NASA/CR-2002-211942

Biaxial Testing of 2195 Aluminum Lithium Alloy Using Cruciform Specimens

W. M. Johnston , W. D. Pollock, and D. S. Dawicke
Analytical Services & Materials, Inc., Hampton, Virginia

October 2002

The NASA STI Program Office ... in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results ... even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA STI Help Desk at (301) 621-0134

- Phone the NASA STI Help Desk at (301) 621-0390

- Write to:
  NASA STI Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076-1320

NASA/CR-2002-211942

Biaxial Testing of 2195 Aluminum Lithium Alloy Using Cruciform Specimens

W. M. Johnston, W. D. Pollock, and D. S. Dawicke
Analytical Services & Materials, Inc., Hampton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

Prepared for Langley Research Center
under Contract NAS1-96014

October 2002

Available from:

NASA Center for AeroSpace Information (CASI)
7121 Standard Drive
Hanover, MD 21076-1320
(301) 621-0390

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, VA 22161-2171
(703) 605-6000

Biaxial Testing of Aluminum-Lithium Alloy 2195 Using Cruciform Specimens

W.M. Johnston, W.D. Pollock. and D.S Dawicke
Analytical Services & Materials, Inc.
Hampton, Virginia

ABSTRACT

A cruciform biaxial test specimen was used to test the effect of biaxial loading on the yield behavior of aluminum-lithium alloy 2195. Fifteen cruciform specimens were tested from two thicknesses of 2195-T8 plate, 0.45 in. and 1.75 in. These results were compared to the results from uniaxial tensile tests of the same alloy, and cruciform biaxial tests of aluminum alloy 2219-T87.

KEYWORDS

Biaxial, Finite Element Analysis, 2195-T8, 2219-T87, von Mises, Yield Surface, Yield Locus, Aluminum Alloy, Aluminum-Lithium Alloy.

INTRODUCTION

Aircraft and spacecraft structures are often subjected to multi-axial stresses. These structures are designed and sized using various yield criteria. These yield criteria relate the multi-axial stress state to yielding based on assumptions about the material behavior. The Space Shuttle External Tank was initially designed using the maximum shear stress yield criterion. This criterion has been shown to be accurate for ductile, isotropic materials and requires only a uniaxial tensile test to characterize the material yielding behavior. For non-isotropic materials, the maximum shear stress yield criterion can result in either over-designed or under-designed structures, depending on the material behavior and the stresses in the structure. Testing that simulates the multi-axial stress state is often preferred to validate the load carrying capability of the material.

The Space Shuttle External Tank is fabricated from aluminum alloy 2219, a ductile, isotropic material whose behavior agrees well with the von Mises yield theory [1]. Figure 1 shows the maximum shear stress and von Mises yield theories. At stress ratios of 1:0, 1:1 and 0:1, both theories are equal. Elsewhere however, the maximum shear stress theory predicts lower yield strength. During the Super Lightweight Tank Program, the Space Shuttle External Tank was redesigned using aluminum-lithium (Al-Li) alloy 2195-T8. This alloy is not isotropic, and has significantly weaker tensile strength for orientations other than the rolling direction. Due to this non-isotropic strength behavior, uncertainty existed regarding safe use of biaxial yield criterions which use a single yield strength value. Therefore, testing was performed to confirm both that the design criteria used would not allow yielding, and that the design was not overly conservative.

Additionally, the proof testing of the External Tank is performed at room temperature, but the tank's operating temperature is cryogenic. For Al 2219, this is conservative because the fracture toughness and yield strength increase with decreasing temperature. However, the combined effects of biaxial loading and decreased test temperature on 2195 were unknown.

The objectives of this research were:(1) to determine the yield behavior of Al-Li 2195-T8 for two material thicknesses under various biaxial loading conditions and compare the results to Al 2219; and (2) to determine yield behavior of Al-Li 2195 at -320°F, using a biaxial displacement ratio which simulates the proof test of the External Tank, for comparison with the room temperature response of the two materials.

SPECIMEN DESIGN AND TESTING PROCEDURE

Room temperature uniaxial tensile tests were conducted on subsize dogbone specimens in accordance with ASTM B557 [2]. Strains were measured with extensometers (1-in. gage length) positioned on both sides of the specimen. Transverse strain gages were also applied to selected specimens to determine Poison's ratio.

The biaxial specimen design and testing procedures were identical to the 2219 tests conducted by Dawicke and Pollock [1]. All cruciform specimens had a 0.08-in.-thick gage section and were instrumented with 52 strain gages, as shown in Figure 2. All of the gages were back-to-back with the odd numbered gages on the front of the specimen and the even numbered gages on the back. An 80 channel data acquisition system with a collection rate of 30 data points per second was used to collect the data at 5 second intervals. The tests were performed on a four-actuator servo-hydraulic test stand in stroke control with a constant ratio between longitudinal (L) and transverse (T) displacement. Tests were conducted at a constant displacement rate of 0.005 in./second on the major loading axis until a strain level of 12,000 microstrain was obtained in the gage section. Next, the specimens were unloaded (in stroke control at 0.005 inch/second) by 20-40 kips to allow the determination of unloading compliance. The specimens were then loaded at a displacement rate of 0.003 in./second until failure. Other than a single test at –320°F, all biaxial tests were performed at room temperature (75°F).

MATERIAL

Al-Li alloy 2195 is being used in launch vehicle applications due to it's high strength, low density and good cryogenic fracture toughness. Two plate gages of the 2195 alloy, supplied by McCook Metals, were examined in this investigation: 0.45-in.-thick plate with a composition of 3.97Cu, 0.92Li, 0.33Mg, 0.32Ag, 0.14Zr, balance Al; and 1.75-in.-thick plate with a composition of 4.04Cu, 0.94Li, 0.35Mg, 0.33Ag, 0.15Zr, balance Al. The 0.45-in.-thick plate came from material LOT 940M013A and was solution heat treated at 940-960°F for at least 120 minutes, water quenched, then stretched 3.5% and aged for 40 hours at 290°F. The 1.75-in.-thick plate came from material LOT 940M015A and was solution heat treated at 940-960°F for at least 150 minutes, water quenched, then stretched 3.5% and aged for 36 hours at 300°F.

NUMERICAL ANALYSIS

The cruciform biaxial test produces measurements of strain as a function of applied load. The determination of a biaxial yield stress locus requires strain as a function of stress. For a cruciform specimen, numerical analysis is required to determine the relationship between applied load and local stress. A numerical analysis that included a 2-D treatment of anisotropic behavior was not available. Therefore, the biaxial yield behavior of 2195 was compared to 2219 using the 0.2% offset yield load instead of stress.

RESULTS

Uniaxial Results

The tensile strength, 0.2% yield strength and elongation to failure for the 0.45-in.-thick 2195-T8 aluminum plate are listed in Table 1. Tensile tests conducted in the rolling or longitudinal (L) direction, long-transverse (T) direction, and at several intermediate angles illustrate the variation in uniaxial properties with respect to the orientation of the loading axis relative to the rolling direction. The tensile and the yield strengths follow similar trends (as shown in Figure 3), with a maximum in the L orientation and a minimum at 55°. An 18% difference exists between the maximum (83.3 ksi in the L orientation) and the minimum (62.5 ksi at 55°) observed yield strength. The maximum elongation to failure (also shown in Figure 3) occurs at 60° (14.9%) and the minimum occurs in the L orientation (8.5%). These differences in properties with loading axis orientation illustrate the extent of anisotropic behavior in the 2195-T8 alloy.

Biaxial Results

Biaxial tests were performed on 2195-T8 cruciform panels machined from the t/2 (mid-plane) location of a 0.45-in.-thick plate and from the t/6 location of a 1.75-in.-thick plate. Seven biaxial displacement ratios were tested at room temperature and yield results are summarized in Tables 2 and 3 for the 0.45-in. and 1.75-in.-thick plates, respectively. An additional test was conducted for the 0.45-in.-thick plate material immersed in liquid nitrogen (-320°F). The results from the baseline 0.25-in.-thick 2219-T87 plate biaxial tests are presented in Table 4 for comparison [1]. A typical load-strain history from a 1:1 (L:T) applied displacement ratio test on 0.45-in.-thick plate is shown in Figure 4 which includes output from opposing strain gages and extensometers near the center of the specimen. See Figure 2 for strain gage and extensometer positions. A 2000 microstrain (0.2%) offset was used to obtain the 0.2% yield load. The strain gages remained intact well beyond the strain level needed to obtain the yield load.

The 0.2% yield load for the two thicknesses of the 2195-T8 material and the baseline 2219-T87 material is shown in Figure 5, plotted in terms of the applied load in the longitudinal and long-transverse directions. The 2219-T87 material was only tested in one quadrant because of the isotropic behavior of the material. This figure indicates that the maximum shear stress approach provided conservative results for all tests conducted when a net section stress was considered. Both thicknesses of 2195-T8 exceeded the yield load of the 2219-T87 material by about 30%. The effective increase is enhanced considering the density of 2195 is 0.095 lbs/in^3 as compared to 0.103 lbs/in^3 for 2219.

The cryogenic (-320°F) test for the 0.45-in.-thick 2195-T8 material was performed at a displacement ratio of 1:2 (L:T), closely simulating the proof test load ratio. At -320°F the yield load was approximately 20% greater than the yield load obtained at room temperature, as shown in Figure 6.

SUMMARY AND CONCLUDING REMARKS

Tensile tests were performed to demonstrate the anisotropy of Al-Li alloy 2195-T8. Cruciform biaxial tests were used to determine the effect of biaxial loading on yield strength for specimens machined from two thicknesses of 2195-T8, 0.45 in. and 1.75 in. Tests were conducted at seven biaxial load ratios for each plate thickness. The 0.2% yield load was determined from these tests and compared to the baseline aluminum alloy 2219.

The results of this study indicate that the uniaxial tensile strength of 2195-T8 is anisotropic. The rolling direction has the highest tensile strength, and an 18% reduction in strength was found at 55°. Although this degradation in properties was expected for the uniaxial tests, the biaxial yield results indicate that the maximum shear stress approach provided conservative results for all tests conducted when a net section stress was considered.

The yield load loci for 0.45-in. and 1.75-in.-thick 2195-T8 plates show a significant increase in strength when compared to the 2219 results for the same displacement ratio. Both plate thicknesses of 2195-T8 showed similar results. The yield load at -320°F was 20% higher than the value at room temperature for the 0.45-in.-thick 2195-T8 plate at a 1:2 biaxial displacement ratio.

Reference:

[1] "Biaxial Testing of 2219 Aluminum Alloy Using Cruciform Specimens", NASA CR-4782, D.S. Dawicke & Wm.D. Pollock, Aug 1997.

[2] ASTM B557-94, 1998 Annual Book of ASTM Standards, vol. 2.02, Aluminum an Magnesium Alloys.

Table 1. Uniaxial Tensile Test Summary 2195-T8, from t/2 of 0.45-in. Plate

Orientation	Tensile Strength (ksi)	0.2% Offset Yield Strength (ksi)	Elongation to Failure (%)
L - 1	88.6	84.0	7.0
L - 2	88.2	82.6	9.9
Avg - Longitudinal	88.4	83.3	8.5
45° - 1	76.3	71.0	12.7
45° - 2	76.2	71.0	*
Avg - 45° from Rolling Direction	76.3	71.0	12.7
55° - 1	73.8	67.8	14.7
55° - 2	74.1	68.5	14.6
Avg - 55° from Rolling Direction	74.0	68.2	14.7
60° - 1	76.7	68.6	*
60° - 2	76.3	68.1	14.9
Avg - 60° from Rolling Direction	76.5	68.4	14.9
65° - 1	82.9	72.5	14.5
65° - 2	80.5	70.2	*
Avg - 65° from Rolling Direction	81.7	71.4	14.5
70° - 1	82.5	73.5	8.3
70 ° - 3	82.1	72.3	10.1
Avg - 70° from Rolling Direction	82.3	72.9	9.2
LT - 1	85.8	80.2	13.1
LT - 2	84.9	79.6	9.2
Avg - Long Transverse	85.4	79.9	11.2

* Failed outside extensometer gauge length

Table 2. Biaxial Test Summary 2195-T8, from t/2 location of 0.45-in Plate

Applied Displacement Ratio (L:LT)	Longitudinal Load at 0.2% Offset Plastic Strain (kips)	Long Transverse Load at 0.2% Offset Plastic Strain (kips)
0:1	0.00	64.6
1:5	27.6	71.9
1:2	47.0	72.5
1:1	70.1	72.4
2:1	73.3	43.2
5:1	74.1	28.2
1:0	66.1	0.00
1:2 @ -320°F	60.1	86.5

Table 3. Biaxial Test Summary 2195-T8, from t/6 location of 1.75-in. Plate

Applied Displacement Ratio (L:LT)	Longitudinal Load at 0.2% Plastic Strain (kips)	Long Transverse Load at 0.2% Plastic Strain (kips)
0:1	0.00	64.0
1:5	26.4	70.4
1:5	29.5	69.7
1:2	45.6	69.0
1:1	71.5	68.2
5:1	68.1	22.0
1:0	66.6	0.00

Table 4. Biaxial Test Summary 2219-T87, from t/2 location of 0.25-in. Plate [1]

Applied Displacement Ratio	Longitudinal Load at 0.2% Plastic Strain (kips)	Long Transverse Load at 0.2% Plastic Strain (kips)
1:0	48.3	0
20:1	55.5	10.9
5:1	55.8	18.3
2.5:1	52.9	28.8
2.5:1	55.7	37.2
1:1	50.7	50.7
1.18:1	54.2	52.8

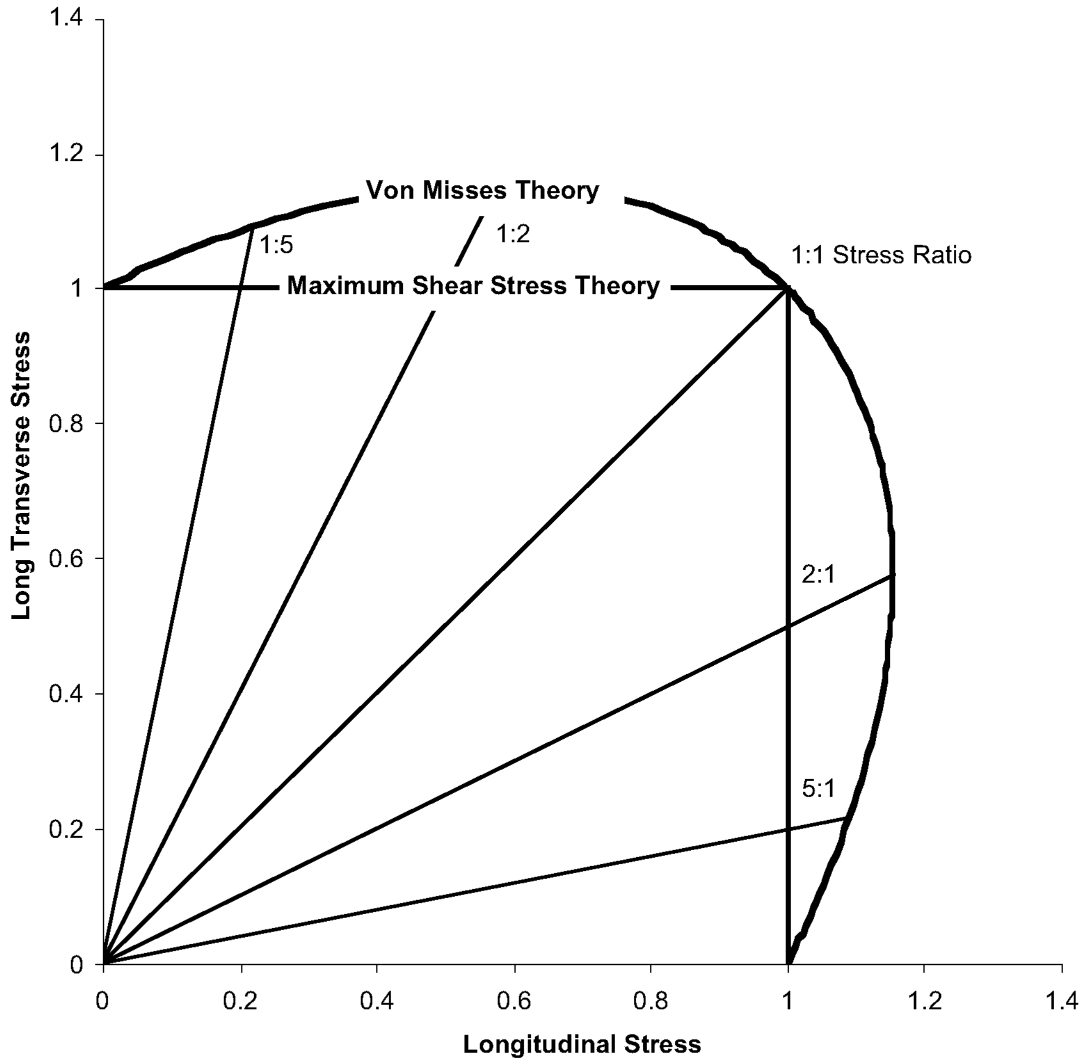

Figure 1. Comparison of von Mises' and maximum shear stress theory yield loci for ducitle, isotropic materials. Ratios are the applied stress ratios (σL:σLT).

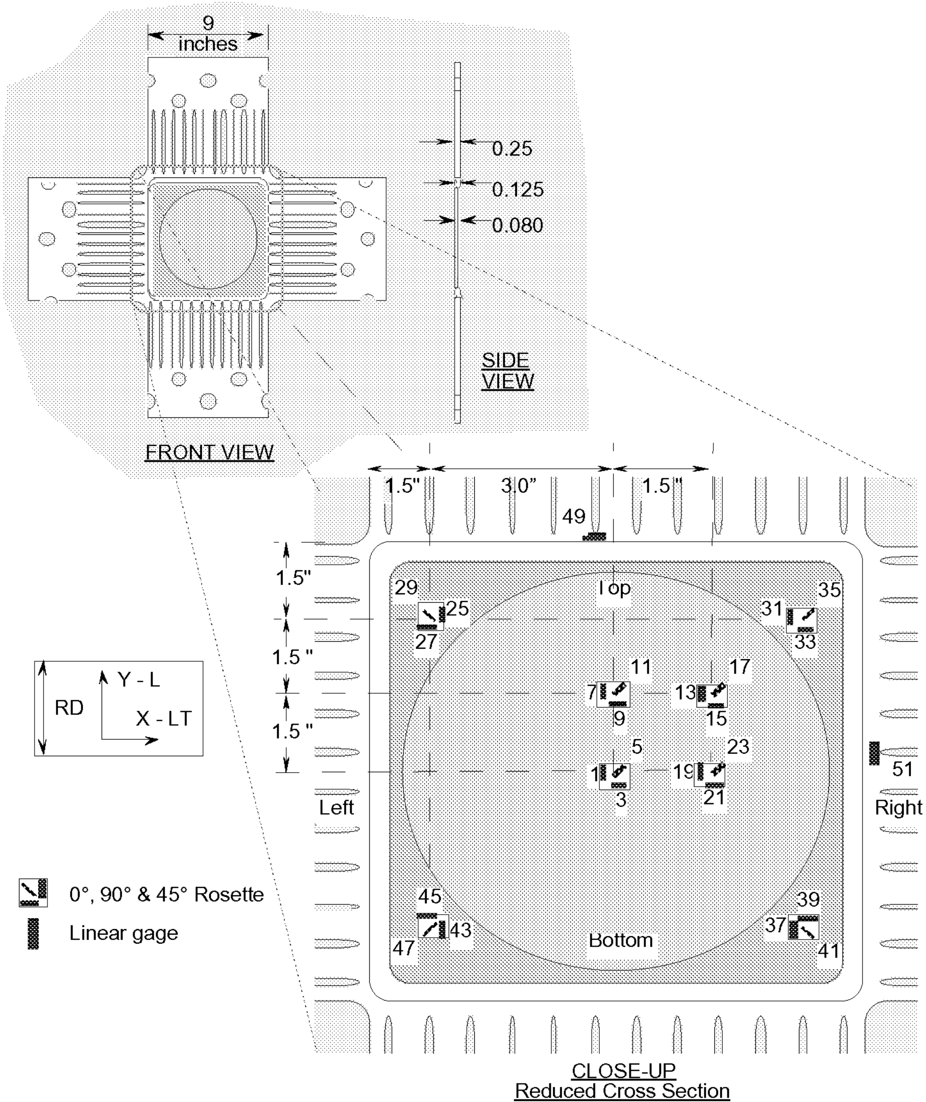

Figure 2. Schematic of the cruciform specimen and 52 strain gage layout. The numbers are the gage number, odd on one side and even on the other. 1.0-in. extensometers are centered and aligned with the major loading axis.

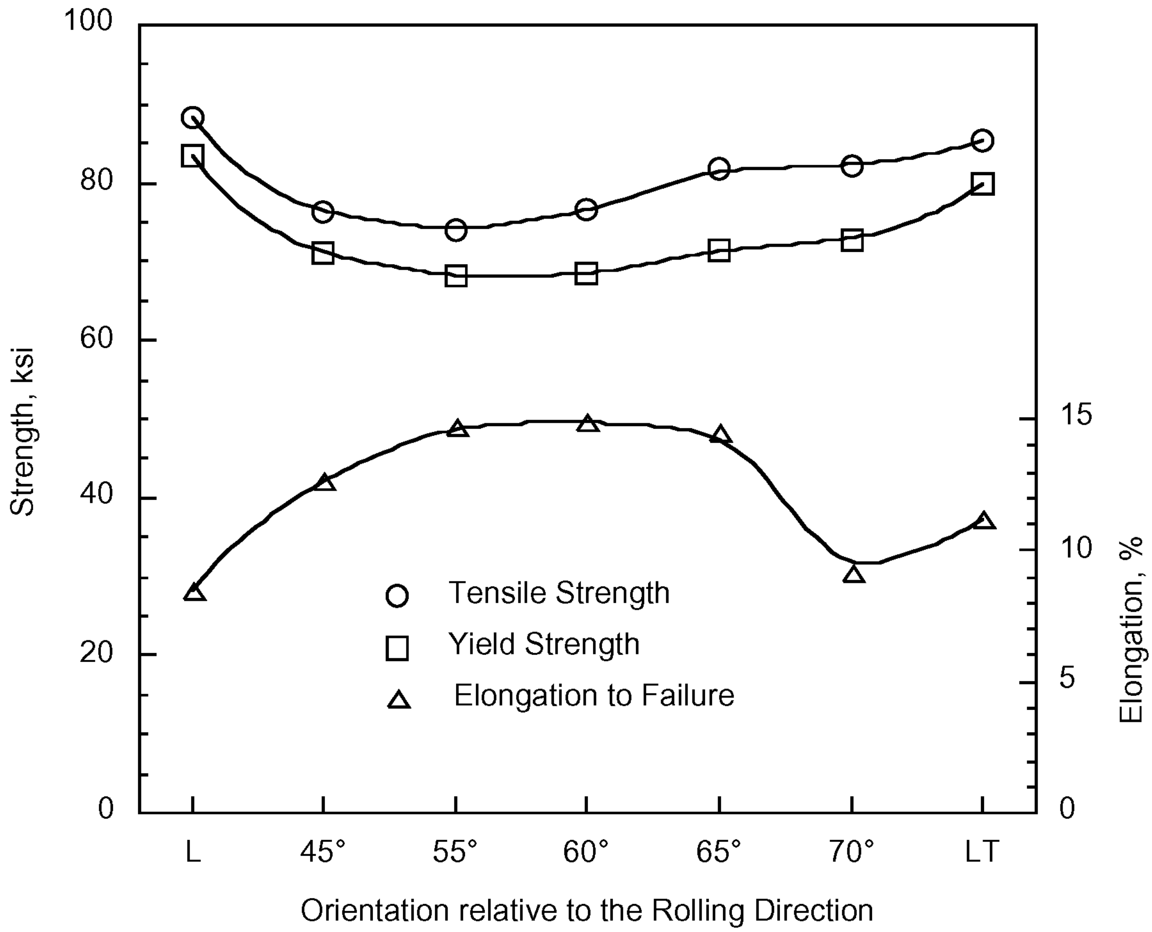

Figure 3. Uniaxial tensile results as a function of orientation for 2195-T8, from t/2 of 0.45-in.-thick plate. Lines indicate trends between discreet data points, not a continuum of data.

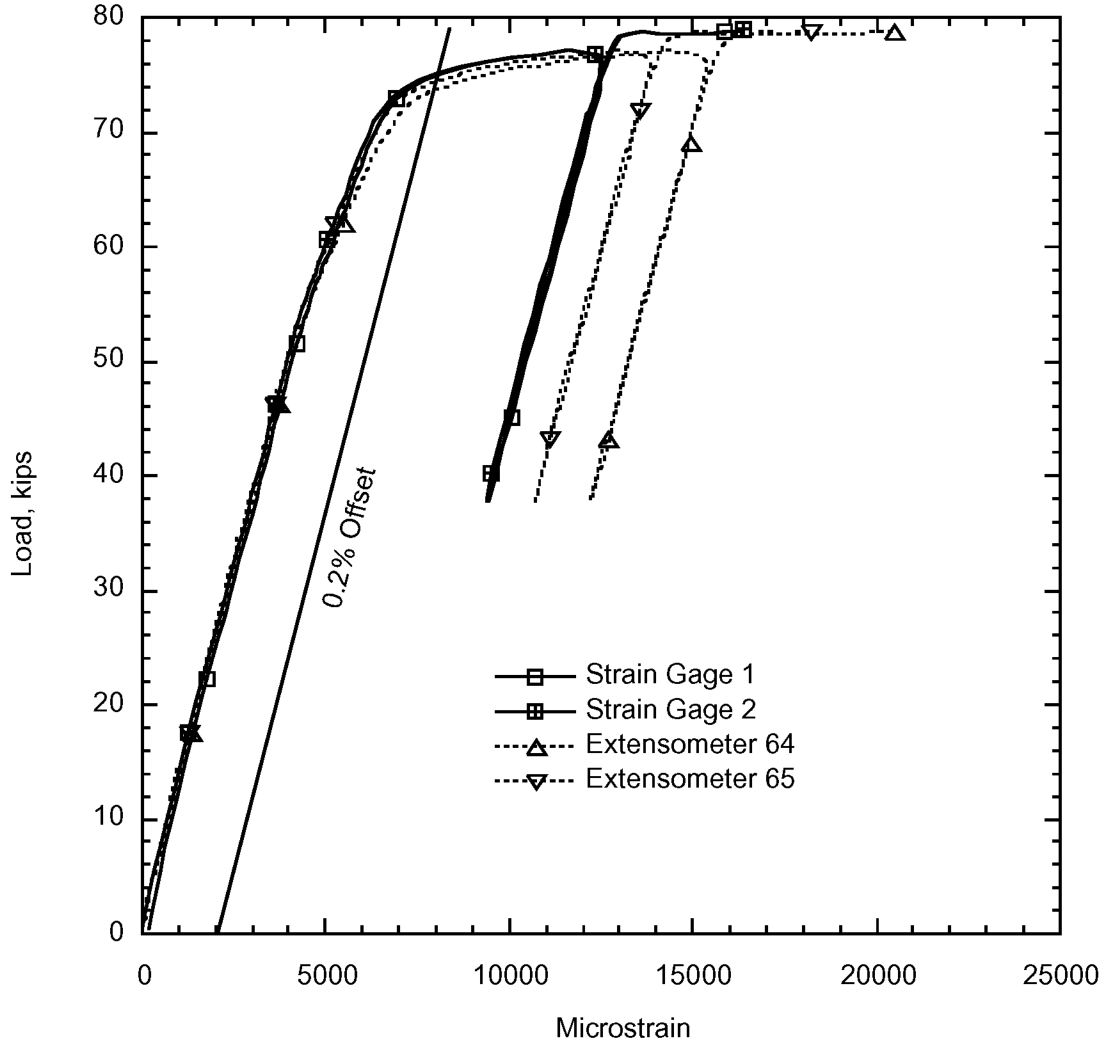

Figure 4. Strain response as a function of load for center of biaxial panel. The 0.2% strain is exceeded prior to failure. See Figure 2 for gage and extensometer location.

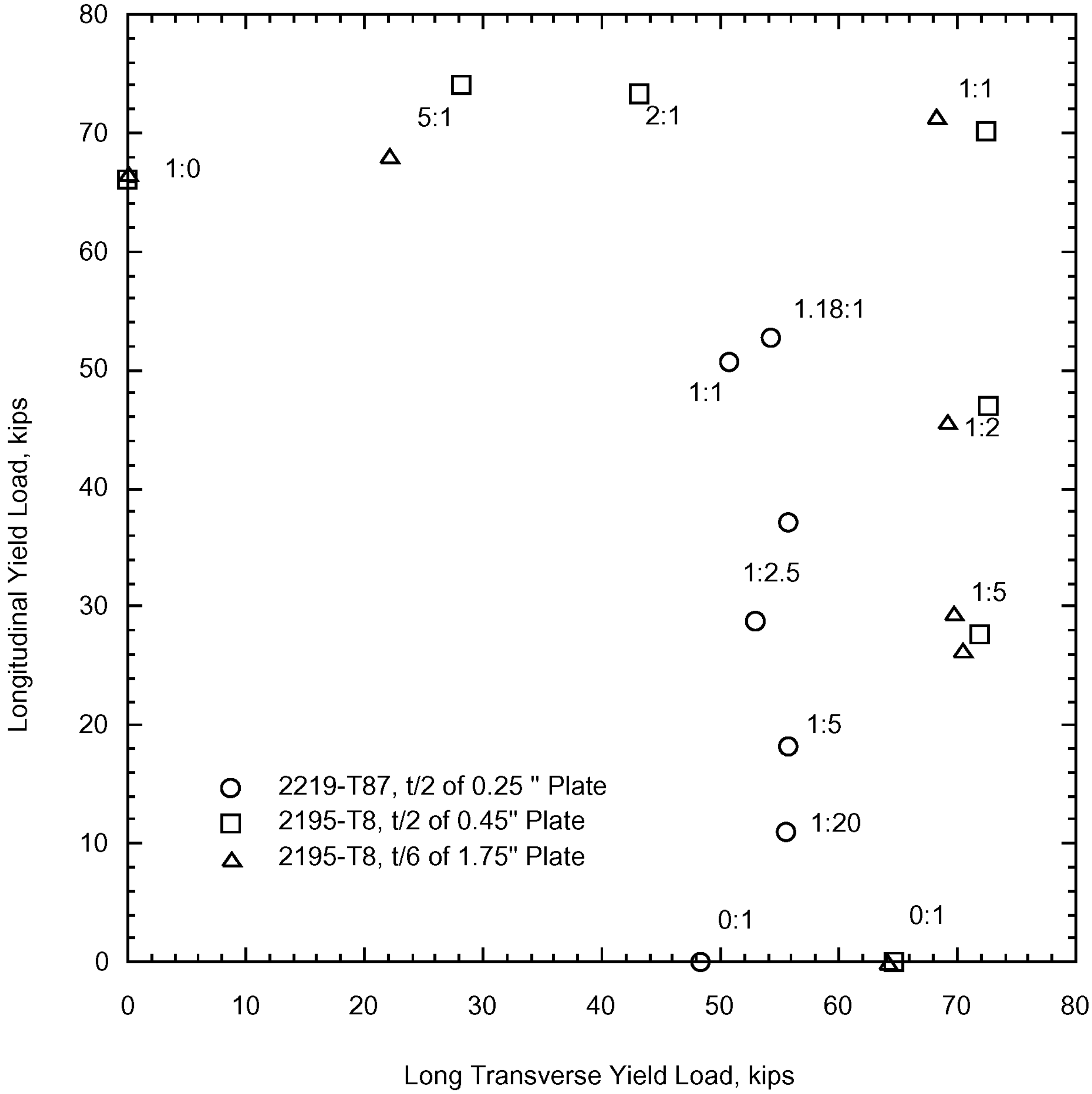

Figure 5. Biaxial yield load results for Al-Li 2195-T8 plates and baseline alloy Al 2219-T87 tested at room temperature.

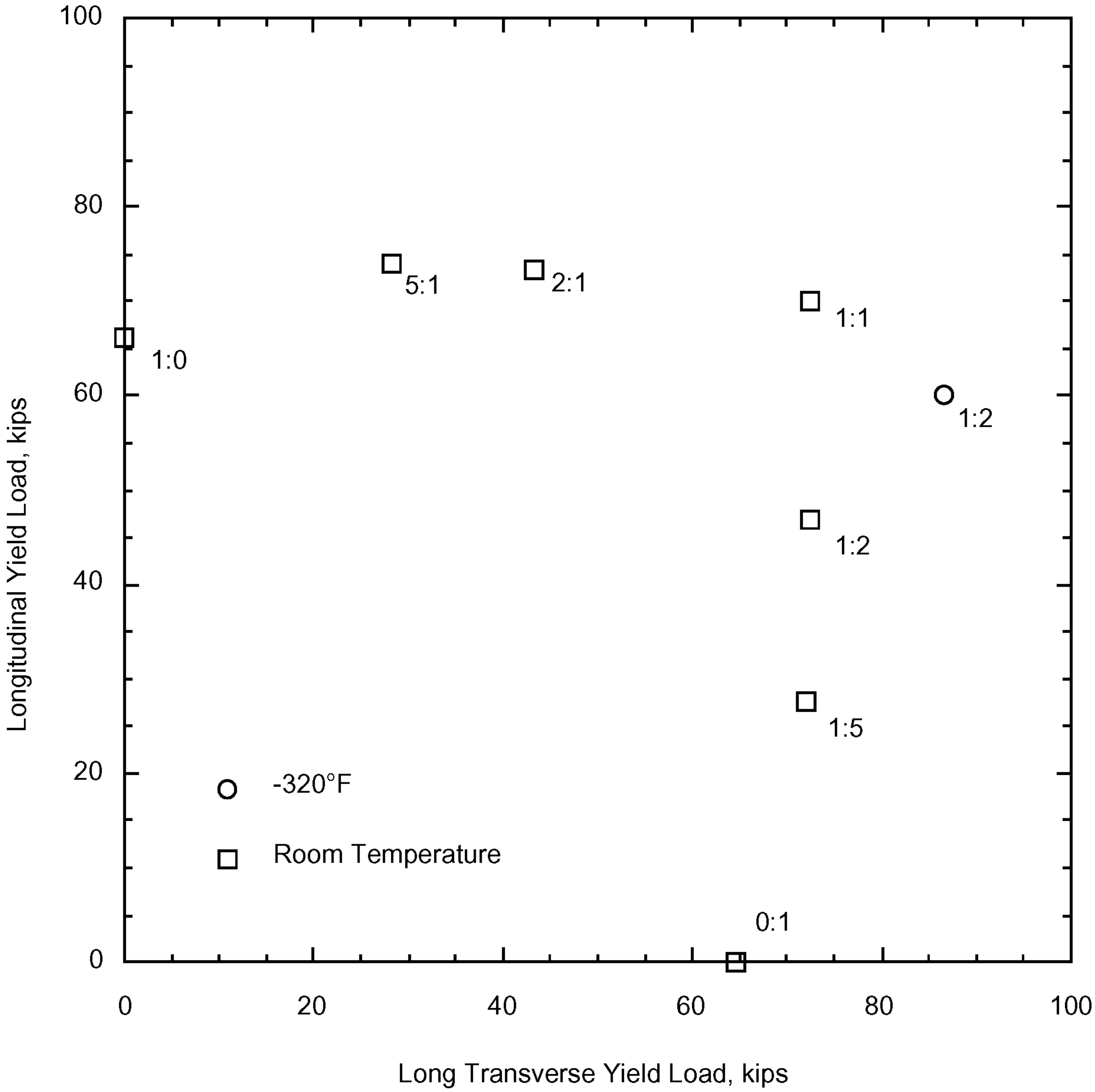

Figure 7. Room Temperature biaxial results and the 1:2 stroke ratio test at -320°F for 0.45-in.-thick 2195-T8 plate.

APPENDIX

Biaxial tests were performed at stroke ratios of 0:1, 1:5, 1:2, 1:1, 2:1, 5:1, and 1:0 at room temperature and 1:2 at -320°F on 0.45" thick 2195-T8 plate. Biaxial tests were performed at stroke ratios of 0:1, 1:5, 1:2, 1:1, 5:1 and 1:0 at room temperature at t/6 of 1.75-in.-thick 2195 plate. The load-strain measurements for each test are given in Figures A-1 through a-15, respectively. The 0.2% yield load is shown in each figure relative the strains measured at the center of the gage section. The yield loads correspond to the data points shown in Figures 5 and 6.

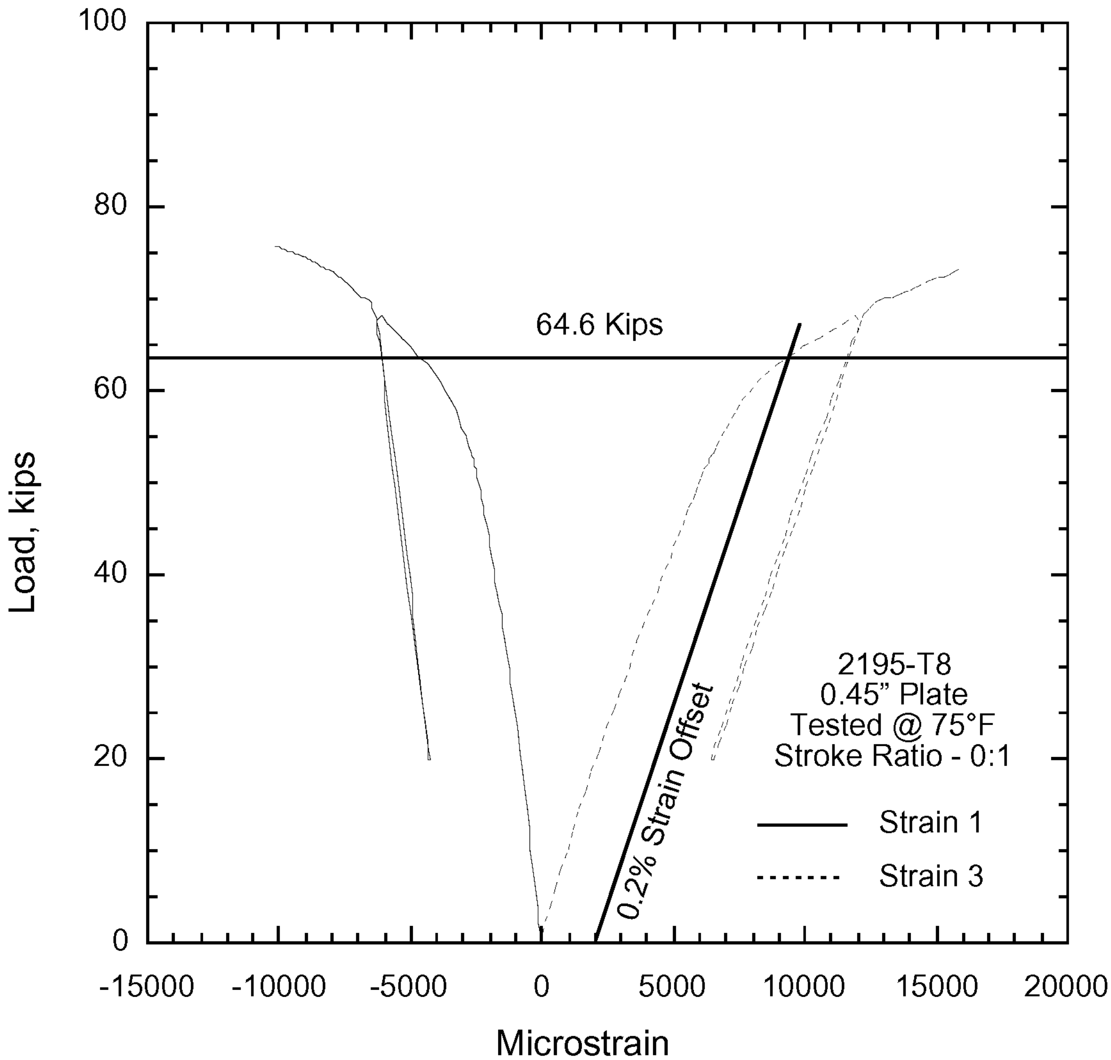

Figure A-1 Load plotted against strain for the center gages of a cruciform biaxial panel (stroke ratio 0:1).

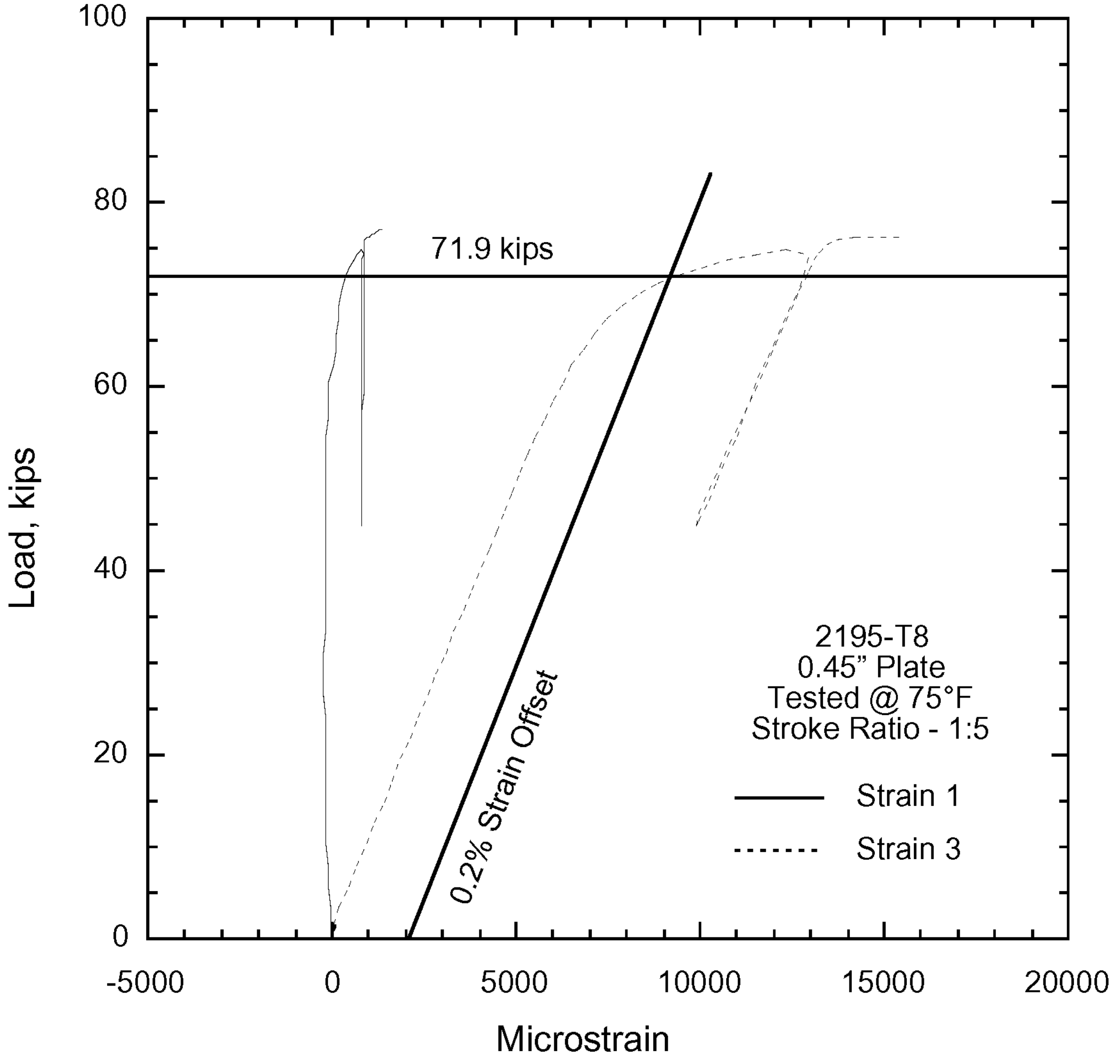

Figure A-2 Load plotted against strain for the center gages of a cruciform biaxial panel (stroke ratio 1:5).

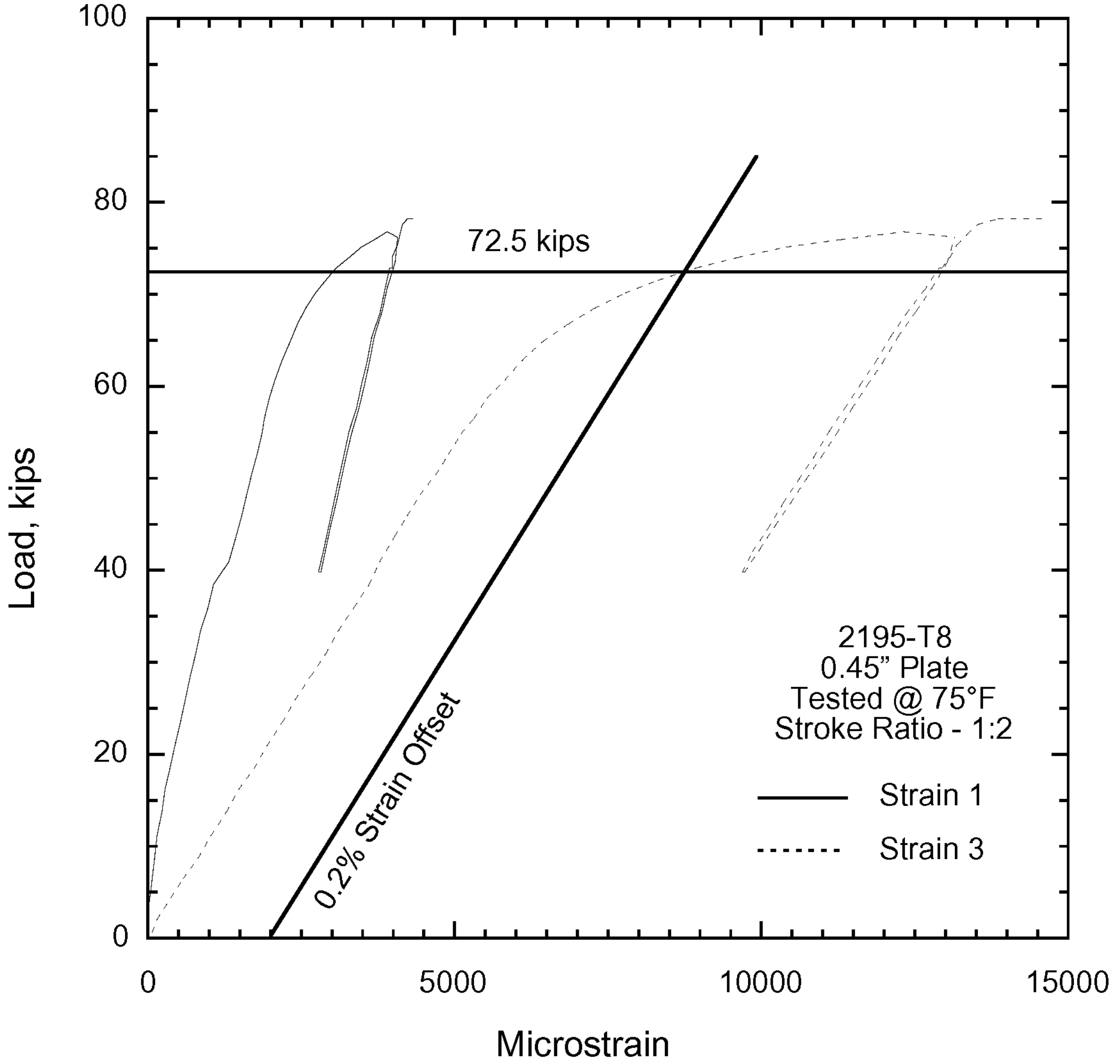

Figure A-3 Load plotted against strain for the center gages of a cruciform biaxial panel (stroke ratio 1:2).

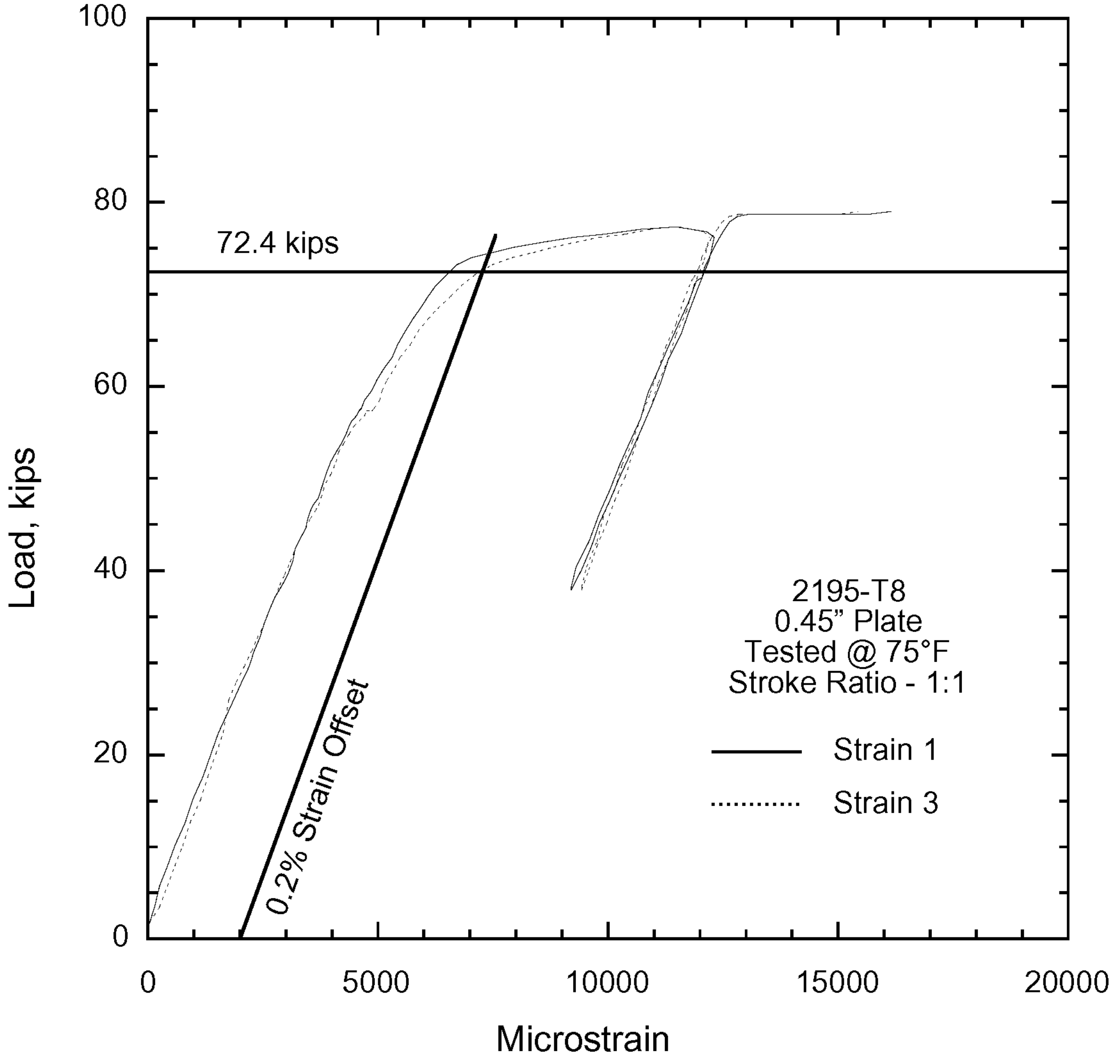

Figure A-4 Load plotted against strain for the center gages of a cruciform biaxial panel (stroke ratio 1:1).

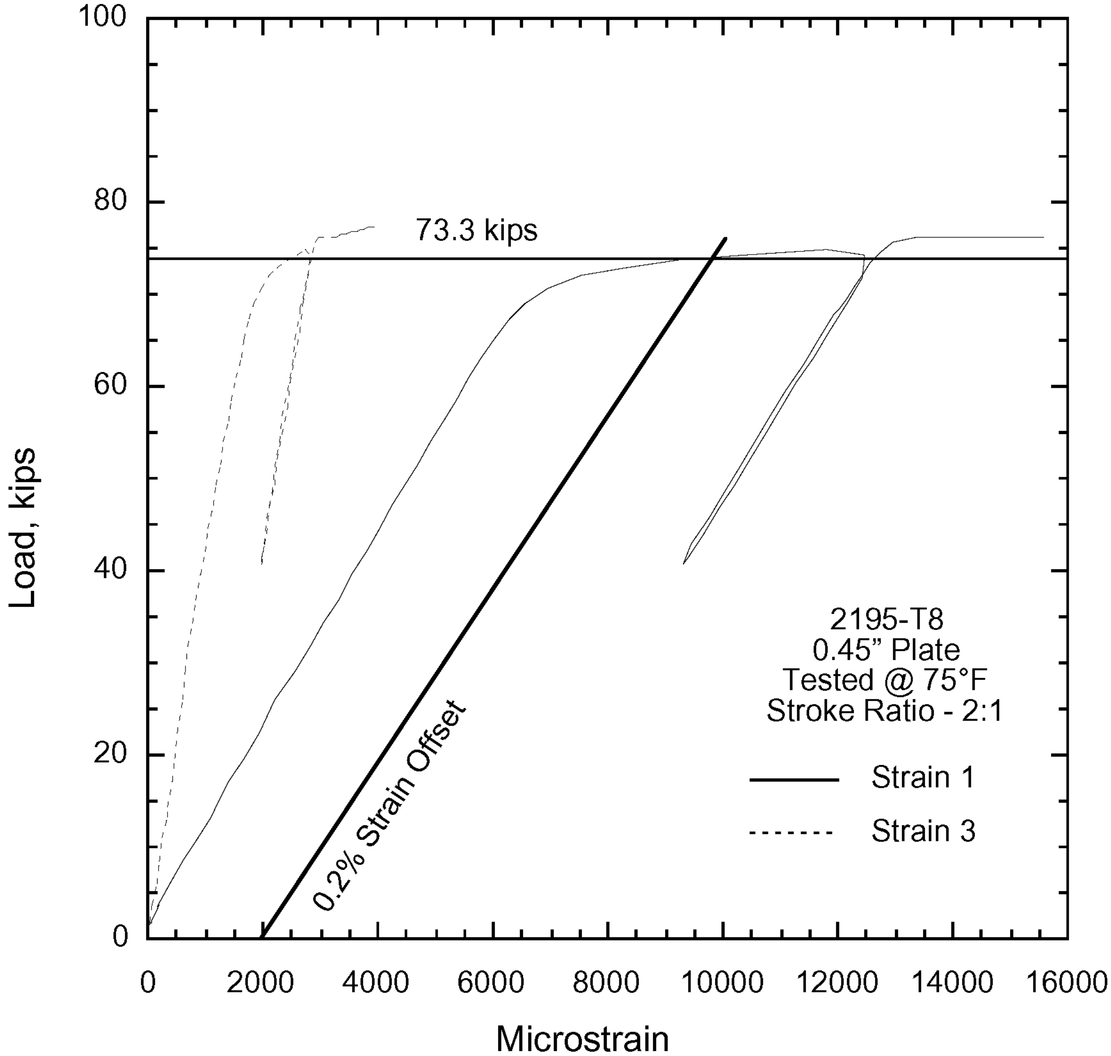

Figure A-5 Load plotted against strain for the center gages of a cruciform biaxial panel (stroke ratio 2:1).

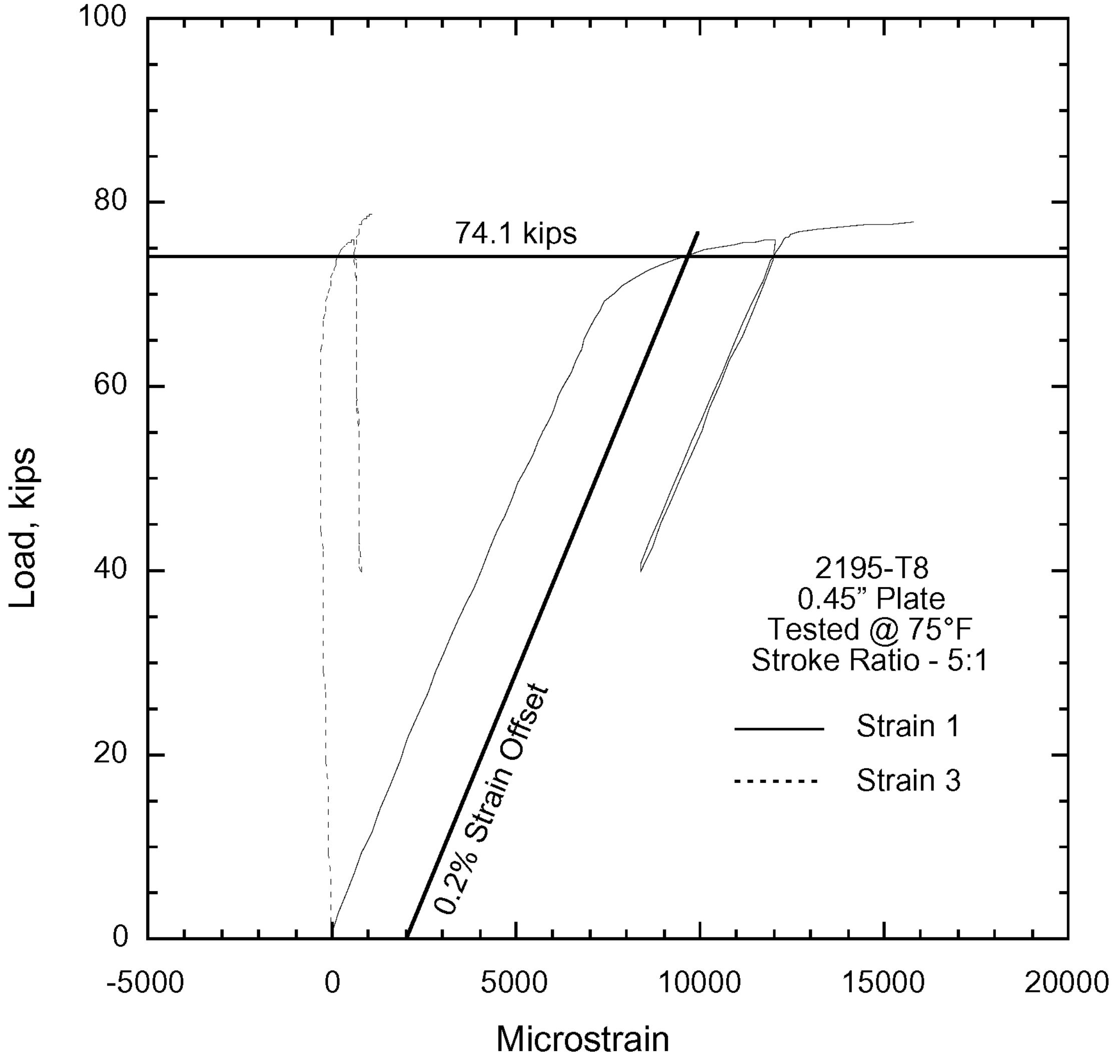

Figure A-6 Load plotted against strain for the center gages of a cruciform biaxial panel (stroke ratio 5:1).

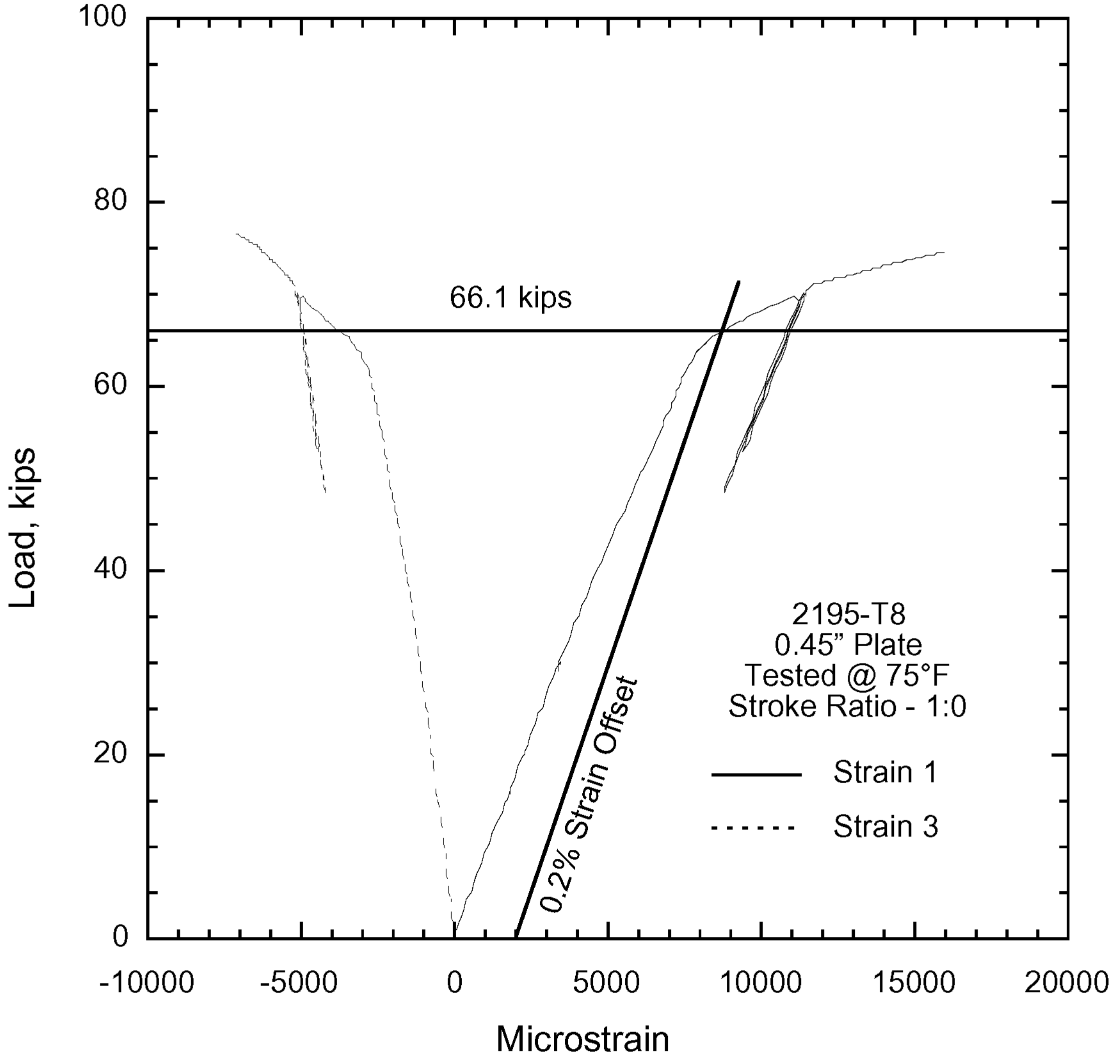

Figure A-7 Load plotted against strain for the center gages of a cruciform biaxial panel (stroke ratio 1:0).

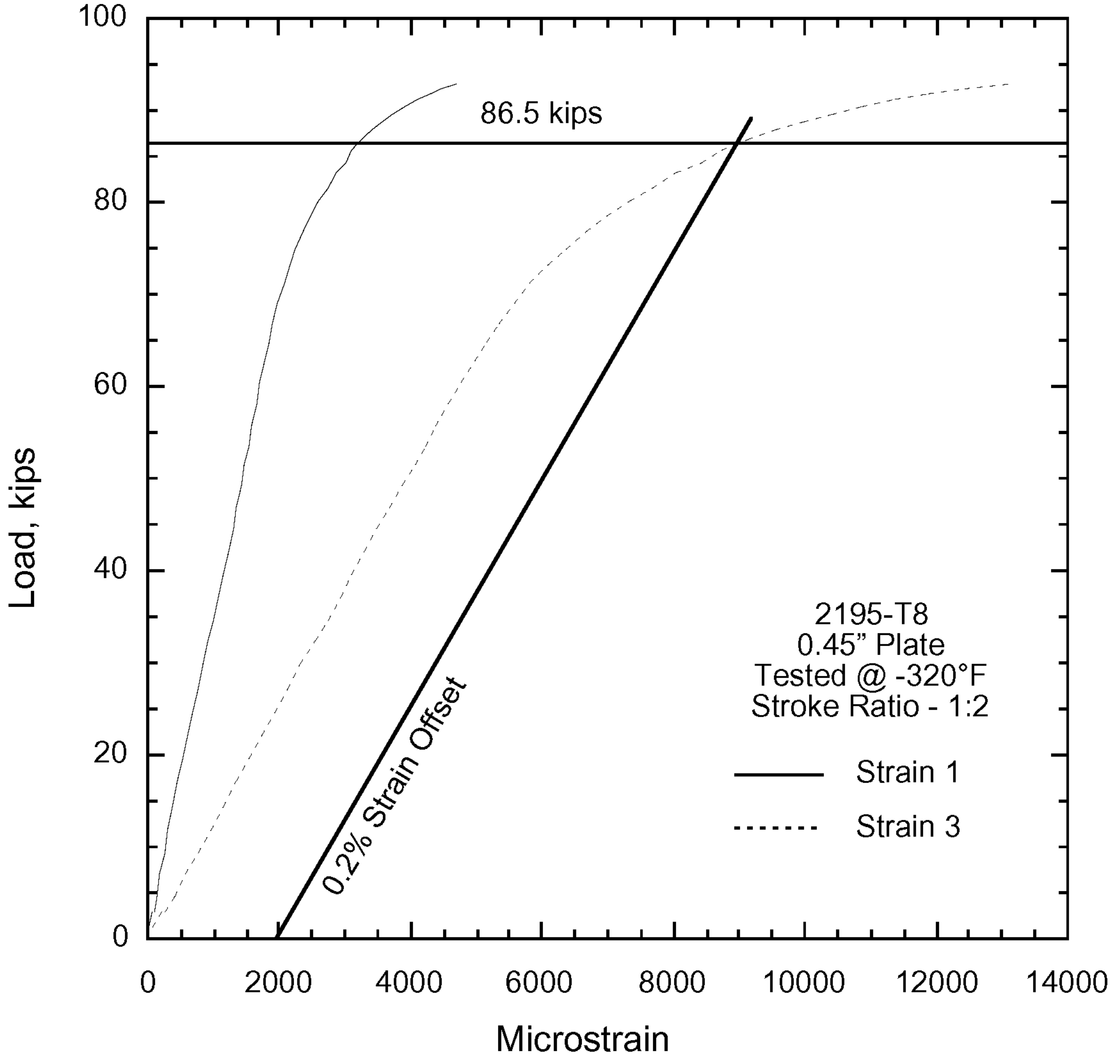

Figure A-8 Load plotted against strain for the center gages of a cruciform biaxial panel (stroke ratio 1:2).

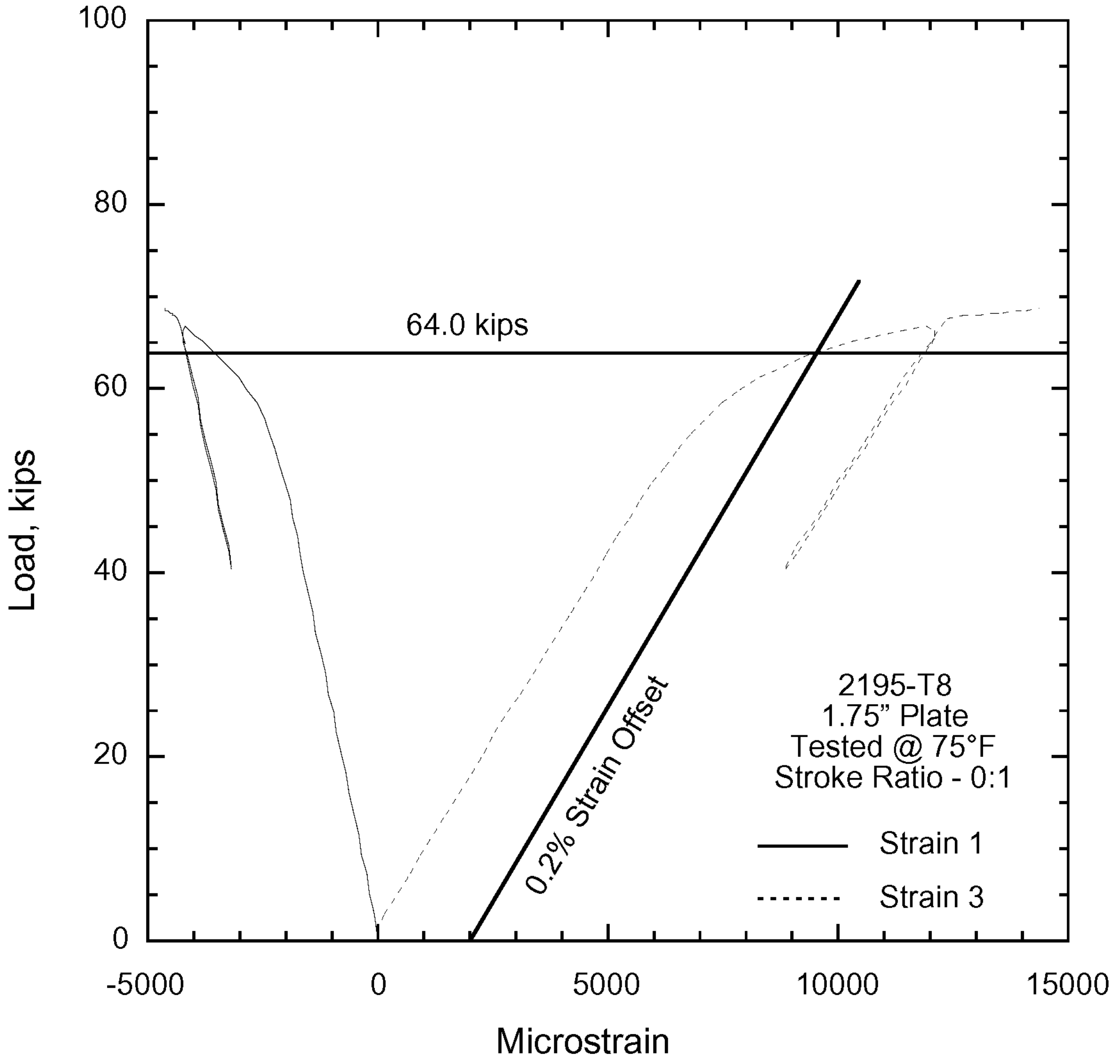

Figure A-9 Load plotted against strain for the center gages of a cruciform biaxial panel (stroke ratio 0:1).

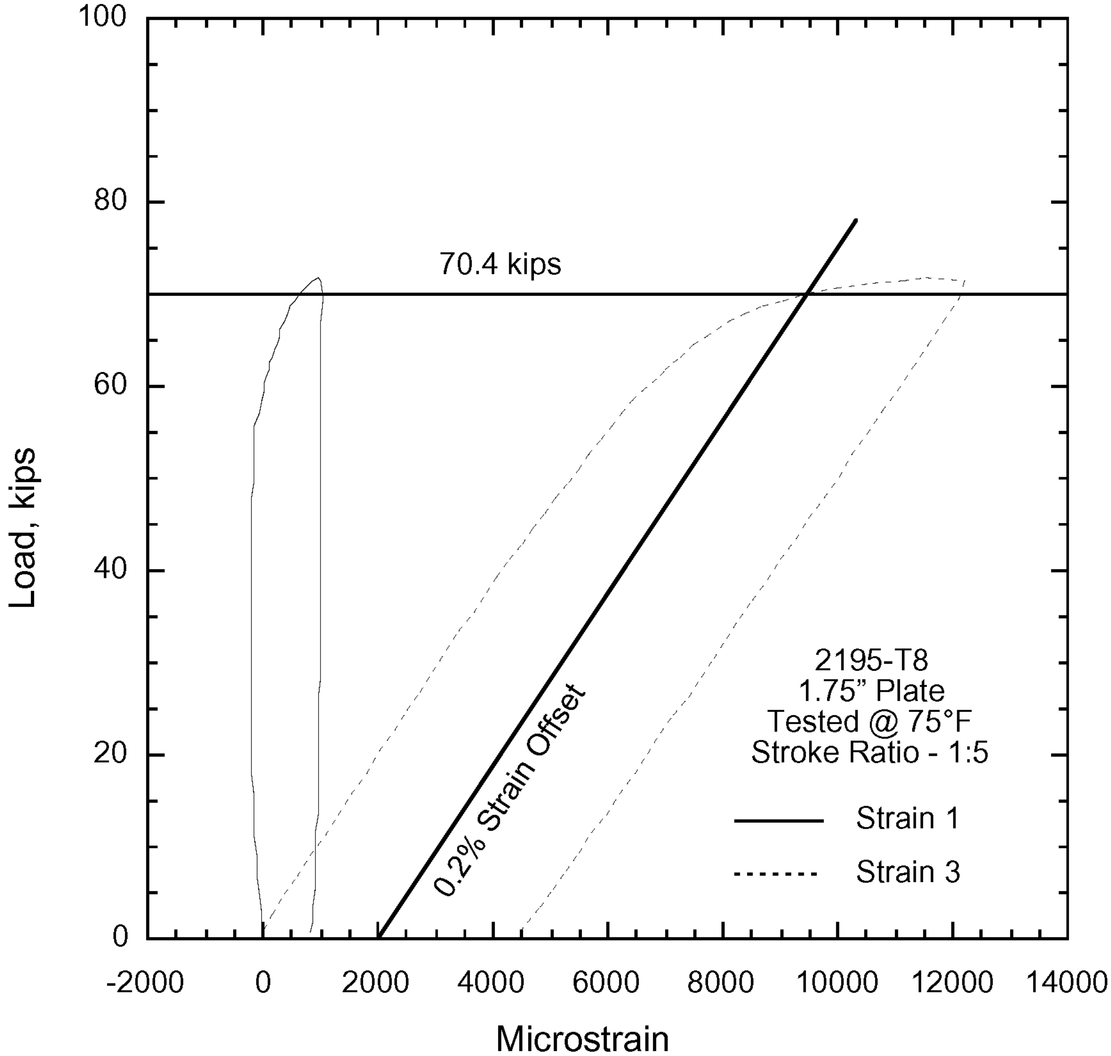

Figure A-10 Load plotted against strain for the center gages of a cruciform biaxial panel (stroke ratio 1:5).

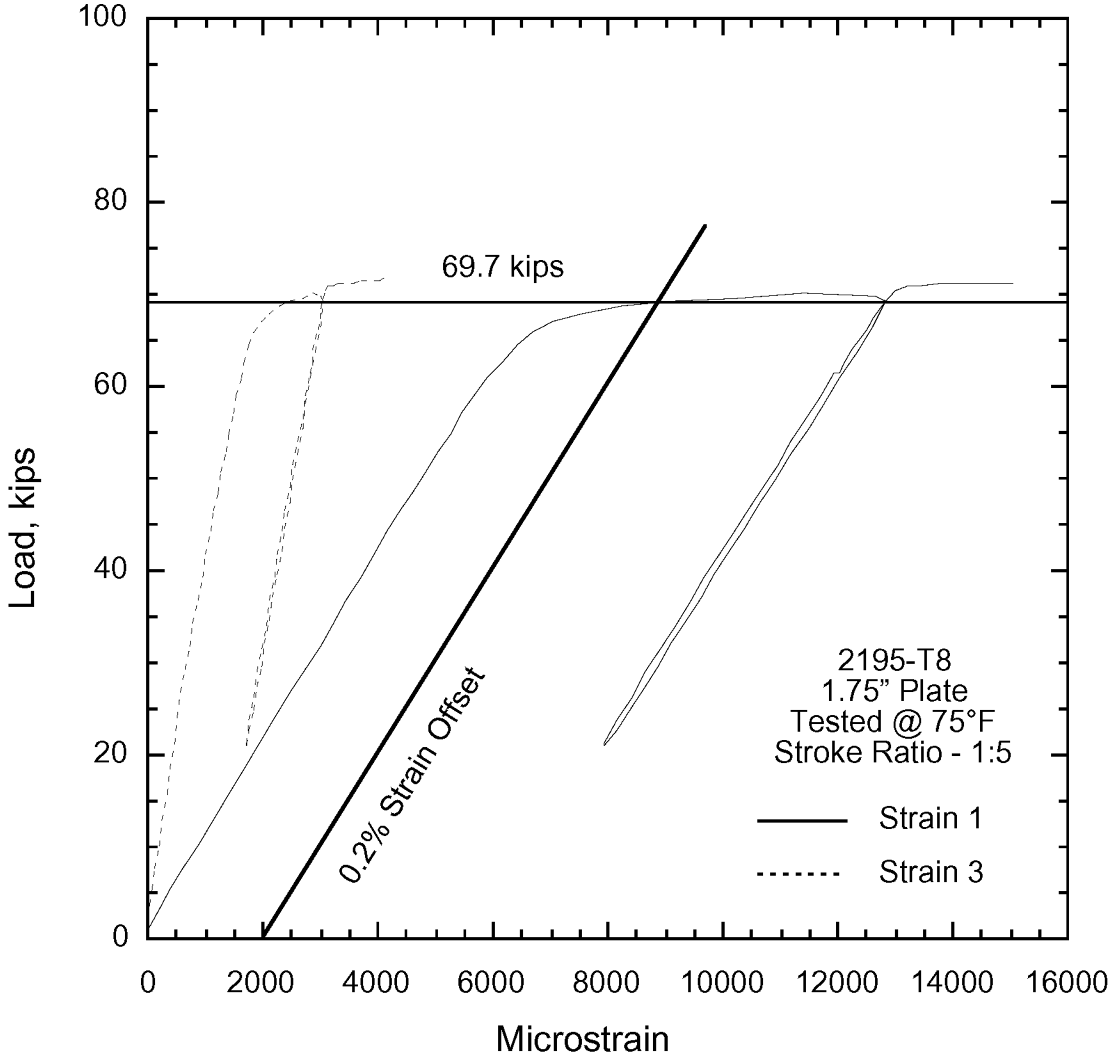

Figure A-11 Load plotted against strain for the center gages of a cruciform biaxial panel (stroke ratio 2:1).

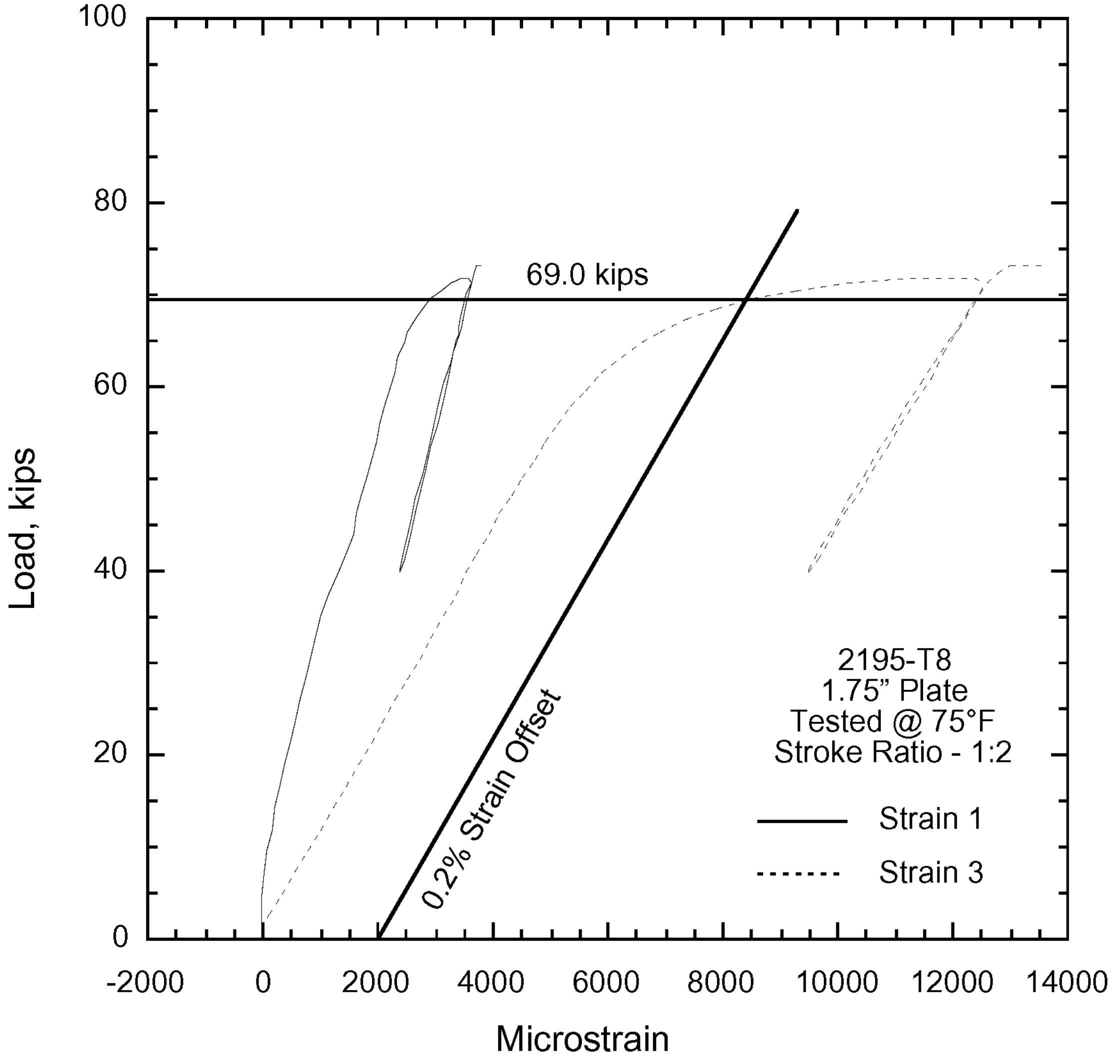

Figure A-12 Load plotted against strain for the center gages of a cruciform biaxial panel (stroke ratio 1:2).

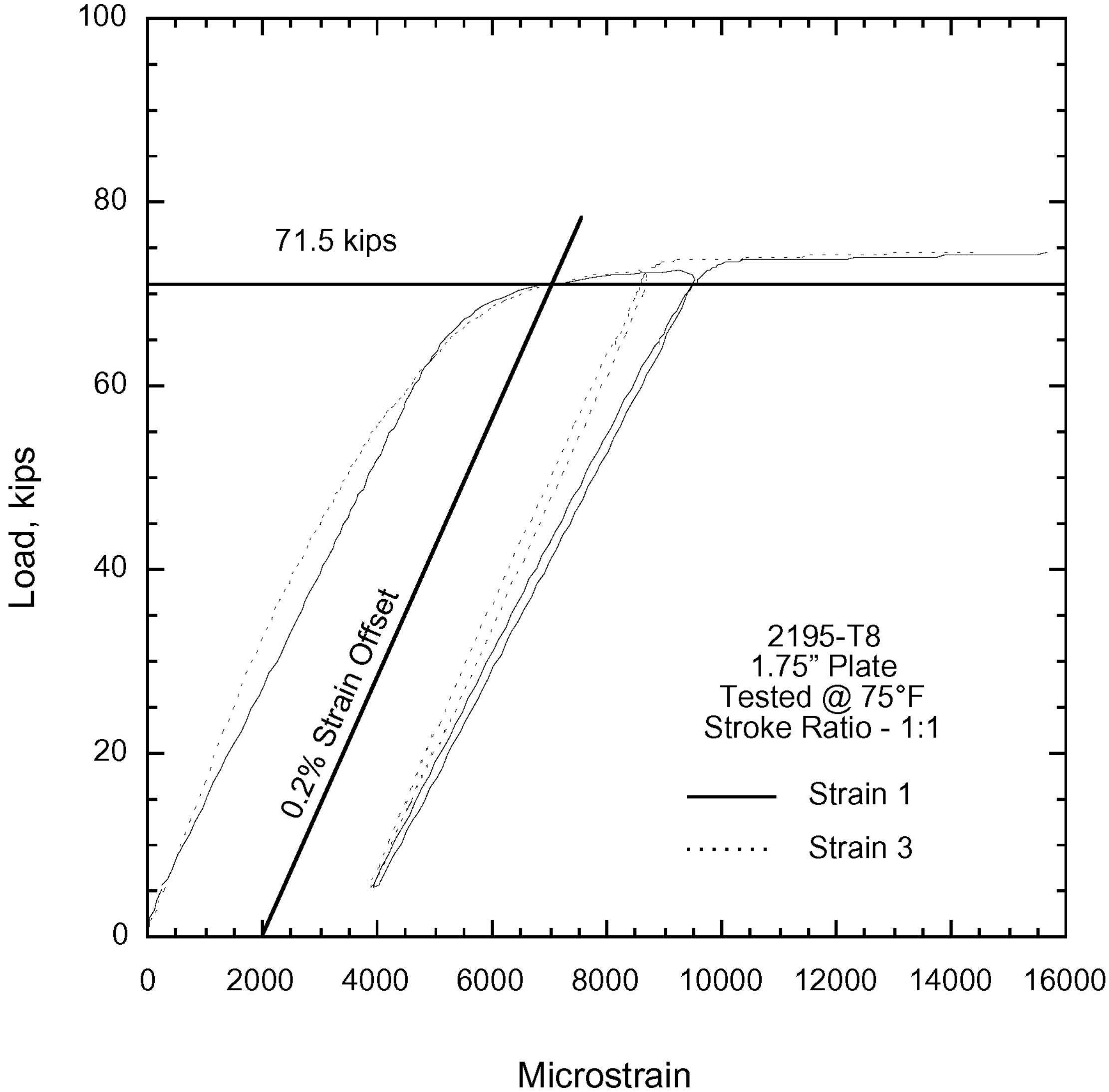

Figure A-13 Load plotted against strain for the center gages of a cruciform biaxial panel (stroke ratio 1:1).

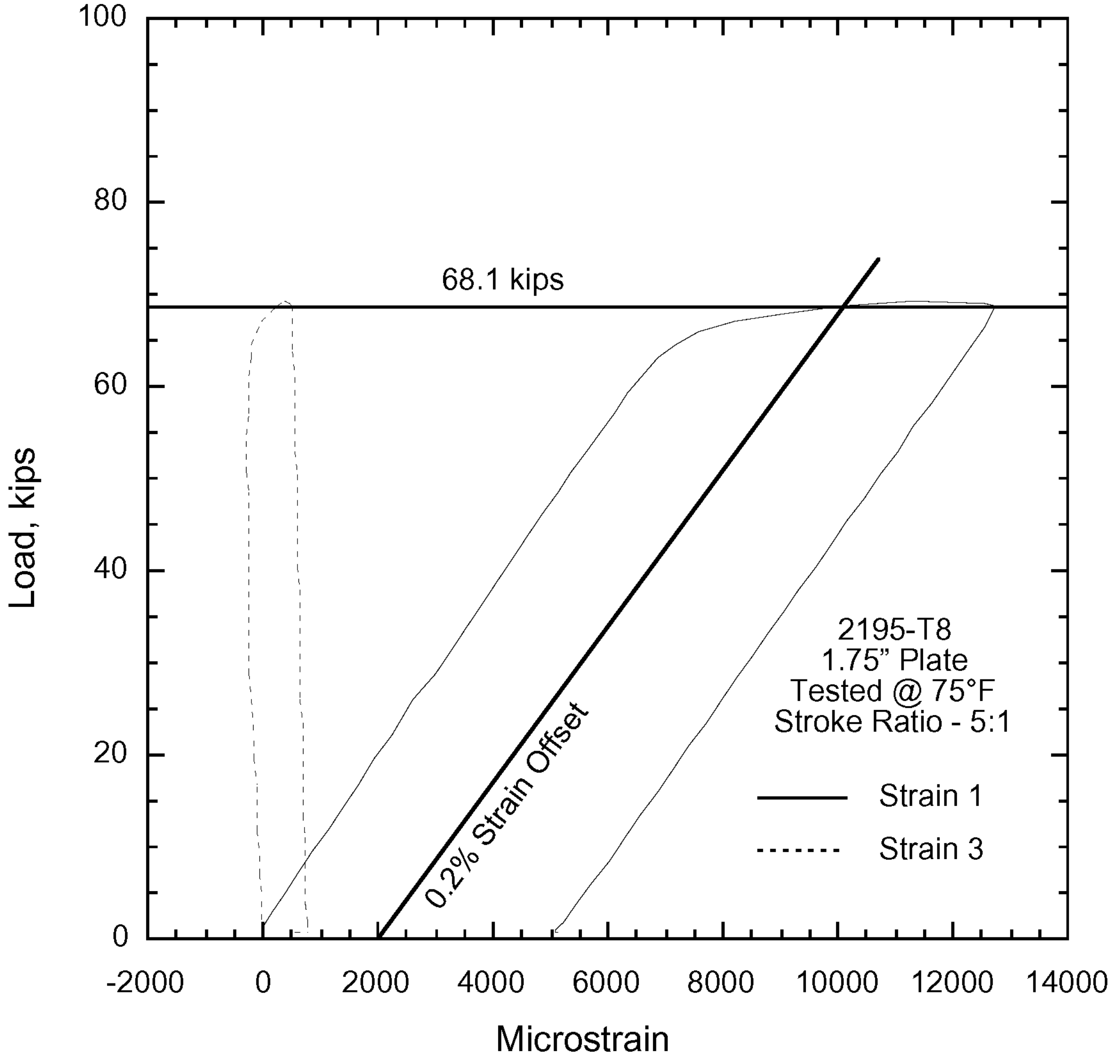

Figure A-14 Load plotted against strain for the center gages of a cruciform biaxial panel (stroke ratio 5:1).

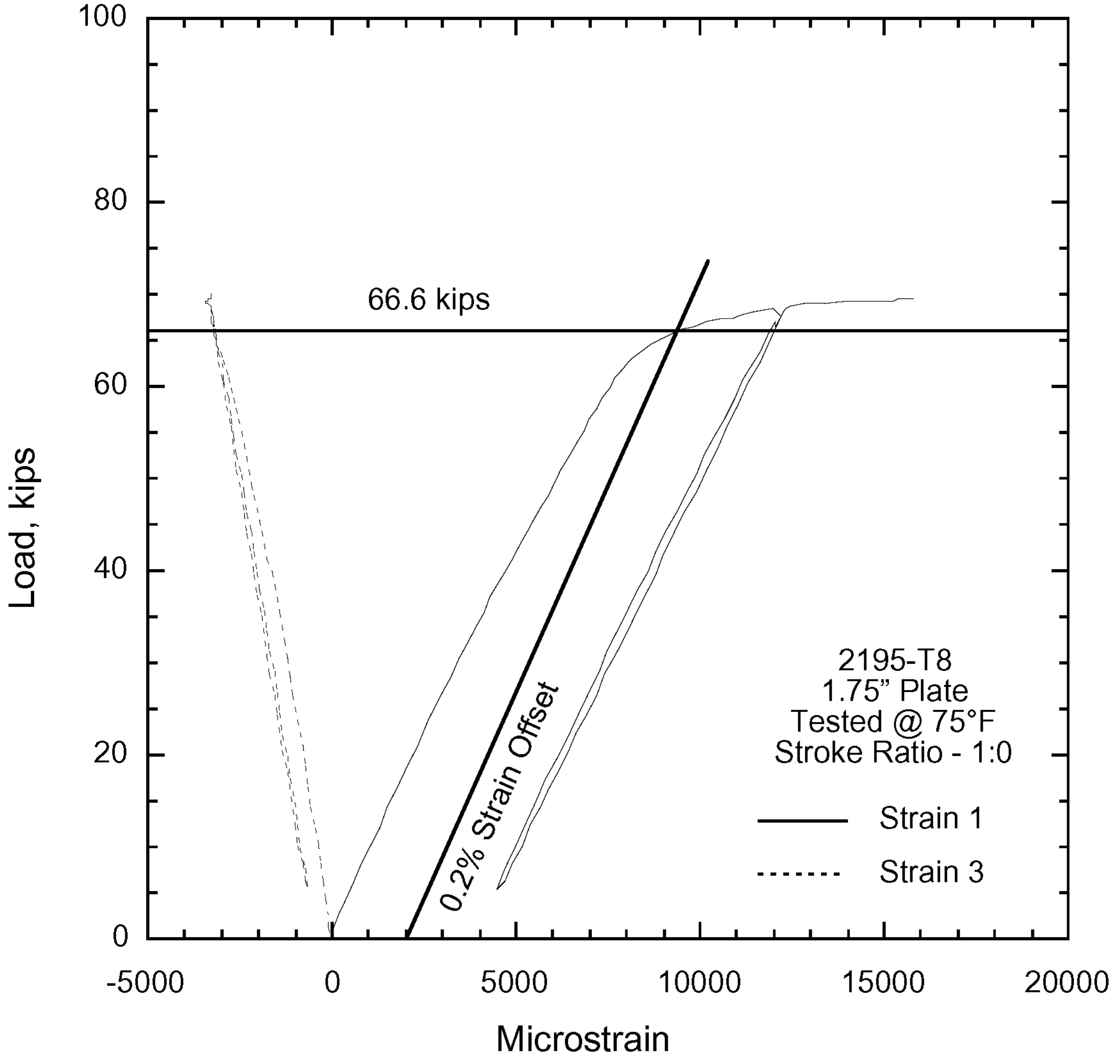

Figure A-15 Load plotted against strain for the center gages of a cruciform biaxial panel (stroke ratio 1:0).

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.			
1. AGENCY USE ONLY (*Leave blank*)	**2. REPORT DATE** October 2002	**3. REPORT TYPE AND DATES COVERED** Contractor Report	
4. TITLE AND SUBTITLE Biaxial Testing of 2195 Aluminum Lithium Alloy Using Cruciform Specimens			**5. FUNDING NUMBERS** NAS1-96014 713-50-02-51
6. AUTHOR(S) W. M. Johnston, W. D. Pollock, and D. S. Dawicke			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Analytical Services & Materials, Inc. Hampton, Virginia 23666			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Langley Research Center Hampton, VA 23681-2199			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER** NASA/CR-2002-211942
11. SUPPLEMENTARY NOTES Langley Technical Monitor: John A. Wagner			
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Category 26 Distribution: Standard Availability: NASA CASI (301) 621-0390			**12b. DISTRIBUTION CODE**
13. ABSTRACT (*Maximum 200 words*) A cruciform biaxial test specimen was used to test the effect of biaxial load on the yield of aluminum-lithium alloy 2195. Fifteen cruciform specimens were tested from 2 thicknesses of 2195-T8 plate, 0.45 in. and 1.75 in. These results were compared to the results from uniaxial tensile tests of the same alloy, and cruciform biaxial tests of aluminum alloy 2219-T87.			
14. SUBJECT TERMS Biaxial, Finite Element Analysis, 2195-T8, 2219-T87, von Mises, Yield Surface, Yield Locus, Aluminum Alloy, Aluminum-Lithium Alloy			**15. NUMBER OF PAGES** 32 **16. PRICE CODE**
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z-39-18
298-102