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THE MECHANICAL BEHAVIOR OF CROSS-ROLLED BERYLLIUM SHEET

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ABSTRACT

In response to the failure of a conical section of the Insat C satellite during certification testing, the use of beryllium for payload structures, particularly in the sheet product form, is being reevaluated. A test program was initiated to study the tensile, shear, and out-of-plane failure modes of beryllium cross-rolled sheet and to apply the data to the development of an appropriate failure criterion. Tensile test results indicated that sanding the surface of beryllium sheet has no significant effect on yield strength, but can produce a profound reduction in ultimate strength and ductility. Biaxial and shear test results were found to be in good agreement with results obtained by finite element analysis. Critical examination of these test results may contribute to the modification of a JSC policy for the use of beryllium in orbiter and payload structures.

INTRODUCTION

Beryllium has been a material of considerable interest to aerospace structural designers, due to its high strength, high stiffness, and low density. Hot-pressed beryllium block has been successfully applied to 23 space shuttle parts, including the navigation base [1]. In addition, beryllium is manufactured in the sheet product form [2-10], which is a useful material for satellite primary structure. The most recently developed commercial grade of cross-rolled beryllium sheet is designated as SR-200E [9-10]. References [1, 11-12] provide an overview of some of the applications of beryllium in spacecraft structures. Although the aerospace industry has experienced success in using beryllium, extra care must be taken in both the design and manufacturing of beryllium structures. For example, determining a design criterion which provides an acceptable margin of safety is essential to the reliable application of beryllium [13]. However, identifying such a design criterion that adequately describes the behavior of beryllium is difficult because this material is anisotropic and exhibits both ductile and brittle characteristics. Another obstacle to the increased use of beryllium structure has been its low fracture toughness and susceptibility to brittle fracture [14-15]. Even though recently developed grades of beryllium sheet have exhibited an improved ductility in the longitudinal and transverse directions, ductility in the thickness direction is still severely limited. Also, beryllium is characterized by tensile properties which are very sensitive to surface finish [16-19]. Machining procedures induce twinning at the surface, which can lead to brittle fracture. Annealing or etching after machining can eliminate twinning, and orbiter beryllium parts are etched to a minimum depth of 0.006 in. [1].

In the early 1980's, a conical section of the Insat C spacecraft (built by Ford Aerospace Co., Palo Alto, California) failed during certification testing for flight as a Space Transportation System (STS) payload. From the resulting investigation, Ford Aerospace personnel concluded that the failure was due to excessive out-of-plane stresses, which developed during the torquing sequence required to mate the beryllium structure to the vibration test cruciform. Because of this experience, materials engineers at Johnson Space Center (JSC) became interested in the subject of the design of beryllium structures, and in particular in identifying a failure criterion that could be applied to the use of beryllium sheet in orbiter structures and payloads. This provided the initiative to begin a test program at JSC directed toward developing a better understanding of the mechanical behavior of beryllium. Emphasis was placed on studying the effects of surface finish and out-of-plane displacements on beryllium sheet. In conjunction with this study, an extensive literature search was conducted to locate papers regarding such topics as the physical/mechanical behavior of beryllium, failure criteria which can be used for anisotropic materials, and the manufacturing and processing of beryllium. A bibliography listing of these references has been included in the appendix of this report.

The objective of this paper is to present the results from the tensile, shear, and biaxial tests which were conducted using 0.10 in. thick beryllium SR-200E cross-rolled sheet. Shear and biaxial test results are compared with numerical (finite element) solutions, and the constants for the Tsai-Wu failure criterion are derived.

EXPERIMENTAL PROCEDURE

Materials

Cross-rolled beryllium sheet (SR-200E) was the primary material used for this study and specimens for mechanical testing were obtained in the machined and etched condition from two sources. Disc specimens for biaxial testing and tensile specimens were obtained from Electrofusion Corp., and tensile and shear specimens were purchased from Brush Wellman, Inc. In addition to the cross-rolled beryllium, aluminum 2024-T81 sheet and aluminum 7075-T6 sheet were used as reference materials.

Tensile Tests

Tensile tests of the beryllium material were performed according to the procedures established by ASTM test specification E-8 [20], using the flat tensile specimen geometry shown in figure 1. Three longitudinal (L) and three longitudinal transverse (LT) tensile specimens (Electrofusion), each with a test section of 2.25 x 0.50 x 0.10 in., were tested in laboratory air at room temperature. For each of three specimens (EF-T1, EF-T2, and EF-L3), a ladder gage, which employed a stack of 10 single strain gages, was attached to the front face along the gage length, and very small strain gages were attached to the two edges. In addition, EF-T2 and EF-L3 were instrumented with biaxial strain gages. The other three specimens (EF-T3, EF-L1, and EF-L2) were instrumented with front and back face single strain gages only. The strain gages enabled close observation of the stress–strain behavior of the material, and the ladder gages were especially helpful in the detection of Lüders bands. In addition, six longitudinal tensile specimens (Brush Wellman), each having a test section of 1.25 x 0.25 x 0.10 in., were tested in laboratory air at room temperature. Ladder strain gages were used to examine the tensile behavior of specimens BW-L1 and BW-L2, and front and back single strain gages were used for the remaining specimens. The surface finish of the Brush Wellman specimens was varied by sanding the gage lengths with 280 or 400 grit paper. The yield strength for each of the Electrofusion and Brush Wellman tensile specimens was determined as the stress corresponding to the onset of the yielding phenomenon, rather than the 0.2% offset yield strength.

Biaxial Tests

An approximation of in-plane biaxial testing was accomplished using the loading configuration shown in figure 2. Two 2024-T81 and two beryllium disc specimens (6.50 in. dia. x 0.10 in. thick), were loaded in this manner (figure 2), using a support ring (6-in. dia.) and a load ring (1- or 2-in. dia.). Three linear variable displacement transducers (LVDTs) were attached to the support ring for verification of the planarity and even distribution of the loading. In order to observe the stress distribution, each disc was instrumented with 16 biaxial strain gages, as shown in figure 3, which measured strain in both the radial (R) and circumferencial (C) directions. Each beryllium specimen was loaded and unloaded to 50%, 75%, and 100% of the average uniaxial yield strength, and then loaded to failure. The two aluminum specimens were loaded to 75% of the yield strength, unloaded, and then loaded to failure. Load–strain data from all 16 strain gages were recorded continuously. Stresses were calculated using the average elastic modulus for the appropriate material and strain gage data according to the following equation: $\sigma = E\epsilon$. For each of the load levels, both the maximum stress and the stress at the center of the specimen were calculated.

Shear Tests

Several shear specimen designs were considered, and a sketch of the specimen design that was chosen is shown in figure 4a. One aluminum 7075-T6 specimen was used to verify the validity of the specimen design and test procedures before the five 0.10 in. thick beryllium shear specimens were tested. Each specimen was adhesively bonded to a test fixture, using 3M adhesive AF3109-2 and primer EC3960. The setup was then loaded, as shown in figure 4b, at a crosshead rate of 0.02 in/min until the shear specimen failed. The specimens were also instrumented with shear and rosette strain gages, and load–strain data were continuously recorded for determination of yield and ultimate shear strengths.

FINITE ELEMENT MODELS

Finite element models of the shear and biaxial specimens were developed, and the analytical results were compared with experimental data. The biaxial tests were modeled using the MSC/NASTRAN finite element analysis program, and the shear specimen model was formulated using the MSC/PROBE finite element code.

The biaxial plate specimen was modeled using a 3-dimensional finite element mesh, which consisted of 10 layers. Each layer was axisymmetric, and modeled a quarter of the plate, using 81 QUAD4 elements and 33 TRIA elements (see figure 5). Both linear and nonlinear finite element results were generated for the aluminum and beryllium specimens by applying the appropriate load level to the model using boundary conditions corresponding to both the 1- and 2-in. load rings. The nonlinear analysis incorporated geometric nonlinearities into the model, but did not consider the effect of material nonlinearities. Both linear and nonlinear results were obtained for the 2024-T81 specimens using an input load which would produce a stress corresponding to 75% of the average uniaxial yield strength. For the SR-200E beryllium, linear results were generated for 50%, 75%, and 100% of the average uniaxial yield strength, as well as for the failure stress. Nonlinear beryllium results were obtained at 100% of the average yield, and at failure.

The shear specimen model (see figure 6) was a 2-dimensional membrane model, consisting of 36 triangular and 12 quadrilateral elements. This linear model was constrained along edge A, and a constant displacement was applied to the specimen along edge B, in the negative Y direction.

The magnitude of the displacement was determined from the experimental failure strain. Figure 7 shows both the deformed (solid lines) and undeformed (dashed lines) shapes of the shear finite element model. The resultant stress field was compared with the ultimate shear stress results obtained from testing.

EXPERIMENTAL RESULTS

Tensile Results

Table 1 summarizes the tensile results obtained from the six Electrofusion and six Brush Wellman test specimens. The two Electrofusion specimens tested in the longitudinal direction, which were not sanded for the application of ladder strain gages (EF-L1 and EF-L2), produced an average yield strength of 60.0 ksi, an average ultimate strength of 77.0 ksi, and an average elongation of 16%. The unsanded Brush Wellman specimen (BW-L1) produced a yield strength of 50.3 ksi, an ultimate strength of 71.0 ksi, and an elongation of 20%. Although the data are few, this demonstrates a fair amount of variability in tensile properties between lots of cross-rolled beryllium sheet. The only unsanded specimen which was tested in the transverse direction (EF-T3) produced a yield strength of 60.2 ksi and an ultimate strength of 72.1 ksi, with an elongation of 25%. Figure 8 presents the load–time curve for specimen EF-T3, demonstrating the presence of a distinct yield point. This yield point phenomenon was the typical transition mode from elastic to plastic deformation for both the L and LT specimens. Table 2 compares the average unsanded tensile properties obtained from this program with various other tensile data available for cross-rolled beryllium sheet. Limited data were available for SR-200E [9,10], while more extensive tensile data were found in older reports for previous grades of cross-rolled sheet [5,7,21].

Table 1 also presents the tensile results from the Electrofusion specimens (EF-T1, EF-T2, and EF-L3) that were mistakenly sanded at 45° angles to the direction of loading (in a cross-hatched pattern) prior to the ladder strain gage application. This sanding procedure produced the undesirable effect of reducing the elongation from an average of 17.3% to less than 1% in the longitudinal direction, and from 25.2% to less than 1% in the transverse direction. This decrease in ductility was accompanied by a reduction of the ultimate strength from an average of 75.0 ksi to 60.1 ksi in the longitudinal direction, and from 72.1 ksi to an average of 60.1 ksi in the transverse direction. The yield strength, however, was not significantly affected by sanding procedures.

In addition, Table 1 presents the tensile results indicating the effects of sanding the Brush Wellman specimens with various grades of sand paper. Sanding one side of specimen BW-L2 lightly in a cross-hatched pattern with 400 grit paper did not affect the tensile properties significantly. Sanding the specimens using 280 grit paper, however, produced a variable reduction in ductility. Specimen BW-L3, which was sanded lightly on one side, showed a decrease in ductility to about 5%, while specimen BW-L4, which was sanded vigorously on both sides, showed no decrease in tensile properties. Specimens BW-L6 and BW-L7, which were sanded in the transverse direction on all four sides of the gage length with 280 grit paper, showed a consistent decrease in elongation to less than 1%.

Biaxial Results

The results from the biaxial tests of the beryllium discs which were tested with the 1-in. load ring (specimen B-1) and with the 2-in. load ring (specimen B-2) are listed in table 3. Each specimen was loaded and unloaded to 50%, 75%, and 100% of the average uniaxial yield strength, and then loaded to failure. In table 3, the strain gage which registered the maximum strain at each load level is indicated. The maximum strain for specimen B-1 was measured by strain gage SG-2-R, which was located at the center of the specimen, for every load level. For specimen B-2, the maximum strain was found to occur at strain gage SG-4-C, which was located adjacent to the load ring, for the first three load levels. However, when the specimen was loaded to failure, the maximum strain level was registered by strain gage SG-12-R. Table 3 also lists both the maximum and center stresses that were calculated for each load level. The maximum and center stresses for the 1-in. load ring specimen coincided, since the maximum stress was located at the center of the specimen. In contrast, the maximum stress for the 2-inch load ring test was observed by the strain gages adjacent to the load ring. The fact that the maximum stress for specimen B-2 was adjacent to the load ring indicates the influence of the larger bending moment present in this specimen as compared with specimen B-1. Therefore, the results from specimen B-1 should provide a better approximation of an in-plane biaxial stress state.

Figures 9 and 10 show the load–strain data from specimens B-1 and B-2 during the runs in which they were loaded to failure. Since a distinct yield point is not demonstrated in either figure, and the load–strain curves are not linear at any point, values for a biaxial yield strength have not been reported. The failure load for specimen B-1 was measured to be 1346 lb., and the failure load for specimen B-2 was found to be 2117 lb. These loads were used as the input loading conditions to the finite element models for the failure cases. Failure stresses were calculated for each specimen, using the maximum strain measurements at failure. Specimen B-1 failed at 121.0 ksi, and specimen B-2 failed at 135.0 ksi. It is evident from these failure data that the load-carrying capability of beryllium cross-rolled sheet is not reduced by the application of out-of-plane displacements, if it is not in combination with other stresses. In fact, the average failure stress from these two specimens is 128 ksi, which is almost double the average uniaxial tensile strength.

A photograph of the failed 1-in. load ring specimen is shown in figure 11, indicating a shattered appearance and fairly uniform, pie-shaped fracture pieces. Examination of the pieces indicated that the fracture initiated at the center of the disc, corresponding to the region of maximum stress. Likewise, figure 12 is a photograph of the broken pieces of the beryllium disc which was shattered using the 2-in. load ring. For this loading condition, the fracture was determined to have initiated adjacent to the load ring. This area corresponds to the region of maximum strain, which was detected by strain gage SG-4-C.

Shear Results

The load–strain data that were obtained from the 7075-T6 shear specimen and the beryllium shear specimen S-5 are presented in figures 13 and 14, respectively. The 7075-T6 specimen failed in a shear mode along a straight line between the notches, as expected. This test established confidence in the specimen design and testing procedures. Table 4 summarizes the results from the beryllium shear tests. All of the specimens demonstrated a distinct change in load–strain behavior at a stress of approximately 30 ksi. This may correspond to the change in fracture path of the specimen or possibly to the onset of cracking. Final fracture stresses (shear ultimate strength values), based on the net section of material between the notches, ranged from 38 to 45 ksi. In contrast to the 7075 results, the beryllium specimens failed in a tensile mode, such that the fracture initiated at the notch and propagated parallel to the slope of the notch (see photograph in figure 15). The beryllium shear specimens were tested in both the pristine and sanded conditions. Unlike the tensile results, however, sanding the shear specimens did not significantly reduce the ultimate strength, and a substantial amount of strain occurred after the shear yield.

DISCUSSION OF RESULTS

Yield Point Phenomenon

As seen from the load–time curve for specimen EF-T3 (figure 8), the onset of yielding was followed by a region of discontinuous yielding and a distinct yield point. Researchers have associated such behavior with the formation of Lüders bands on the surface of beryllium [23-24]. This plateau of discontinuous yielding was investigated with the use of ladder strain gages. The results from the ladder gages demonstrated the presence of Lüders bands by indicating that adjacent segments of material yielded sequentially, thus producing a "zipping" effect. Even the tensile specimens that exhibited less than 1% elongation showed indications of the presence of Lüders bands. Since Lüders bands were observed in both pristine and sanded tensile specimens, this phenomenon does not appear to control the amount of elongation observed at final fracture. Thus, while the formation of Lüders bands seems to be a typical part of the deformation process in cross-rolled beryllium sheet, Lüders bands do not seem to play a significant role in ductility.

Surface Damage

The tensile results from the beryllium specimens that were sanded imply that the loss in ductility is primarily due to the introduction of surface damage from the sanding procedure. This agrees with results from Hanafee [16], which demonstrated that induced surface roughness directly lowers the ultimate strength and ductility of beryllium, but does not affect the yield strength. However, the Electrofusion tensile results may be in conflict with another report by Hanafee [22], which concluded that sanding isostatically pressed beryllium block with 320 grit sand paper, prior to application of strain gages, does not produce damage (in the form of scratches and/or twinning) that is significant enough to affect its tensile behavior. Such a difference might indicate that beryllium cross-rolled sheet is more susceptible to surface damage than isostatically pressed block. Also, it is unclear at this time what relationship, if any, exists between sanding direction and reduction in ductility. In order to resolve these issues and fully define the effects of different sanding techniques on beryllium, an extensive study, which should include careful microscopy work to document scratches and twins, would be required.

Biaxial Finite Element Analyses

Both linear and nonlinear finite element analyses of the aluminum and beryllium biaxial tests were performed to substantiate the experimental results. For the aluminum biaxial tests, the load corresponding to 75% of the average uniaxial yield stress was used as the load input to the finite element model. For the beryllium tests, the loads corresponding to 50%, 75%, and 100% of the average yield stress and the measured failure loads were used as the input loading conditions for the finite element analyses.

Table 5 shows a comparison of the biaxial disc test results at each load level with the results from the linear finite element analyses. The stresses and deflections which are compared in this table represent values calculated at the center of each disc. The validity of the finite element model was supported by a comparison between finite element and experimental results for the two aluminum discs. The agreement between the beryllium analytical and experimental results were also fairly good, except at the failure stress. Since geometric and material nonlinear effects were not considered, the difference between predicted and experimental results increased over the material's linear range, and was an important contributing factor to the particularly poor agreement obtained at failure.

Table 6 presents a comparison of the biaxial disc results with the results from the nonlinear finite element analyses. Again, the stresses and deflections listed in this table were determined at the center of each disc. This model incorporated the geometric nonlinearities associated with the load application. The calculated deflections from these nonlinear cases were closer to experimental values than the linear results for almost every load level. Also, the calculated center stresses were closer to the stresses determined from strain gage measurements than the results from the linear analyses. The greatest improvements to the analytical values were realized in the prediction of the center stress and deflection at failure. However, it is anticipated that a model which includes the effects of both geometric and material nonlinearities would produce even better results.

Shear Finite Element Analysis

The shear stress contours obtained from the shear finite element analysis are graphically depicted in figure 16. The central region of the specimen indicated shear stresses which ranged from 46.2 ksi to 49.8 ksi. This agrees roughly with the experimentally determined shear stress of 43.6 ksi. The limitation of this finite element analysis is that it cannot adequately predict the tensile failure mode that was observed in the shear test specimens.

In general, while finite element analyses are capable of identifying regions of maximum strain in a specific part or specimen, they are limited because they do not provide enough information to enable predictions regarding the failure mode of a particular test. For this reason, mechanisms for failure should be proposed, verified through experiment, and used for the development of an appropriate failure model.

Failure Criterion

In addition to applying reliable finite element codes, effective methods for design must utilize a failure criterion that is applicable for a particular material. Several research efforts have been aimed at defining failure criteria that can be applied to brittle materials, such as beryllium [25-30]. One criterion for failure that may be applicable to beryllium, and is often used for anisotropic materials, such as composites, is the Tsai-Wu failure criterion [31], which has the following contracted tensor formulation:

$$f(\sigma_k) = F_i\sigma_i + F_{ij}\sigma_i\sigma_j = 1 \tag{1}$$

which reduces to

$$F_1\sigma_1 + F_2\sigma_2 + F_{11}\sigma_1{}^2 + F_{22}\sigma_2{}^2 + F_{12}\sigma_1\sigma_2 + F_{66}\sigma_6{}^2 = 1 \tag{2}$$

for an orthotropic material under plane stress conditions. The F_i and F_{ij} coefficients may be determined empirically according to the following equations:

$$F_1 = \frac{1}{\sigma_{Lt}} + \frac{1}{\sigma_{Lc}} \tag{3}$$

$$F_2 = \frac{1}{\sigma_{Tt}} + \frac{1}{\sigma_{Tc}} \tag{4}$$

$$F_{11} = \frac{-1}{\sigma_{Lt}\sigma_{Lc}} \tag{5}$$

$$F_{22} = \frac{-1}{\sigma_{Tt}\sigma_{Tc}} \tag{6}$$

$$F_{12} = [1 - \sigma_B(F_1 + F_2) - \sigma_B{}^2(F_{11} + F_{22})]/2\sigma_B{}^2 \tag{7}$$

$$F_{66} = [4 - \sigma_{45}(F_1 + F_2) - \sigma_{45}{}^2(F_{11} + +2F_{12} + F_{22})]/\sigma_{45}{}^2 \tag{8}$$

where σ_{Lt} and σ_{Tt} are uniaxial tensile data in the longitudinal and transverse directions, respectively, and σ_{Lc} and σ_{Tc} are uniaxial compressive data in the longitudinal and transverse directions, respectively, and σ_B is the biaxial failure stress, and σ_{45} is the failure stress from a 45° off-axis tensile test, and σ_S is the shear stress.

Tsai-Wu failure coefficients were calculated on the basis of both the yield and ultimate mechanical properties that are listed in table 7. Since neither the biaxial tests nor the 45° off-axis tensile tests demonstrated distinct yield points, the failure stresses were also used as yield strength values. The Tsai-Wu coefficients that were calculated using equations (3) through (8) are presented in table 8. Figure 17 presents the seven sets of data points plotted together with the boundary of the failure criterion derived for zero in-plane shear stress ($\sigma_6 = 0$). It is encouraging to note that the shear data are in good agreement with this failure criterion, which uses coefficients that were generated using the other experimental data. Figure 18 compares the yield criterion for zero shear stress with the cases in which the shear stress is 15 ksi (corresponding to half of the shear yield) and 30 ksi (shear yield). As expected, this figure demonstrates that the addition of in-plane shear stress reduces the failure envelope.

The Tsai-Wu failure criterion is only a two-dimensional model, however, and therefore cannot predict the failure of materials which are subject to triaxial stresses. Out-of-plane stresses, such as those which produced the Insat satellite failure that prompted this investigation, can produce such triaxial stresses in cross-rolled beryllium sheet. It is expected that the failure envelope is reduced by such an addition, but the critical stresses can not be predicted without the use of a three-dimensional failure criterion. Therefore, NASA/JSC is sponsoring ongoing research in this area at Texas A&M University [32-33].

CONCLUSIONS

1. The average tensile properties of the beryllium cross-rolled sheet in the etched and pristine condition were determined to be σ_{ys}=59.8 ksi, σ_{ult}=75.3 ksi, in the absence of sanding.

2. Sanding the tensile specimens adversely affected the ductility and ultimate strength of the beryllium, but was not observed to affect the yield strength. Sanding the shear specimens did not significantly affect the shear strength.

3. Lüders bands were observed in both the sanded and unsanded beryllium tensile specimens, regardless of the measured elongation-to-failure. This implies that the Lüders phenomenon does not control the fracture mode or significantly contribute to the ductility of cross-rolled beryllium sheet.

4. The beryllium disc which was tested with the 1-in. load ring produced a biaxial failure stress of 121.0 ksi. Because the bending moment was lower than that present in the specimen tested with the 2-in. load ring, this configuration provided a better approximation of an in-plane biaxial stress state.

5. The beryllium shear specimens failed in a tensile mode and exhibited unconventional fracture paths. Failure stresses for the beryllium shear specimens ranged from 38 to 45 ksi, based on the net section of material between the notches. These values oversimplify the failure process, since the specimens did not fail in "true shear", but do agree with shear stresses predicted by the Tsai-Wu failure criterion.
6. Results from the linear finite element analyses of the biaxial and shear tests agreed roughly with experimental results. A nonlinear model of the biaxial disc generated failure stresses which agreed better with experimental values. These finite element analyses have a limited application in terms of predicting the failure modes and mechanisms of beryllium, so they should be used in conjunction with an appropriate failure criterion.
7. The Tsai-Wu failure criterion provides an adequate two-dimensional model for predicting failure in cross-rolled beryllium sheet. However, a three-dimensional failure criterion would be needed to predict the effect of out-of-plane stresses, such as the assembly stresses that contributed to the Insat failure.

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Table 1.– Beryllium SR-200E Tensile Test Results

Specimen ID *	σ_{ys} (ksi)	σ_{ult} (ksi)	Elong. (percent)	Crosshead Rate (in/min)
EF-L1	60.0	76.7	19.3	0.02
EF-L2	60.0	77.3	12.6	0.01
EF-L3 †	59.3	60.8	1.2	0.005
EF-T1 †	58.7	60.2	1.2	0.005
EF-T2 †	58.7	59.9	<1	0.01
EF-T3	60.2	72.1	25.2	0.01
BW-L1	50.3	71.0	20.0	0.02
BW-L2 **	54.6	72.6	21.6	0.02
BW-L3 ††	52.6	60.6	5.0	0.02
BW-L4 ***	52.6	71.5	20.0	0.02
BW-L6 †††	—	49.4	<1	0.02
BW-L7 †††	—	49.8	<1	0.02

Notes:

*	EF = Electrofusion, BW = Brush Wellman, L = longitudinal, T = long transverse
†	Specimen sanded at 45° angles to loading direction prior to strain gaging
**	One side sanded lightly with 400 grit paper at 45° angles to loading direction
††	One side sanded lightly in longitudinal direction with 280 grit paper
***	Both sides sanded vigorously in longitudinal direction with 280 grit paper
†††	All four sides sanded vigorously in transverse direction with 280 grit paper

Table 2.– Comparison of Beryllium Cross-Rolled Sheet Tensile Results

Source	Orient.	σ_{ys} (ksi)	σ_{ult} (ksi)	Elong. (%)
NASA/JSC (1991) SR-200E (0.10 in. thk.)	L † LT †	56.8 60.2	75.0 72.1	17.3 25.2
Kovarik (1984) [9] SR-200E (0.020 – 0.047 in. thk.)	L * LT *	57 58	n/a n/a	n/a n/a
Marder (1986) [10] SR-200E (0.021 – 0.250 in. thk.)	L †† LT ††	50 50	70 70	10 10
MIL-HDBK-5E (1987) [21] SR-200D (0.07 – 0.25 in. thk.)	L †† LT ††	43 43	65 65	5 5
Fenn, et.al. (1967) [7] S-200 (0.077 in. thk.)	L LT	54 56	78 80	16 16
Ingels (1966) [5] (0.02 – 0.12 in. thk.)	L LT	51-63 50-61	78-85 70-86	10-24 7-25

Notes:

† Average of unsanded data in Table 1

* Average 0.2% offset yield strength from 12 specimens

†† Minimum design properties

Table 3.– Biaxial Data for B-1 and B-2 Specimens

Percent of YS	Load (lb.)	Center Stress (ksi)	Maximum Stress (ksi)	Location of Max. Stress
SR-200E Beryllium, 1-in. Load Ring				
50 %	209	27.8	27.8	SG-2-R
75 %	312	42.0	42.0	SG-2-R
100 %	421	55.1	55.1	SG-2-R
failure	1346	121.0	121.0	SG-2-R
SR-200E Beryllium, 2-in. Load Ring				
50 %	335	27.3	30.1	SG-4-C
75 %	499	41.1	43.0	SG-4-C
100 %	665	53.8	55.1	SG-4-C
failure	2117	120.0	135.0	SG-12-R

Table 4.– Beryllium SR-200E Shear Test Results

Specimen ID	Shear Yield Stress (ksi)	Shear Ultimate Stress (ksi)	Remarks
S-1	29.7	— †	unsanded
S-2	29.7	43.6	unsanded
S-3	30.0	45.1	sanded *
S-4	29.5	44.6	sanded ††
S-5	29.5	38.5	sanded **

Notes:

†	Fixture-to-specimen bond failed during loading
*	Both sides sanded longitudinally with 400 grit paper
††	Both sides sanded longitudinally with 280 grit paper
**	Both sides sanded at 45° to loading direction (parallel to notch)

Table 5.– Comparison of Biaxial Test and Linear Finite Element Results

Percent of YS	Load (lb.)	Predicted Stress (ksi)	Experimental Stress (ksi)	Predicted δ (in.)	Experimental δ (in.)
2024-T81 Aluminum, 1-in. Load Ring					
75 %	291	37.2	35.5	0.122	0.099
2024-T81 Aluminum, 2-in. Load Ring					
75 %	458	37.5	33.3	0.162	0.115
SR-200E Beryllium, 1-in. Load Ring					
50 %	209	24.7	27.8	0.027	0.027
75 %	312	36.8	42.0	0.040	0.039
100 %	421	46.8	55.1	0.053	0.050
failure	1346 *	150.9	121.0	0.170	0.116
SR-200E Beryllium, 2-in. Load Ring					
50 %	335	26.4	27.3	0.037	0.040
75 %	499	39.2	41.1	0.054	0.056
100 %	665	49.3	53.8	0.072	0.069
failure	2117 *	156.8	120.0 **	0.229	0.144

* Failure load

** Maximum failure stress = 135 ksi (adjacent to load ring)

Notes:
Both predicted and experimental stresses were determined at the center of each disc specimen. This coincides with the maximum stress for the 1-in. load ring condition, but the maximum stress for the 2-in. load ring condition occurred adjacent to the ring.

Table 6.– Comparison of Biaxial Test and Nonlinear Finite Element Results

Percent of YS	Load (lb.)	Predicted Stress (ksi)	Experimental Stress (ksi)	Predicted δ (in.)	Experimental δ (in.)
2024-T81 Aluminum, 1-in. Load Ring					
75 %	291	32.8	35.5	0.094	0.099
2024-T81 Aluminum, 2-in. Load Ring					
75 %	458	28.7	33.3	0.112	0.115
SR-200E Beryllium, 1-in. Load Ring					
100 %	421	47.3	55.1	0.049	0.050
failure	1346 *	123.2	121.0	0.112	0.116
SR-200E Beryllium, 2-in. Load Ring					
100 %	665	47.2	53.8	0.062	0.069
failure	2117 *	106.0	120.0 **	0.130	0.144

* Failure load

** Maximum failure stress = 135 ksi (adjacent to load ring)

Notes:
Both predicted and experimental stresses were determined at the center of each disc specimen. This coincides with the maximum stress for the 1-in. load ring condition, but the maximum stress for the 2-inch load ring condition occurred adjacent to the ring.

Table 7.– Mechanical Properties Used for Tsai-Wu Analysis

Test Type	Yield Strength (ksi)	Ultimate Strength (ksi)
σ_{Lt}	56.8	75.0
σ_{Tt}	60.2	72.1
σ_{Lc}	-50.0 *	-95.6 [32]
σ_{Tc}	-57.5 *	-100.3 [32]
σ_B †	121.0	121.0
σ_{45}	77.3 *	77.3 [32]
σ_S **	29.7	43.6

Notes:

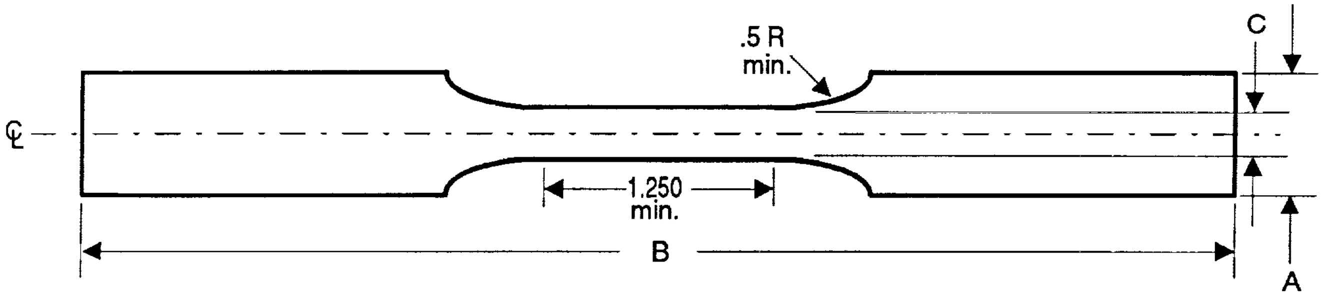
* Unpublished data, P.N. Roschke, et. al, Texas A&M University, 1990

† Failure stress of 1-in. load ring specimen

** Used for comparison; not used to determine failure coefficients

Table 8.– Tsai-Wu Failure Coefficients for Beryllium SR-200E Based on English Units

Basis	F_1	F_2	F_{11}	F_{22}	F_{12}	F_{66}
yield	$-2.394\text{x}10^{-3}$	$-7.800\text{x}10^{-4}$	$3.521\text{x}10^{-4}$	$2.889\text{x}10^{-4}$	$-2.726\text{x}10^{-4}$	$6.557\text{x}10^{-4}$
ultimate	$2.873\text{x}10^{-3}$	$3.900\text{x}10^{-3}$	$1.395\text{x}10^{-4}$	$1.383\text{x}10^{-4}$	$-1.324\text{x}10^{-4}$	$4.812\text{x}10^{-4}$



Dimension	As-machined	As-etched
A	0.627 ±.008	0.625 ±.010
B	$6.005^{+.008}_{-.000}$	$6.000^{+.010}_{-.000}$
C	$0.254^{+.002}_{-.001}$	0.250 ±.002

* nominal dimensions in inches

Figure 1.- Full scale schematic diagram showing the geometry and dimensions of the Brush Wellman tensile specimens.

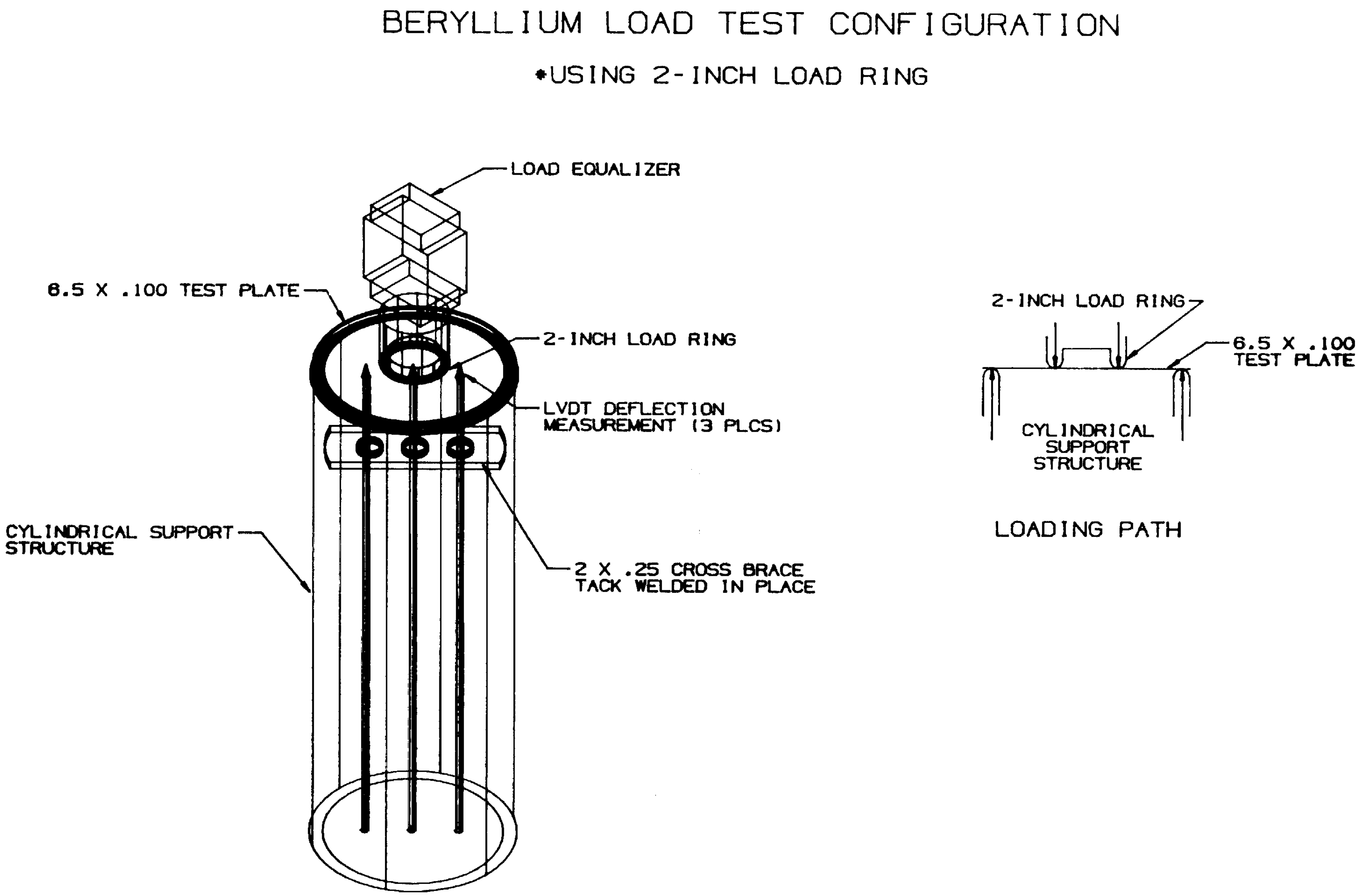


Figure 2.- Loading configuration for the out-of-plane biaxial disc testing.

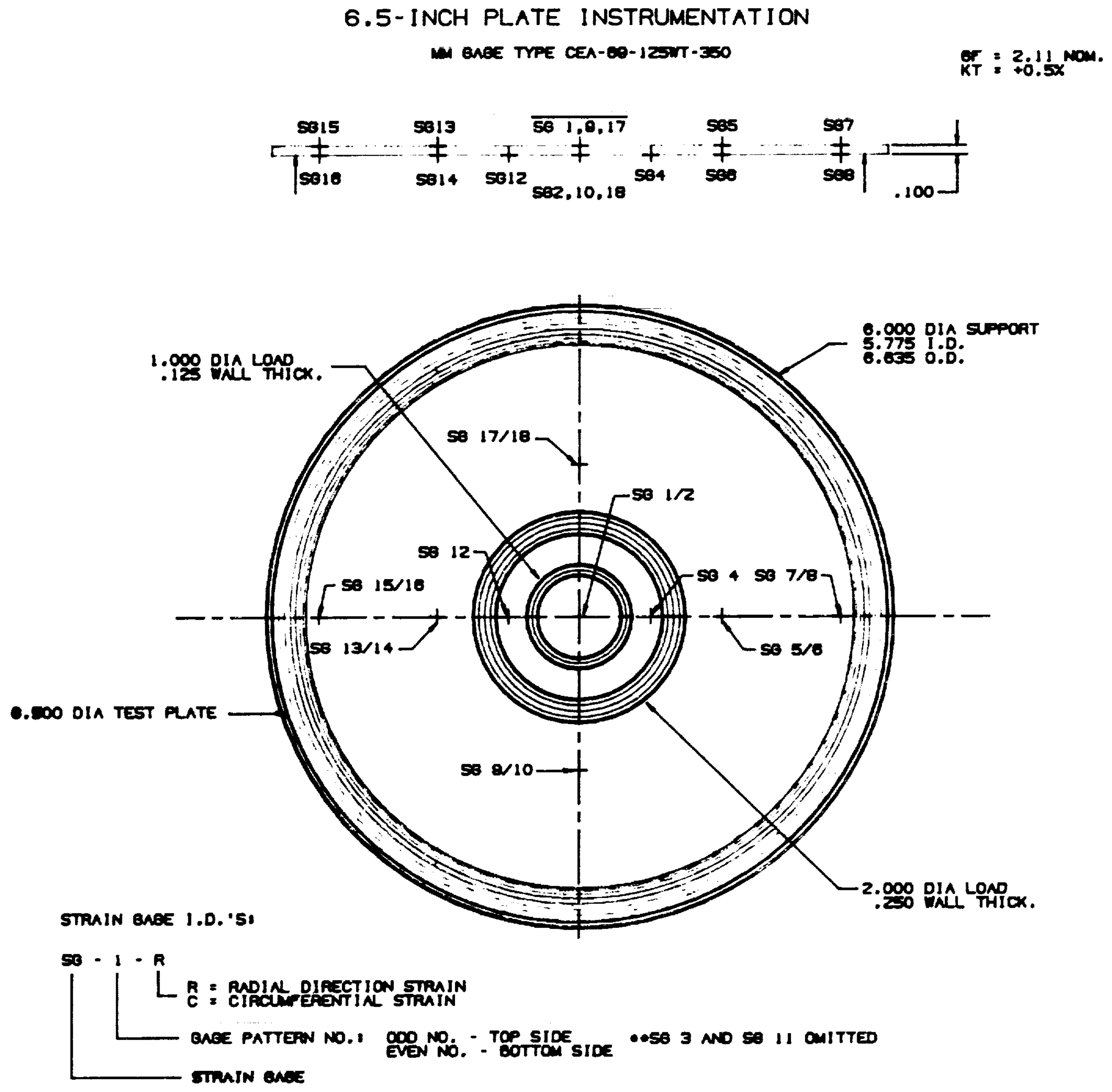


Figure 3.- Sketch of a biaxial disc specimen, showing the placement of the 16 back-to-back biaxial strain gages.

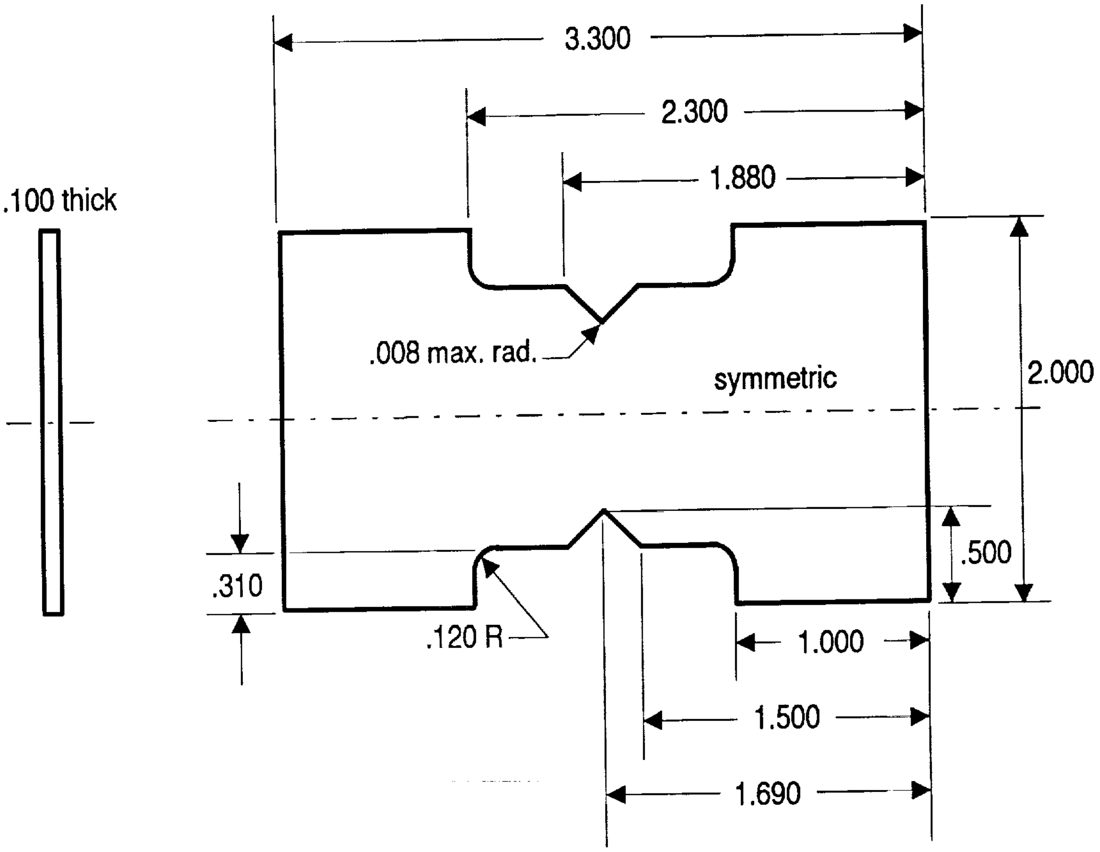


Figure 4a.- Full scale schematic diagram showing the geometry and dimensions of the shear specimens.

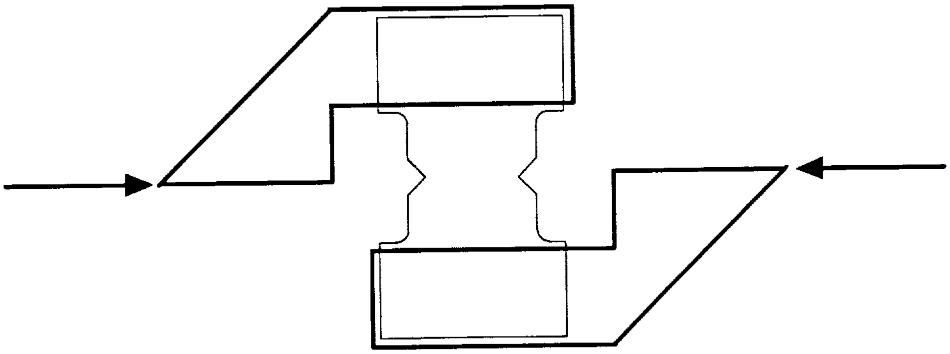


Figure 4b.- Schematic diagram showing the loading configuration for shear testing.

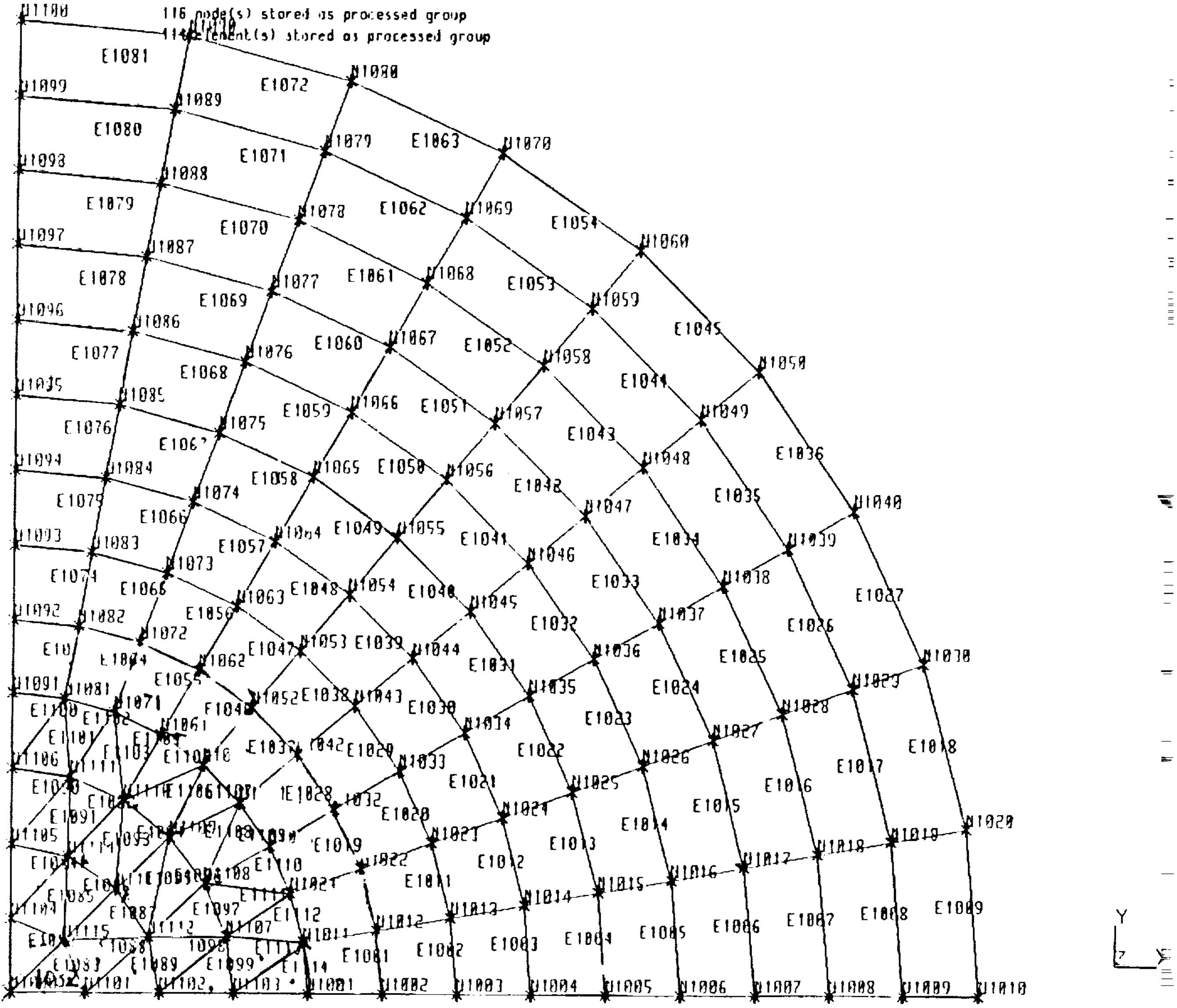


Figure 5.- Finite element mesh for the axisymmetric model used for NASTRAN analysis of the biaxial test condition.

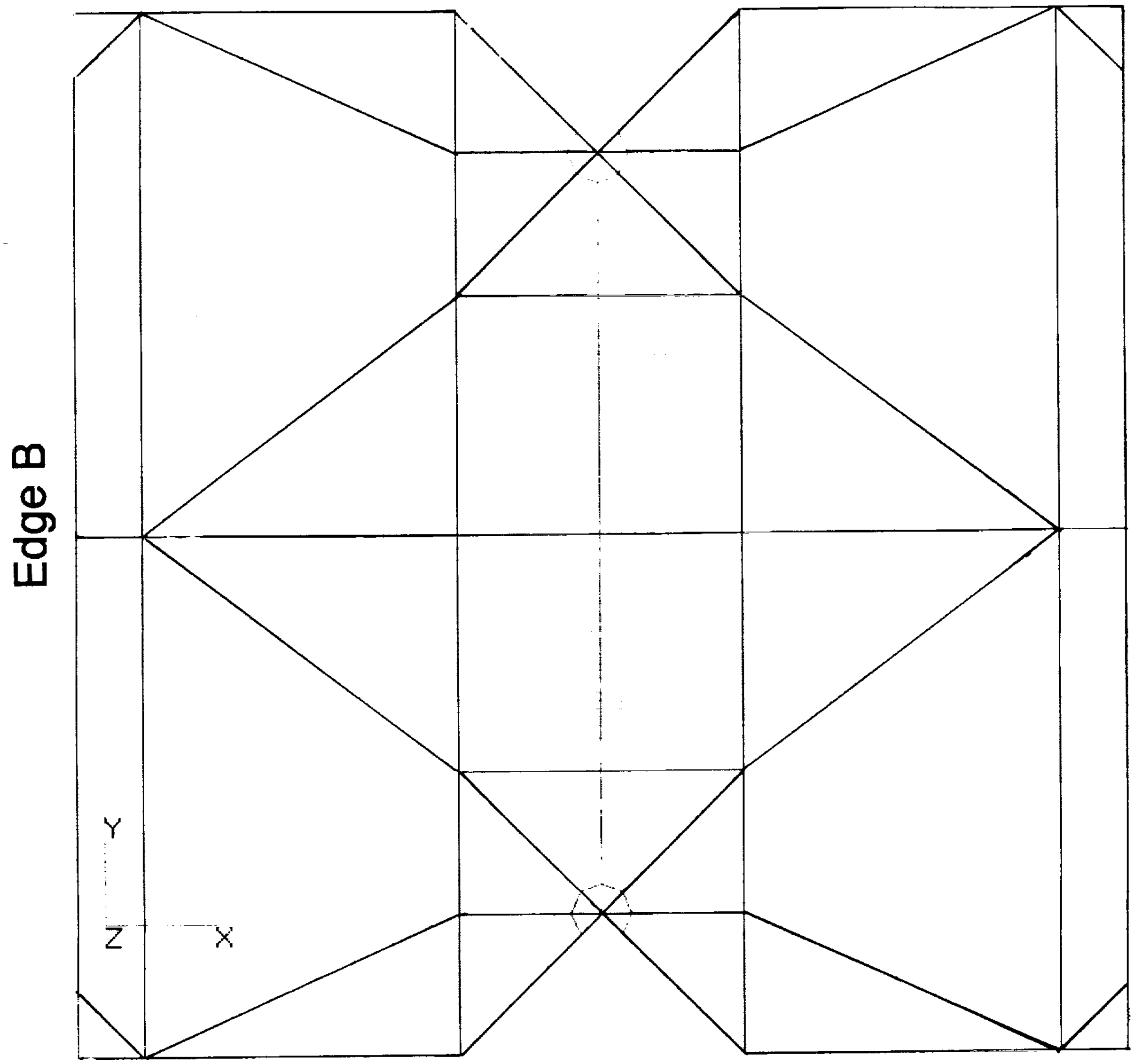


Figure 6.- Two-dimensional finite element model used for MSC/PROBE analysis of the shear test condition.

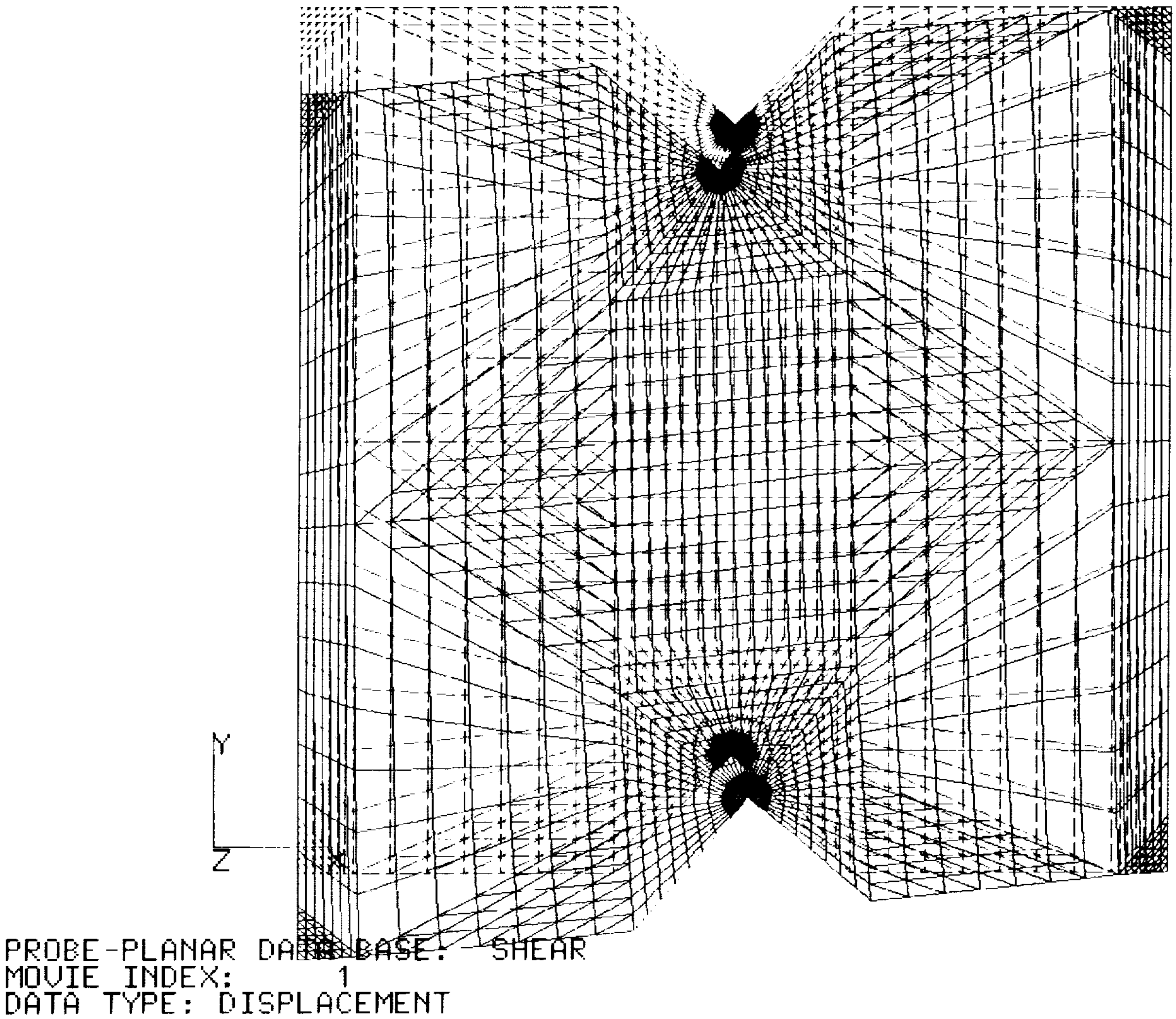
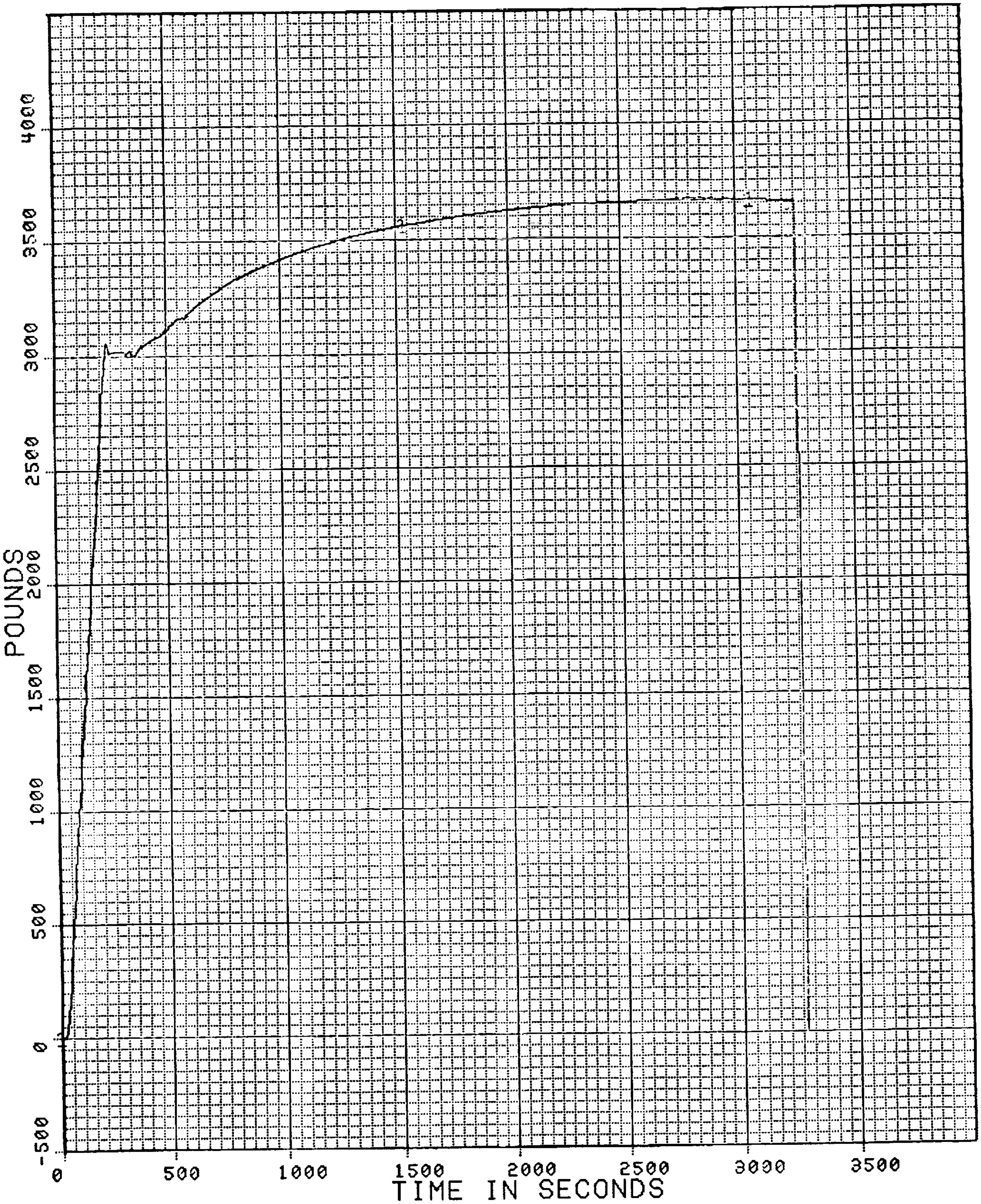


Figure 7.- Diagram showing both the deformed and undeformed shapes of the shear finite element model.



igure 8.- Load–time curve for tensile specimen EF-T3.

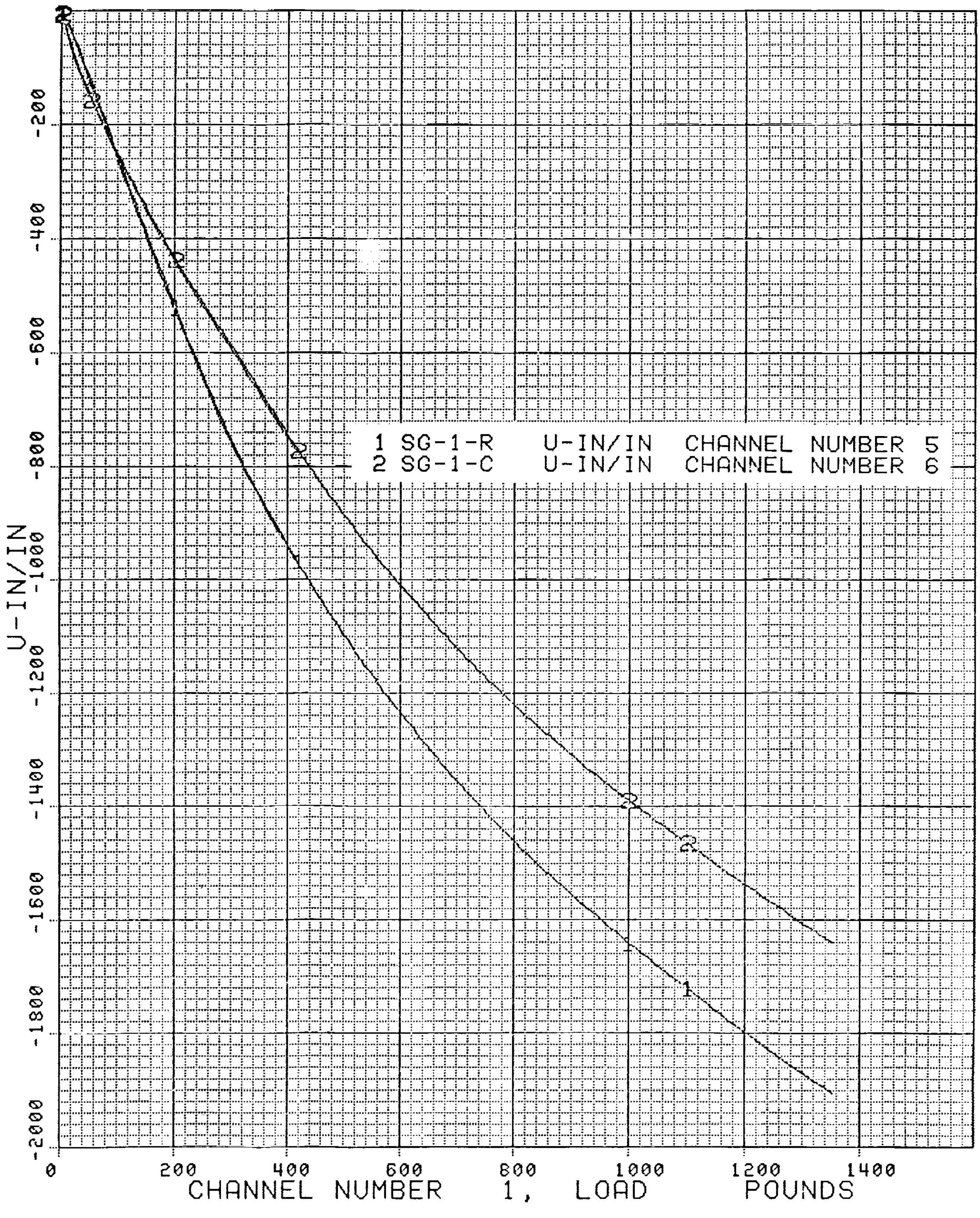


Figure 9.- Load–strain data obtained from beryllium disc B-1, which was loaded to failure using the 1-in. load ring.

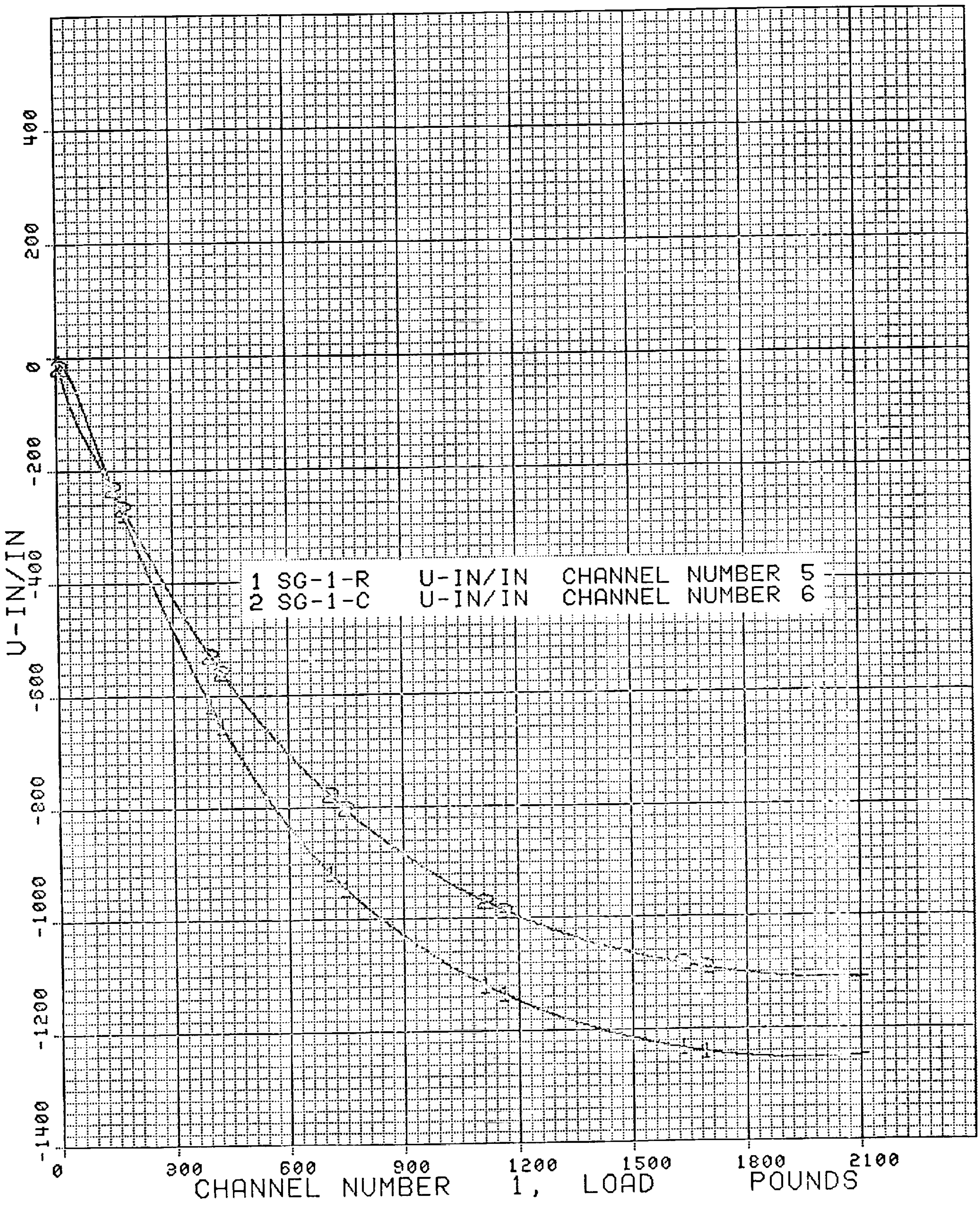


Figure 10.- Load–strain data obtained from beryllium disc B-2, which was loaded to failure using the 2-in. load ring.

Figure 11.- Photograph of the failed beryllium disc B-1, which was tested biaxially with the 1-in. load ring.

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Figure 12.- Photograph of the failed beryllium disc B-2, which was tested biaxially with the 2-in. load ring.

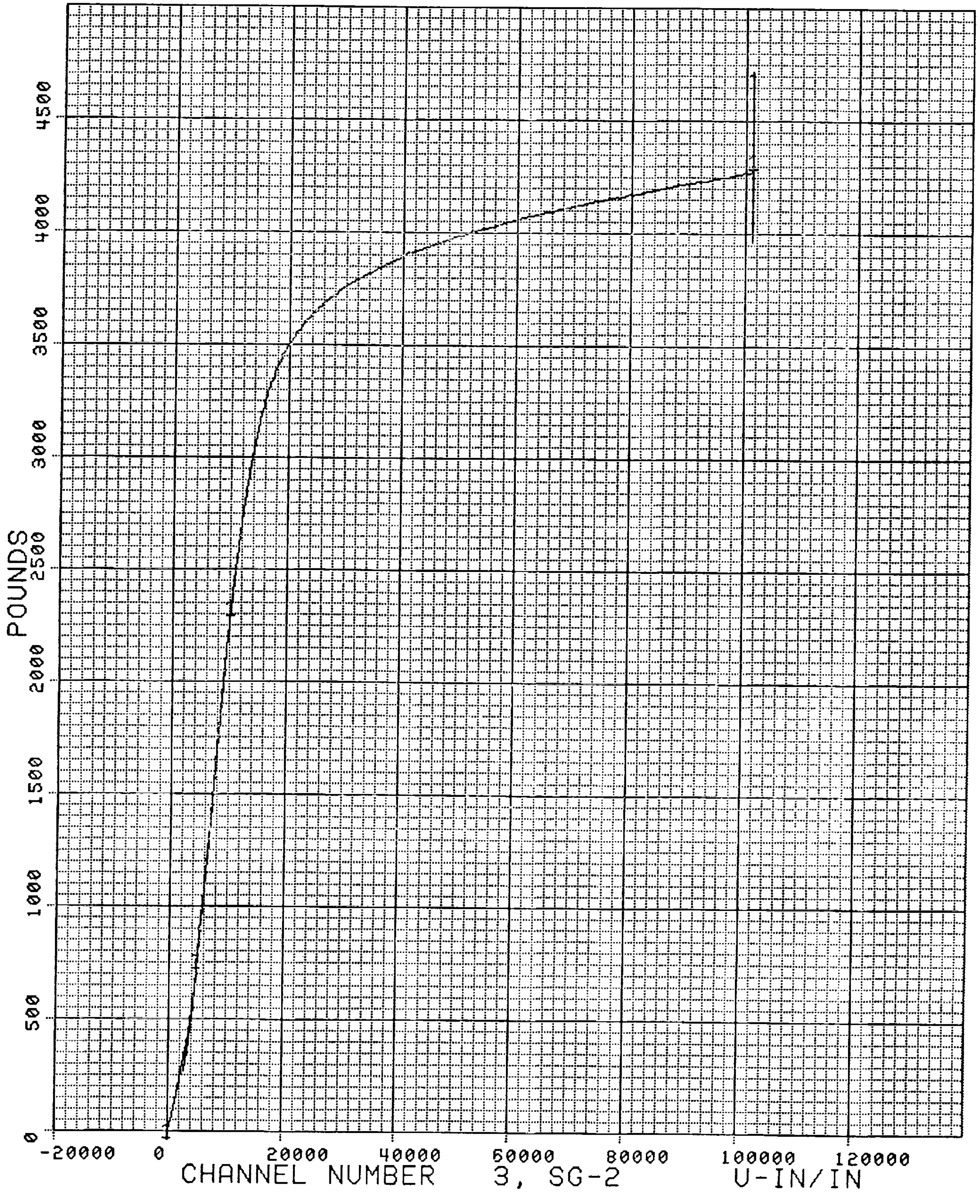

Figure 13.- Load–strain data obtained from 7075-T6 shear specimen.

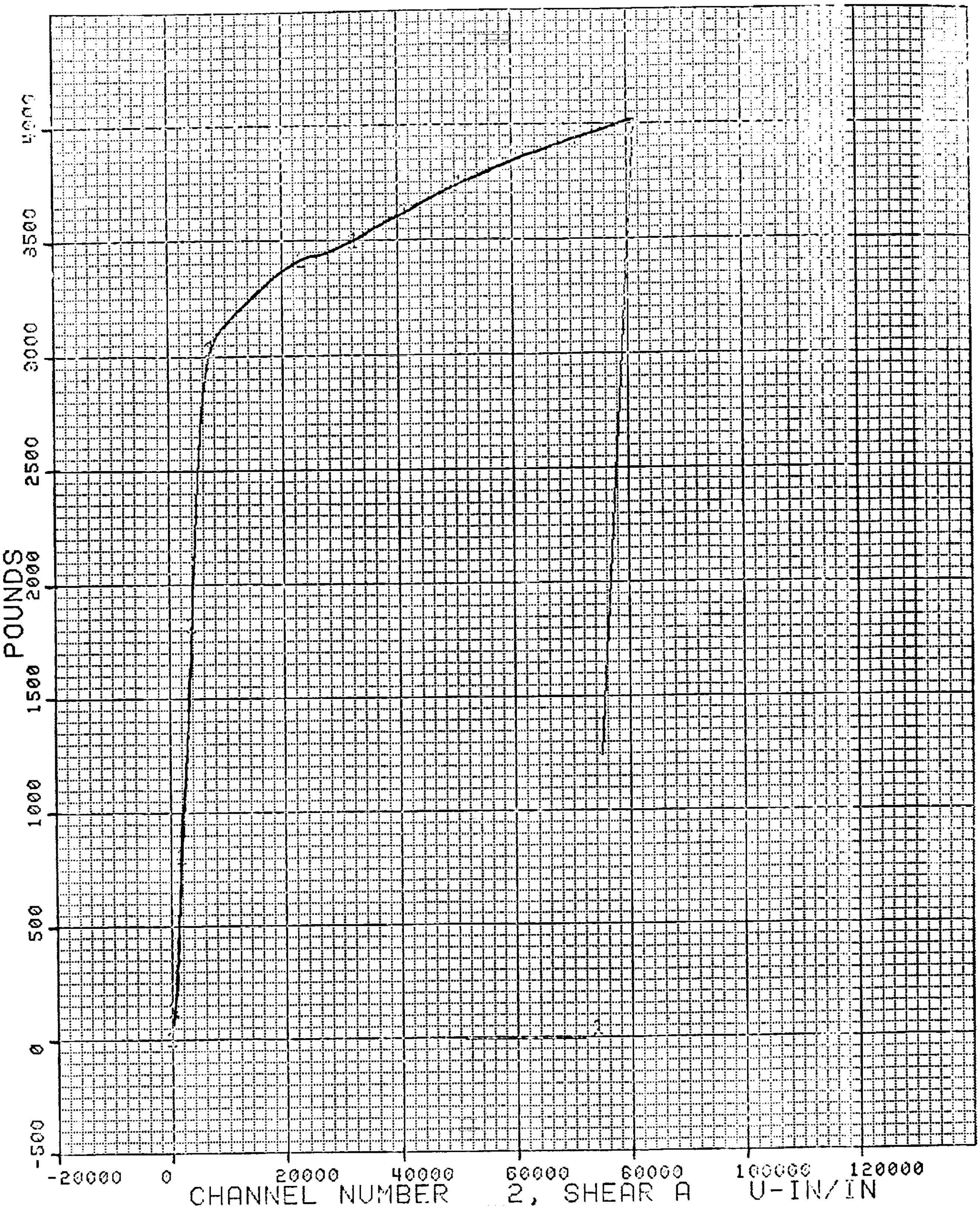

Figure 14.- Load–strain data obtained from beryllium shear specimen S-5.

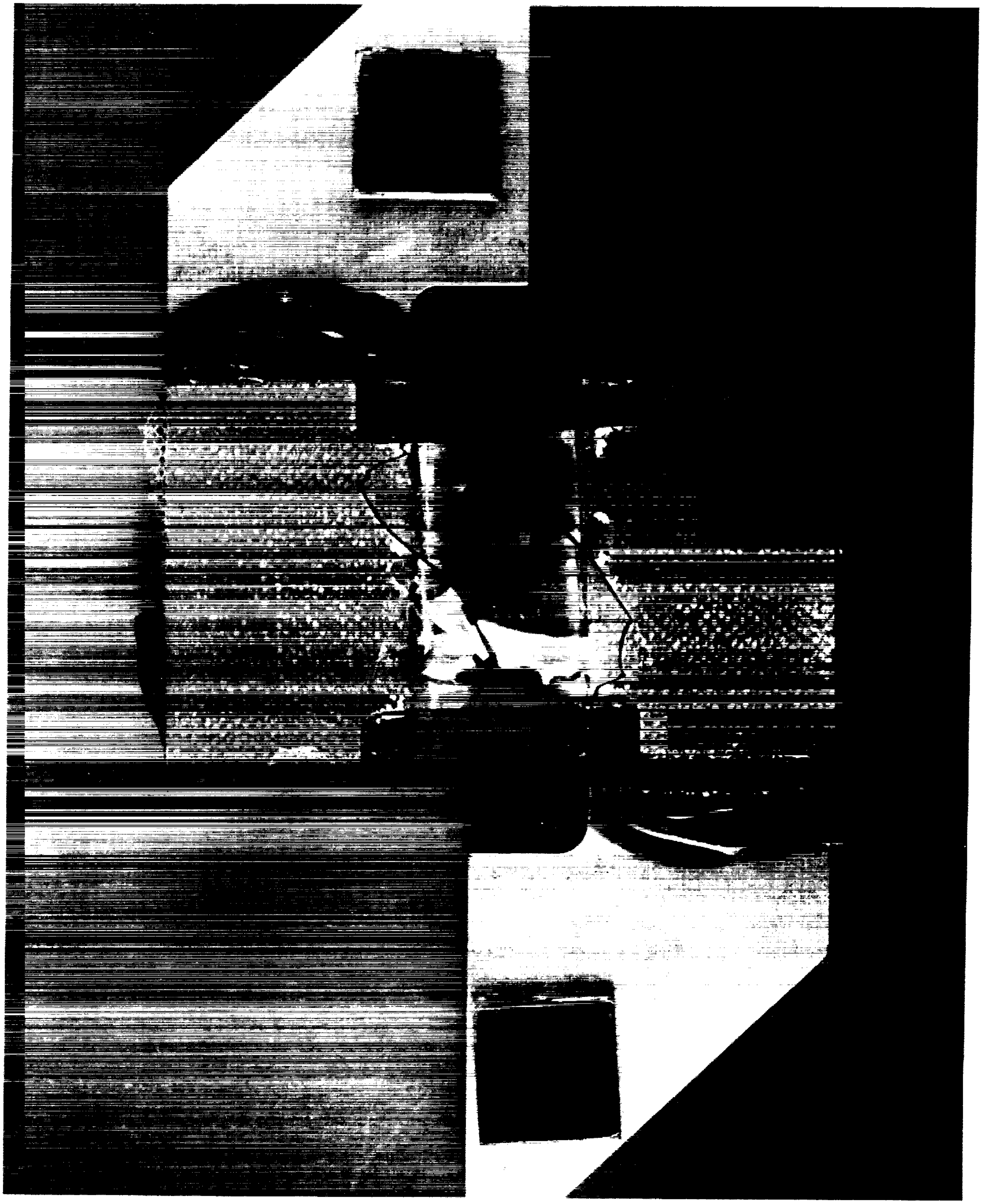

Figure 15.- Photograph of failed beryllium shear specimen, indicating unconventional fracture propagation path.

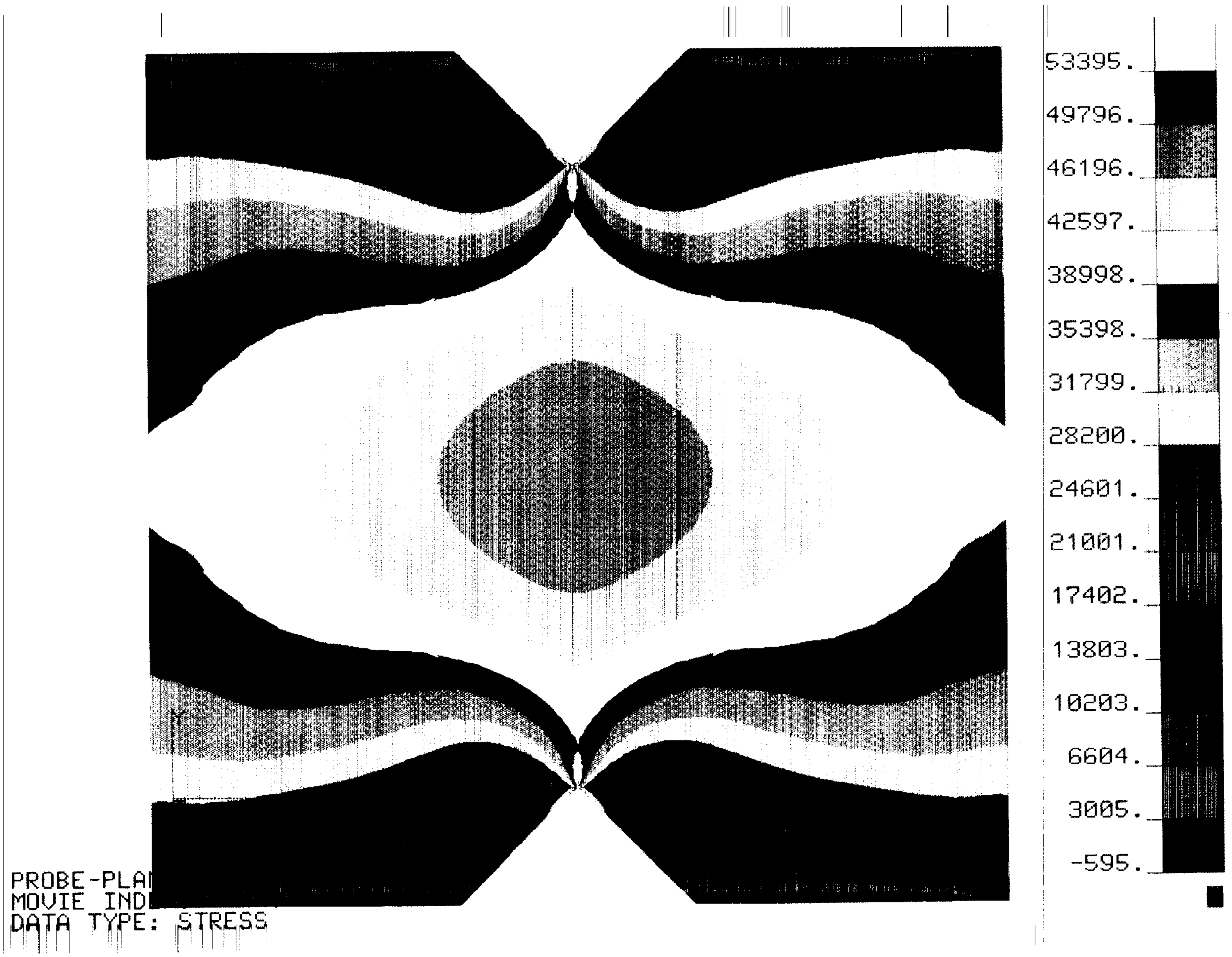

Figure 16.- Shear stress contours obtained from finite element analysis of beryllium shear specimen.

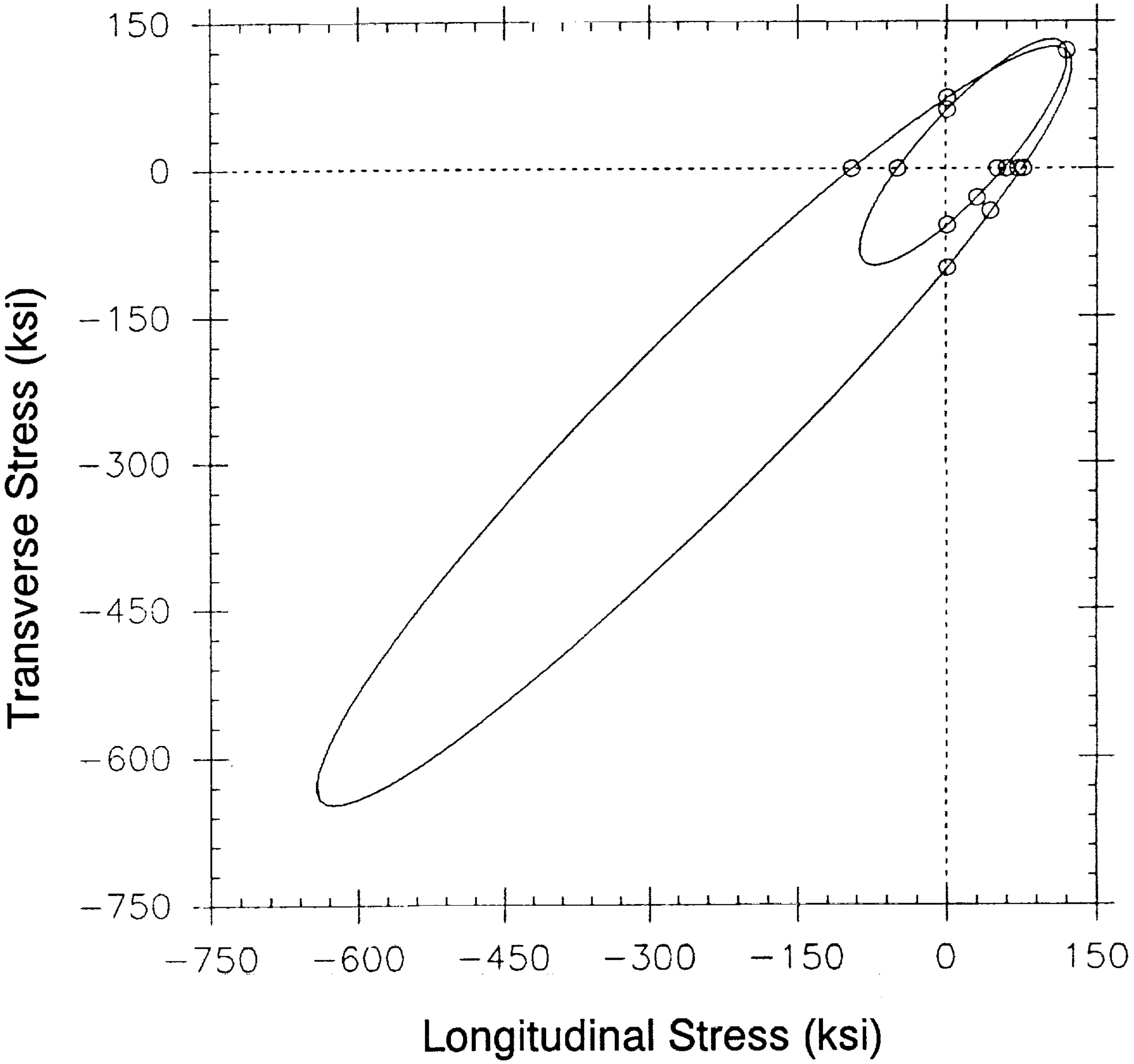

Figure 17.- Tsai-Wu failure criterion plot for beryllium SR-200E cross-rolled sheet, based on both the yield and ultimate conditions.

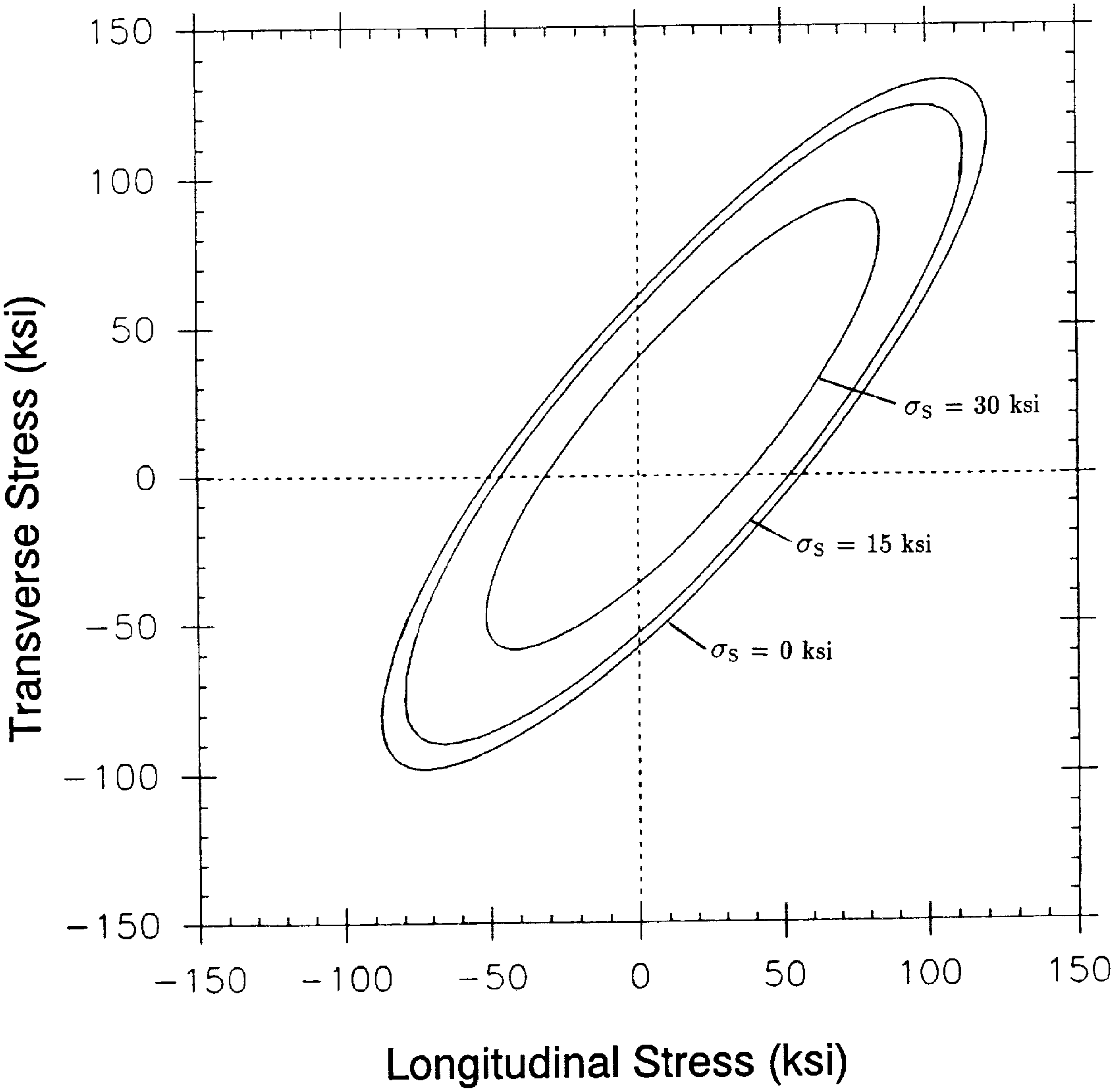

Figure 18.- Comparison of the beryllium SR-200E Tsai-Wu yield criteria for stress states which include an in-plane shear stress of 0, 15, or 30 ksi.

APPENDIX

The bibliography that follows contains references to conference papers, journal articles, books, and technical reports that provide information regarding many aspects of the processing, physical/mechanical behavior, design, and use of beryllium as a structural material. References to relevant product information and property data are also included. The bibliography is ordered according to increasing access number by which the material is filed.

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13. ABSTRACT *(Maximum 200 words)*

In response to the failure of a conical section of the Insat C satellite during certification testing, the use of beryllium for payload structures, particularly in sheet product form, is being reevaluated. A test program was initiated to study the tensile, shear, and out-of-plane failure modes of beryllium cross-rolled sheet and to apply the data to the development of an appropriate failure criterion. Tensile test results indicated that sanding the surface of beryllium sheet has no significant effect on yield strength but can produce a profound reduction in ultimate strength and ductility. Biaxial and shear test results were found to be in good agreement with results obtained by finite element analysis. Critical examination of these test results may contribute to the modification of a JSC policy for the use of beryllium in orbiter and payload structures.

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Beryllium, Cross-rolled sheet, Sheet metal, Failure criterion, Biaxial, Shear, Tensile, Tests, Mechanical testing

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