4	.06	
23	16	.113	.75	66	.1099		.007265		16.8		.08	.371
24	16	.113	.75	600	.0714		.00398		17.7	17.7	.06	
25	16	.113	1.00	66	.1300		.00848		17.8		.12	
26	16	.113	1.00	66	.1149	.1186	.007897	.00795	17.2	17.5	.02	
27	16	.113	1.00	66	.1110		.007485		17.5		0	.345
28	16	.113	1.00	600	.0725		.003933		18.1		.11	
29	16	.113	1.00	600	.0721	.0679	.004133	.0027	18.0	18.4	.09	
30	16	.113	1.00	600	.0592		.0032		19.0		.07	

TABLE V.- COMPRESSIVE PROPERTIES OF $[0,\pm 45,90]_{2S}$; HTS-1/PMR-15 SPECIMENS

(a) SI Units

Test	Number of plies	Laminate thickness, cm	Width, cm	Temperature, K	σ_{ult}, MPa	Average σ_{ult}, MPa	ϵ_{ult}	Average ϵ_{ult}	$E_{\epsilon=0.002}$, GPa	Average $E_{\epsilon=0.002}$, GPa	$\left(\frac{\Delta\epsilon}{\epsilon}\right)_{\epsilon=0.002}$	ν_I
31	16	0.269	0.635	294	430		0.0117		44.3		0.09	
32	16	.269	.635	294	370	420	.00974	0.001	45.7	45.1	.11	
33	16	.269	.635	294	460		.00863		45.2		.10	0.204
34	16	.269	1.27	294	360		.00887					
35	16	.269	1.27	294	320	350	.00867	.00877		42.5		.293
36	16	.269	1.27	294	370				42.5		.2	
37	16	.269	1.27	589	300		.0065		47.5		.2	
38	16	.269	1.27	589	300	293		.0065		42.1		.317
39	16	.269	1.27	589	270				41.3		.06	
40	16	.269	1.27	589	300				37.6		.04	.338
41	16	.269	1.91	293	380				49.6		.06	
42	16	.269	1.91	293	270	347		.00856	47.7	49.9	.02	.367
43	16	.269	1.91	293	390		.00856		52.4		.01	.324
44	16	.269	1.91	589	300	300	.0069	.00768	48.9	49.6	.07	
45	16	.269	1.91	589	300		.00846		50.2		.07	.271
46	16	.269	2.54	293	330		.01		53.3		.03	
47	16	.269	2.54	293	340	347	.00846	.00923	44.2	47.4	.07	
48	16	.269	2.54	293	370				44.8		.05	.309
49	16	.269	2.54	589	300				49.4		.17	
50	16	.269	2.54	589	310	307	.00657	.00678	45.5	47.3	.14	
51	16	.269	2.54	589	310		.00699		47.1		.09	.328

TABLE V.- Concluded

(b) U.S. Customary Units

Test	Number of plies	Laminate thickness, in.	Width, in.	Temperature, ^{o}F	σ_{ult}, psi	Average σ_{ult}, psi	ε_{ult}	Average ε_{ult}	$E_{\varepsilon=0.002}$, psi	Average $E_{\varepsilon=0.002}$, psi	$\left(\frac{\Delta\varepsilon}{\varepsilon}\right)_{\varepsilon=0.002}$	ν_I
31	16	0.105	0.25	70	0.0624×10^6		0.0117		6.4×10^6		0.09	
32	16	.105	.25	70	.0537	0.0609×10^6	.00974	0.001	6.6	6.5×10^6	.11	
33	16	.105	.25	70	.0667		.00863		6.6		.10	0.204
34	16	.105	.50	70	.0522		.00887					
35	16	.105	.50	70	.0464	.0508	.00867	.00877		6.2		.293
36	16	.105	.50	70	.0537				6.2		.2	
37	16	.105	.50	600	.0435		.0065		6.9		.2	
38	16	.105	.50	600	.0435	.0425		.0065		6.1		.317
39	16	.105	.50	600	.0392				6.0		.06	
40	16	.105	.50	600	.0435				5.5		.04	.338
41	16	.105	.75	68	.0551				7.2		.06	
42	16	.105	.75	68	.0392	.0503		.00856	6.9	7.2	.02	.367
43	16	.105	.75	68	.0566		.00856		7.6		.01	.324
44	16	.105	.75	600	.0435	.0435	.0069	.00768	7.1	7.2	.07	
45	16	.105	.75	600	.0435		.00846		7.3		.07	.271
46	16	.105	1.00	68	.0479		.01		7.7		.03	
47	16	.105	1.00	68	.0493	.0503	.00846	.00923	6.4	6.9	.07	
48	16	.105	1.00	68	.0537				6.5		.05	.309
49	16	.105	1.00	600	.0435				7.2		.17	
50	16	.105	1.00	600	.0450	.0445	.00657	.00678	6.6	6.9	.14	
51	16	.105	1.00	600	.0450		.00699		6.8		.09	.328

TABLE VI.- COMPRESSIVE PROPERTIES OF $[\pm 45]_{5S}$; HTS-2/PMR-15 SPECIMENS

(a) SI Units

Test	Number of plies	Laminate thickness, cm	Width, cm	Temperature, K	σ_{ult}, MPa	Average σ_{ult}, MPa	ε_{ult}	Average ε_{ult}	$E_{\varepsilon=0.002}$, GPa	Average $E_{\varepsilon=0.002}$, GPa	$\left(\frac{\Delta\varepsilon}{\varepsilon}\right)_{\varepsilon=0.002}$	ν_I
66	20	0.381	0.635	290	116		0.0132		15.8		0.08	
67	20	.381	.635	290	110	112	.0102	0.0126	16.1	16.1	.07	
68	20	.381	.635	290	109		.0144		16.4		.04	0.0462
78	20	.381	.635	589	48.3	48.3						
69	20	.381	1.27	290	126		.0164		15.8		.06	
70	20	.381	1.27	290	125	124	.0259	.02	14.1	15.1	.08	
71	20	.381	1.27	290	121		.0178		15.4		.02	.131
79	20	.381	1.27	589	58.4	68.8	.0109	.0109	5.64	7.06	.03	
80	20	.381	1.27	589	79.1				8.48		.08	
72	20	.381	1.91	290	146		.0222		15.3		.06	
73	20	.381	1.91	290	143	144	.021	.0241	15.1	14.9	.09	
74	20	.381	1.91	290	143		.0291		14.3		.04	.147
81	20	.381	1.91	589	61.8	61.8			4.65	4.65	.03	
75	20	.381	2.54	300	163		.0216		16.6		.03	
76	20	.381	2.54	290	163	164	.0227	.0232	17.3	17.1	.08	.18
77	20	.381	2.54	290	165		.0253		17.3		.07	
82	20	.381	2.54	589	74.5		.0113		7.2		.05	
83	20	.381	2.54	589	83.1	71.1	.0149	.0131	8.4	6.9	.07	
84	20	.381	2.54	589	55.8				5.2		.06	

TABLE VI.- Concluded

(b) U.S. Customary Units

Test	Number of plies	Laminate thickness, in.	Width, in.	Temperature, ^{o}F	σ_{ult}, psi	Average σ_{ult}, psi	ϵ_{ult}	Average ϵ_{ult}	$E_{\epsilon=0.002}$, psi	Average $E_{\epsilon=0.002}$, psi	$\left(\frac{\Delta\epsilon}{\epsilon}\right)_{\epsilon=0.002}$	ν_I
66	20	0.150	0.25	62	0.0168×10^6		0.0132		2.3×10^6		0.08	
67	20	.150	.25	62	.0160	0.0162×10^6	.0102	0.0126	2.3	2.3×10^6	.07	
68	20	.150	.25	62	.0158		.0144		2.4		.04	0.0462
78	20	.150	.25	600	.0070	.0070						
69	20	.150	.50	62	.0183		.0164		2.3		.06	
70	20	.150	.50	62	.0181	.0180	.0259	.02	2.0	2.2	.08	
71	20	.150	.50	62	.0175		.0178		2.2		.02	.131
79	20	.150	.50	600	.0085	.0100	.0109	.0109	.8	1.0	.03	
80	20	.150	.50	600	.0115				1.2		.08	
72	20	.150	.75	62	.0212		.0222		2.2		.06	
73	20	.150	.75	62	.0207	.0209	.021	.0241	2.2	2.2	.09	
74	20	.150	.75	62	.0207		.0291		2.1		.04	.147
81	20	.150	.75	600	.0090	.0090			.7	.7	.03	
75	20	.150	1.00	80	.0236		.0216		2.4		.03	
76	20	.150	1.00	62	.0236	.0238	.0227	.0232	2.5	2.5	.08	.18
77	20	.150	1.00	62	.0239		.0253		2.5		.07	
82	20	.150	1.00	600	.0108		.0113		1.0		.05	
83	20	.150	1.00	600	.0121	.0103	.0149	.0131	1.2	1.0	.07	
84	20	.150	1.00	600	.0081				.8		.06	

TABLE VII.- COMPRESSIVE PROPERTIES OF [90]; HTS-2/PMR-15 SPECIMENS

(a) SI Units

Test	Number of plies	Laminate thickness, cm	Width, cm	Temperature, K	σ_{ult}, MPa	Average σ_{ult}, MPa	ϵ_{ult}	Average ϵ_{ult}	$E_{\epsilon=0.002}$, GPa	Average $E_{\epsilon=0.002}$, GPa	$\left(\frac{\Delta\epsilon}{\epsilon}\right)_{\epsilon=0.002}$	ν_I
52	20	0.361	1.27	290	210	206	0.0305	0.0292	8.75	8.96	0.06	
53	20	.361	1.27	290	201		.0279		9.16		.03	
54	20	.361	1.91	300	181		.0249		9.18		.05	
55	20	.361	1.91	300	142	154	.0192	.0241	9.18	9.04	.03	
56	20	.361	1.91	300	139		.0282		8.76		.07	0.0354
57	20	.361	1.91	589	65.1		.0165		5.47		.07	
58	20	.361	1.91	589	53.6	58.8	.0145	.0139	5.13	5.7	.16	
59	20	.361	1.91	589	57.8		.0108		6.51		.03	
60	20	.361	2.54	300	185		.0267		8.94		.08	
61	20	.361	2.54	300	181	172	.026	.0241	8.99	9.22	.03	
62	20	.361	2.54	300	151		.0195		9.74		.01	.0287
63	20	.361	2.54	589	81.4				6.39		.01	.0227
64	20	.361	2.54	589	62.7	72.6	.0155	.0165	5.87	6.1	0	
65	20	.361	2.54	589	73.8		.0175		6.04		0	

(b) U.S. Customary Units

Test	Number of plies	Laminate thickness, in.	Width, in.	Temperature, °F	σ_{ult}, psi	Average σ_{ult}, psi	ϵ_{ult}	Average ϵ_{ult}	$E_{\epsilon=0.002}$, psi	Average $E_{\epsilon=0.002}$, psi	$\left(\frac{\Delta\epsilon}{\epsilon}\right)_{\epsilon=0.002}$	ν_I
52	20	0.142	0.50	62	0.0304×10^6	0.0299×10^6	0.0305	0.0292	1.3×10^6	1.3×10^6	0.06	
53	20	.142	.50	62	.0292		.0279		1.3		.03	
54	20	.142	.75	80	.0263		.0249		1.3		.05	
55	20	.142	.75	80	.0206	.0223	.0192	.0241	1.3	1.3	.03	
56	20	.142	.75	80	.0202		.0282		1.3		.07	0.0354
57	20	.142	.75	600	.0094		.0165		.8		.07	
58	20	.142	.75	600	.0078	.0085	.0145	.0139	.7	.8	.16	
59	20	.142	.75	600	.0084		.0108		.9		.03	
60	20	.142	2.54	80	.0268		.0267		1.3		.08	
61	20	.142	2.54	80	.0262	.0249	.026	.0241	1.3	1.3	.03	
62	20	.142	2.54	80	.0219		.0195		1.4		.01	.0287
63	20	.142	2.54	600	.0118				.9		.01	.0227
64	20	.142	2.54	600	.0091	.0105	.0155	.0165	.8	.9	0	
65	20	.142	2.54	600	.0107		.0175		.9		0	

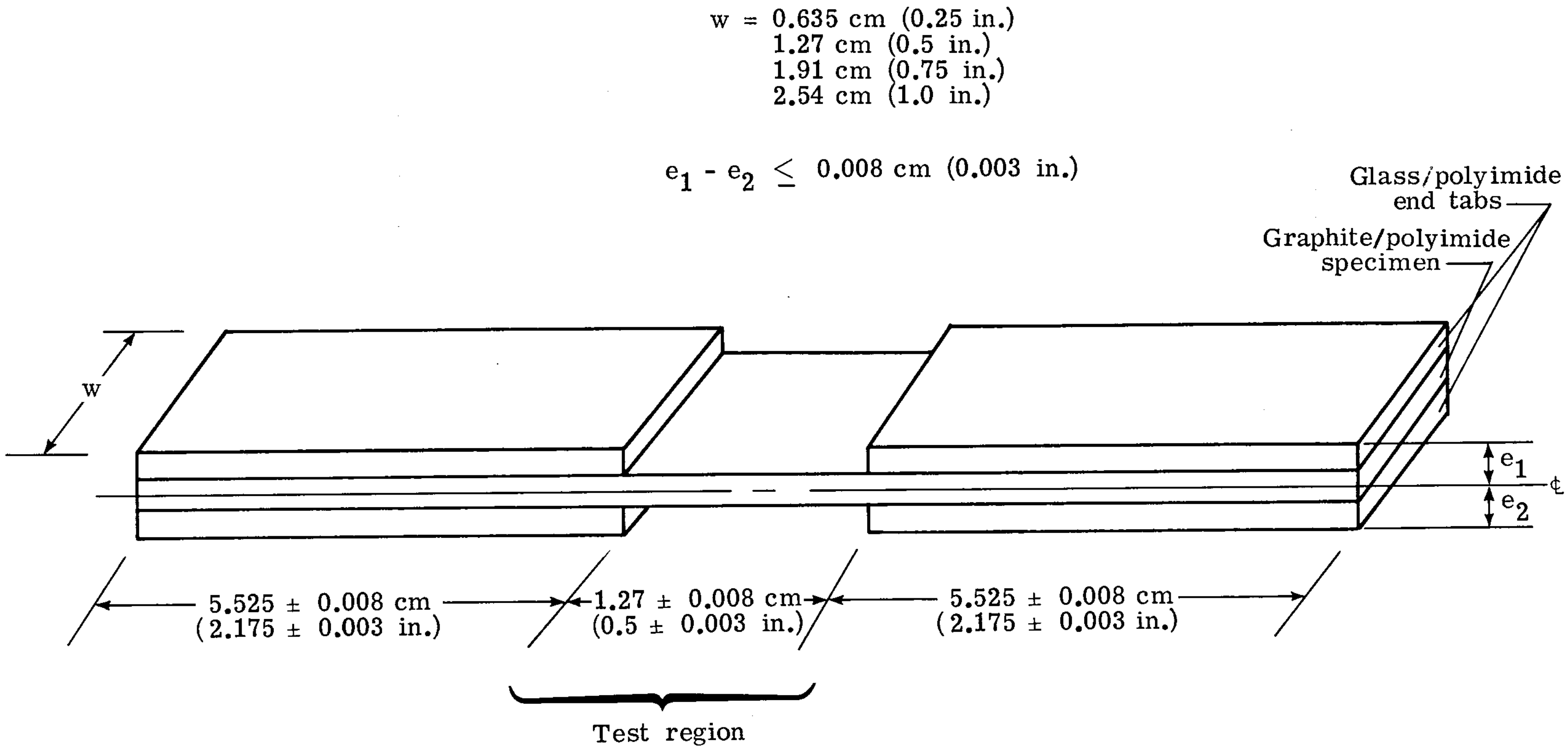
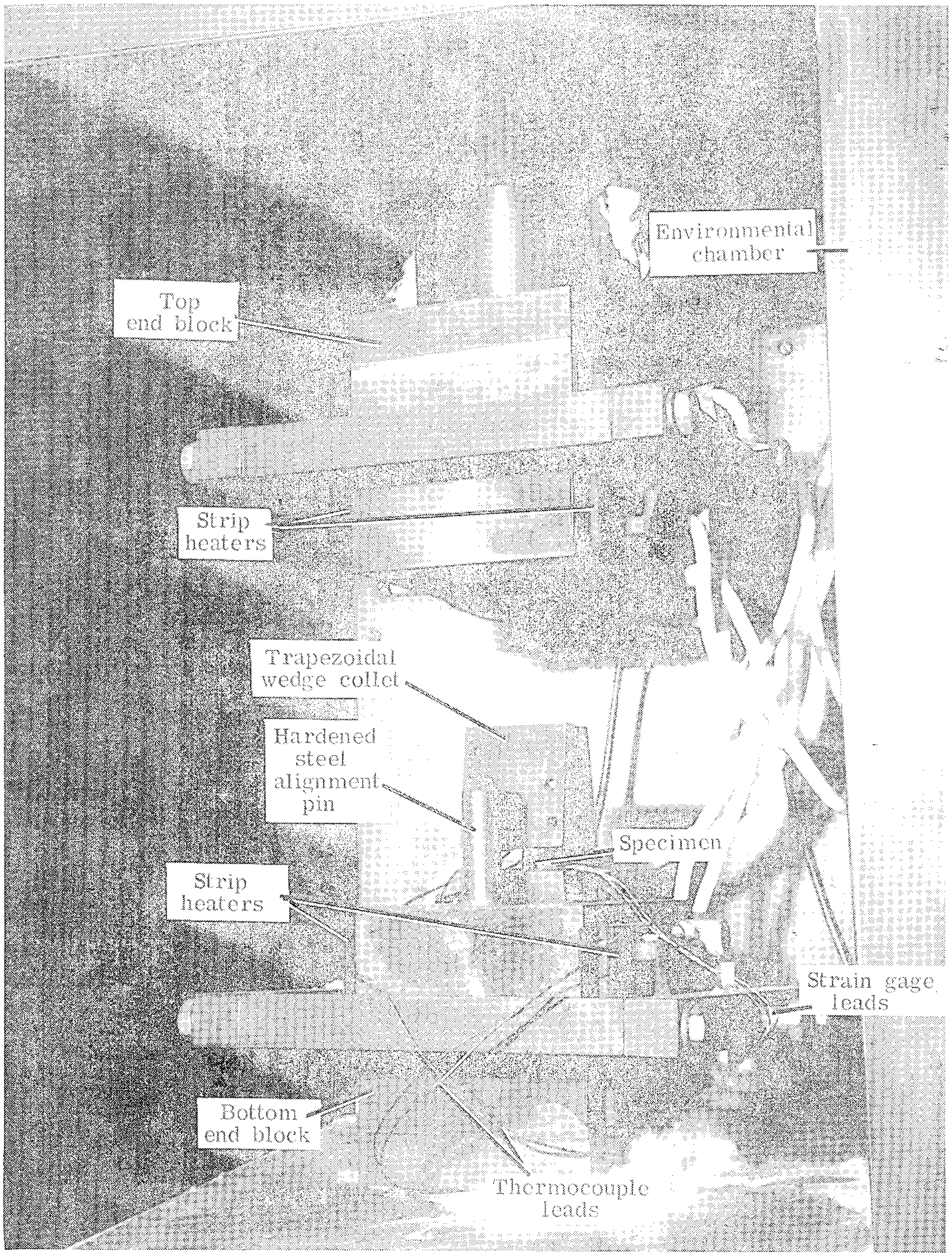
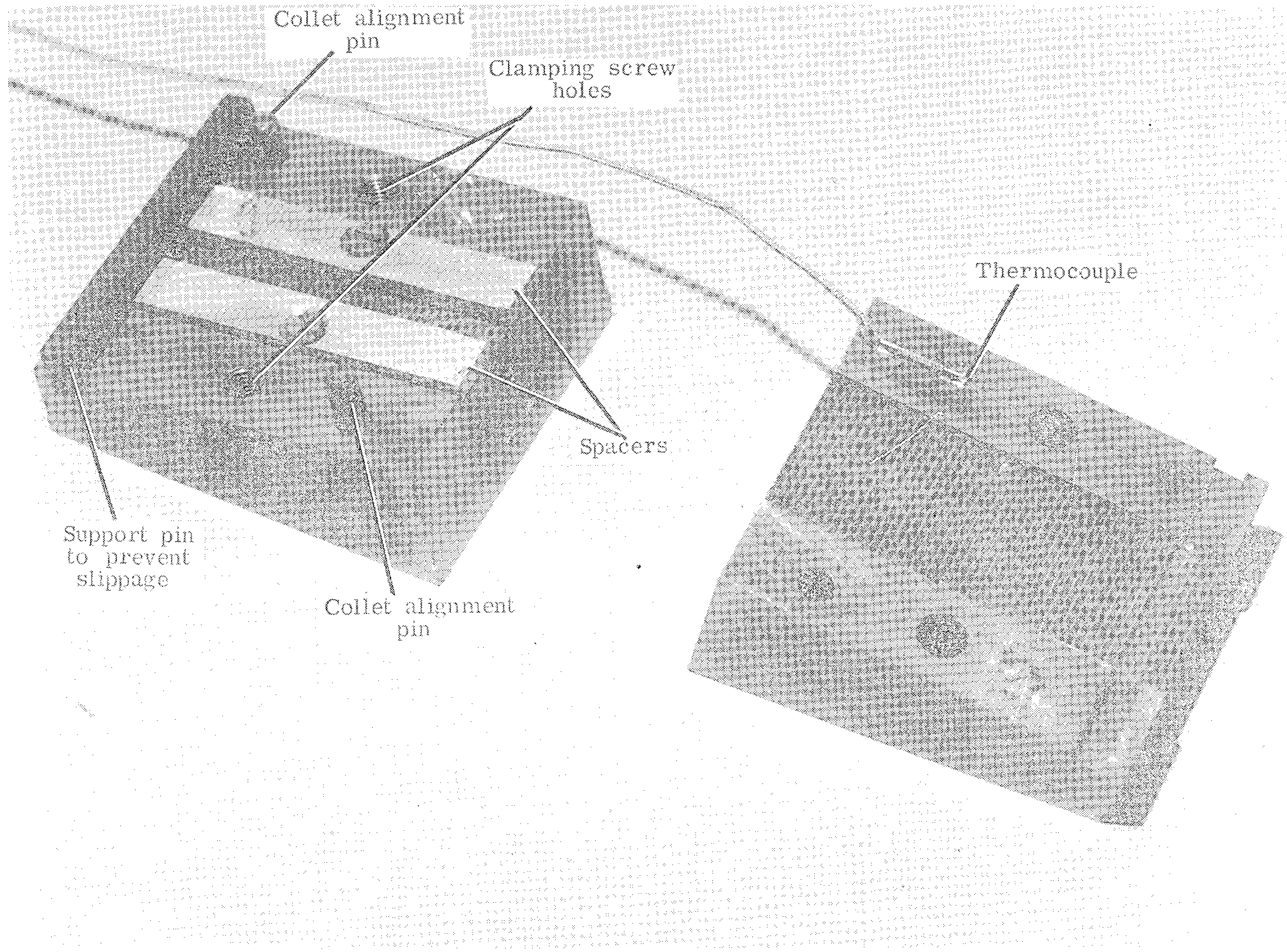


Figure 1.- The IITRI compression specimen.



L-78-4940.1

Figure 2.- The IITRI test specimen and fixture in environmental chamber.



L-78-3778.1

Figure 3.- Modified trapezoidal wedge collet.

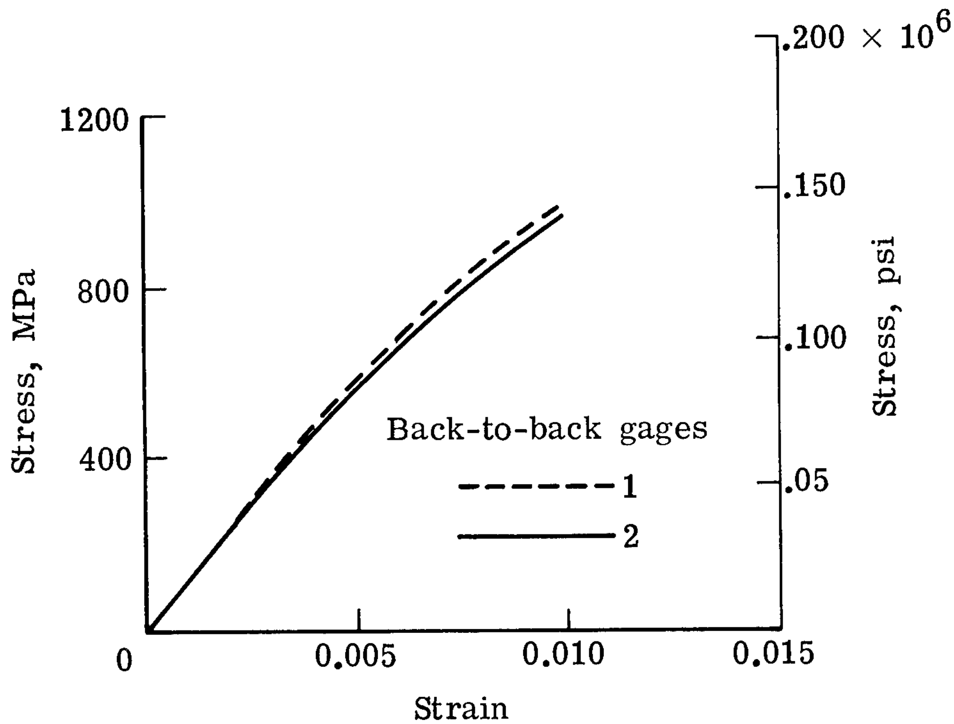


Figure 4.- Variation in back-to-back strains of $[0]_{15}$, HTS-1/PMR-15 specimen at room temperature. Test 14.

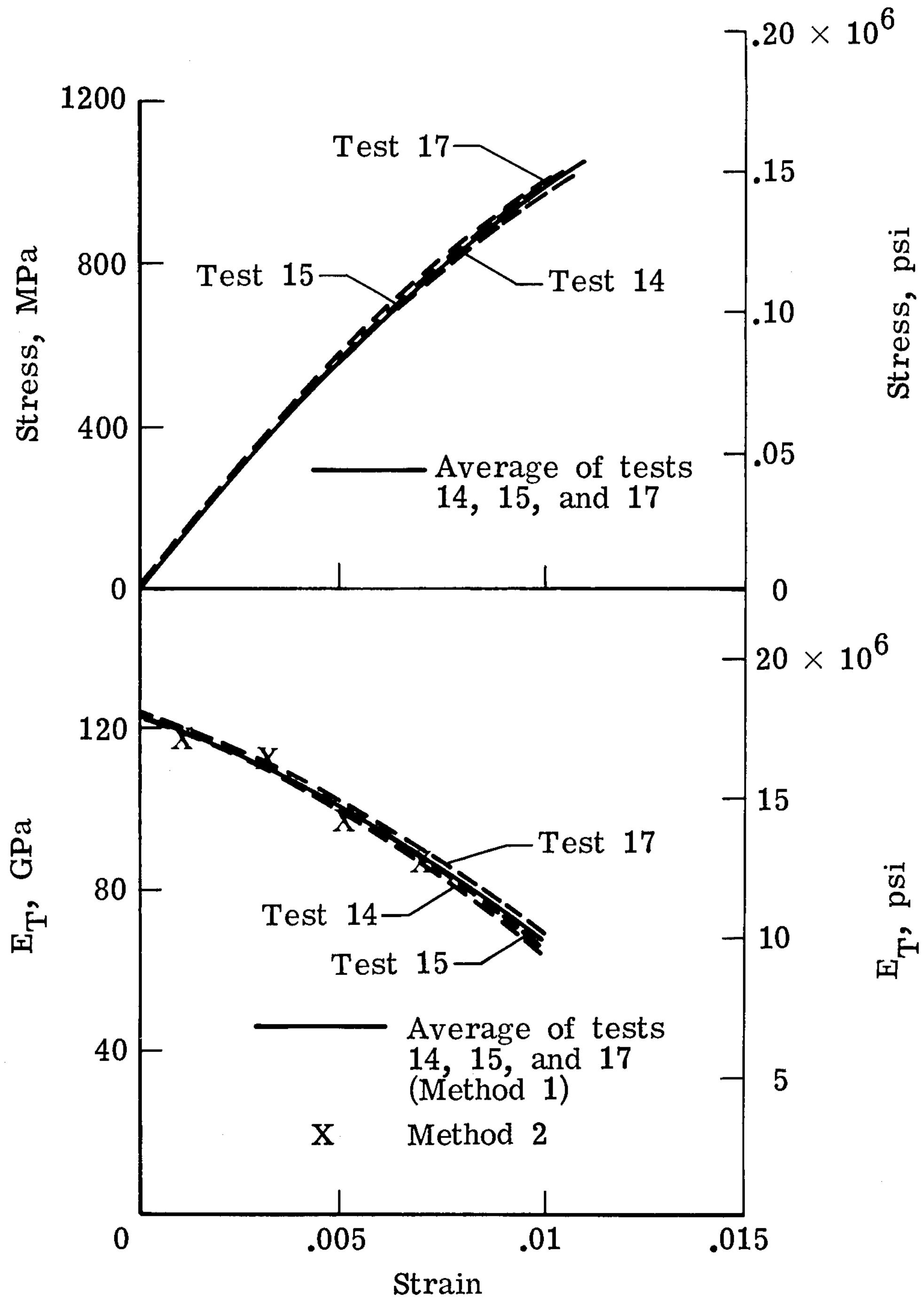


Figure 5.- Comparison of several individual test-case curves and average curves for $[0]_{15}$,HTS-1/PMR-15 composite at room temperature. w = 1.27 cm (0.5 in.); tests 14, 15, and 17.

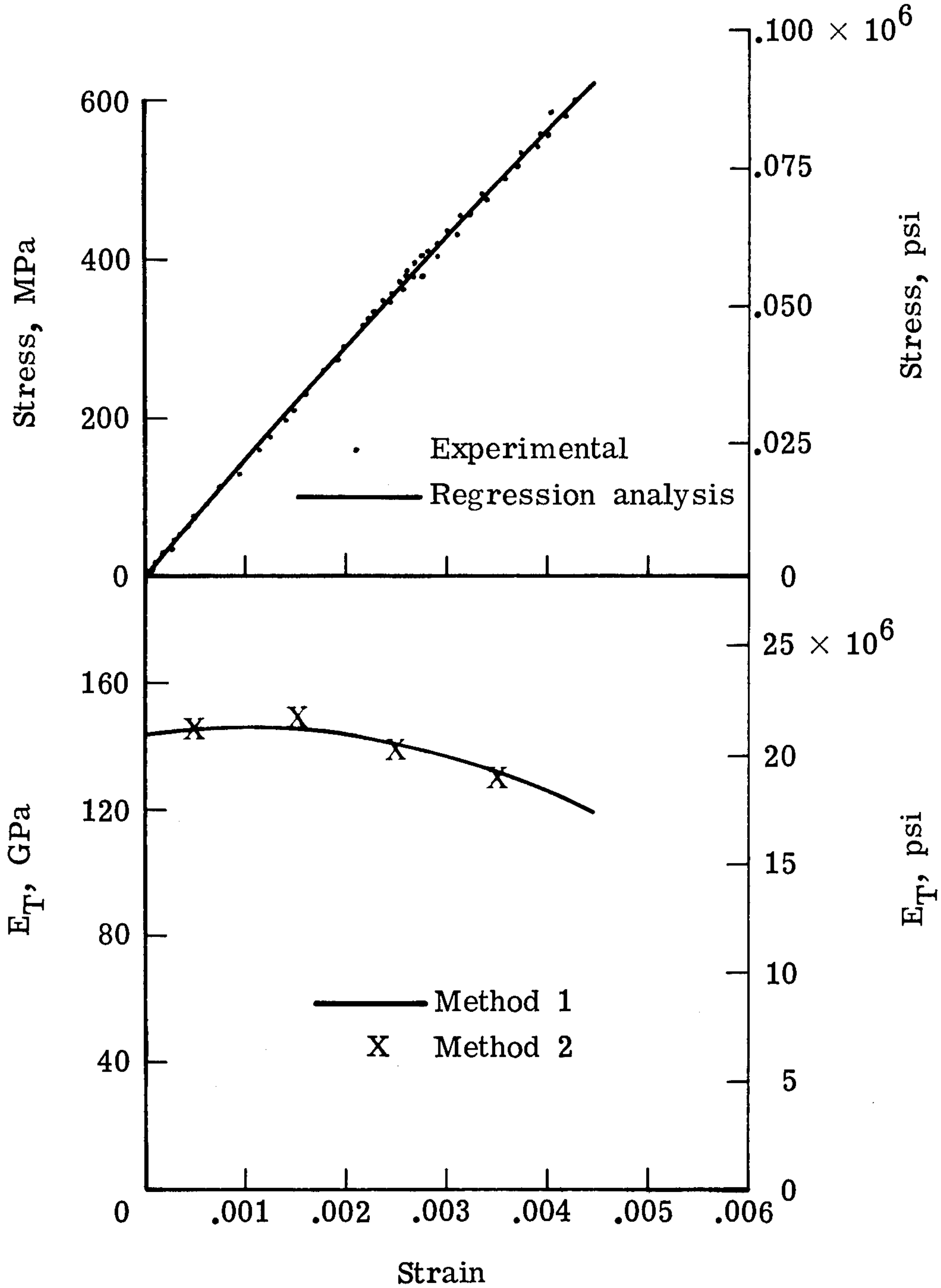


Figure 6.- Compression diagrams for $[0]_{15}$, HTS-1/PMR-15 composite at 589 K (600° F). w = 1.27 cm (0.5 in.); tests 18 and 19.

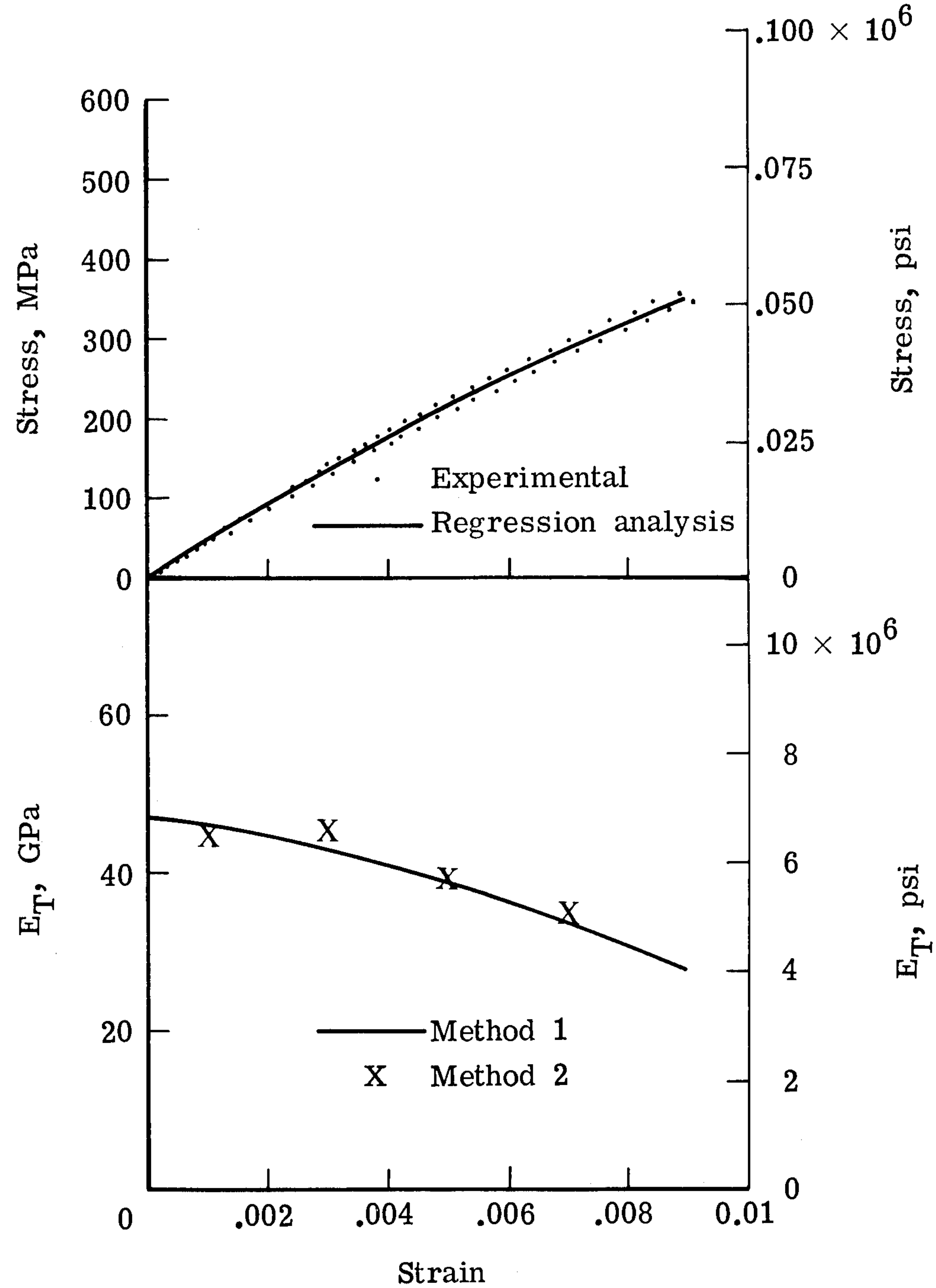


Figure 7.- Compression diagrams for $[0,\pm45,90]_{2S}$, HTS-1/PMR-15 composite at room temperature. w = 1.27 cm (0.5 in.); tests 34, 35, and 36.

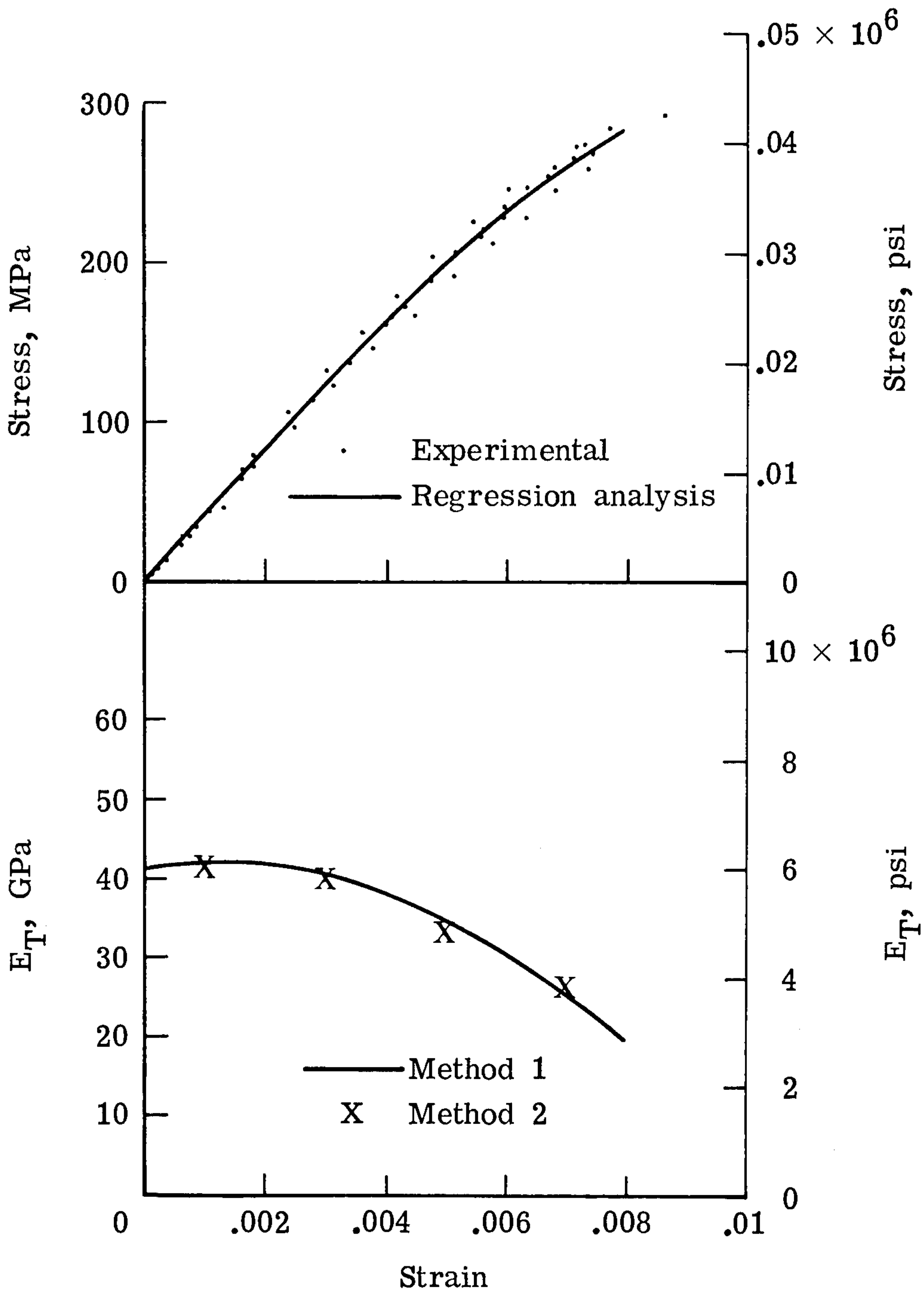


Figure 8.- Compression diagrams for $[0,\pm45,90]_{2S}$, HTS-1/PMR-15 composite at 589 K (600° F). w = 1.27 cm (0.5 in.); tests 37, 38, 39, and 40.

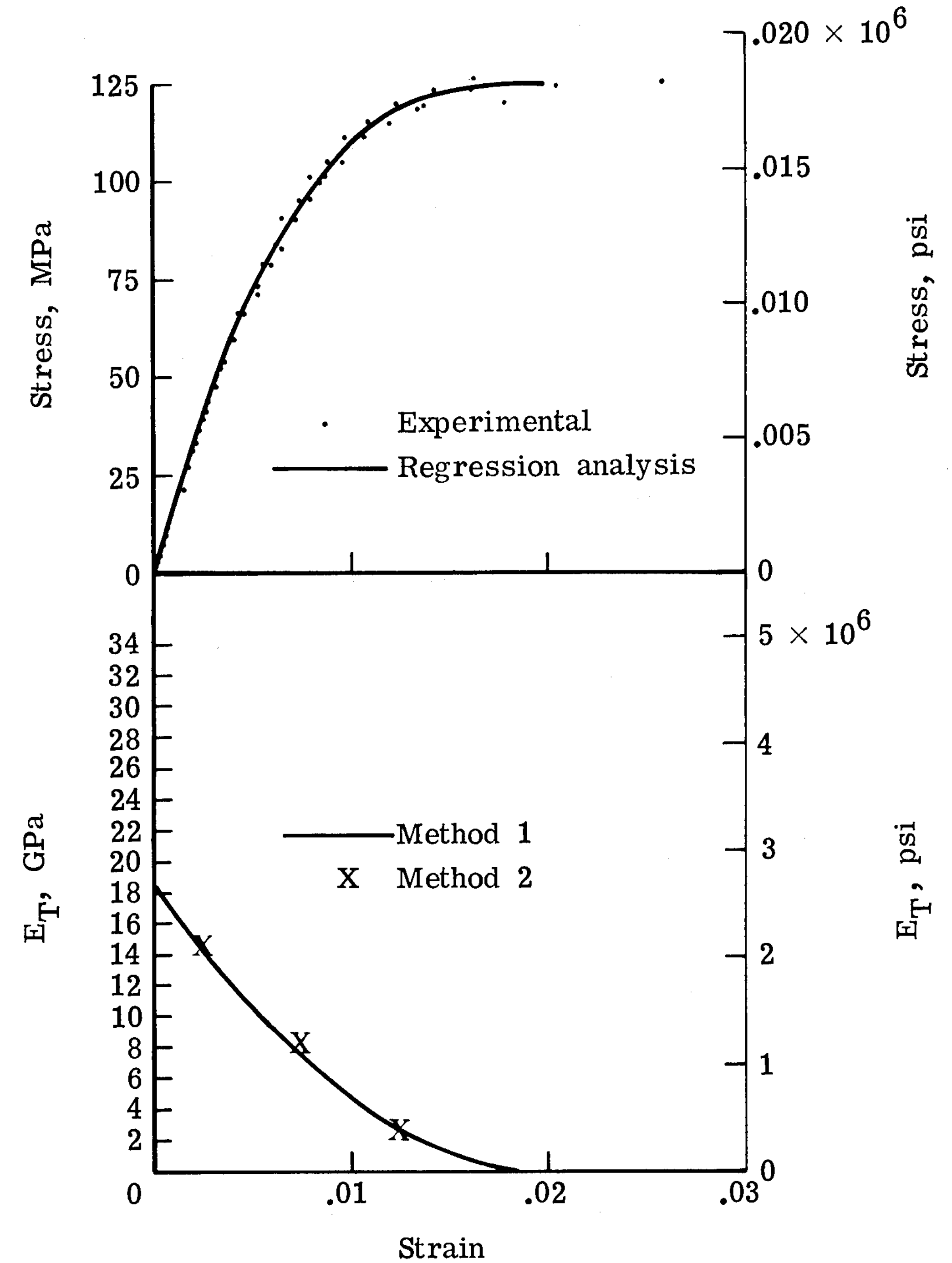


Figure 9.- Compression diagrams for $[\pm 45]_{5S}$, HTS-2/PMR-15 composite at room temperature. w = 1.27 cm (0.5 in.); tests 69, 70, and 71.

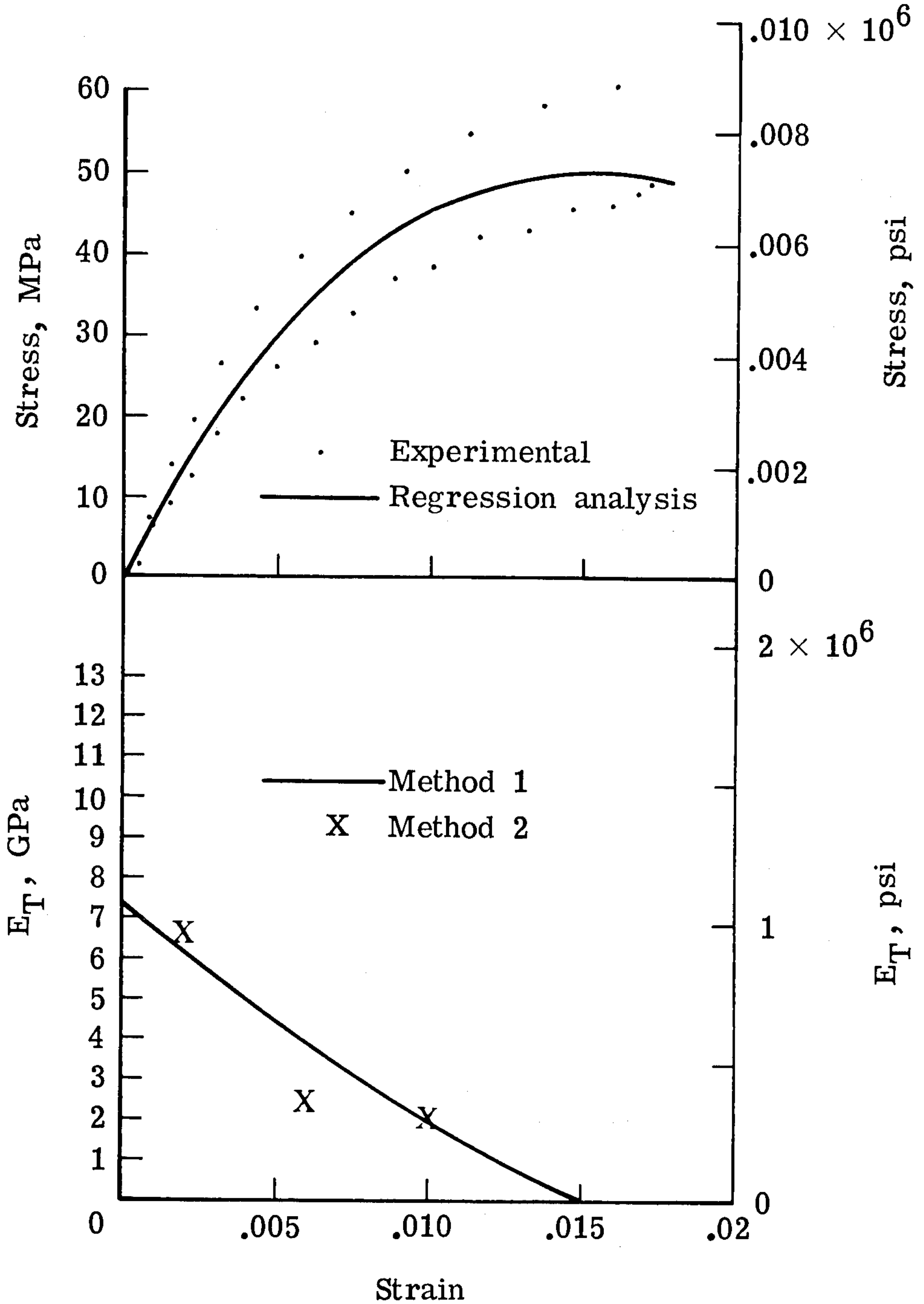


Figure 10.- Compression diagrams for $[\pm 45]_{5S}$, HTS-2/PMR-15 composite at 589 K (600° F). w = 1.27 cm (0.5 in.); tests 79 and 80.

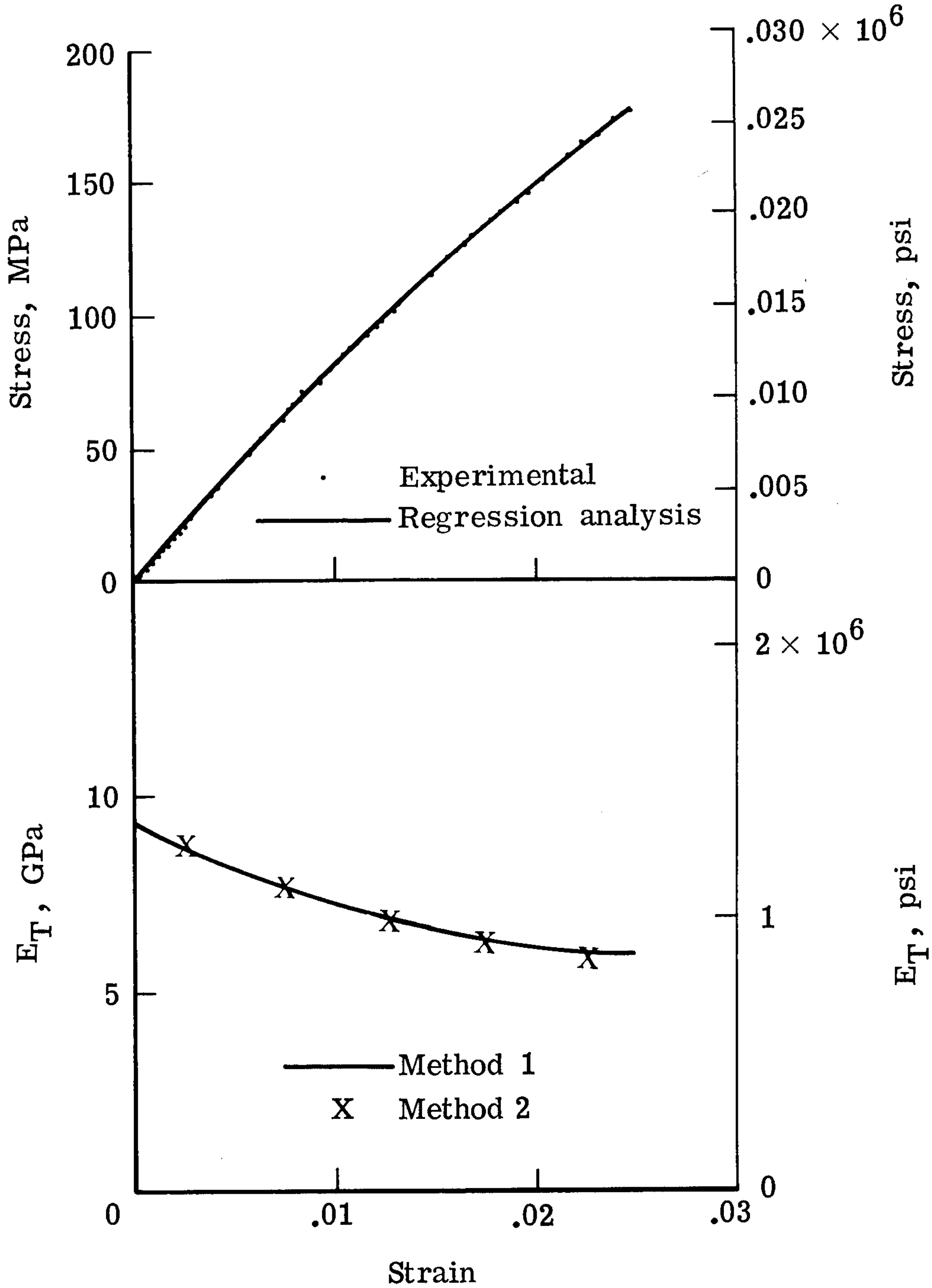


Figure 11.- Compression diagrams for $[90]_{20}$, HTS-2/PMR-15 composite at room temperature. w = 1.91 cm (0.75 in.); tests 54, 55, and 56.

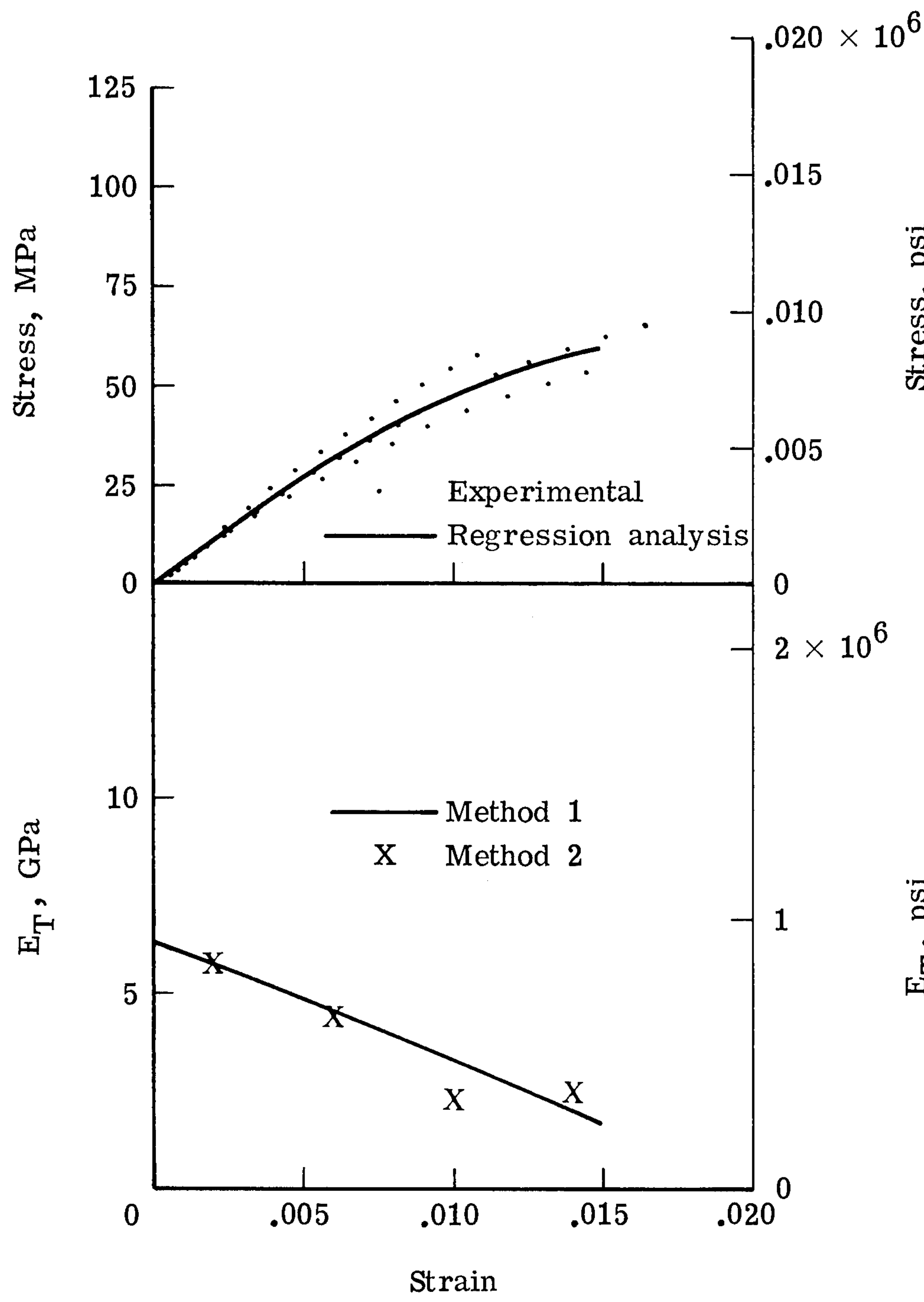


Figure 12.- Compression diagrams for $[90]_{20}$, HTS-2/PMR-15 composite at 589 K (600° F). w = 1.91 cm (0.75 in.); tests 57, 58, and 59.

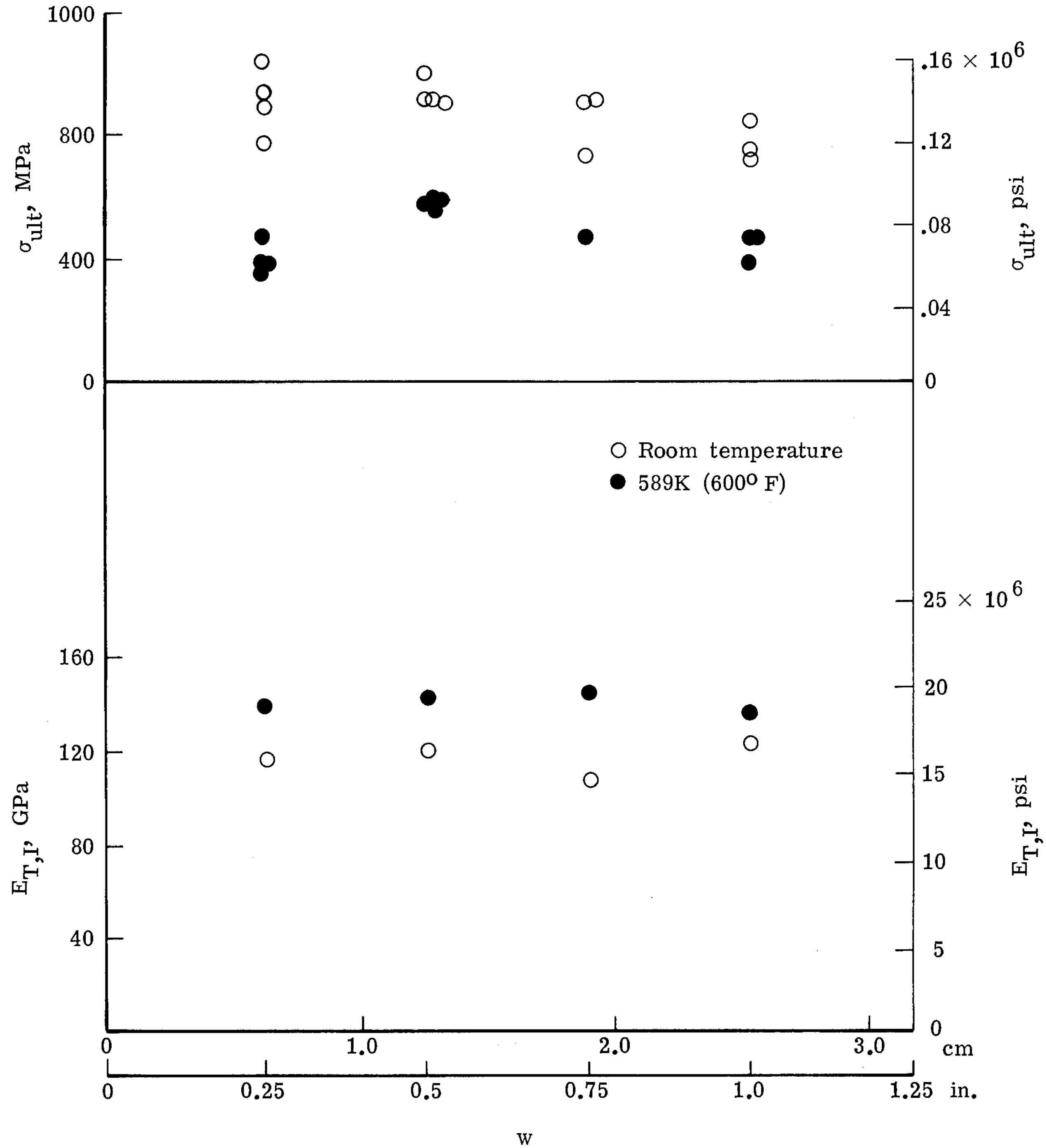


Figure 13.- Effect of width on σ_{ult} and $E_{T,I}$ of unidirectional specimens.

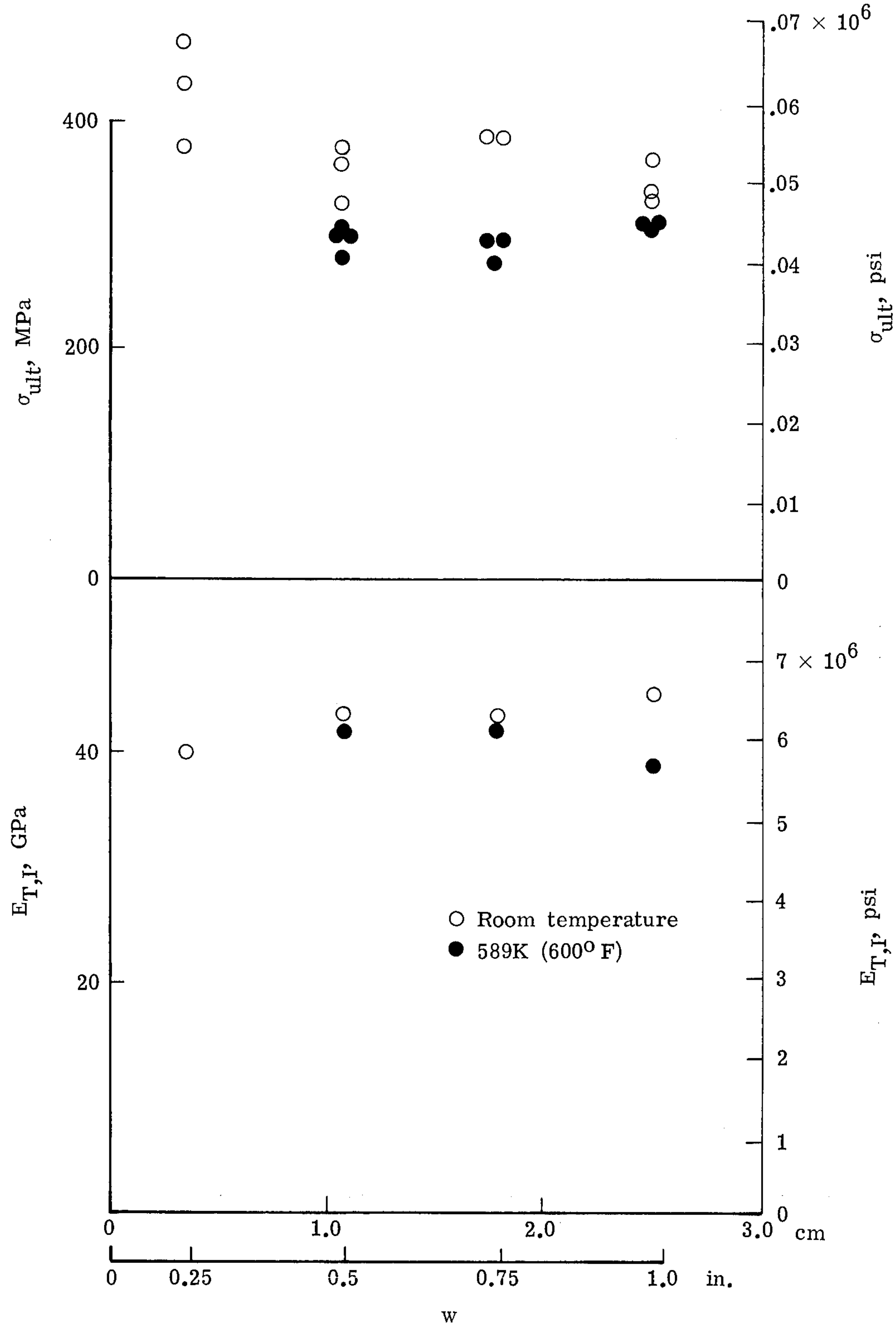


Figure 14.- Effect of width on σ_{ult} and $E_{T,I}$ of $[0,\pm45,90]_{2S}$ specimens.

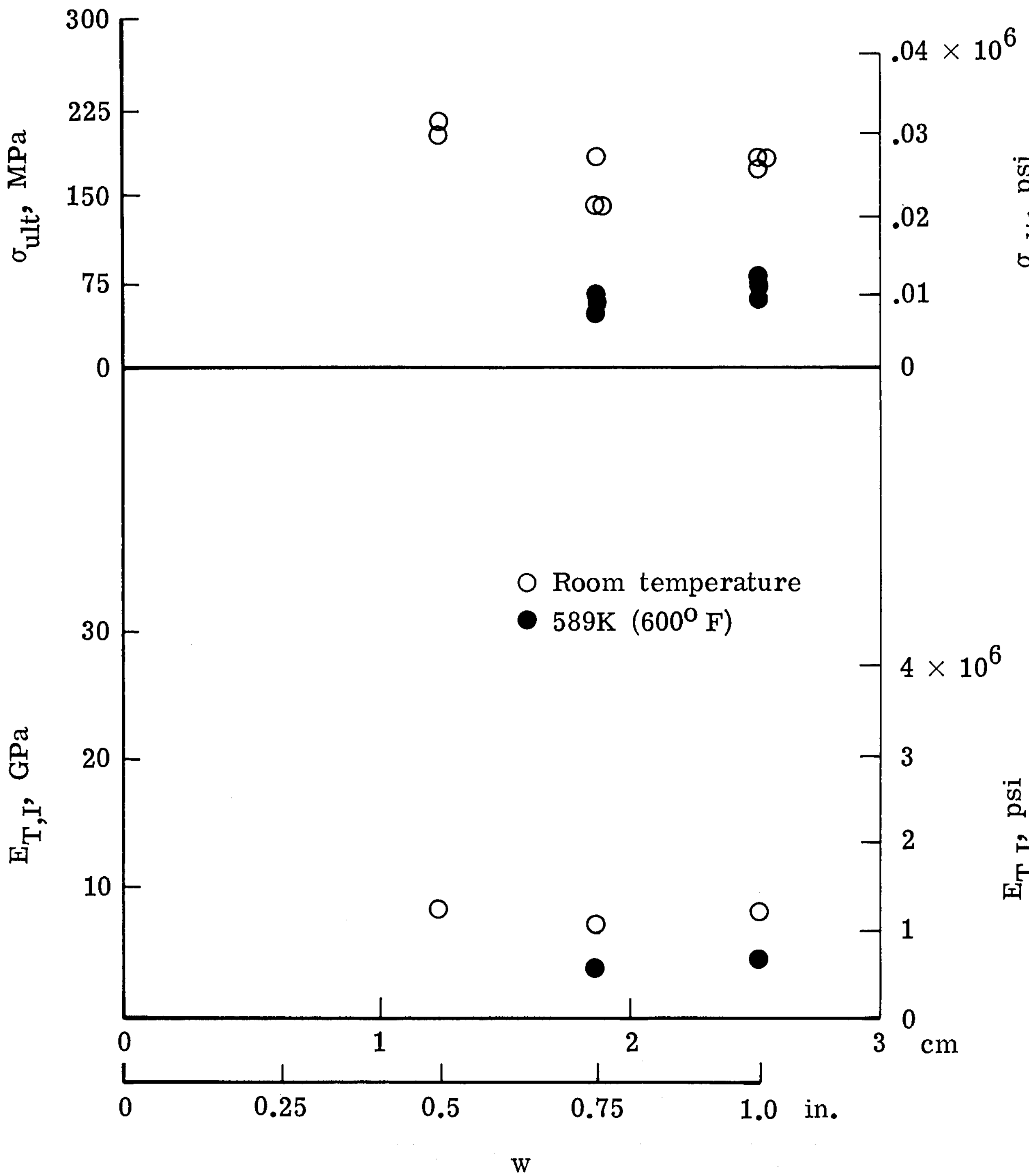


Figure 15.- Effect of width on σ_{ult} and $E_{T,I}$ of $[90]_{20}$ specimens.

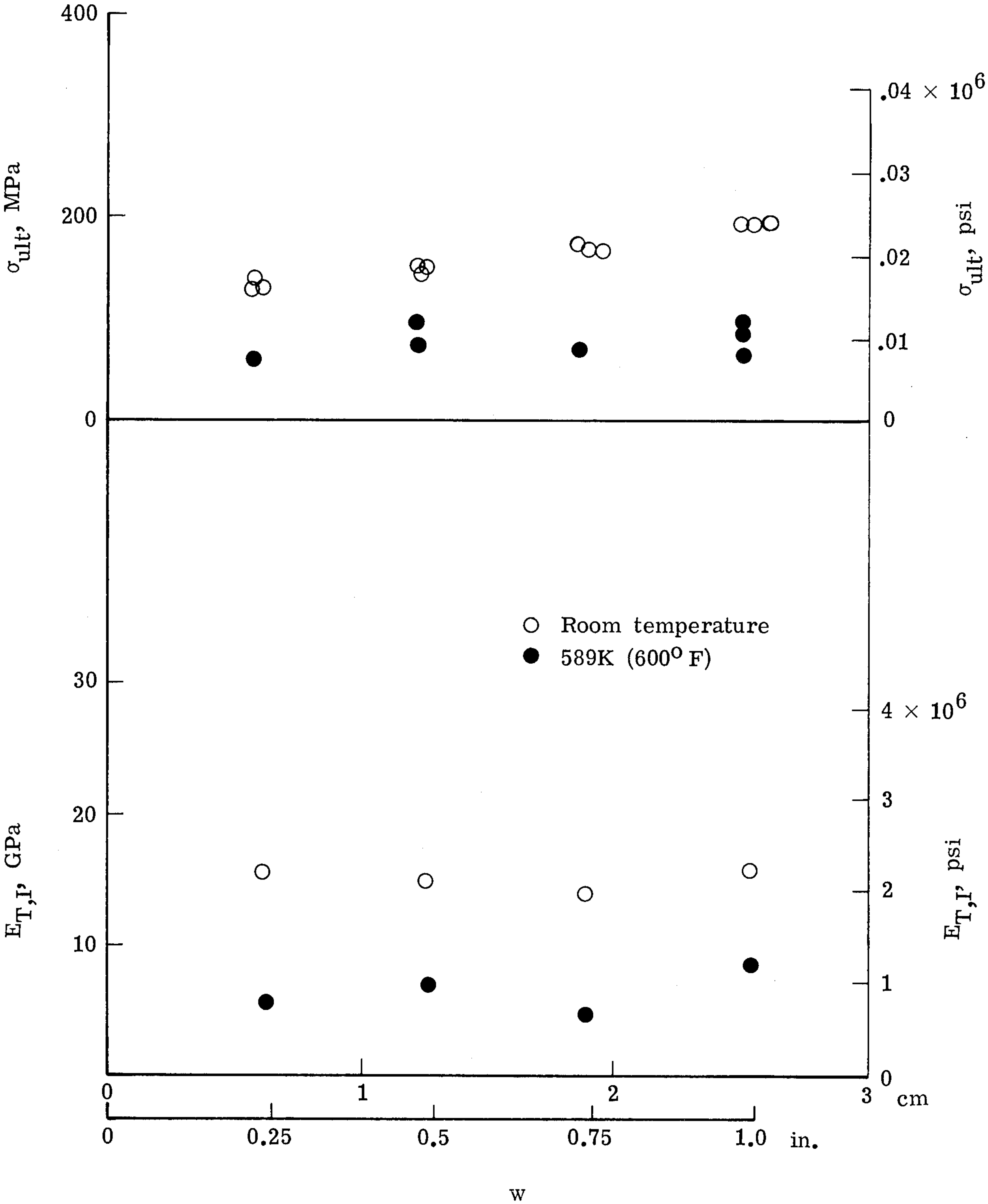
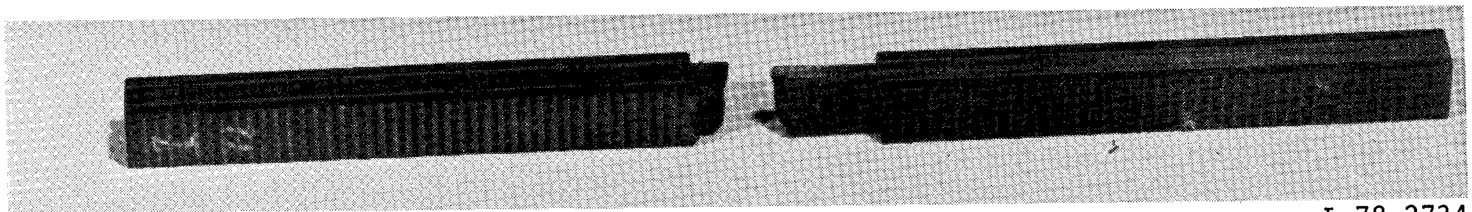
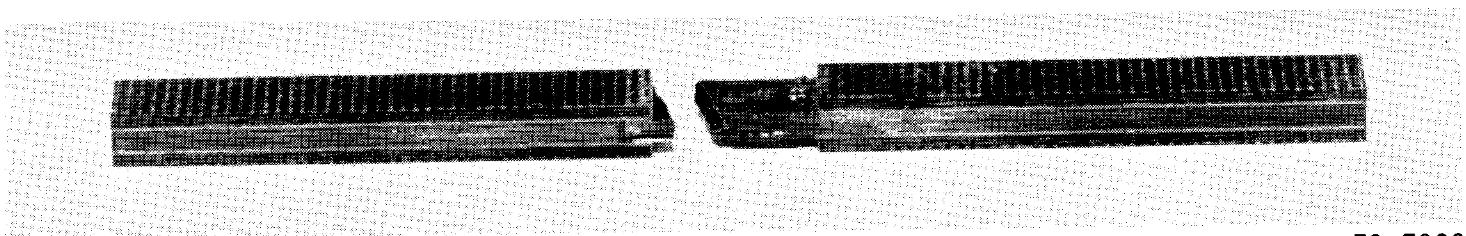


Figure 16.- Effect of width on σ_{ult} and $E_{T,I}$ of $[\pm 45]_{5S}$ specimens.



L-78-2734

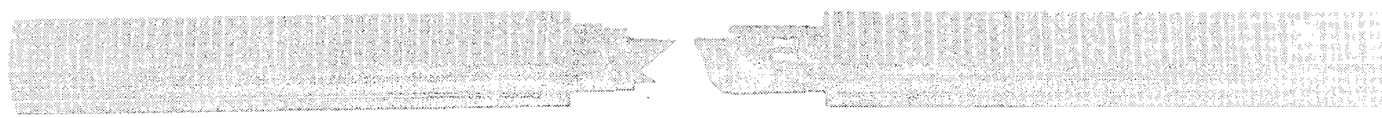
(a) Right-angle fracture.



L-78-7900

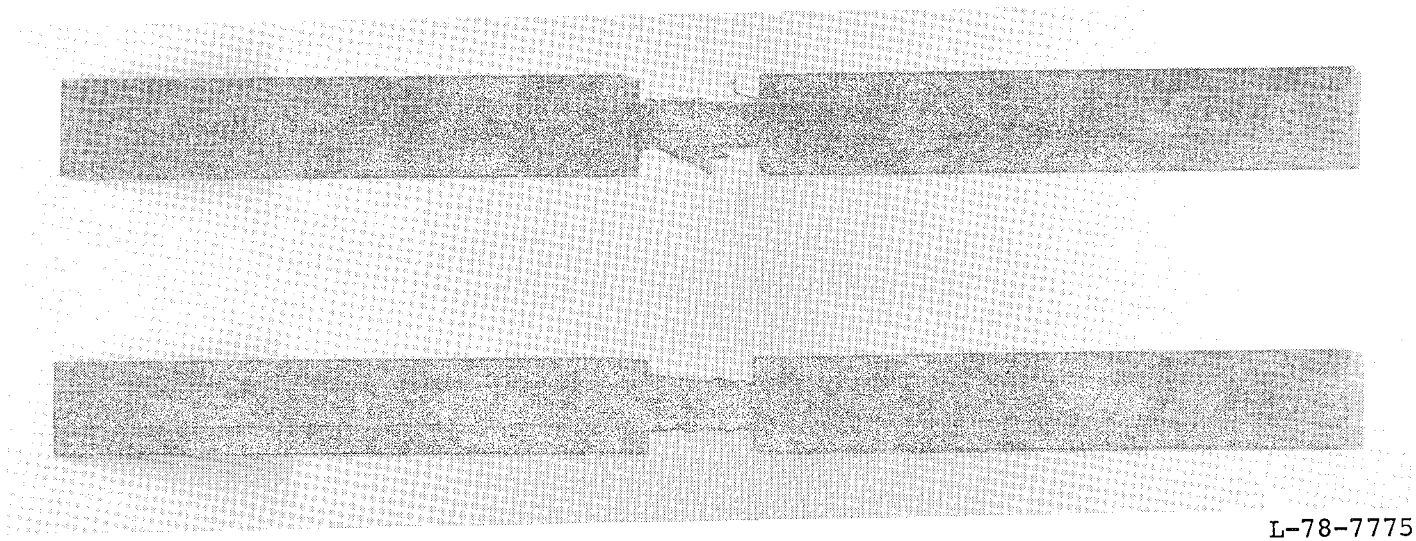
(b) Inclined fracture.

Figure 17.- Failed unidirectional, HTS-1/PMR-15 specimens. w = 0.635 cm (0.25 in.); 15 plies.



L-78-2733

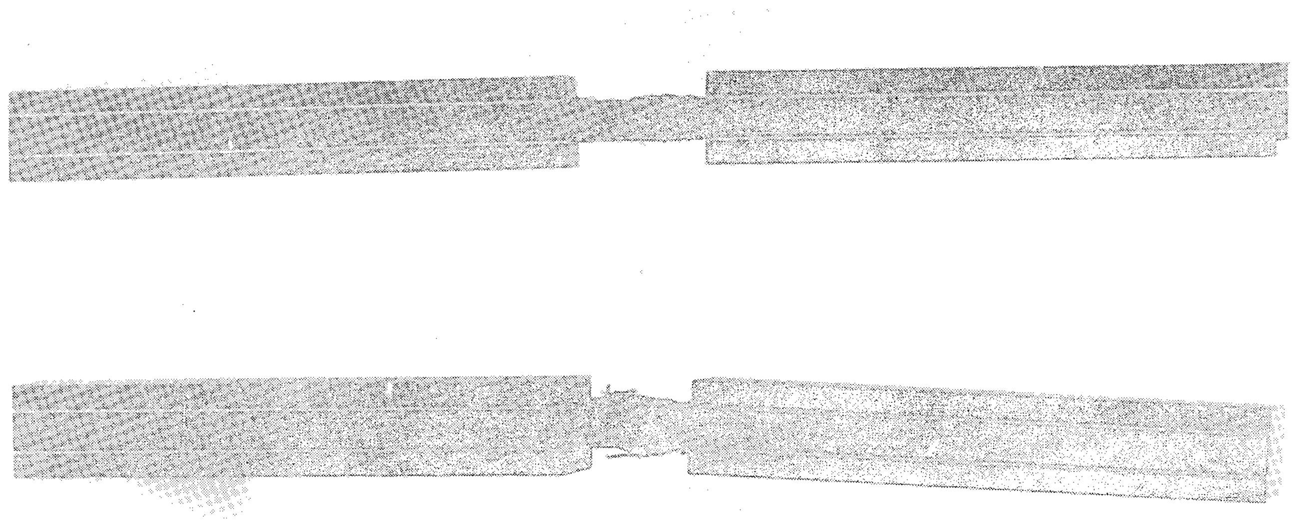
Figure 18.- Failed $[0,\pm 45,90]_{2S}$, HTS-1/PMR-15 specimens. w = 0.635 cm (0.25 in.); 20 plies.



L-78-7775

(a) Room temperature.

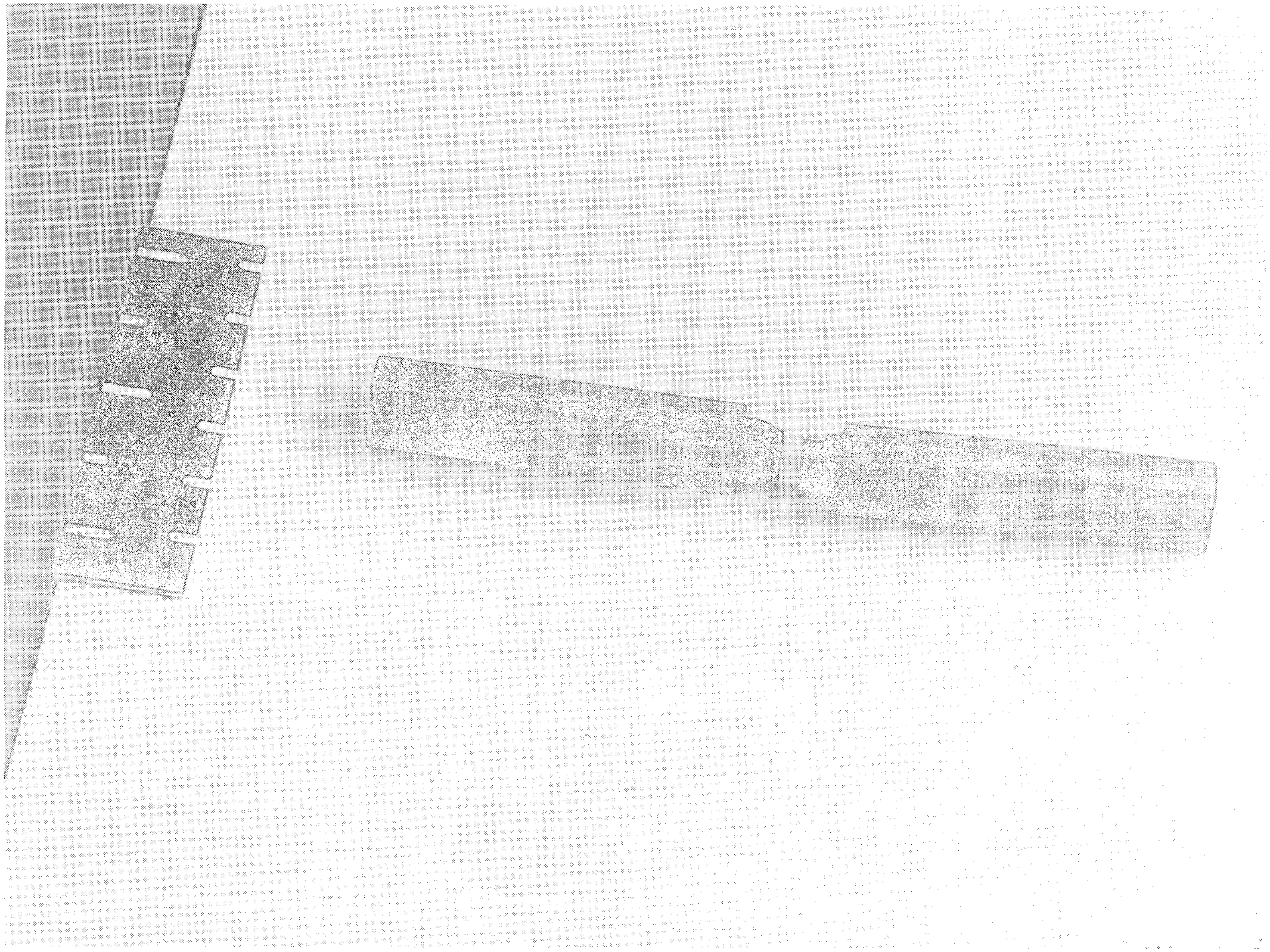
Figure 19.- Failed $[\pm 45]_{5S}$, HTS-2/PMR-15 specimens.



L-78-7773

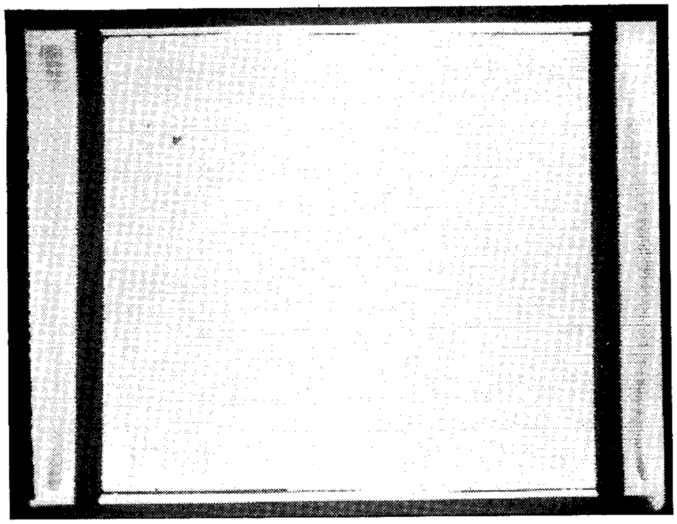
(b) 589 K (600° F).

Figure 19.- Concluded.

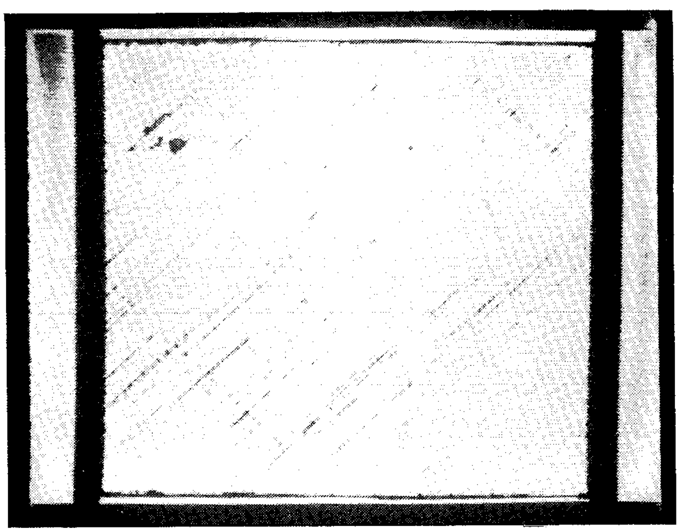


L-78-5076

Figure 20.- Failed $[90]_{20}$, HTS-2/PMR-15 specimens. w = 1.27 cm (0.5 in.); 20 plies.



(a) 20 Hz.



(b) 15 Hz.

L-79-271

Figure 21.- Ultrasonic scans of $[\pm 45]_{5S}$ HTS-2/PMR-15 specimens.

1. Report No. NASA TP-1496	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle ELEVATED-TEMPERATURE APPLICATION OF THE IITRI COMPRESSION TEST FIXTURE FOR GRAPHITE/POLYIMIDE FILAMENTARY COMPOSITES		5. Report Date September 1979
		6. Performing Organization Code
7. Author(s) B. Basava Raju, Charles J. Camarda, and Paul A. Cooper		8. Performing Organization Report No. L-12704
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665		10. Work Unit No. 524-71-03-02
		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Paper
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		14. Sponsoring Agency Code

15. Supplementary Notes

B. Basava Raju: NRC-NASA Resident Research Associate.

16. Abstract

Seventy-nine graphite/polyimide compression specimens were tested to investigate experimentally the IITRI test method for determining compressive properties of composite materials at room and elevated temperatures (589 K (600° F)).

Minor modifications were made to the standard IITRI fixture and a high degree of precision was maintained in specimen fabrication and load alignment. Specimens included four symmetric laminate orientations designated as [0], $[0,\pm45,90]_{2S}$, [90], and $[\pm45]_{5S}$. Specimens of various widths were tested to evaluate the effect of width on measured modulus and strength. In most cases three specimens of each width were tested at room and elevated temperature and a polynomial regression analysis was used to reduce the data.

Scatter of replicate tests and back-to-back strain variations were low, and no specimens failed by instability. Variation of specimen width had a negligible effect on the measured ultimate strengths and initial moduli of the specimens. Measured compressive strength and stiffness values were sufficiently high for the material to be considered a usable structural material at temperatures as high as 589 K (600° F).

17. Key Words (Suggested by Author(s)) High temperature tests; Composite materials; Compressive strength; Compressive modulus; Compression tests; Graphite/polyimide		18. Distribution Statement Unclassified - Unlimited. Subject Category 24	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 45	22. Price* $4.50

*For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1979