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SUMMARY

The results of an experimental program to determine the bolted-joint strength and failure modes of graphite/polyimide laminates are presented. Sixteen-ply, quasi-isotropic laminates of Celion 6000/PMR-15 and Celion 6000/LARC-160 with a fiber orientation of $[0/45/90/-45]_{2S}$ were evaluated. Tensile and open-hole specimens were tested at room temperature to establish laminate tensile strength and net tensile strength at an unloaded bolt hole. Double-lap joint specimens with a single 4.83-mm (0.19-in.) diameter bolt torqued to 1.7 N-m (15 lbf-in.) were tested in tension at temperatures of 116 K (-250°F), 297 K (75°F), and 589 K (600°F). The joint ratios of w/d (specimen width to hole diameter) and e/d (edge distance to hole diameter) were varied from 4 to 6 and from 2 to 4, respectively. The effect of joint geometry and temperature on failure mode and joint stresses are shown. Joint stresses calculated at maximum load for each joint geometry and test temperature are reported. Five failure modes were observed for the double-lap joint specimens. For all joint ratios tested, net-tension, bearing, and shear-out stresses decreased with increasing temperature from 116 K (-250°F) to 589 K (600°F). Joint strength in net tension, bearing, and shear-out at 116 K (-250°F), 297 K (75°F), and 589 K (600°F) are given for the Celion 6000/PMR-15 and Celion 6000/LARC-160 laminates.

INTRODUCTION

The development of graphite/polyimide composites offers the potential of significant weight savings compared with metallic or other composite materials in a variety of structures that operate at elevated temperature (ref. 1). Studies have been conducted at Langley Research Center on the application of graphite/polyimide composites to the Space Shuttle orbiter and supersonic cruise aircraft. In particular, the Composites for Advanced Space Transportation Systems (CASTS) project was initiated to develop graphite-reinforced polyimide composite structures for aerospace vehicles (ref. 2). Included in the research project was the design and development of attachment methods for composite components. As a part of this technology-development effort, the load-carrying capabilities of joint geometries and the associated failure modes were needed for bolted-joint design. Therefore, an experimental study was conducted to obtain bolted-joint strength and failure modes for graphite/polyimide laminates.

The selection of test laminates, fastener, and temperatures were the results of near- and far-term objectives of the CASTS project (refs. 1 and 2). The test matrix of joint variables selected for this study was based on experimental data reported for graphite- and glass-reinforced epoxy laminates (refs. 3 through 6). This paper presents experimental data obtained for graphite/polyimide laminates of Celanese Celion 6000/PMR-15 and Celion 6000/LARC-160. Laminate tensile strength and net tensile strength at an unloaded bolt hole were determined at room temperature. Double-lap joint specimens with a single torqued bolt were tested in tension to failure at low, room, and elevated temperatures. Joint ratios of w/d (specimen width to hole diameter) and e/d (edge distance to hole diameter) were varied to obtain failure modes and joint failure stresses in net tension, bearing, and shear-out.

Experimental results are presented to show the effect of joint geometry and temperature on joint failure stresses and modes. Joint strengths in net tension, bearing, and shear-out at all test temperatures are reported.

SYMBOLS

Measurements and calculations were made in the U.S. Customary Units. They are presented herein in the International System of Units (SI) with the equivalent values given parenthetically in the U.S. Customary Units.

d	hole diameter, mm (in.)
d_b	bolt diameter, mm (in.)
e	center of hole to edge distance, mm (in.)
F_v	fiber volume fraction, percent
P	load, N (lbf)
T_g	glass transition temperature, K (°F)
t	specimen thickness, mm (in.)
w	specimen width, cm (in.)
σ_b	nominal bearing stress, MPa (ksi)
σ_{nt}	nominal net-section tensile stress, MPa (ksi)
σ_{so}	nominal shear-out stress, MPa (ksi)

MATERIALS

Two graphite/polyimide composite materials, Celion 6000/PMR-15 and Celion 6000/LARC-160, were selected for evaluation. A 16-ply quasi-isotropic laminate with a fiber orientation of $[0/45/90/-45]_{2S}$ was chosen for characterization. Laminate and specimen fabrication was performed both in-house and on contract for the Celion 6000/PMR-15 material system. The in-house Celion 6000/PMR-15 specimens were obtained from a single 127-cm by 66-cm (50-in. by 26-in.) laminate. Processing details for the in-house specimens are reported in reference 7. The laminate had a fiber volume fraction F_v of 55 percent and a glass transition temperature T_g of 589 K (600°F). The contract Celion 6000/PMR-15 specimens were obtained from two 76-cm by 46-cm (30-in. by 18-in.) laminates. Processing details for the contract specimens are reported in reference 8. The laminates had an F_v value of 64 percent and a T_g value of 595 K (612°F). Laminate and specimen fabrication was performed in-house for the Celion 6000/LARC-160 material system. Specimens were obtained from a single 127-cm by 66-cm (50-in. by 26-in.) laminate. Processing details are reported in reference 7. The Celion 6000/LARC-160 laminate had an F_v value of 56 percent and a T_g value of 609 K (636°F). All specimens were tested in the as-received condition.

TEST PARAMETERS AND SPECIMENS

Tensile strength and modulus for each of the graphite/polyimide laminates were determined at room temperature from tensile specimens. Reduction in laminate tensile strength resulting from the stress concentration around a circular hole was determined from open-hole specimens from the in-house Celion 6000/PMR-15 laminate. Joint strengths for a single fastener in double-lap shear specimens were determined at 116 K (-250°F), 297 K (75°F), and 589 K (600°F).

Tensile Specimens

The Celion 6000/PMR-15 tensile specimens were 2.54 cm (1.00 in.) wide by 27.9 cm (11.0 in.) long with 6.4-cm (2.5-in.) doublers at each end. (See fig. 1(a).) The nominal thicknesses were 2.79 mm (0.11 in.) for specimens machined from the in-house laminate and 2.29 mm (0.09 in.) for specimens machined from the contract laminate. The Celion 6000/LARC-160 specimens were 2.54 cm (1.00 in.) wide by 30.5 cm (12.0 in.) long, and the nominal thickness was 3.05 mm (0.12 in.). Doublers were not used on the Celion 6000/LARC-160 specimens because of specimen failures at the doublers during preliminary tests. For the Celion 6000/LARC-160 specimens, grip length was increased to 7.6 cm (3.0 in.), and specimen length was increased by 2.5 cm (1.0 in.) to maintain a 15.2-cm (6.0-in.) long test section.

Open-Hole Specimens

Open-hole specimens were fabricated from the in-house Celion 6000/PMR-15 laminate. Specimens were 24.1 cm (9.5 in.) long with widths of 1.93 cm (0.76 in.), 2.41 cm (0.95 in.), and 2.90 cm (1.14 in.). Each specimen had two test holes of 4.83-mm (0.19-in.) nominal diameter located six hole diameters from the doublers, which were 3.8 cm (1.5 in.) long. (See fig. 1(b).) One hole was tested at a time with load transfer through the center doublers and one of the end doublers. The doublers had 6.35-mm (0.25-in.) diameter holes for load transfer.

Bolted-Joint Specimens

Room temperature.- A typical bolted-joint-specimen configuration for room-temperature tests is shown in figure 2(a). Specimens had four test holes with a 4.83-mm (0.19-in.) nominal diameter. After the two outer holes were individually tested, the specimens were cut to another edge distance e for the two inner holes. Load transfer was through the doublers and the test holes. Edge distances were 0.97 cm (0.38 in.), 1.45 cm (0.57 in.), and 1.93 cm (0.76 in.). Specimen widths were 1.93 cm (0.76 in.), 2.41 cm (0.95 in.), and 2.90 cm (1.14 in.). The Celion 6000/PMR-15 specimens were 17.8 cm (7.0 in.) in length with 3.8-cm (1.5-in.) long doublers, whereas the Celion 6000/LARC-160 specimens were 19.1 cm (7.5 in.) long with 5.1-cm (2.0-in.) long doublers. The inner test holes were approximately five hole diameters from the reinforcing doublers, which had a 6.35-mm (0.25-in.) diameter hole for load transfer.

Low and elevated temperatures.- A typical bolted-joint-specimen configuration for tests at low and elevated temperatures is shown in figure 2(b). Each specimen had a single test hole, nominally 4.83 mm (0.19 in.) in diameter. Edge distances were 0.97 cm (0.38 in.), 1.45 cm (0.57 in.), and 1.93 cm (0.76 in.). Specimen widths were 1.93 cm (0.76 in.), 2.41 cm (0.95 in.), and 2.90 cm (1.14 in.). The Celion 6000/PMR-15 specimens were 20.3 cm (8.0 in.) long with 3.8-cm (1.5-in.) long doublers, and the Celion 6000/LARC-160 specimens were 22.9 cm (9.0 in.) long with 5.1-cm (2.0-in.) long doublers.

TEST APPARATUS AND INSTRUMENTATION

All specimens were tested in a 534-kN (120 000-lbf) capacity hydraulic testing machine except the Celion 6000/LARC-160 tensile specimens, which were tested in a 245-kN (55 000-lbf) capacity hydraulic testing machine. Load was applied to the Celion 6000/PMR-15 tensile specimens through wedge grips. Load was applied to the Celion 6000/LARC-160 tensile specimens through hydraulic grips, using a grip pressure of 6.89 MPa (1000 psi), and through cellulose acetate shims between the specimen ends and the grip faces. For open-hole and bolted-joint specimens, load was applied through load links (steel plates 3.05 mm (0.12 in.) thick and 2.5 cm (1.0 in.) wide). The load links were pin-connected at the loading heads using 1.270-cm (0.500-in.) diameter pins and slotted grips. For open-hole specimens, the load links were clamped to the specimen doublers with 6.35-mm (0.25-in.) diameter bolts torqued to 3.4 N-m (30 lbf-in.). When bolted-joint specimens were tested, the upper load links had 4.83-mm (0.19-in.) diameter holes. These load links were clamped to the specimen with a nominal 4.83-mm (0.19-in.) diameter bolt torqued to 1.7 N-m (15 lbf-in.), which provided the double-lap test joint. (See fig. 3.)

Tensile specimens were instrumented with back-to-back strain gages at the center of the specimen test section. Load and strain were recorded on an X-Y recorder. For open-hole and bolted-joint specimen tests, load and loading-head displacement were recorded on an X-Y plotter. Loading-head displacement was measured with a direct-current displacement transducer (DCDT).

The tests at low and elevated temperatures were performed in a test chamber using liquid nitrogen and cartridge heaters. The interior of the test chamber, shown in figure 3, is 15.2 cm (6.0 in.) wide, 8.9 cm (3.5 in.) deep, and 20.3 cm (8.0 in.) high. In order to monitor test temperature, a copper-constantan thermocouple was clamped to the graphite/polyimide specimens 6.35 mm (0.25 in.) below the test joint.

Preliminary test runs were conducted on a representative test joint to determine uniformity of temperature across the test joint, temperature control settings for the oven, and test procedures. Preliminary tests were conducted at 116 K (-250°F) and 589 K (600°F), with five thermocouples in the double-lap test-joint area. No temperature difference was measured at 116 K (-250°F) across the joint area, and a difference of only 1 K (2°F) was measured at 589 K (600°F).

TEST PROCEDURES

Tensile and Open-Hole Specimens

Tensile specimens were aligned and clamped in the specimen grips. Load was applied at a rate of 5.34 kN/min (1200 lbf/min) to failure. Load-strain response and maximum load from the test-machine indicator were recorded.

Open-hole specimens were mounted in the test machine by aligning the doubler holes with the load-link holes. The bolts were inserted in the holes, and the nuts were turned until the load-link plates contacted the doublers without applying a clamping force. A tensile preload of approximately 445 N (100 lbf) was applied to the specimens before torquing the 6.35-mm (0.25-in.) bolts to 3.4 N-m (30 lbf-in.). Load was applied at a rate of 2.67 kN/min (600 lbf/min) to failure. Load-deflection response and maximum load from the test-machine indicator were recorded.

Bolted-Joint Specimens

Test procedures for all bolted-joint specimens were the same except for the establishment of temperature for the specimens at low (116 K (-250°F)) and elevated (589 K (600°F)) temperatures prior to loading. Each specimen was mounted in the load train by aligning the specimen holes with the corresponding load-link holes and inserting the appropriate bolt. The nuts were turned until the load-link plates contacted the specimen surfaces without applying a clamping force. A tensile preload of approximately 445 N (100 lbf) was applied to the specimens before torquing the 4.83-mm (0.19-in.) test bolt to 1.7 N-m (15 lbf-in.) and the 6.35-mm (0.25-in.) doubler bolt to 3.4 N-m (30 lbf-in.). The clamping force was applied to the load-link plates rather than directly to the specimen. A load rate of 2.67 kN/min (600 lbf/min) was set within the linear load-deflection response of the specimen, and the corresponding head speed was maintained to specimen failure. Load-deflection response and maximum load from the test-machine indicator were recorded.

Prior to loading, specimens at low and elevated temperatures were enclosed in a split test chamber which was precooled or preheated to the appropriate test temperature. This was accomplished by opening the chamber door, rotating the chamber until the specimen was properly aligned in slots through the upper and lower chamber walls, and closing the chamber door. (See fig. 3.) For specimens tested at 116 K (-250°F), 20 minutes was required for the specimen to reach a stable test temperature. For specimens tested at 589 K (600°F), 37 minutes was required for the specimen to reach a stable test temperature. Both types of specimens were held at test temperature an additional 10 minutes before loading to failure.

TEST RESULTS

Tensile Tests

Tensile-test results obtained at room temperature are presented in table I. Average tensile properties of the in-house Celion 6000/PMR-15 and the Celion 6000/LARC-160 laminates were essentially the same. The in-house Celion 6000/PMR-15 specimens had a tensile strength of 469 MPa (68.0 ksi) and a Young's modulus of 45.6 GPa (6.61×10^6 psi). The Celion 6000/LARC-160 specimens had a tensile strength of 479 MPa (69.5 ksi) and a Young's modulus of 43.4 GPa (6.30×10^6 psi). The average tensile strength of 396 MPa (57.4 ksi) for the contract Celion 6000/PMR-15 laminate was low compared with the in-house laminate. The tensile strength of the contract specimens was expected to be higher than the in-house specimens because the contract laminate had a higher fiber volume fraction F_v (64 percent) than the in-house laminate (55 percent). This difference in fiber volume fraction was reflected in the elastic modulus of the laminates. Young's modulus was 52.7 GPa (7.65×10^6 psi) for the contract specimens and 45.6 GPa (6.61×10^6 psi) for the in-house specimens of Celion 6000/PMR-15. Failure of the contract Celion 6000/PMR-15 specimens at the tapered doublers and an ultimate tensile strain of only 0.79 percent cast doubt on the validity of the tensile strength obtained for the contract laminate.

Open-Hole Tests

Open-hole test results obtained at room temperature from specimens fabricated from the in-house Celion 6000/PMR-15 laminate are reported in table II. The effect of the 4.83-mm (0.19-in.) diameter hole on tensile strength was determined from specimens with $w/d = 4$, 5, and 6. Average net tensile strength was calculated for each value of w/d, based on failure load and net-section area at the hole. No significant difference in net tensile strength was obtained over the range of w/d values tested. The average net tensile strength for all the open-hole specimens was 363 MPa (52.6 ksi). Based on laminate strength obtained from tensile tests, this stress value translates into a 23-percent reduction in laminate strength due to the stress concentration around the unloaded hole.

Bolted-Joint Tests

Specimen and test data are presented for in-house Celion 6000/PMR-15 in tables III, IV, and V, for contract Celion 6000/PMR-15 in tables VI, VII, and VIII, and for Celion 6000/LARC-160 in tables IX, X, and XI. Net-tension, bearing, and shear-out stresses were calculated at maximum load using the following equations:

$$\sigma_{nt} = \frac{P}{(w - d)t}$$

$$\sigma_b = \frac{P}{d_b t}$$

$$\sigma_{so} = \frac{P}{2\left(e - \frac{d}{2}\right)t}$$

Failure mode data for all specimen tests are summarized in table XII. Average values of net-tension, bearing, and shear-out stresses at failure were calculated for each joint geometry and test temperature, and the results are presented in table XIII.

Failure modes.- Five failure modes were observed. The failure modes are defined as bearing, net tension, shear-out, multiple, and combination. Typical examples of failures are shown in figure 4. The multiple and combination failures appear to be a combination of cleavage or shear-out and net-tension failure. The major difference between these two failure modes is the occurrence of net-tension failure on both sides of the bolt hole in the multiple mode.

Determination of failure mode was based upon visual examination of the failed specimen and the record of load-displacement. Typical recordings of bearing and net-tension failures at the three test temperatures are shown in figure 5 for in-house Celion 6000/PMR-15 specimens. The magnitude of displacement and shape of the curve were distinctive for each of these failure modes.

One objective of the test program was to obtain laminate joint strengths from single-mode failures in net tension, bearing, and shear-out. For the Celion 6000/PMR-15 laminates, only the shear-out mode at 116 K (-250°F) was not obtained. Table XII shows that in most cases the in-house and contract specimens of Celion 6000/PMR-15 had the same failure modes at corresponding joint ratios and test temperatures. Bearing failure at lower joint ratios at 116 K (-250°F) and 297 K

(75°F) for the contract specimens was attributed to a thinner laminate. The contract laminate had a nominal thickness of 2.29 mm (0.09 in.) compared with a nominal thickness of 2.79 mm (0.11 in.) for the in-house laminate. For the Celion 6000/LARC-160 laminate, the bearing failure mode was not obtained at 116 K (-250°F) and 589 K (600°F). At these temperatures, $e/d > 4$ at $w/d \geqslant 6$ would be required to obtain a bearing failure mode. A bearing stress value obtained from a specimen that had a two-mode failure rather than just a bearing failure could be low and not indicative of joint bearing strength.

Joint stresses.- Stress values reported herein were calculated at maximum load. Maximum load was achieved sometime after laminate damage had been initiated, as indicated by the load-displacement curves in figure 5. The average value of net-tension, bearing, and shear-out stress for each joint geometry and test temperature are reported in table XIII. The test results showed no significant differences in maximum joint stresses between the graphite/polyimide laminates at corresponding test conditions. In general, the contract Celion 6000/PMR-15 specimens had joint stresses slightly higher than in-house specimens at corresponding joint ratios and temperatures. In general, Celion 6000/LARC-160 specimens had joint stresses slightly lower at 116 K (-250°F) and 297 K (75°F), but slightly higher at 589 K (600°F), than in-house Celion 6000/PMR-15 specimens at the same joint ratios.

The effect of joint geometry and temperature on the net-tension and bearing stresses at failure are shown in figures 6 through 8. Net-tension and bearing stresses decrease with increasing temperature from 116 K (-250°F) to 589 K (600°F) for all values of w/d and e/d tested. For any given temperature and value of e/d, the net-tension stress decreases with increasing w/d, and bearing stress decreases with decreasing w/d, as expected. The effect of temperature and e/d on the shear-out stresses of specimens for $w/d = 6$ are shown in figure 9. Shear-out stress also decreases with increasing temperature from 116 K (-250°F) to 589 K (600°F) for all joint ratios. At any test temperature, shear-out stress decreases with increasing e/d. Table XIV lists joint strengths in net tension, bearing, and shear-out for all test temperatures. The average bearing strength for the Celion 6000/PMR-15 specimens was 1310 MPa (190 ksi) at 116 K (-250°F), 1076 MPa (156 ksi) at 297 K (75°F), and 738 MPa (107 ksi) at 589 K (600°F). The average bearing strength for the Celion 6000/LARC-160 specimens was $\geqslant$1248 MPa (181 ksi) at 116 K (-250°F), 1069 MPa (155 ksi) at 297 K (75°F), and $\geqslant$745 MPa (108 ksi) at 589 K (600°F).

CONCLUSIONS

An experimental study was conducted to determine failure modes and bolted-joint strengths for graphite/polyimide laminates of Celanese Celion 6000/PMR-15 and Celion 6000/LARC-160. The 16-ply, quasi-isotropic laminates had a fiber orientation of $[0/45/90/-45]_{2S}$. Double-lap joint specimens with a single 4.83-mm (0.19-in.) diameter bolt torqued to 1.7 N-m (15 lbf-in.) were tested in tension at 116 K (-250°F), 297 K (75°F), and 589 K (600°F). The following conclusions are based on the experimental results presented herein:

1. The effect of a 4.83-mm (0.19-in.) diameter hole on the Celion 6000/PMR-15 laminate was a 23-percent reduction in net tensile strength at 297 K (75°F) due to the stress concentration around the unloaded hole.

2. Five failure modes were obtained and were defined as bearing, net tension, shear-out, multiple, and combination.

3. There were no significant differences in maximum joint stresses between the laminates at corresponding test conditions.

4. Laminate joint strengths were obtained from single-mode failures in net tension, bearing, and shear-out, except for shear-out at 116 K (-250°F) in the Celion 6000/PMR-15 specimens and bearing at 116 K (-250°F) and 589 K (600°F) in the Celion 6000/LARC-160 specimens.

5. The average bearing strength for the Celion 6000/PMR-15 specimens was 1310 MPa (190 ksi) at 116 K (-250°F), 1076 MPa (156 ksi) at 297 K (75°F), and 738 MPa (107 ksi) at 589 K (600°F). The average bearing strength for the Celion 6000/LARC-160 specimens was >1248 MPa (181 ksi) at 116 K (-250°F), 1069 MPa (155 ksi) at 297 K (75°F), and >745 MPa (108 ksi) at 589 K (600°F).

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TABLE I.- TENSILE PROPERTIES OF QUASI-ISOTROPIC GRAPHITE/POLYIMIDE LAMINATES AT ROOM TEMPERATURE

Material system	Specimen	Ultimate tensile strength, MPa (ksi)	Ultimate tensile strain, percent	Young's modulus, GPa (10^6 psi)
In-house Celion 6000/PMR-15;	1TR	483 (70.1)	1.09	45.4 (6.58)
F_v = 55.0 percent;	2TR	457 (66.3)	1.07	44.0 (6.38)
T_g = 589 K (600°F)	3TR	482 (69.9)	1.07	45.8 (6.64)
	4TR	444 (64.4)	1.00	45.9 (6.65)
	5TR	472 (68.5)	1.04	45.9 (6.66)
	6TR	476 (69.0)	1.04	46.3 (6.72)
Average		469 (68.0)	1.05	45.6 (6.61)
Contract Celion 6000/PMR-15;	105-1	379 (55.0)	0.70	58.1 (8.42)
F_v = 64.0 percent;	105-2	425 (61.6)	.88	49.6 (7.19)
T_g = 595 K (612°F)	105-3	383 (55.5)	.80	50.6 (7.34)
Average		396 (57.4)	0.79	52.7 (7.65)
Celion 6000/LARC-160;	1T-N	499 (72.4)	1.21	43.0 (6.24)
F_v = 56.0 percent;	2T-N	484 (70.2)	1.14	44.9 (6.51)
T_g = 609 K (636°F)	3T-N	457 (66.3)	1.13	43.2 (6.26)
	4T-N	456 (66.2)	1.13	42.5 (6.16)
	5T-N	478 (69.3)	1.20	42.6 (6.18)
	6T-N	486 (70.5)	1.21	43.1 (6.25)
	7T-N	495 (71.8)	1.18	44.7 (6.49)
Average		479 (69.5)	1.17	43.4 (6.30)

TABLE II.- RESULTS OF OPEN-HOLE CELION 6000/PMR-15 SPECIMENS TESTED AT ROOM TEMPERATURE

Specimen	Hole diameter, mm (in.)	Width, mm (in.)	Average thickness, mm (in.)	w/d	Failure load, kN (lbf)	Net-tensile strength, MPa (ksi)
10H-76W-1	4.849 (0.1909)	19.261 (0.7583)	2.802 (0.1103)	4.0	14.81 (3330)	367 (53.2)
-2	4.849 (.1909)	19.218 (.7566)	2.797 (.1101)	4.0	14.55 (3270)	362 (52.5)
20H-76W-1	4.851 (.1910)	19.215 (.7565)	2.814 (.1108)	4.0	14.03 (3155)	347 (50.4)
-2	4.854 (.1911)	19.169 (.7547)	2.797 (.1101)	4.0	14.06 (3160)	352 (51.0)
					Average	357 (51.8)
10H-95W-1	4.851 (0.1910)	24.074 (0.9478)	2.797 (0.1101)	5.0	19.37 (4355)	361 (52.3)
-2	4.859 (.1913)	24.110 (.9492)	2.791 (.1099)	5.0	18.86 (4240)	351 (50.9)
20H-95W-1	4.862 (.1914)	24.006 (.9451)	2.746 (.1081)	4.9	19.37 (4355)	369 (53.5)
-2	4.859 (.1913)	23.990 (.9445)	2.761 (.1087)	4.9	19.75 (4440)	374 (54.2)
					Average	363 (52.6)
10H-114W-1	4.849 (0.1909)	28.727 (1.131)	2.794 (0.1100)	5.9	23.53 (5290)	353 (51.2)
-2	4.851 (.1910)	28.778 (1.133)	2.758 (.1086)	5.9	24.24 (5450)	367 (53.3)
20H-114W-1	4.849 (.1909)	28.829 (1.135)	2.804 (.1104)	6.0	24.64 (5540)	367 (53.2)
-2	4.851 (.1910)	28.804 (1.134)	2.776 (.1093)	5.9	25.27 (5680)	380 (55.1)
					Average	367 (53.2)

TABLE III.- BOLTED-JOINT DATA FOR IN-HOUSE CELION 6000/PMR-15 SPECIMENS TESTED AT 116 K (-250°F)

Failure mode key:	T	Net tension	C	Combination
	B	Bearing	M	Multiple

(a) SI Units

Specimen	Bolt diameter, mm	Hole diameter, mm	Width, mm	Edge distance, mm	Average thickness, mm	Maximum load, kN	Net-tension stress, MPa	Bearing stress, MPa	Shear-out stress, MPa	Failure mode
1L-76W-57	4.928	4.953	19.337	14.630	2.626	12.19	323	942	191	T
3L		4.948	19.355	14.585	2.697	13.06	336	982	200	T
2L-76W-76	4.928	4.953	19.355	19.393	2.624	14.23	376	1101	161	T
3L		4.950	19.289	19.307	2.743	14.10	359	1043	152	T
1L-95W-57	4.928	4.953	24.171	14.587	2.720	14.90	285	1111	226	T
2L		4.953	24.181	14.519	2.733	15.30	291	1136	232	T
3L		4.948	24.130	14.549	2.761	14.86	281	1091	223	T
1L-95W-76	4.928	4.953	24.160	19.357	2.779	16.88	316	1233	180	T
3L		4.953	24.160	19.444	2.771	16.57	312	1213	177	T
1L-114W-38	4.928	4.938	28.956	9.713	2.731	11.79	180	876	298	C
2L		4.935	29.007	9.685	2.761	11.99	181	881	301	M
3L		4.948	28.981	9.682	2.692	11.99	185	904	309	C
1L-114W-57	4.928	4.961	28.981	14.587	2.728	15.10	230	1123	228	C
2L		4.958	28.956	14.516	2.738	15.01	228	1113	228	M
3L		4.950	28.981	14.559	2.731	15.84	241	1177	240	M
1L-114W-76	4.928	4.945	29.032	19.809	2.761	17.75	267	1304	191	B
2L		4.938	28.956	19.324	2.705	16.59	256	1245	182	B
3L		4.950	28.981	19.378	2.746	17.30	262	1278	186	B

TABLE III.- Concluded

(b) U.S. Customary Units

Specimen	Bolt diameter, in.	Hole diameter, in.	Width, in.	Edge distance, in.	Average thickness, in.	Maximum load, lbf	Net-tension stress, ksi	Bearing stress, ksi	Shear-out stress, ksi	Failure mode
1L-76W-57	0.1940	0.1950	0.7613	0.5760	0.1034	2740	46.8	136.6	27.7	T
3L		.1948	.7620	.5742	.1062	2935	48.7	142.4	29.0	T
2L-76W-76	0.1940	0.1950	0.7620	0.7635	0.1033	3200	54.6	159.7	23.3	T
3L		.1949	.7594	.7601	.1080	3170	52.0	151.3	22.1	T
1L-95W-57	0.1940	0.1950	0.9516	0.5743	0.1071	3350	41.3	161.2	32.8	T
2L		.1950	.9520	.5716	.1076	3440	42.2	164.8	33.7	T
3L		.1948	.9500	.5728	.1087	3340	40.7	158.3	32.3	T
1L-95W-76	0.1940	0.1950	0.9512	0.7621	0.1094	3795	45.9	178.8	26.1	T
3L		.1950	.9512	.7655	.1091	3725	45.2	176.0	25.6	T
1L-114W-38	0.1940	0.1944	1.140	0.3824	0.1075	2650	26.1	127.1	43.2	C
2L		.1943	1.142	.3813	.1087	2695	26.2	127.8	43.6	M
3L		.1948	1.141	.3812	.1060	2695	26.9	131.1	44.8	C
1L-114W-57	0.1940	0.1953	1.141	0.5743	0.1074	3395	33.4	162.9	33.1	C
2L		.1952	1.140	.5715	.1078	3375	33.1	161.4	33.0	M
3L		.1949	1.141	.5732	.1075	3560	35.0	170.7	34.8	M
1L-114W-76	0.1940	0.1947	1.143	0.7799	0.1087	3990	38.7	189.2	27.7	B
2L		.1944	1.140	.7608	.1065	3730	37.1	180.6	26.4	B
3L		.1949	1.141	.7629	.1081	3890	38.0	185.4	27.0	B

TABLE IV.- BOLTED-JOINT DATA FOR IN-HOUSE CELION 6000/PMR-15 SPECIMENS TESTED AT 297 K (75°F)

Failure mode key:	
T	Net tension
B	Bearing
S	Shear-out
M	Multiple

(a) SI Units

Specimen	Bolt diameter, mm	Hole diameter, mm	Width, mm	Edge distance, mm	Average thickness, mm	Maximum load, kN	Net-tension stress, MPa	Bearing stress, MPa	Shear-out stress, MPa	Failure mode
1R-76W-57-1	4.928	4.953	19.365	14.526	2.776	11.92	298	871	179	T
-2		4.961	19.309	14.460	2.713	12.41	319	929	191	T
2R-76W-57-1		4.943	19.385	14.542	2.771	12.37	309	906	185	T
-2		4.953	19.332	14.493	2.720	11.85	303	885	181	T
1R-76W-76-3	4.928	4.943	19.362	19.243	2.769	12.12	303	890	130	T
-4		4.950	19.317	19.266	2.731	12.72	324	943	139	T
2R-76W-76-3		4.976	19.355	19.248	2.776	11.97	300	875	129	T
-4		4.940	19.317	19.266	2.743	12.74	323	940	139	T
1R-95W-57-1	4.928	4.953	23.906	14.488	2.781	11.61	221	847	174	M
-2		4.950	24.122	14.542	2.751	13.12	249	968	198	M
2R-95W-57-1		4.943	24.209	14.488	2.761	12.94	243	951	195	M
-2		4.935	24.145	14.516	2.751	13.72	260	1013	207	M
1R-95W-76-3	4.928	4.945	24.072	19.266	2.776	13.81	260	1010	148	B
-4		4.943	24.074	19.258	2.758	13.90	263	1021	150	B-T
2R-95W-76-3		4.953	24.194	19.246	2.756	14.10	266	1041	152	B
-4		4.953	24.155	19.251	2.766	14.50	273	1065	157	B
1R-114W-38-1	4.928	4.950	28.956	9.591	2.797	9.43	141	685	237	S
-2		4.950	28.956	9.690	2.769	9.27	139	680	232	S
2R-114W-38-1		4.956	28.931	9.606	2.743	10.12	154	749	259	S
-2		4.953	28.956	9.614	2.743	9.83	150	727	251	S
1R-114W-57-1	4.928	4.935	29.007	14.359	2.830	14.03	206	1007	208	M
-2		4.945	28.956	14.506	2.784	12.14	182	885	181	S
2R-114W-57-1		4.940	28.981	14.542	2.809	13.08	194	945	193	M
-2		4.945	28.956	14.478	2.758	13.46	203	990	203	M
1R-114W-76-3	4.928	4.950	29.007	19.281	2.827	13.75	202	987	145	B
-4		4.968	28.981	19.243	2.802	14.86	221	1076	158	B
2R-114W-76-3		4.958	28.981	19.261	2.804	15.30	228	1108	163	B-T
-4		4.956	28.956	19.220	2.758	13.46	203	989	145	B

TABLE IV.- Concluded

(b) U.S. Customary Units

Specimen	Bolt diameter, in.	Hole diameter, in.	Width, in.	Edge distance, in.	Average thickness, in.	Maximum load, lbf	Net-tension stress, ksi	Bearing stress, ksi	Shear-out stress, ksi	Failure mode
1L-76W-57-1	0.1940	0.1950	0.7624	0.5719	0.1093	2680	43.2	126.4	25.9	T
-2		.1953	.7602	.5693	.1068	2790	46.2	134.7	27.7	T
2R-76W-57-1		.1946	.7632	.5725	.1091	2780	44.8	131.4	26.8	T
-2		.1950	.7611	.5706	.1071	2665	44.0	128.3	26.3	T
1R-76W-76-3	0.1940	0.1946	0.7623	0.7576	0.1090	2725	44.0	129.1	18.9	T
-4		.1949	.7605	.7585	.1075	2860	47.0	136.8	20.1	T
2R-76W-76-3		.1959	.7620	.7578	.1093	2690	43.5	126.9	18.7	T
-4		.1945	.7605	.7585	.1080	2865	46.9	136.4	20.1	T
1R-95W-57-1	0.1940	0.1950	0.9412	0.5704	0.1095	2610	32.0	122.9	25.2	M
-2		.1949	.9497	.5725	.1083	2950	36.1	140.4	28.7	M
2R-95W-57-1		.1946	.9531	.5704	.1087	2910	35.3	138.0	28.3	M
-2		.1943	.9506	.5715	.1083	3085	37.7	146.9	30.0	M
1R-95W-76-3	0.1940	0.1947	0.9477	0.7585	0.1093	3105	37.7	146.5	21.5	B
-4		.1946	.9478	.7582	.1086	3125	38.2	148.1	21.8	B-T
2R-95W-76-3		.1950	.9525	.7577	.1085	3170	38.6	151.0	22.1	B
-4		.1950	.9510	.7579	.1089	3260	39.6	154.5	22.7	B
1R-114W-38-1	0.1940	0.1949	1.140	0.3776	0.1101	2120	20.4	99.3	34.4	S
-2		.1949	1.140	.3815	.1090	2085	20.2	98.6	33.7	S
2R-114W-38-1		.1951	1.139	.3782	.1080	2275	22.3	108.6	37.5	S
-2		.1950	1.140	.3785	.1080	2210	21.7	105.5	36.4	S
1R-114W-57-1	0.1940	0.1943	1.142	0.5653	0.1114	3155	29.9	146.0	30.2	M
-2		.1947	1.140	.5711	.1096	2730	26.4	128.4	26.3	S
2R-114W-57-1		.1945	1.141	.5725	.1106	2940	28.1	137.1	28.0	M
-2		.1947	1.140	.5700	.1086	3025	29.5	143.6	29.5	M
1R-114W-76-3	0.1940	0.1949	1.142	0.7591	0.1113	3090	29.3	143.1	21.0	B
-4		.1956	1.141	.7576	.1103	3340	32.0	156.1	22.9	B
2R-114W-76-3		.1952	1.141	.7583	.1104	3440	33.0	160.7	23.6	B-T
-4		.1951	1.140	.7567	.1086	3025	29.5	143.4	21.1	B

TABLE V.- BOLTED-JOINT DATA FOR IN-HOUSE CELION 6000/PMR-15 SPECIMENS TESTED AT 589 K (600°F)

Failure mode key: T Net tension
B Bearing
S Shear-out

(a) SI Units

Specimen	Bolt diameter, mm	Hole diameter, mm	Width, mm	Edge distance, mm	Average thickness, mm	Maximum load, kN	Net-tension stress, MPa	Bearing stress, MPa	Shear-out stress, MPa	Failure mode
1E-76W-57	4.928	4.945	19.337	14.602	2.687	7.61	197	574	117	T
2E		4.948	19.355	14.658	2.675	8.23	214	625	126	T
3E		4.953	19.286	14.597	2.769	7.83	197	547	117	T
1E-76W-76	4.928	4.950	19.352	19.398	2.728	8.54	217	636	92	B-T
2E		4.956	19.347	19.340	2.746	8.47	214	626	92	B-T
3E		4.953	19.309	19.474	2.761	8.52	215	626	91	B-T
1E-95W-57	4.928	4.953	24.155	14.524	2.756	8.52	161	627	128	B-S
2E		4.953	24.160	14.105	2.753	8.27	157	609	129	B-S
3E		4.956	24.186	14.481	2.786	8.47	158	617	127	B-S
1E-95W-76	4.928	4.956	24.181	19.421	2.830	9.72	179	697	101	B-T
2E		4.953	24.178	19.154	2.812	9.43	174	681	101	B-T
3E		4.943	24.163	19.375	2.789	9.39	175	683	99	B-T
1E-114W-38	4.928	4.938	28.981	9.688	2.794	7.27	108	528	180	S
2E		4.945	28.956	9.614	2.786	6.94	103	505	174	S
3E		4.948	28.981	9.662	2.690	6.27	97	473	162	S
1E-114W-57	4.928	4.956	28.981	14.547	2.766	8.63	130	633	129	B-S
2E		4.953	28.956	14.488	2.766	8.54	129	627	128	B-S
3E		4.953	28.956	14.488	2.761	8.47	128	623	128	B-S
1E-114W-76	4.928	4.978	28.981	19.454	2.764	9.50	143	697	101	B
2E		4.940	28.981	19.340	2.733	9.56	145	710	103	B
3E		4.950	28.981	19.388	2.758	9.59	145	705	103	B

TABLE V.- Concluded

(b) U.S. Customary Units

Specimen	Bolt diameter, in.	Hole diameter, in.	Width, in.	Edge distance, in.	Average thickness, in.	Maximum load, lbf	Net-tension stress, ksi	Bearing stress, ksi	Shear-out stress, ksi	Failure mode
1E-76W-57	0.1940	0.1947	0.7613	0.5749	0.1058	1710	28.5	83.3	16.9	T
2E		.1948	.7620	.5771	.1053	1850	31.0	90.6	18.3	T
3E		.1950	.7593	.5747	.1090	1760	28.6	83.2	16.9	T
1E-76W-76	0.1940	0.1949	0.7619	0.7637	0.1074	1920	31.5	92.2	13.4	B-T
2E		.1951	.7617	.7614	.1081	1905	31.1	90.8	13.3	B-T
3E		.1950	.7602	.7667	.1087	1915	31.2	90.8	13.2	B-T
1E-95W-57	0.1940	0.1950	0.9510	0.5718	0.1085	1915	23.4	91.0	18.6	B-S
2E		.1950	.9512	.5553	.1084	1860	22.7	88.4	18.7	B-S
3E		.1951	.9522	.5701	.1097	1905	22.9	89.5	18.4	B-S
1E-95W-76	0.1940	0.1951	0.9520	0.7646	0.1114	2185	25.9	101.1	14.7	B-T
2E		.1950	.9519	.7541	.1107	2120	25.3	98.7	14.6	B-T
3E		.1946	.9513	.7628	.1098	2110	25.4	99.1	14.4	B-T
1E-114W-38	0.1940	0.1944	1.141	0.3814	0.1100	1635	15.7	76.6	26.1	S
2E		.1947	1.140	.3785	.1097	1560	15.0	73.3	25.3	S
3E		.1948	1.141	.3804	.1059	1410	14.1	68.6	23.5	S
1E-114W-57	0.1940	0.1951	1.141	0.5727	0.1089	1940	18.8	91.8	18.7	B-S
2E		.1950	1.140	.5704	.1089	1920	18.7	90.9	18.6	B-S
3E		.1950	1.140	.5704	.1087	1905	18.5	90.3	18.5	B-S
1E-114W-76	0.1940	0.1960	1.141	0.7659	0.1088	2135	20.8	101.1	14.7	B
2E		.1945	1.141	.7614	.1076	2150	21.1	103.0	15.0	B
3E		.1949	1.141	.7633	.1086	2155	21.0	102.3	14.9	B

TABLE VI.- BOLTED-JOINT DATA FOR CONTRACT CELION 6000/PMR-15 SPECIMENS TESTED AT 116 K (-250°F)

Failure mode key: T Net tension; B Bearing; S Shear-out; C Combination; M Multiple

(a) SI Units

Specimen	Bolt diameter, mm	Hole diameter, mm	Width, mm	Edge distance, mm	Average thickness, mm	Maximum load, kN	Net-tension stress, MPa	Bearing stress, MPa	Shear-out stress, MPa	Failure mode
2L-76W-57	4.790	4.841	19.289	14.300	2.248	11.25	347	1045	211	T
4L		4.821	19.274	14.521	2.261	12.19	373	1125	223	T
5L		4.836	19.347	14.094	2.286	11.85	357	1082	222	T
1L-76W-76	4.790	4.793	19.309	19.408	2.118	10.96	356	1080	152	T
2L		4.793	19.390	19.329	2.230	10.74	330	1005	142	T
3L		4.793	19.340	19.329	2.169	10.79	342	1038	147	T
2L-95W-57	4.790	4.823	24.272	14.399	2.263	12.08	274	1114	223	B-S
3L		4.796	24.239	14.313	2.240	13.08	300	1218	245	T
4L		4.796	24.168	14.422	2.235	14.83	343	1385	276	B-C
4L-95W-76	4.790	4.811	24.153	19.342	2.096	13.19	325	1314	185	B-S
5L		4.801	24.183	19.492	2.070	12.25	305	1236	173	B-T
6L		4.808	24.227	19.482	2.098	12.43	305	1237	174	B
1L-114W-38	4.790	4.811	28.943	9.657	2.261	11.39	209	1051	347	C
2L		4.808	28.959	9.581	2.212	10.41	195	982	328	C
3L		4.829	28.936	9.368	2.182	10.59	201	1013	349	C
1L-114W-57	4.790	4.803	28.913	14.453	2.248	13.77	254	1278	254	B-C
2L		4.790	28.948	14.430	2.235	13.75	254	1284	256	B-M
3L		4.821	28.961	14.496	2.253	13.39	246	1240	246	B-C
1L-114W-76	4.790	4.796	28.834	19.256	2.187	14.61	278	1395	198	B
3L		4.813	28.839	19.439	2.106	12.94	256	1283	181	B
4L		4.803	28.931	19.332	2.090	13.52	268	1351	191	B

TABLE VI.- Concluded

(b) U.S. Customary Units

Specimen	Bolt diameter, in.	Hole diameter, in.	Width, in.	Edge distance, in.	Average thickness, in.	Maximum load, lbf	Net-tension stress, ksi	Bearing stress, ksi	Shear-out stress, ksi	Failure mode
2L-76W-57	0.1886	0.1906	0.7594	0.5630	0.0885	2530	50.3	151.6	30.6	T
4L		.1898	.7588	.5717	.0890	2740	54.1	163.2	32.3	T
5L		.1904	.7617	.5549	.0900	2665	51.8	157.0	32.2	T
1L-76W-76	0.1886	0.1887	0.7602	0.7641	0.0834	2465	51.7	156.7	22.1	T
2L		.1887	.7634	.7610	.0878	2415	47.9	145.8	20.6	T
3L		.1887	.7614	.7610	.0854	2425	49.6	150.6	21.3	T
2L-95W-57	0.1886	0.1899	0.9556	0.5669	0.0891	2715	39.8	161.6	32.3	B-S
3L		.1888	.9543	.5635	.0882	2940	43.5	176.7	35.5	T
4L		.1888	.9515	.5678	.0880	3335	49.7	200.9	40.0	B-C
4L-95W-76	0.1886	0.1894	0.9509	0.7615	0.0825	2965	47.2	190.6	26.9	B-S
5L		.1890	.9521	.7674	.0815	2755	44.3	179.2	25.1	B-T
6L		.1893	.9538	.7670	.0826	2795	44.3	179.4	25.2	B
1L-114W-38	0.1886	0.1894	1.1395	0.3802	0.0890	2560	30.3	152.5	50.4	C
2L		.1893	1.1401	.3772	.0871	2340	28.3	142.4	47.6	C
3L		.1901	1.1392	.3688	.0859	2380	29.2	146.9	50.6	C
1L-114W-57	0.1886	0.1891	1.1383	0.5690	0.0885	3095	36.8	185.4	36.9	B-C
2L		.1886	1.1397	.5681	.0880	3090	36.9	186.2	37.1	B-M
3L		.1898	1.1402	.5707	.0887	3010	35.7	179.9	35.7	B-C
1L-114W-76	0.1886	0.1888	1.1352	0.7581	0.0861	3285	40.3	202.3	28.7	B
3L		.1895	1.1354	.7653	.0829	2910	37.1	186.1	26.2	B
4L		.1891	1.1390	.7611	.0823	3040	38.9	195.9	27.7	B

TABLE VII.- BOLTED-JOINT DATA FOR CONTRACT CELION 6000/PMR-15 SPECIMENS TESTED AT 297 K (75°F)

[Failure mode key: T Net tension S Shear-out
B Bearing C Combination]

(a) SI Units

Specimen	Bolt diameter, mm	Hole diameter, mm	Width, mm	Edge distance, mm	Average thickness, mm	Maximum load, kN	Net-tension stress, MPa	Bearing stress, MPa	Shear-out stress, MPa	Failure mode
1R-76W-57-2	4.790	4.803	19.324	14.415	2.088	9.45	312	943	188	T
2R-76W-57-1		4.796	19.431	14.348	2.162	10.70	339	1036	207	T
-2		4.796	19.373	14.379	2.139	9.34	300	911	182	T
1R-76W-76-3	4.790	4.806	19.314	19.421	2.098	10.61	348	1054	148	T
-4		4.798	19.334	19.164	2.144	9.74	312	949	136	B-T
2R-76W-76-3		4.808	19.431	19.271	2.169	10.23	323	985	140	B
4		4.808	19.401	19.296	2.182	10.85	341	1038	148	B-T
1R-95W-57-1	4.790	4.790	24.112	14.453	2.261	10.90	250	1011	200	B
-2		4.790	24.234	14.295	2.250	10.96	251	1018	205	B-C
2R-95W-57-1		4.803	24.194	14.280	2.228	10.74	248	1009	203	B-C
-2		4.806	24.140	14.288	2.273	11.52	262	1057	213	B-C
1R-95W-76-3	4.790	4.806	24.140	19.319	2.240	11.74	271	1096	155	B
-4		4.811	24.194	19.271	2.273	11.74	267	1077	153	B
2R-95W-76-3		4.813	24.237	19.299	2.223	12.63	293	1187	168	B
-4		4.806	24.171	19.395	2.281	11.32	256	1038	146	B
1R-114W-38-1	4.790	4.803	28.923	9.545	2.217	8.21	154	771	259	S
-2		4.796	28.842	9.530	2.027	7.38	152	758	255	S
2R-114W-38-1		4.811	28.956	9.581	2.235	7.96	148	743	248	S
-2		4.806	28.964	9.558	2.090	7.56	150	756	253	S
1R-114W-57-1	4.790	4.818	28.986	14.267	2.139	10.68	207	1040	210	B
-2		4.801	29.058	14.422	2.141	11.39	219	1110	221	B
2R-114W-57-1		4.806	28.865	14.432	2.075	10.19	204	1025	204	B
-2		4.811	29.027	14.435	2.093	9.76	192	976	194	B-C
1R-114W-76-3	4.790	4.811	29.007	19.347	2.268	12.25	223	1131	159	B
-4		4.806	29.007	19.345	2.240	12.32	228	1151	162	B
2R-114W-76-3		4.823	28.956	19.456	2.146	11.83	228	1153	162	B
-4		4.806	29.007	19.472	2.111	10.41	203	1027	138	B

TABLE VII.- Concluded

(b) U.S. Customary Units

Specimen	Bolt diameter, in.	Hole diameter, in.	Width, in.	Edge distance, in.	Average thickness, in.	Maximum load, lbf	Net-tension stress, ksi	Bearing stress, ksi	Shear-out stress, ksi	Failure mode
1R-76W-57-2	0.1886	0.1891	0.7608	0.5675	0.0822	2125	45.2	136.7	27.3	T
2R-76W-57-1		.1888	.7650	.5649	.0851	2405	49.1	150.3	30.0	T
-2		.1888	.7627	.5661	.0842	2100	43.5	132.1	26.4	T
1R-76W-76-3	0.1886	0.1892	0.7604	0.7646	0.0826	2385	50.5	152.9	21.5	T
-4		.1889	.7612	.7545	.0844	2190	45.3	137.7	19.7	B-T
2R-76W-76-3		.1893	.7650	.7587	.0854	2300	46.8	142.9	20.3	B
-4		.1893	.7638	.7597	.0859	2440	49.5	150.6	21.4	B-T
1R-95W-57-1	0.1886	0.1886	0.9493	0.5690	0.0890	2450	36.2	146.7	29.0	B
-2		.1886	.9541	.5628	.0886	2465	36.4	147.6	29.7	B-C
2R-95W-57-1		.1891	.9525	.5622	.0877	2415	36.0	146.4	29.4	B-C
-2		.1892	.9504	.5625	.0895	2590	38.0	153.3	30.9	B-C
1R-95W-76-3	0.1886	0.1892	0.9504	0.7606	0.0882	2640	39.3	159.0	22.5	B
-4		.1894	.9525	.7587	.0895	2640	38.7	156.2	22.2	B
2R-95W-76-3		.1895	.9542	.7598	.0875	2840	42.5	172.1	24.4	B
-4		.1892	.9516	.7636	.0898	2545	37.2	150.6	21.2	B
1R-114W-38-1	0.1886	0.1891	1.1387	0.3758	0.0873	1845	22.3	111.8	37.6	S
-2		.1888	1.1355	.3752	.0798	1660	22.0	109.9	37.0	S
2R-114W-38-1		.1894	1.1400	.3772	.0880	1790	21.4	107.8	36.0	S
-2		.1892	1.1403	.3763	.0823	1700	21.7	109.7	36.7	S
1R-114W-57-1	0.1886	0.1897	1.1412	0.5617	0.0842	2400	30.0	150.9	30.5	B
-2		.1890	1.1440	.5678	.0843	2560	31.8	161.0	32.1	B
2R-114W-57-1		.1892	1.1364	.5682	.0817	2290	29.6	148.7	29.6	B
-2		.1894	1.1428	.5683	.0824	2195	27.9	141.6	28.1	B-C
1R-114W-76-3	0.1886	0.1894	1.1420	0.7617	0.0893	2755	32.4	164.0	23.1	B
-4		.1892	1.1420	.7616	.0882	2770	33.0	166.9	23.5	B
2R-114W-76-3		.1899	1.1400	.7660	.0845	2660	33.1	167.3	23.5	B
-4		.1892	1.1420	.7666	.0831	2340	29.5	149.0	20.0	B

TABLE VIII.- BOLTED-JOINT DATA FOR CONTRACT CELION 6000/PMR-15 SPECIMENS TESTED AT 572 K (570°F)

Failure mode key: T Net tension
B Bearing
S Shear-out

(a) SI Units

Specimen	Bolt diameter, mm	Hole diameter, mm	Width, mm	Edge distance, mm	Average thickness, mm	Maximum load, kN	Net-tension stress, MPa	Bearing stress, MPa	Shear-out stress, MPa	Failure mode
1E-76W-57	4.790	4.839	19.177	14.321	2.261	7.01	216	647	130	T
3E		4.877	19.309	14.384	2.278	6.58	200	603	121	T
6E		4.864	19.286	14.277	2.245	5.83	180	542	110	T
4E-76W-76	4.790	4.798	19.362	19.390	2.129	6.23	201	611	86	B-T
5E		4.803	19.352	19.329	2.146	7.47	239	729	103	B-T
6E		4.790	19.368	19.279	2.223	7.72	239	725	103	B-T
1E-95W-57	4.790	4.829	24.094	14.409	2.202	7.05	166	670	134	B-S
5E		4.811	24.150	14.435	2.256	7.09	163	658	130	B-S
6E		4.806	24.191	14.432	2.233	6.96	161	650	130	B-S
1E-95W-76	4.790	4.790	24.214	19.342	2.118	7.52	183	742	105	B-T
2E		4.811	24.186	19.413	2.113	7.58	185	749	105	B-T
3E		4.813	24.158	19.416	2.098	7.81	192	776	110	B-T
4E-114W-38	4.790	4.821	28.953	9.495	2.238	6.25	110	583	197	S
5E		4.790	28.948	9.563	2.271	6.21	113	569	190	S
6E		4.790	28.938	9.545	2.223	6.18	114	581	194	S
4E-114W-57	4.790	4.806	28.928	14.409	2.202	7.76	146	734	147	B-S
5E		4.811	28.913	14.458	2.195	7.96	150	757	150	B-S
6E		4.811	28.933	14.387	2.189	7.52	142	715	143	B-S
2E-114W-76	4.790	4.811	28.999	19.243	2.065	8.01	161	811	115	B
5E		4.813	28.893	19.261	2.029	7.43	152	763	109	B
6E		4.793	28.854	19.362	2.040	7.34	150	754	106	B

TABLE VIII.- Concluded

(b) U.S. Customary Units

Specimen	Bolt diameter, in.	Hole diameter, in.	Width, in.	Edge distance, in.	Average thickness, in.	Maximum load, lbf	Net-tension stress, ksi	Bearing stress, ksi	Shear-out stress, ksi	Failure mode
1E-76W-57	0.1886	0.1905	0.7550	0.5638	0.0890	1575	31.3	93.8	18.9	T
3E		.1920	.7602	.5663	.0897	1480	29.0	87.5	17.5	T
6E		.1915	.7593	.5621	.0884	1310	26.1	78.6	15.9	T
4E-76W-76	0.1886	0.1889	0.7623	0.7634	0.0838	1400	29.1	88.6	12.5	B-T
5E		.1891	.7619	.7610	.0845	1680	34.7	105.7	14.9	B-T
6E		.1886	.7625	.7590	.0875	1735	34.6	105.2	14.9	B-T
1E-95W-57	0.1886	0.1901	0.9486	0.5673	0.0867	1585	24.1	97.2	19.4	B-S
5E		.1894	.9508	.5683	.0888	1595	23.6	95.5	18.9	B-S
6E		.1892	.9524	.5682	.0879	1565	23.3	94.3	18.8	B-S
1E-95W-76	0.1886	0.1886	0.9533	0.7615	0.0834	1690	26.5	107.6	15.2	B-T
2E		.1894	.9522	.7643	.0832	1705	26.9	108.6	15.3	B-T
3E		.1895	.9511	.7644	.0826	1755	27.9	112.5	15.9	B-T
4E-114W-38	0.1886	0.1898	1.1399	0.3738	0.0881	1405	16.8	84.6	28.6	S
5E		.1886	1.1397	.3765	.0894	1395	16.4	82.5	27.6	S
6E		.1886	1.1393	.3758	.0875	1390	16.6	84.2	28.2	S
4E-114W-57	0.1886	0.1892	1.1389	0.5673	0.0867	1745	21.2	106.4	21.3	B-S
5E		.1894	1.1383	.5692	.0864	1790	21.8	109.8	21.8	B-S
6E		.1894	1.1391	.5664	.0862	1690	20.6	103.7	20.8	B-S
2E-114W-76	0.1886	0.1894	1.1417	0.7576	0.0813	1800	23.3	117.6	16.7	B
5E		.1895	1.1375	.7583	.0799	1670	22.1	110.6	15.8	B
6E		.1887	1.1360	.7623	.0803	1650	21.7	109.3	15.4	B

TABLE IX.- BOLTED-JOINT DATA FOR CELION 6000/LARC-150 SPECIMENS TESTED AT 116 K (-250°F)

Failure mode key:		
	T Net tension	C Combination
	B Bearing	M Multiple
	S Shear-out	

(a) SI Units

Specimen	Bolt diameter, mm	Hole diameter, mm	Width, mm	Edge distance, mm	Average thickness, mm	Maximum load, kN	Net-tension stress, MPa	Bearing stress, MPa	Shear-out stress, MPa	Failure mode
1L-76W-57	4.780	4.841	19.317	14.458	2.962	13.08	305	925	183	T
3L		4.844	19.319	14.473	2.964	14.95	348	1053	210	T
2L-76W-76	4.780	4.839	19.319	19.291	2.992	15.28	352	1067	151	T
3L		4.844	19.309	19.301	3.028	16.01	365	1108	156	T
1L-95W-57	4.780	4.841	24.130	14.437	3.043	15.97	272	1100	219	T
2L		4.844	24.125	14.420	3.076	15.35	259	1043	208	T
3L		4.836	24.133	14.460	3.073	16.41	277	1116	222	T
1L-95W-76	4.780	4.839	24.130	19.268	3.071	18.15	306	1233	175	T
2L		4.846	24.130	19.291	3.071	17.57	296	1194	170	T
3L		4.844	24.122	19.276	3.056	17.39	295	1143	169	T
1L-114W-38	4.780	4.846	28.976	9.561	3.053	10.74	145	737	246	S
2L		4.844	28.969	9.594	3.048	11.70	159	803	268	S
3L		4.846	28.953	9.576	3.051	12.23	166	839	281	S
1L-114W-57	4.780	4.851	28.941	14.463	3.040	15.24	208	1049	208	C
2L		4.846	28.964	14.463	3.035	15.79	216	1088	216	M
3L		4.846	28.976	14.463	3.038	16.10	220	1109	220	M
1L-114W-76	4.780	4.851	28.986	19.177	3.053	18.62	252	1277	182	B-T
2L		4.839	28.961	19.172	3.056	17.68	240	1213	172	B-T
3L		4.849	28.971	19.187	3.023	18.06	248	1250	178	B-T

TABLE IX.- Concluded

(b) U.S. Customary Units

Specimen	Bolt diameter, in.	Hole diameter, in.	Width, in.	Edge distance, in.	Average thickness, in.	Maximum load, lbf	Net-tension stress, ksi	Bearing stress, ksi	Shear-out stress, ksi	Failure mode
1L-76W-57	0.1882	0.1906	0.7605	0.5692	0.1166	2940	44.3	134.2	26.6	T
3L		.1907	.7606	.5698	.1167	3360	50.5	152.7	30.4	T
2L-76W-76	0.1882	0.1905	0.7606	0.7595	0.1178	3435	51.1	154.7	21.9	T
3L		.1907	.7602	.7599	.1192	3600	53.0	160.7	22.6	T
1L-95W-57	0.1882	0.1906	0.9500	0.5684	0.1198	3590	39.5	159.6	31.7	T
2L		.1907	.9498	.5677	.1211	3450	37.5	151.3	30.2	T
3L		.1904	.9501	.5693	.1210	3690	40.2	161.8	32.2	T
1L-95W-76	0.1882	0.1905	0.9500	0.7586	0.1209	4080	44.4	178.9	25.4	T
2L		.1908	.9500	.7595	.1209	3950	43.0	173.2	24.6	T
3L		.1907	.9497	.7589	.1203	3910	42.8	173.0	24.5	T
1L-114W-38	0.1882	0.1908	1.1408	0.3764	0.1202	2415	21.1	106.9	35.7	S
2L		.1907	1.1405	.3777	.1200	2630	23.1	116.4	38.8	S
3L		.1908	1.1399	.3770	.1201	2750	24.1	121.7	40.7	S
1L-114W-57	0.1882	0.1910	1.1394	0.5694	0.1197	3425	30.2	152.2	30.2	C
2L		.1908	1.1403	.5694	.1195	3550	31.3	157.8	31.3	M
3L		.1908	1.1408	.5694	.1196	3620	31.9	160.9	31.9	M
1L-114W-76	0.1882	0.1910	1.1412	0.7550	0.1202	4185	36.6	185.2	26.4	B-T
2L		.1905	1.1402	.7548	.1203	3975	34.8	175.9	25.0	B-T
3L		.1909	1.1406	.7554	.1190	4060	35.9	181.3	25.8	B-T

TABLE X.- BOLTED-JOINT DATA FOR CELION 6000/LARC-160 SPECIMENS TESTED AT 297 K (75°F)

[Failure mode key: T Net tension; B Bearing; S Shear-out; C Combination]

(a) SI Units

Specimen	Bolt diameter, mm	Hole diameter, mm	Width, mm	Edge distance, mm	Average thickness, mm	Maximum load, kN	Net-tension stress, MPa	Bearing stress, MPa	Shear-out stress, MPa	Failure mode
1R-76W-57-1	4.780	4.841	19.314	14.435	2.977	13.34	310	936	187	T
2R-76W-57-1		4.834	19.299	14.437	2.974	13.61	316	959	190	T
-2		4.841	19.307	14.448	2.969	13.23	308	932	185	T
2R-76W-76-3	4.780	4.836	19.304	19.357	2.979	13.57	315	951	134	T
-4		4.844	19.312	19.365	2.977	13.75	319	964	137	T
1R-95W-57-1	4.780	4.841	24.135	14.430	2.985	13.72	238	963	192	B-C
-2		4.841	24.125	14.435	2.967	14.01	245	987	197	B-T
2R-95W-57-1		4.851	24.133	14.440	2.995	13.66	236	954	190	B-T
-2		4.841	24.117	14.455	2.977	13.77	240	965	192	B-T
1R-95W-76-3	4.780	4.846	24.138	19.248	2.990	14.72	255	1028	146	B
-4		4.849	24.130	19.258	2.974	14.79	258	1042	148	B-T
2R-95W-76-3		4.849	24.135	19.360	3.000	15.48	268	1081	152	B-T
-4		4.846	24.125	19.296	2.977	15.17	264	1064	151	B-T
1R-114W-38-1	4.780	4.851	28.923	9.599	2.997	10.28	143	718	239	S
-2		4.851	28.931	9.589	2.807	9.85	138	697	232	S
2R-114W-38-1		4.846	28.918	9.632	2.997	10.32	143	721	239	S
-2		4.859	28.920	9.604	2.959	9.88	139	699	232	S
1R-114W-57-1	4.780	4.856	28.923	14.481	3.007	13.95	192	969	192	B-S
-2		4.839	28.915	14.458	2.964	14.72	206	1038	206	B-S
2R-114W-57-1		4.846	28.920	14.450	3.005	14.01	194	974	194	B-S
-2		4.834	28.918	14.432	2.959	14.01	197	991	197	B-S
1R-114W-76-3	4.780	4.839	28.920	19.248	3.012	15.46	213	1074	152	B
-4		4.836	28.926	19.230	2.997	15.75	218	1100	157	B-T
2R-114W-76-3		4.846	28.923	19.256	3.005	15.03	208	1045	149	B
-4		4.844	28.928	19.243	2.987	14.99	208	1051	149	B

TABLE X.- Concluded

(b) U.S. Customary Units

Specimen	Bolt diameter, in.	Hole diameter, in.	Width, in.	Edge distance, in.	Average thickness, in.	Maximum load, lbf	Net-tension stress, ksi	Bearing stress, ksi	Shear-out stress, ksi	Failure mode
1R-76W-57-1	0.1882	0.1906	0.7604	0.5683	0.1172	3000	44.9	135.7	27.1	T
2R-76W-57-1		.1903	.7598	.5684	.1171	3060	45.9	139.1	27.6	T
-2		.1906	.7601	.5688	.1169	2975	44.7	135.2	26.9	T
2R-76W-76-3	0.1882	0.1904	0.7600	0.7621	0.1173	3050	45.7	138.0	19.5	T
-4		.1907	.7603	.7624	.1172	3090	46.3	139.8	19.8	T
1R-95W-57-1	0.1882	0.1906	0.9502	0.5681	0.1175	3085	34.5	139.6	27.8	B-C
-2		.1906	.9498	.5683	.1168	3150	35.5	143.2	28.5	B-T
2R-95W-57-1		.1910	.9501	.5685	.1179	3070	34.3	138.3	27.5	B-T
-2		.1906	.9495	.5691	.1172	3095	34.8	140.0	27.9	B-T
1R-95W-76-3	0.1882	0.1908	0.9503	0.7578	0.1177	3310	37.0	149.1	21.2	B
-4		.1909	.9500	.7582	.1171	3325	37.4	151.1	21.4	B-T
2R-95W-76-3		.1909	.9502	.7622	.1181	3480	38.8	156.8	22.1	B-T
-4		.1908	.9498	.7597	.1172	3410	38.3	154.3	21.9	B-T
1R-114W-38-1	0.1882	0.1910	1.1387	0.3779	0.1180	2310	20.7	104.1	34.7	S
-2		.1910	1.1390	.3775	.1105	2215	20.0	101.1	33.7	S
2R-114W-38-1		.1908	1.1385	.3792	.1180	2320	20.8	104.5	34.6	S
-2		.1913	1.1386	.3781	.1165	2220	20.1	101.4	33.7	S
1R-114W-57-1	0.1882	0.1912	1.1387	0.5701	0.1184	3135	27.9	140.6	27.9	B-S
-2		.1905	1.1384	.5692	.1167	3310	29.9	150.5	29.9	B-S
2R-114W-57-1		.1908	1.1386	.5689	.1183	3150	28.1	141.3	28.1	B-S
-2		.1903	1.1385	.5682	.1165	3150	28.5	143.8	28.6	B-S
1R-114W-76-3	0.1882	0.1905	1.1386	0.7578	0.1186	3475	30.9	155.8	22.1	B
-4		.1904	1.1388	.7571	.1180	3540	31.6	159.5	22.7	B-T
2R-114W-76-3		.1908	1.1387	.7581	.1183	3380	30.2	151.6	21.6	B
-4		.1907	1.1389	.7576	.1176	3370	30.2	152.5	21.6	B

TABLE XI.- BOLTED-JOINT DATA FOR CELION 6000/LARC-160 SPECIMENS TESTED AT 589 K (600°F)

Failure mode key:
T Net tension
B Bearing
S Shear-out

(a) SI Units

Specimen	Bolt diameter, mm	Hole diameter, mm	Width, mm	Edge distance, mm	Average thickness, mm	Maximum load, kN	Net-tension stress, MPa	Bearing stress, MPa	Shear-out stress, MPa	Failure mode
1E-76W-57	4.780	4.841	19.299	14.481	2.901	9.39	224	676	134	T
2E		4.846	19.307	14.468	2.982	9.25	214	649	129	T
3E		4.849	19.309	14.450	3.018	9.52	219	658	131	T
1E-76W-76	4.780	4.844	19.394	19.274	3.023	9.88	225	683	97	T
2E		4.849	19.268	19.279	3.015	9.83	226	683	97	T
3E		4.846	19.317	19.289	3.007	10.08	232	701	99	T
1E-95W-57	4.780	4.846	24.130	14.437	3.002	10.23	177	714	142	B-T
2E		4.844	24.102	14.450	3.007	8.81	152	612	122	B-T
3E		4.836	24.094	14.442	3.010	9.27	160	645	128	B-T
1E-95W-76	4.780	4.849	24.150	19.266	3.007	10.81	186	752	107	B-T
2E		4.844	24.143	19.268	3.012	10.56	182	734	104	B-T
3E		4.844	24.122	19.246	3.015	10.36	179	721	102	B-T
1E-114W-38	4.780	4.839	28.938	9.609	3.056	7.25	99	497	165	S
2E		4.856	28.910	9.627	3.002	7.67	106	536	177	S
3E		4.851	28.923	9.583	2.990	7.32	102	511	171	S
1E-114W-57	4.780	4.851	28.931	14.468	3.005	9.83	136	683	136	B-S
2E		4.849	28.905	14.465	3.020	9.83	135	681	135	B-S
3E		4.844	28.938	14.475	3.028	10.45	143	723	143	B-S
1E-114W-76	4.780	4.836	28.936	19.182	3.025	11.43	157	791	112	B-T
2E		4.844	28.938	19.177	3.002	10.36	143	724	103	B-T
3E		4.839	28.928	19.180	2.946	10.16	143	723	103	B-T

TABLE XI.- Concluded

(b) U.S. Customary Units

Specimen	Bolt diameter, in.	Hole diameter, in.	Width, in.	Edge distance, in.	Average thickness, in.	Maximum load, lbf	Net-tension stress, ksi	Bearing stress, ksi	Shear-out stress, ksi	Failure mode
1E-76W-57	0.1882	0.1906	0.7598	0.5701	0.1142	2110	32.5	98.1	19.5	T
2E		.1908	.7601	.5696	.1174	2080	31.1	94.1	18.7	T
3E		.1909	.7602	.5689	.1188	2140	31.7	95.5	19.0	T
1E-76W-76	0.1882	0.1907	0.7602	0.7588	0.1190	2220	32.7	99.1	14.1	T
2E		.1909	.7586	.7590	.1187	2210	32.8	99.1	14.0	T
3E		.1908	.7605	.7594	.1184	2265	33.6	101.6	14.4	T
1E-95W-57	0.1882	0.1908	0.9500	0.5684	0.1182	2300	25.6	103.6	20.6	B-T
2E		.1907	.9489	.5689	.1184	1980	22.0	88.8	17.7	B-T
3E		.1904	.9486	.5686	.1185	2085	23.2	93.5	18.6	B-T
1E-95W-76	0.1882	0.1909	0.9508	0.7585	0.1184	2430	27.0	109.0	15.5	B-T
2E		.1907	.9505	.7586	.1186	2375	26.4	106.5	15.1	B-T
3E		.1907	.9497	.7577	.1187	2330	25.9	104.5	14.8	B-T
1E-114W-38	0.1882	0.1905	1.1393	0.3783	0.1203	1630	14.3	72.1	23.9	S
2E		.1912	1.1382	.3790	.1182	1725	15.4	77.7	25.7	S
3E		.1910	1.1387	.3773	.1177	1645	14.8	74.1	24.8	S
1E-114W-57	0.1882	0.1910	1.1390	0.5696	0.1183	2210	19.7	99.1	19.7	B-S
2E		.1909	1.1380	.5695	.1189	2210	19.6	98.7	19.6	B-S
3E		.1907	1.1393	.5699	.1192	2350	20.8	104.9	20.8	B-S
1E-114W-76	0.1882	0.1904	1.1392	0.7552	0.1191	2570	22.7	114.7	16.3	B-T
2E		.1907	1.1393	.7550	.1182	2330	20.8	105.0	14.9	B-T
3E		.1905	1.1389	.7551	.1160	2285	20.8	104.8	14.9	B-T

TABLE XII.- SUMMARY OF FAILURE MODE DATA FROM BOLTED-JOINT TESTS

[Failure Mode Key: T Net tension; B Bearing; S Shear-out; C Combination; M Multiple]

(a) Joints tested at 116 K (-250°F)

w/d	e/d	Specimen failure mode								
		Celion 6000/PMR-15						Celion 6000/ LARC-160		
		In-house			Contract					
4	3	T	T		T	T	T	T	T	
	4	T	T		T	T	T	T	T	
5	3	T	T	T	T	B-S	B-C	T	T	T
	4	T	T		B-S	B-T	B	T	T	T
6	2	C	C	M	C	C	C	S	S	S
	3	C	M	M	B-C	B-C	B-M	C	M	M
	4	B	B	B	B	B	B	B-T	B-T	B-T

(b) Joints tested at 297 K (75°F)

w/d	e/d	Specimen failure mode											
		Celion 6000/PMR-15								Celion 6000/ LARC-160			
		In-house				Contract							
4	3	T	T	T	T	T	T	T		T	T	T	
	4	T	T	T	T	T	B-T	B-T	B	T	T		
5	3	M	M	M	M	B-C	B-C	B-C	B	B-C	B-T	B-T	B-T
	4	B-T	B	B	B	B	B	B	B	B-T	B-T	B-T	B
6	2	S	S	S	S	S	S	S	S	S	S	S	S
	3	S	M	M	M	B-C	B	B	B	B-S	B-S	B-S	B-S
	4	B-T	B	B	B	B	B	B	B	B-T	B	B	B

(c) Joints tested at 589 K (600°F)[a]

w/d	e/d	Specimen failure mode								
		Celion 6000/PMR-15						Celion 6000/ LARC-160		
		In-house			Contract					
4	3	T	T	T	T	T	T	T	T	T
	4	B-T	B-T	B-T	B-T	B-T	B-T	T	T	T
5	3	B-S	B-S	B-S	B-S	B-S	B-S	B-T	B-T	B-T
	4	B-T	B-T	B-T	B-T	B-T	B-T	B-T	B-T	B-T
6	2	S	S	S	S	S	S	S	S	S
	3	B-S	B-S	B-S	B-S	B-S	B-S	B-S	B-S	B-S
	4	B	B	B	B	B	B	B-T	B-T	B-T

[a]Contract Celion 6000/PMR-15 tested at 572 K (570°F).

TABLE XIII.- SUMMARY OF MAXIMUM JOINT STRESSES FROM BOLTED-JOINT TESTS

(a) Joint stresses at 116 K (-250°F)

Composite		w/d	e/d	Maximum stresses[a]		
				Net tension, MPa (ksi)	Bearing, MPa (ksi)	Shear-out, MPa (ksi)
Celion 6000/PMR-15	In-house	3.9	2.9	330 (47.8)	962 (139.5)	196 (28.4)
	Contract	4.0	3.0	359 (52.1)	1085 (157.3)	219 (31.7)
Celion 6000/LARC-160		4.0	3.0	327 (47.4)	989 (143.5)	197 (28.5)
Celion 6000/PMR-15	In-house	3.9	3.9	367 (53.3)	1072 (155.5)	157 (22.7)
	Contract	4.0	4.0	343 (49.7)	1041 (151.0)	147 (21.3)
Celion 6000/LARC-160		4.0	4.0	359 (52.1)	1087 (157.7)	154 (22.3)
Celion 6000/PMR-15	In-house	4.9	2.9	288 (41.7)	1113 (161.4)	227 (32.9)
	Contract	5.0	3.0	305 (44.3)	1239 (179.7)	248 (35.9)
Celion 6000/LARC-160		5.0	3.0	270 (39.1)	1087 (157.6)	216 (31.4)
Celion 6000/PMR-15	In-house	4.9	3.9	314 (45.6)	1223 (177.4)	179 (25.9)
	Contract	5.0	4.0	312 (45.3)	1262 (183.1)	177 (25.7)
Celion 6000/LARC 160		5.0	4.0	299 (43.4)	1207 (175.0)	171 (24.8)
Celion 6000/PMR-15	In-house	5.8	2.0	182 (26.4)	887 (128.7)	303 (43.9)
	Contract	6.0	2.0	202 (29.3)	1016 (147.3)	341 (49.5)
Celion 6000/LARC-160		6.0	2.0	157 (22.8)	793 (115.0)	265 (38.4)
Celion 6000/PMR-15	In-house	5.8	2.9	233 (33.8)	1138 (165.0)	232 (33.6)
	Contract	6.0	3.0	252 (36.5)	1267 (183.8)	252 (36.6)
Celion 6000/LARC-160		6.0	3.0	214 (31.1)	1082 (157.0)	214 (31.1)
Celion 6000/PMR-15	In-house	5.8	3.9	261 (37.9)	1276 (185.1)	186 (27.0)
	Contract	6.0	4.0	268 (38.8)	1343 (194.8)	190 (27.5)
Celion 6000/LARC-160		6.0	4.0	247 (35.8)	1247 (180.8)	177 (25.7)

[a]Average of test data.

TABLE XIII.- Continued

(b) Joint stresses at 297 K (75°F)

Composite		w/d	e/d	Maximum stresses[a]		
				Net tension, MPa (ksi)	Bearing, MPa (ksi)	Shear-out, MPa (ksi)
Celion 6000/PMR-15	In-house	3.9	2.9	308 (44.6)	898 (130.2)	184 (26.7)
	Contract	4.0	3.0	316 (45.9)	963 (139.7)	192 (27.9)
Celion 6000/LARC-160		4.0	3.0	312 (45.2)	943 (136.7)	188 (27.2)
Celion 6000/PMR-15	In-house	3.9	3.9	313 (45.4)	912 (132.3)	134 (19.5)
	Contract	4.0	4.0	331 (48.0)	1007 (146.0)	143 (20.7)
Celion 6000/LARC-160		4.0	4.0	317 (46.0)	958 (138.9)	136 (19.7)
Celion 6000/PMR-15	In-house	4.9	2.9	243 (35.3)	945 (137.1)	194 (28.1)
	Contract	5.0	3.0	253 (36.7)	1024 (148.5)	205 (29.8)
Celion 6000/LARC-160		5.0	3.0	240 (34.8)	967 (140.3)	192 (27.9)
Celion 6000/PMR-15	In-house	4.9	3.9	265 (38.5)	1034 (150.0)	152 (22.0)
	Contract	5.0	4.0	272 (39.4)	1100 (159.5)	156 (22.6)
Celion 6000/LARC-160		5.0	4.0	261 (37.9)	1054 (152.8)	150 (21.7)
Celion 6000/PMR-15	In-house	5.8	2.0	146 (21.2)	710 (103.0)	245 (35.5)
	Contract	6.0	2.0	151 (21.9)	757 (109.8)	254 (36.8)
Celion 6000/LARC-160		6.0	2.0	141 (20.4)	709 (102.8)	236 (34.2)
Celion 6000/PMR-15	In-house	5.8	2.9	197 (28.5)	957 (138.8)	197 (28.5)
	Contract	6.0	3.0	205 (29.8)	1038 (150.6)	208 (30.1)
Celion 6000/LARC-160		6.0	3.0	197 (28.6)	994 (144.1)	197 (28.6)
Celion 6000/PMR-15	In-house	5.8	3.9	214 (31.0)	1040 (150.8)	153 (22.2)
	Contract	6.0	4.0	221 (32.0)	1116 (161.8)	155 (22.5)
Celion 6000/LARC-160		6.0	4.0	212 (30.7)	1068 (154.9)	152 (22.0)

[a]Average of test data.

TABLE XIII.- Concluded

(c) Joint stresses at 589 K (600°F)[a]

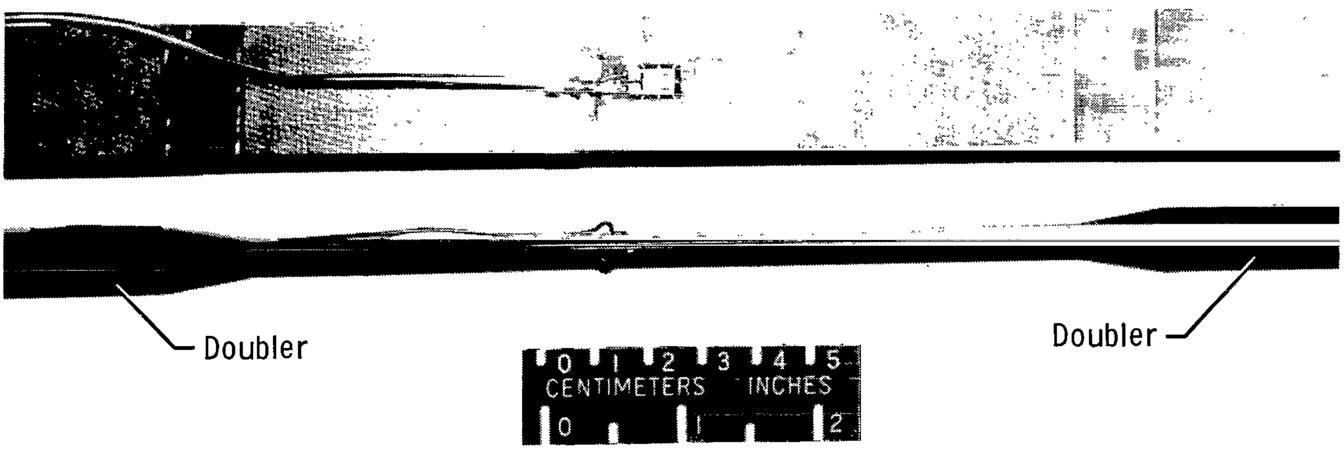
Composite		w/d	e/d	Maximum stresses[b]		
				Net tension, MPa (ksi)	Bearing, MPa (ksi)	Shear-out, MPa (ksi)
Celion 6000/PMR-15	In-house	3.9	2.9	203 (29.4)	591 (85.7)	120 (17.4)
	Contract	4.0	3.0	199 (28.8)	597 (86.6)	120 (17.4)
Celion 6000/LARC-160		4.0	3.0	219 (31.8)	661 (95.9)	132 (19.1)
Celion 6000/PMR-15	In-house	3.9	3.9	216 (31.3)	629 (91.3)	92 (13.3)
	Contract	4.0	4.0	226 (32.8)	688 (99.8)	97 (14.1)
Celion 6000/LARC-160		4.0	4.0	228 (33.0)	689 (99.9)	98 (14.2)
Celion 6000/PMR-15	In-house	4.9	2.9	159 (23.0)	618 (89.6)	128 (18.6)
	Contract	5.0	3.0	163 (23.7)	660 (95.7)	131 (19.0)
Celion 6000/LARC-160		5.0	3.0	163 (23.6)	657 (95.3)	131 (19.0)
Celion 6000/PMR-15	In-house	4.9	3.9	176 (25.5)	687 (99.6)	101 (14.6)
	Contract	5.0	4.0	187 (27.1)	756 (109.6)	107 (15.5)
Celion 6000/LARC-160		5.0	4.0	182 (26.4)	736 (106.7)	104 (15.1)
Celion 6000/PMR-15	In-house	5.8	2.0	103 (14.9)	502 (72.8)	172 (25.0)
	Contract	6.0	2.0	114 (16.6)	578 (83.8)	194 (28.1)
Celion 6000/LARC-160		6.0	2.0	102 (14.8)	514 (74.6)	171 (24.8)
Celion 6000/PMR-15	In-house	5.8	2.9	129 (18.7)	627 (91.0)	128 (18.6)
	Contract	6.0	3.0	146 (21.2)	736 (106.7)	147 (21.3)
Celion 6000/LARC-160		6.0	3.0	138 (20.0)	696 (100.9)	138 (20.0)
Celion 6000/PMR-15	In house	5.8	3.9	145 (21.0)	704 (102.1)	103 (14.9)
	Contract	6.0	4.0	154 (22.4)	776 (112.5)	110 (16.0)
Celion 6000/LARC-160		6.0	4.0	148 (21.4)	746 (108.2)	106 (15.4)

[a]Contract Celion 6000/PMR-15 stresses at 572 K (570°F)
[b]Average of test data.

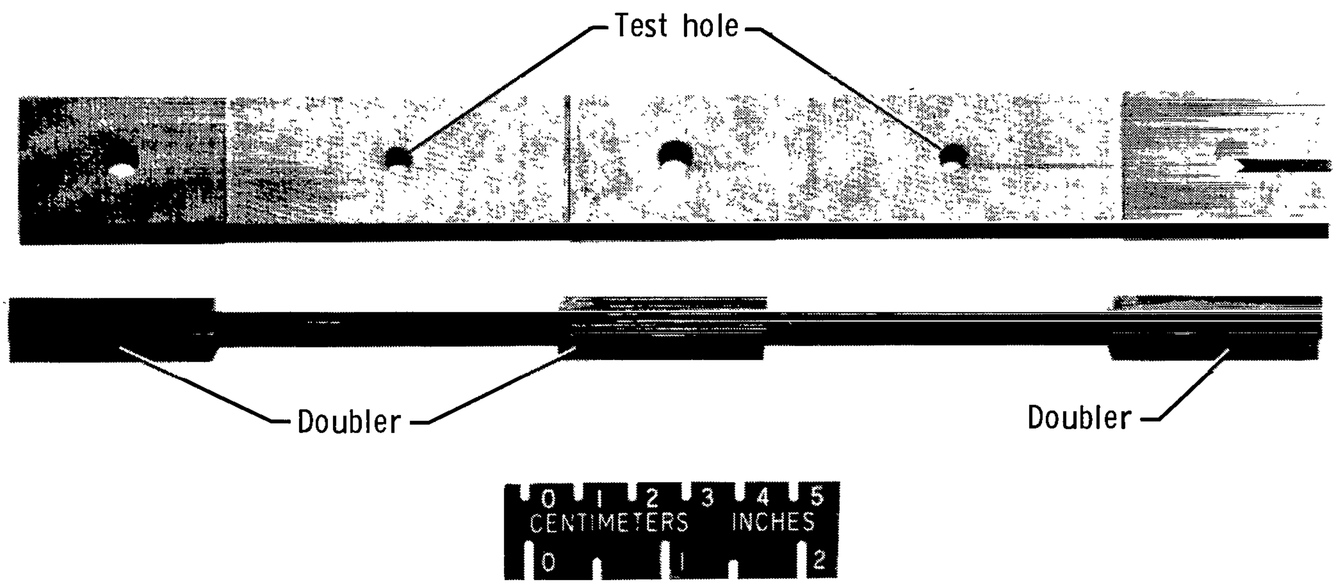
TABLE XIV.- JOINT-STRENGTH DATA FOR GRAPHITE/POLYIMIDE

LAMINATES DETERMINED FROM BOLTED-JOINT TESTS

Composite		Joint strength		
		Net tension, MPa (ksi)	Bearing, MPa (ksi)	Shear-out, MPa (ksi)
		116 K (-250°F)		
Celion 6000/PMR-15	In-house	367 (53.3)	1276 (185.1)	≥303 (43.9)
	Contract	359 (52.1)	1343 (194.8)	≥341 (49.5)
Celion 6000/LARC-160		359 (52.1)	≥1247 (180.8)	265 (38.4)
		297 K (75°F)		
Celion 6000/PMR-15	In-house	313 (45.4)	1040 (150.8)	245 (35.5)
	Contract	313 (45.4)	1116 (161.8)	254 (36.8)
Celion 6000/LARC-160		317 (46.0)	1068 (154.9)	236 (34.2)
		589 K (600°F)		
Celion 6000/PMR-15	In-house	203 (29.4)	704 (102.1)	172 (25.0)
	Contract	199 (28.8)	776 (112.5)	194 (28.1)
Celion 6000/LARC-160		228 (33.0)	≥746 (108.2)	171 (24.8)



(a) Tensile specimen.



(b) Open-hole specimen.

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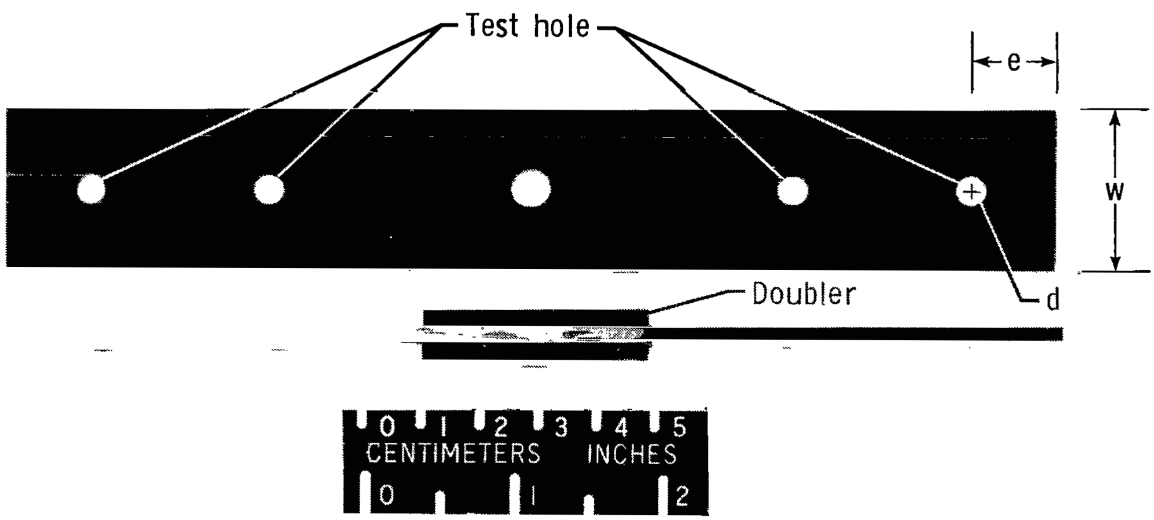
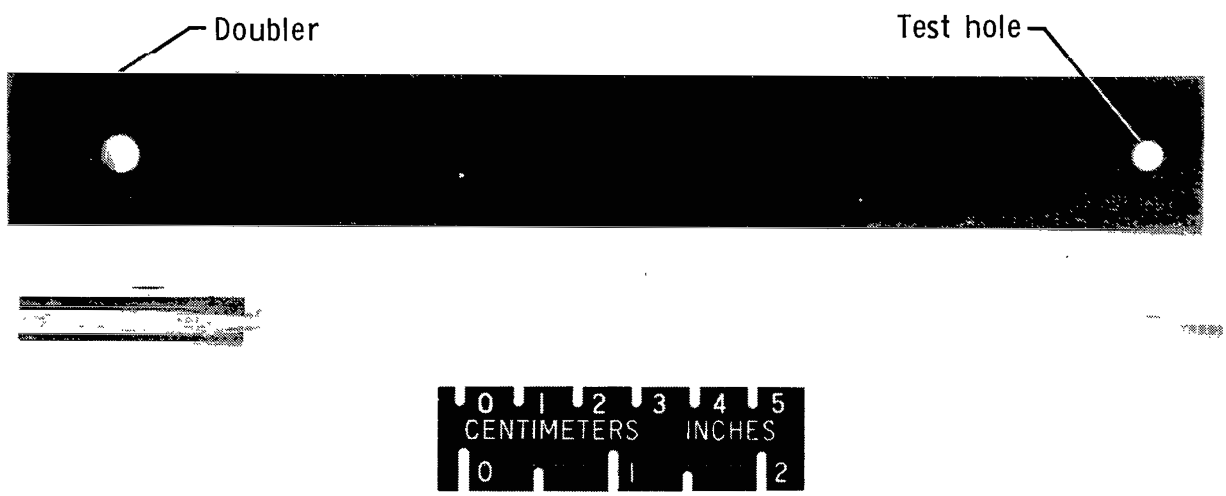
Figure 1.- Typical tensile-strength specimens.



(a) Specimen for room-temperature tests.



(b) Specimen for tests at low and elevated temperatures.

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Figure 2.- Typical bolted-joint specimens.

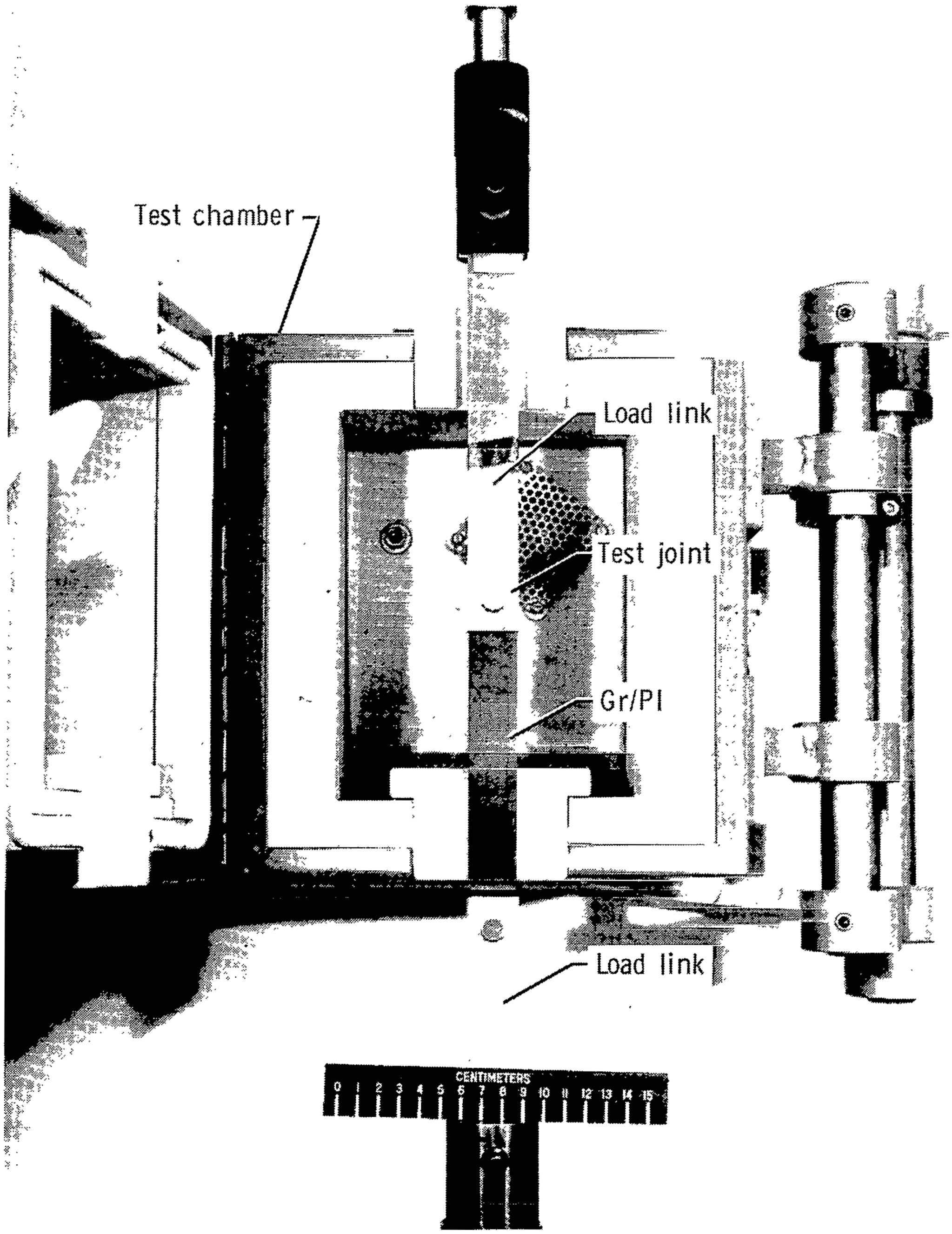

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Figure 3.- Loading and heating apparatus for bolted-joint tests.

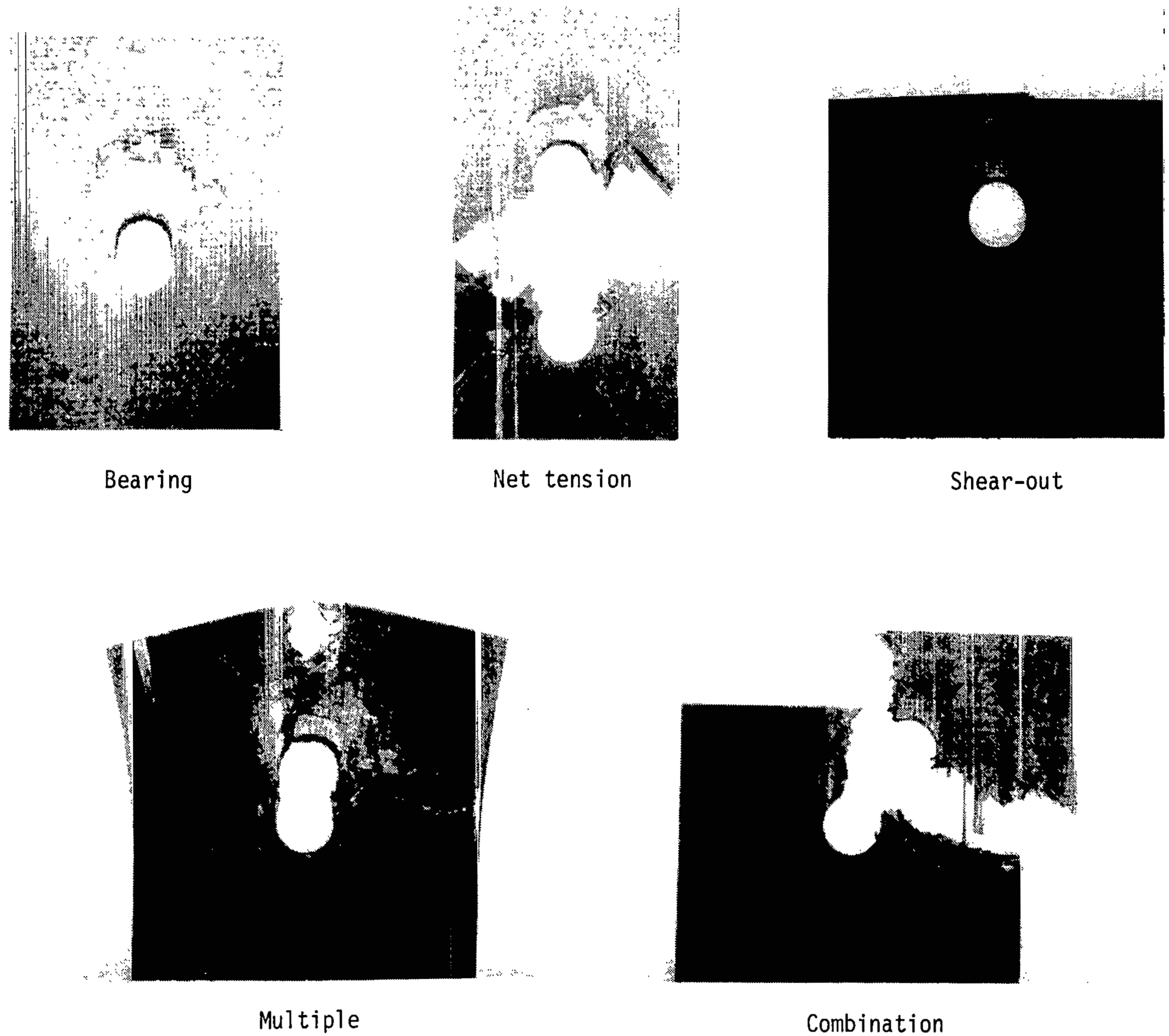

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Figure 4.- Failed bolted-joint specimens representative of the five failure modes observed.

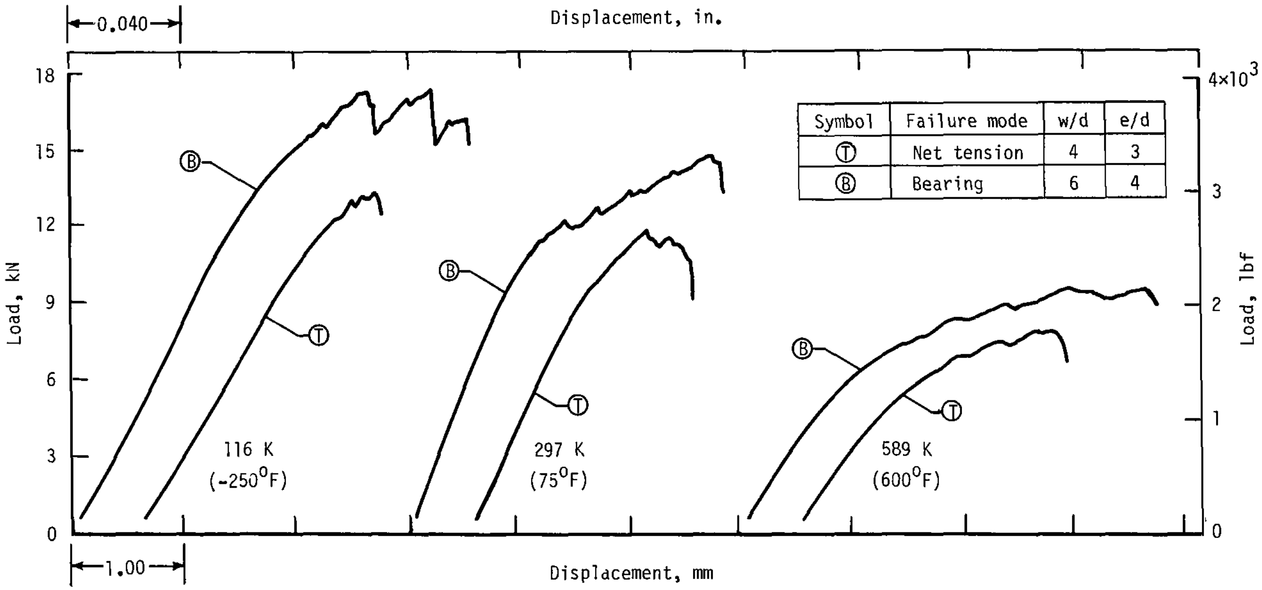

Figure 5.- Typical recordings of load-displacement for net-tension and bearing failures at the three test temperatures.

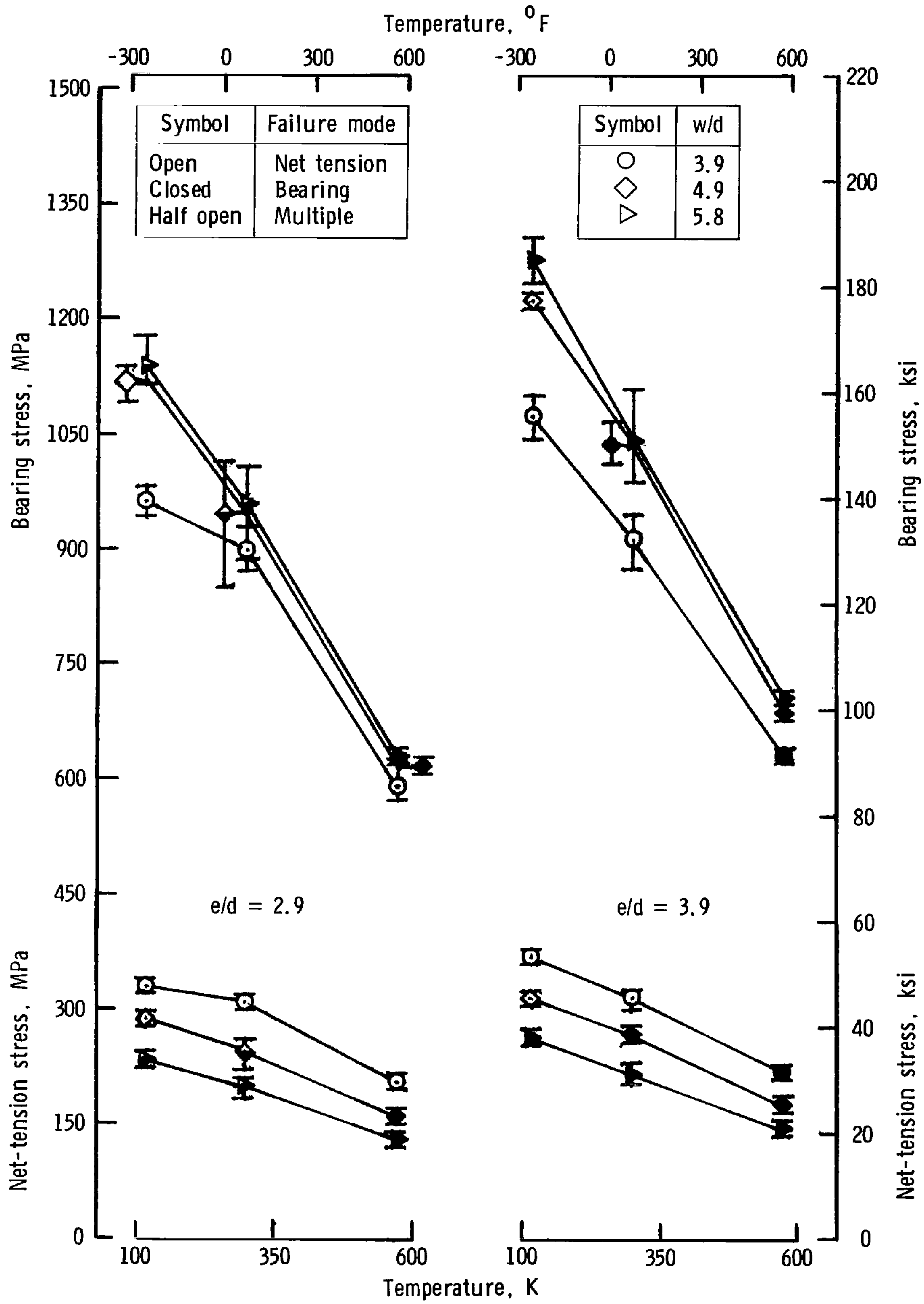

Figure 6.- Effect of joint geometry and temperature on net-tension and bearing stresses in-house for Celion 6000/PMR-15 specimens.

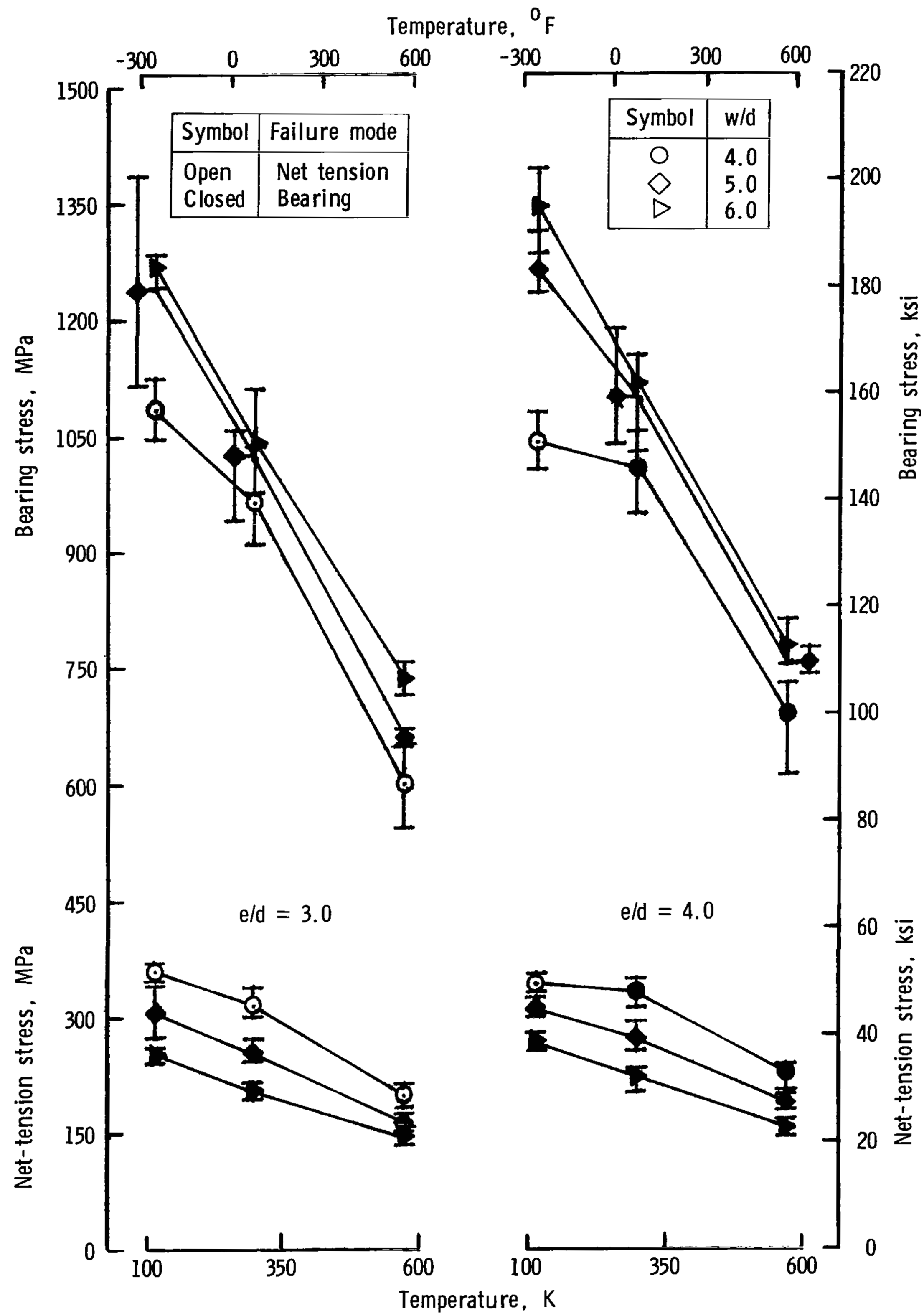

Figure 7.- Effect of joint geometry and temperature on net-tension and bearing stresses for contract Celion 6000/PMR-15 specimens.

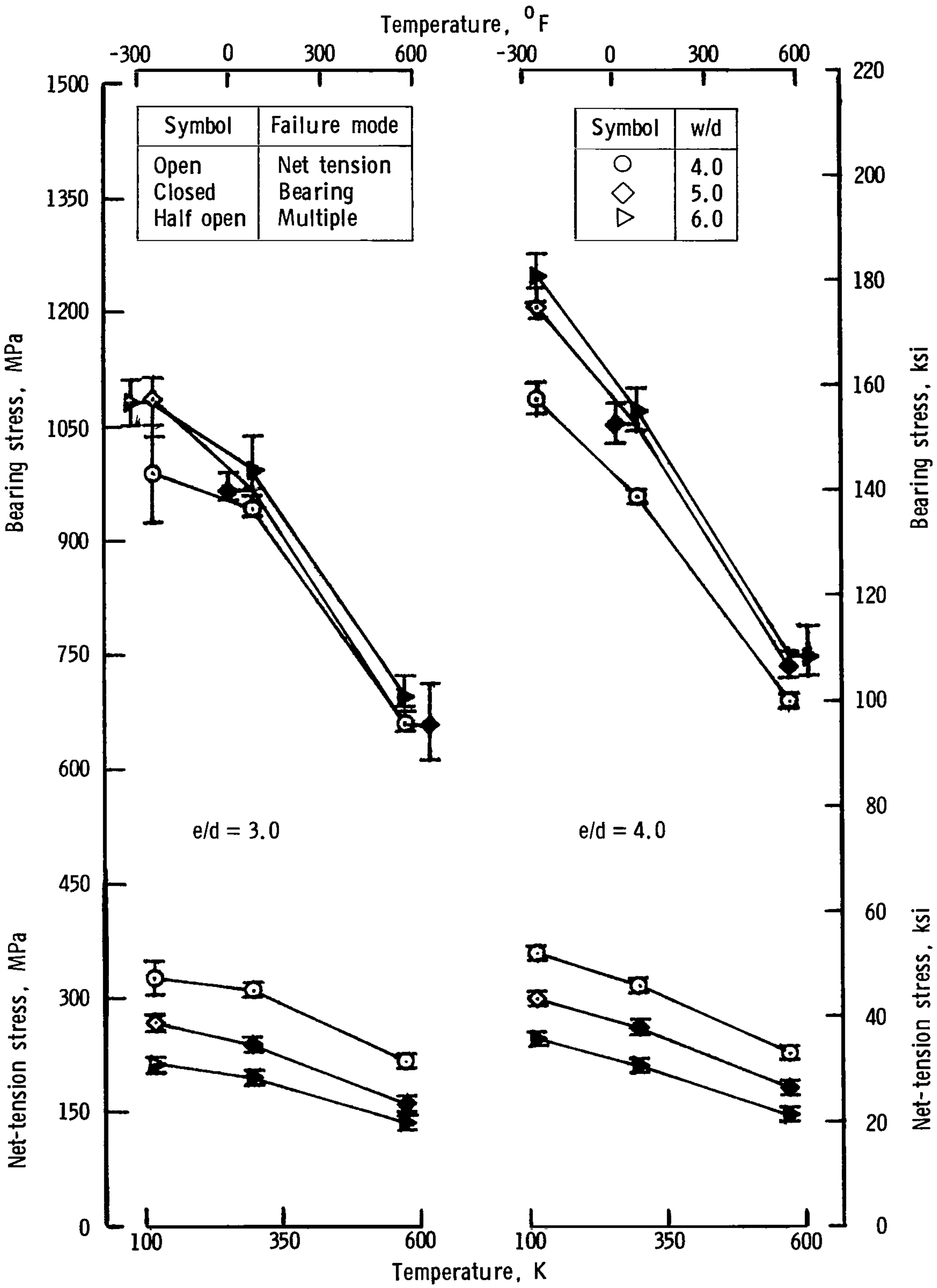

Figure 8.- Effect of joint geometry and temperature on net-tension and bearing stresses for Celion 6000/LARC-160 specimens.

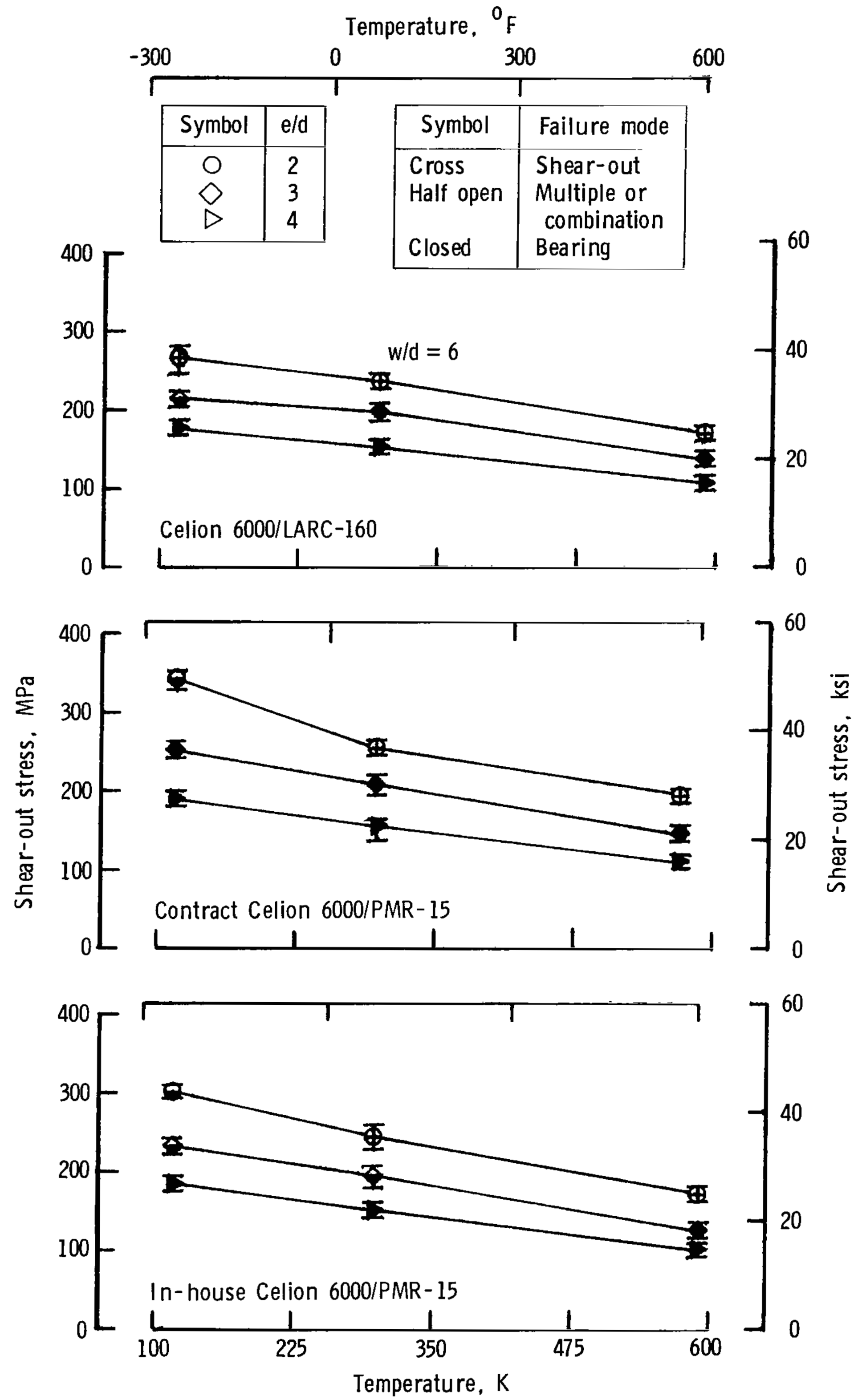

Figure 9.- Effect of temperature and e/d for w/d = 6 on shear-out stresses for graphite/polyimide specimens.

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15. Supplementary Notes

16. Abstract

The results of an experimental program to determine the bolted-joint strength and failure modes for graphite/polyimide laminates are presented. Sixteen-ply, quasi-isotropic laminates of Celanese Celion® 6000/PMR-15 and Celion 6000/LARC-160 with a fiber orientation of $[0/45/90/-45]_{2S}$ were evaluated. Tensile and open-hole specimens were tested at room temperature to establish laminate tensile strength and net tensile strength at an unloaded bolt hole. Double-lap joint specimens with a single 4.83-mm (0.19-in.) diameter bolt torqued to 1.7 N-m (15 lbf-in.) were tested in tension at temperatures of 116 K (-250°F), 297 K (75°F), and 589 K (600°F). The joint ratios of w/d (specimen width to hole diameter) and e/d (edge distance to hole diameter) were varied from 4 to 6 and from 2 to 4, respectively. The effect of joint geometry and temperature on failure mode and joint stresses are shown. Joint stresses calculated at maximum load for each joint geometry and test temperature are reported. Joint strength in net tension, bearing, and shear-out at 116 K (-250°F), 297 K (75°F), and 589 K (600°F) are given for the Celion 6000/PMR-15 and Celion 6000/LARC-160 laminates.

17. Key Words (Suggested by Author(s)) Composite material Graphite/polyimide Quasi-isotropic Bolted joint Joint ratios Joint strength Failure modes Temperature		18. Distribution Statement Unclassified - Unlimited Subject Category 24	
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