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COMPRESSIVE AND COLUMN STRENGTHS OF ALUMINUM TUBING WITH VARIOUS AMOUNTS OF UNIDIRECTIONAL BORON/EPOXY REINFORCEMENT

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16. Abstract

Compressive-crushing and column-buckling tests were performed on aluminum, aluminum reinforced with varying amounts of boron/epoxy, and 11-ply all-boron/epoxy tubes. All tubes were designed to be approximately equal in mass per unit length. The boron/epoxy-aluminum tubes consisted of two, four, six, eight, and 10 plies of boron/epoxy bonded to the outer surface of a series of aluminum tubes with variable diameters and wall thicknesses. Compressive-crushing strength increased approximately linearly with increasing reinforcement from about 46 ksi (320 MN/m^2) for an all-aluminum tube to about 380 ksi (2620 MN/m^2) for an all-boron/epoxy tube of approximately equal mass. Column-buckling strengths for the reinforced tubes were adequately predicted when a shear correction was made to account for the low shear stiffness of the unidirectional boron/epoxy.

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COMPRESSIVE AND COLUMN STRENGTHS OF ALUMINUM TUBING WITH VARIOUS AMOUNTS OF UNIDIRECTIONAL BORON/EPOXY REINFORCEMENT

By H. Benson Dexter
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SUMMARY

Compressive-crushing and column-buckling tests were performed on tubes made of aluminum, aluminum reinforced with varying amounts of boron/epoxy, and boron/epoxy. All tubes were designed to be approximately equal in mass per unit length. The all-aluminum tubes had an outside diameter of 0.50 inch (1.27 cm) and a wall thickness of 0.058 inch (0.147 cm). The boron/epoxy-aluminum tubes consisted of two, four, six, eight, and 10 plies of boron/epoxy bonded to the outer surface of a series of aluminum tubes with decreasing thicknesses. The all-boron/epoxy tubes were of 11-ply construction. Crushing strength increased approximately linearly with increasing reinforcement from about 46 ksi (320 MN/m^2) for an all-aluminum tube to about 380 ksi (2620 MN/m^2) for an all-boron/epoxy tube of approximately equal mass. Column-buckling strengths for the reinforced tubes were adequately predicted when a shear correction was made to account for the low shear stiffness of the unidirectional boron/epoxy.

Elementary thermal-stress theory was used to predict residual stresses and strains in the constituent materials. Stress-strain behavior of the boron/epoxy-aluminum tubes was accurately predicted by the rule of mixtures when thermal stresses and strains, resulting from the cure cycle, for the constituents were considered.

INTRODUCTION

Considerable interest has developed concerning the potential application of advanced filamentary composites to aerospace structures because of the high stiffness and low mass of these materials. However, the potential applications of structural components made entirely from boron/epoxy are limited as a result of fabrication and joining problems inherent with such composites. Recent investigations (refs. 1 and 2) indicate that considerable mass savings are possible if selected parts of conventional metal structures are replaced by boron/epoxy composites. A design concept was described in reference 1 that utilizes composites to reinforce existing metal structures and should merit special attention in the future design of aircraft structures. Considerable mass savings were demonstrated for metal tubular columns reinforced on the surface with uniaxial filamentary composites. Structural elements such as struts and longitudinal stiffeners for shell structures are therefore prime candidates for unidirectional boron/epoxy reinforcement. This concept utilizes a large part of the existing joining and fabrication technology developed for metal aircraft structures.

The primary objective of the current study was to investigate the structural performance of a boron/epoxy-reinforced aluminum structural component for a wide range of reinforcement ratios. The structural performance was demonstrated by changes in crushing and column buckling strengths as a function of the amount of boron/epoxy reinforcement. The specimens used for this investigation consisted of two sets of 6061-T6 aluminum-alloy tubes with varying amounts of boron/epoxy bonded to the external surface, all-boron/epoxy tubes, and all-aluminum tubes. One set of tubes, all of equal mass, was designed to fail by compressive crushing; and the other set, also equal in mass, was designed to fail by column buckling. Both sets were fabricated and tested.

The influence of residual thermal stresses, resulting from the cure cycle, on the stress-strain behavior and the structural performance of the various boron/epoxy-aluminum composites was determined as a function of the reinforcement quantity.

SYMBOLS

The units used for physical quantities defined in this paper are given in both the U.S. Customary Units and in the International System of Units (SI). (See ref. 3.) Conversion factors relating the two systems are given in reference 3, and those pertinent to the present investigation are presented in the appendix.

C	column-end-fixity coefficient
D	effective diameter of tube, inches (meters)
D_i	inside diameter of tube, inches (meters)
E	modulus of elasticity, pounds force/inch^2 (newtons/meter^2)
E_t	tangent modulus of elasticity, pounds force/inch^2 (newtons/meter^2)
$E_{t,1}$	tangent modulus of elasticity prior to yield of aluminum constituent, pounds force/inch^2 (newtons/meter^2)

$E_{t,2}$	tangent modulus of elasticity after yield of aluminum constituent, pounds force/inch^2 (newtons/meter^2)
G_{Al}	shear modulus of aluminum, pounds force/inch^2 (newtons/meter^2)
G_{calc}	shear modulus of composite-reinforced tube calculated by using rule of mixtures, pounds force/inch^2 (newtons/meter^2)
$G_{L,T}$	shear modulus associated with shearing stresses applied parallel and perpendicular to the boron filaments in a unidirectional boron/epoxy composite, pounds force/inch^2 (newtons/meter^2)
K	volumetric ratio of boron in a boron/epoxy composite
L	length of tube between end disks, inches (meters)
t	total wall thickness of composite-reinforced tube, inches (meters)
$\overline{V}$	volume fraction, ratio of constituent volume to total volume of reinforced aluminum tube
α	coefficient of linear thermal expansion, per $^{\circ}$F (per K)
β	ratio of the maximum shearing stress to the average shearing stress in a tubular cross section ($\beta = 2.0$ for a thin-wall circular tube)
ϵ	average axial strain
σ	compressive stress, pounds force/inch^2 (newtons/meter^2)
σ_{cr}	Euler-Engesser stress with shear modification, pounds force/inch^2 (newtons/meter^2)
σ_{max}	average stress at maximum load, pounds force/inch^2 (newtons/meter^2)
σ_r	residual thermal stress, pounds force/inch^2 (newtons/meter^2)
σ_t	Euler-Engesser stress for column, $\dfrac{C\pi^2 E_t}{8(L/D)^2}$, pounds force/inch^2 (newtons/meter^2)

Subscripts:

Al	aluminum
b	boron
b/e	boron/epoxy composite
e	epoxy

TEST SPECIMENS

The test specimens for this investigation consisted of tubes made of 6061-T6 aluminum, of boron/epoxy bonded to aluminum, and of only boron/epoxy. The tubes were fabricated for two distinct types of failures, crushing failure and column buckling. The crushing-failure specimens (see fig. 1) were approximately 3.0 inches (7.6 cm) in length, and the column-buckling specimens were approximately 15 inches (38 cm) in length. In all tubes where boron reinforcement was utilized, the filaments were alined in the direction of the longitudinal axis of the tube. The boron/epoxy material was supplied by an industrial processor in single-ply-sheet form with nominally 220 filaments per inch (87 filaments per cm) of width of sheet. The boron filaments were nominally 4 mils (0.1 mm) in diameter and preimpregnated with EPON 1031/EPON 828/MNA/BDMA epoxy resin. Each ply of boron/epoxy had a glass scrim backing, 1/2 mil (0.01 mm) thick.

The test specimens were specifically designed for studying the effect of using various amounts of reinforcement on the compressive and column-buckling strength of reinforced-aluminum tubes.

The tubes were fabricated with the intention of having all tubes approximately equal in mass. The mass of an aluminum tube with a 0.50-inch (1.27-cm) outside diameter and a 0.058-inch (0.147-cm) thickness was used as a baseline value. Specimen mass was controlled by chemically milling the inner surface of the aluminum tubes in successive increments, which were equivalent to the mass of two plies of boron/epoxy. Prior to bonding the boron/epoxy to the aluminum tube, the aluminum was chemically cleaned with a chromic-sulfuric acid solution.

The fabrication process described in reference 4 was utilized to fabricate the tubes. Layers of boron/epoxy, with width equal to the circumference of the tube, were wrapped around the aluminum tube until the desired wall thickness was obtained. The tubing with boron/epoxy reinforcement was enclosed in a close fitting heat-shrinkable teflon sleeve which, with heat from an electric heat gun, compacted the plies of boron/epoxy and squeezed out any entrapped air. The tubes were then subjected to a cure cycle that consisted of 1 hour exposure at 180° F (355 K) plus 3 hours at 350° F (450 K). A removable teflon rod was used as a mandrel for fabricating the 11-ply all-boron/epoxy tubes.

Uniform filament spacings were obtained by using the fabrication process described in reference 4. Illustrated in figure 2 are photomicrographs of typical two-, six-, and 10-ply boron/epoxy-aluminum tube cross sections. The inner two plies of each cross section illustrate intermeshing which is a result of placing the first layer of boron/epoxy with the scrim backing next to the metal instead of having the scrim between the first and second ply. The scrim was on the outside of all the other plies; this layup sequence resulted in uniform filament separation between plies. The scrim on the first ply was placed next to the metal in order to achieve a better bond between the first ply of boron/epoxy and the metal.

The volume fraction of the filaments was determined from a count of filaments in a typical cross section of each tube, and a nominal 4-mil (0.1-mm) filament diameter was used to compute filament area. The volume of the aluminum and boron/epoxy-aluminum tubes was determined from dimensional measurements. Inspection of several photomicrographs of typical tube cross sections indicated that the volume of voids was small.

METHOD OF TESTING

Prior to testing, the ends of each specimen were mounted in hardened steel disks (see fig. 1) to prevent filament brooming. The machine-grooved close-fitting disks were bonded to the tube ends with a room-temperature-curing epoxy resin. Typical crushing and column-buckling specimens are shown in the testing machine in figures 3 and 4, respectively. Prior to loading, the platens of the testing machine were alined parallel to the disks on the specimen ends to obtain uniform load distribution and to minimize possible eccentricities. Two foil strain gages, bonded on diametrically opposite sides of each tube, were used to obtain axial-strain data. The specimens were loaded at a uniform strain rate of 0.001 per minute until failure of the specimen. All tests were monitored with an oscilloscope to observe stress-strain behavior and the onset of buckling for the column specimens.

EXPERIMENTAL RESULTS

Crushing Tests

Crushing tests were performed on tubes 3.0 inches (7.6 cm) long. As stated before, all the tubes were designed to be approximately equal in mass. Typical compressive stress-strain curves obtained from the tests are shown in figure 5. The stress-strain behavior for the entire range of reinforcement studied in this investigation is illustrated. The stresses are based on the total cross-sectional area of the tubing, and strains were determined from the average of two gages located at the midlength of the specimens. The two-, four-, six-, and eight-ply specimens clearly indicated a knee in the stress-strain curve, whereas the 10- and 11-ply specimens exhibited linear behavior until failure. The knee in the stress-strain curve is a result of stressing the aluminum constituent beyond its elastic limit. However, it is evident that the knee of the stress-strain curves for the various reinforced aluminum tubes does not coincide with the elastic limit of the aluminum stress-strain curve shown in figure 5. The offset between the elastic limit of the aluminum tube and the knee of the various reinforced aluminum tubes is directly related to the residual strains induced during the curing process. These strains are a function of the elastic moduli, coefficients of thermal expansion, and volume fractions of the constituent materials. This phenomenon will be discussed in more detail in the section entitled "Residual Thermal-Stress Calculations."

The tangent modulus of elasticity $E_{t,1}$ below the knee of the stress-strain curve closely correlates with the modulus calculated by using the rule of mixtures. After the elastic limit of the aluminum is reached, the slope of the stress-strain curve for the boron/epoxy-aluminum tubes is reduced and the tangent modulus $E_{t,2}$ results almost entirely from the contribution of the boron/epoxy reinforcement. For the 10-ply boron/epoxy-aluminum tube, the slope is essentially a constant to failure and yielding of the aluminum does not noticeably affect the stress-strain behavior. This behavior is associated with the fact that 90 percent of the total cross-sectional area is high-modulus boron/epoxy, and only 10 percent is low-modulus aluminum. Therefore, the contribution of the aluminum has only a small effect on the over-all tube properties. The stress-strain curve for the 11-ply boron/epoxy tube exhibits linear behavior until failure. Tangent modulus values $E_{t,1}$ and $E_{t,2}$ obtained experimentally for each of the crushing specimens are listed in table I along with the dimensional measurements. The average stress at maximum load σ_{max} and the volume fraction of aluminum and boron/epoxy for each specimen are also given in table I.

Typical failures of the crushing specimens are shown in figure 6. The aluminum tube exhibited the characteristic stress-strain behavior of metals; but, with prolonged straining after yielding of the aluminum, failure occurred at a strain of about $2\frac{1}{2}$ percent by plastic column buckling. The boron/epoxy-aluminum tubes failed abruptly with no noticeable yielding near maximum loading. Longitudinal splitting and breaking of the boron/epoxy and separation of the boron/epoxy from the first ply of scrim cloth was characteristic of the two-, four-, six-, and eight-ply tubes. As shown in figure 6, some of the boron/epoxy was expelled at failure with the first layer of scrim still bonded to the aluminum. Buckles in the aluminum developed in some tubes, probably after debonding of the boron/epoxy from the aluminum tube. Failure of the 10-ply tubes was characterized by longitudinal splitting of both the aluminum and boron/epoxy with the boron/epoxy remaining bonded to the aluminum. Figure 6 also illustrates typical splitting and breaking of the boron filaments for the 11-ply all-boron/epoxy tube.

It is interesting to note in figure 5 that the average strain at failure for all the tubes is between 1.0 and 1.1 percent. The fact that the strains at failure in the all-boron/epoxy and the boron/epoxy-aluminum tubes are about equal indicates that failure is probably initiated in the boron/epoxy. The stress-strain curve in figure 5 for the all-aluminum tube is discontinued at 1.1-percent strain for plotting convenience only.

Column Buckling Tests

Typical stress-strain behavior for a four-ply boron/epoxy-aluminum column is shown in figure 7. The slope of the straight part of the curve is the same as the initial slope shown in figure 5 for the four-ply crushing specimens. Column bending is indicated by the separation of the outer-surface axial strains on opposite sides of the column as shown by the curves in the upper part of figure 7. Buckling was elastic for all columns tested except for the all-aluminum tubes which had some plastic deformation. Table II lists the dimensional measurements and test results of all the columns tested. The stress at maximum load σ_{max} is tabulated for comparison with calculated buckling stresses. The deviation between the experimental and calculated values will be discussed later in the paper.

Typical column failures are illustrated in figure 8. Figure 8(a) illustrates column buckling for typical flat-ended 6061-T6 aluminum columns. The aluminum columns sustained large deflections at maximum load before failure; therefore, some plastic deformations resulted. Figure 8(b) illustrates failure of a four-ply boron/epoxy-aluminum column. The lateral deflection is smaller than for the aluminum tube, and the buckling stress is elastic. Column failure typical of the 11-ply boron/epoxy tubes is illustrated in figure 8(c). Breaking and splintering of filaments occurred at maximum load, and the break appears to have occurred close to an inflection point. This type of failure was also characteristic of the 10-ply boron/epoxy-aluminum columns. At the instant of failure, the shortest part of the failed tube was driven into the longer part; thus splitting occurred as shown in figure 8(c).

DISCUSSION OF RESULTS

The maximum compressive loads sustained by the crushing specimens are plotted in figure 9 as a function of percent of boron/epoxy reinforcement. The compressive loads for the aluminum tubes (no reinforcement), the two-, four-, six-, eight-, and 10-ply boron/epoxy-aluminum tubes, and the 11-ply boron/epoxy tubes (100-percent reinforcement) are plotted. The compressive load varies approximately linearly from about

46 ksi (320 MN/m^2) for the all-aluminum tubes to approximately 380 ksi (2620 MN/m^2) for the 11-ply all-boron/epoxy tube. The experimental data agree quite well with the rule-of-mixtures calculations.

The mass per unit length for each crushing specimen tested is listed in table I. There is a ±5-percent deviation from the average mass for all the tubes listed in table I. This deviation is a result of the inability to precisely control the chemical milling process and the amount of resin flow during the cure of the boron/epoxy. Based on the fact that all the tubes have close to the same mass, the results in figure 9 give some indication of the increase in structural efficiency as more boron/epoxy reinforcement is added to the aluminum.

The effects of various amounts of reinforcement on the buckling strength of the columns are presented in figure 10. The column-buckling stress increases from about 35 ksi (240 MN/m^2) for the all-aluminum columns to about 180 ksi (1240 MN/m^2) for the 11-ply all-boron/epoxy columns. Part of this increase in stress is directly related to a decrease in L/D and should not be interpreted as an increase in structural efficiency due to an increase in reinforcement alone.

It has been demonstrated in reference 5 that the experimental buckling stress for uniaxial all-boron/epoxy columns does not agree with conventional column theory at high stress levels. This disagreement was attributed in part to the low shear stiffness of the boron/epoxy. Figure 11 illustrates this phenomenon for both the all-boron/epoxy columns and the boron/epoxy-aluminum columns of the present investigation. The experimental buckling stress σ_{max} for the 11-ply all-boron/epoxy columns is only about 80 percent of the calculated Euler-Engesser stress σ_t. The low experimental value of σ_{max} can be partially accounted for if appropriate modifications are made to account for shear deflections in the buckled columns. The dashed curve in figure 11 was calculated by using the following equation which accounts for shear deflections:

$$\sigma_{cr} = \frac{\dfrac{C\pi^2 E_t}{8(L/D)^2}}{1 + \dfrac{\beta}{G_{calc}}\left[\dfrac{C\pi^2 E_t}{8(L/D)^2}\right]} \qquad (1)$$

A column-end-fixity coefficient of 3.55 was used to predict the Euler-Engesser buckling stress σ_t. This value, which is about 11 percent lower than the fully clamped value of 4.00, was used because its use made σ_{max}/σ_t for the all-aluminum columns of the present study equal to unity. The all-aluminum columns buckled at stresses which were slightly plastic, and this plasticity may have contributed to the low end-fixity coefficient obtained. It was shown in reference 6 that a reduced end-fixity coefficient was required in analytical predictions when the experimental buckling stress of flat-ended columns approached the yield strength of the material. The columns of the present study with considerable boron/epoxy reinforcement, eight-, 10-, and 11-ply tubes, buckled at stresses well below any inelastic behavior and a somewhat greater end-fixity coefficient could possibly have been used for these data. However, for consistency, a value of $C = 3.55$ was used for all buckling calculations of the present investigation.

The diameter D used in the buckling calculations (eq. (1)) is an effective diameter which when inserted into the familiar equations for modulus times area and modulus times moment of inertia for circular tubes gives the correct stiffness of the tubes. This effective diameter differs from the mean diameter for some of the boron/epoxy-aluminum tubes by as much as 4 percent. The values of L/D used in the buckling calculations are listed in table II.

The curve calculated by using the Euler-Engesser theory with shear modification indicates that the experimental results can be predicted fairly accurately if appropriate shear modifications are made. Shear-modulus values were not measured in this investigation; therefore, experimental shear moduli for the various boron/epoxy-aluminum tubes are not available. However, an average shear modulus of 1230 ksi ($8.5\ GN/m^2$) was reported in reference 5 for similar boron/epoxy material. The shear modulus reported in reference 5 was determined for a volume fraction of boron of 0.52, whereas for the boron/epoxy material used in this investigation the volume fraction of boron ranged from 0.53 to 0.60. In order to obtain shear moduli for the volume fraction of interest in the present study, the Halpin-Tsai equations reported in reference 7 were used to extrapolate the shear modulus measured in reference 5 to other volume fractions. The result is illustrated in figure 12. The circular symbols represent the experimental data obtained in reference 5. A shear modulus of 1610 ksi ($11\ GN/m^2$) was predicted for the 11-ply all-boron/epoxy tubes which had a volume fraction of boron of 0.60. The shear modulus values G_{calc} used in equation (1) for the various boron/epoxy-aluminum tubes are listed in table II and were obtained by using the following rule-of-mixtures relationship:

$$G_{calc} = G_{Al}\overline{V}_{Al} + G_{L,T}\overline{V}_{b/e} \tag{2}$$

A shear modulus of 3800 ksi ($26\ GN/m^2$) was used for aluminum and the appropriate shear moduli $G_{L,T}$ for the boron/epoxy composites were obtained from figure 12. The calculated Euler-Engesser stresses with shear modification σ_{cr} are listed in table II.

RESIDUAL THERMAL-STRESS CALCULATIONS

As stated previously, the knee in the stress-strain curve for the boron/epoxy-aluminum tubes (fig. 5) is offset from the elastic limit of the all-aluminum tube because of residual thermal strains. This offset can be calculated by using elementary thermal-stress theory, as discussed in reference 8. To adequately describe the stress-strain behavior of the boron/epoxy-aluminum tubes, the residual thermal stresses and strains induced upon curing of the boron/epoxy must be determined. The following assumptions were made in the calculations:

(1) Elementary thermal-stress theory for a bar consisting of two materials was used.

(2) Transverse or circumferential stresses in the tube were neglected.

(3) Cured boron/epoxy was treated as one material and aluminum as the other.

The longitudinal modulus of elasticity for the boron/epoxy composite $E_{b/e}$ was evaluated by the rule of mixtures. The longitudinal-thermal-expansion coefficients for the boron/epoxy were obtained from

$$\alpha_{b/e} = \frac{KE_b\alpha_b + (1 - K)E_e\alpha_e}{E_{b/e}} \tag{3}$$

The constituent thermal-expansion coefficients were obtained from references 1 and 9. The coefficients of thermal expansion calculated by using equation (3) for the two-, four-, six-, eight-, and 10-ply tubes, along with the constituent properties are listed in table III. The residual stresses calculated for the boron/epoxy and aluminum for each of the two-, four-, six-, eight-, and 10-ply boron/epoxy-aluminum tubes are also listed in table III. The results of the residual-stress calculations are plotted in figure 13. The residual tensile stress in the aluminum increases from about 13 ksi (90 MN/m^2) for the two-ply boron/epoxy-aluminum tube to about 28 ksi (190 MN/m^2) for the 10-ply boron/epoxy-aluminum tube. The residual compressive stress in the boron/epoxy decreases from about 54 ksi (370 MN/m^2) for the two-ply tube to only about 3 ksi (21 MN/m^2) for the 10-ply boron/epoxy-aluminum tube. The calculated curves in figure 13 are for a ratio of boron volume to boron/epoxy volume K of 0.56, whereas the test specimens cover a range of K from 0.53 to 0.58. Residual stresses calculated for the test specimens agree quite well with the curves calculated for $K = 0.56$.

Stress-strain behavior for the boron/epoxy-aluminum tubes can be predicted by utilizing calculated residual stresses and strains. Stress-strain curves were calculated for two-, six-, and 10-ply boron/epoxy-aluminum tubes by combining the constituent stress-strain curves by the rule of mixtures. Figure 14 shows both experimental and calculated compressive stress-strain behavior for the two-, six-, and 10-ply boron/epoxy-aluminum tubes. There is excellent agreement between the experimental and calculated stress-strain curves. It is also noted that the knee in the stress-strain curve can be predicted when residual stresses and strains are considered. The calculated curves were terminated at the maximum strain obtained experimentally for the tubes tested.

CONCLUDING REMARKS

Compressive-crushing and column-buckling tests were performed on tubes made of aluminum, aluminum reinforced with various amounts of boron/epoxy, and 11-ply boron/epoxy; all tubes were designed to be approximately equal in mass per unit length. Crushing strength increased approximately linearly from about 46 ksi (320 MN/m^2) for the all-aluminum tube to approximately 380 ksi (2620 MN/m^2) for an 11-ply all-boron/epoxy tube.

Column buckling strengths for the reinforced tubes could be adequately predicted when a shear correction was employed.

Stress-strain behavior of boron/epoxy-aluminum tubes can be accurately predicted by the rule of mixtures if residual thermal stresses and strains in the constituents are accounted for.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., May 11, 1970.

APPENDIX

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

The International System of Units (SI) was adopted by the Eleventh General Conference on Weights and Measures, Paris, October 1960 (ref. 3). Conversion factors for the units used herein are given in the following table:

Physical quantity	U.S. Customary Unit	Conversion factor (*)	SI Unit
Length	in.	0.0254	meters (m)
Temperature	(^{o}F + 460)	5/9	Kelvin (K)
Mass	lbm	0.4536	kilograms (kg)
Modulus, stress . . .	psi = lbf/in^2	6.895×10^3	newtons per square meter (N/m^2)

*Multiply value given in U.S. Customary Units by conversion factor to obtain equivalent value in SI Unit.

Prefixes to indicate multiple of units are as follows:

Prefix	Multiple
centi (c)	10^{-2}
milli (m)	10^{-3}
kilo (k)	10^{3}
mega (M)	10^{6}
giga (G)	10^{9}

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TABLE I.- RESULTS FOR CRUSHING SPECIMENS WITH VARIOUS AMOUNTS OF REINFORCEMENT

[Nominal length of tubes, 3.0 inch (7.6 cm); nominal outside diameter of aluminum tube, 0.50 inch (1.27 cm)]

Specimen material	Number of plies of boron/epoxy	t		D_i		Area		Tube mass/length		$E_{t,1}$		$E_{t,2}$		$\overline{V}_{Al}$	$V_{b/e}$	σ_{max}	
		in.	cm	in.	cm	in^2	cm^2	lbm/in.	kg/m	ksi	GN/m^2	ksi	GN/m^2			ksi	MN/m^2
All aluminum	0	0.058	0.147	0.384	0.975	0.081	0.523	0.00786	0.1404	10 000	69	(a)	(a)	1.00	0	----	----
		.058	.147	.384	.975	.081	.523	.00786	.1404	10 000	69	(a)	(a)	1.00	0	----	----
Boron/epoxy-aluminum	2	0.057	0.145	0.406	1.031	0.083	0.535	0.00756	0.1350	14 500	100	7 900	54	0.80	0.20	121.2	836
		.057	.145	.407	1.034	.083	.535	.00755	.1348	14 500	100	7 500	52	.80	.20	116.0	800
	4	0.056	0.142	0.427	1.085	0.085	0.548	0.00751	0.1341	19 200	132	13 900	96	0.62	0.38	180.5	1245
		.056	.142	.428	1.087	.085	.548	.00748	.1336	19 500	134	14 300	99	.63	.37	182.9	1261
	6	0.056	0.142	0.447	1.135	0.089	0.574	0.00731	0.1305	24 000	165	20 800	143	0.45	0.55	259.0	1786
		.056	.142	.447	1.135	.089	.574	.00731	.1305	23 900	165	20 800	143	.45	.55	245.5	1693
	8	0.060	0.152	0.469	1.191	0.100	0.645	0.00747	0.1334	26 000	179	24 700	170	0.24	0.76	277.4	1913
		.061	.155	.469	1.191	.102	.658	.00756	.1350	25 500	176	24 100	166	.24	.76	266.1	1835
	10	0.059	0.150	0.487	1.237	0.101	0.652	0.00745	0.1330	31 200	215	31 200	215	0.10	0.90	312.3	2153
		.058	.147	.487	1.237	.099	.639	.00751	.1341	31 400	216	31 400	216	.10	.90	309.3	2133
All boron/epoxy	11	0.052	0.132	0.514	1.306	0.092	0.594	0.00718	0.1282	37 500	259	37 500	259	0	1.00	375.7	2590

[a] Varies as a function of applied stress.

TABLE II.- RESULTS FOR COLUMN-BUCKLING SPECIMENS WITH VARIOUS AMOUNTS OF REINFORCEMENT

[Nominal length of tubes, 15 inches (38 cm); nominal outside diameter of aluminum tube, 0.50 inch (1.27 cm)]

Specimen material	Number of plies of boron/epoxy	t		D_i		Area		Tube mass/length		$\overline{V}_{Al}$	$\overline{V}_{b/e}$	L/D	σ_{max}		σ_t		G_{calc} (a)		σ_{cr}	
		in.	cm	in.	cm	in^2	cm^2	lbm/in.	kg/m				ksi	MN/m^2	ksi	MN/m^2	ksi	GN/m^2	ksi	MN/m^2
All aluminum	0	0.058	0.147	0.384	0.975	0.081	0.523	0.00787	0.1405	1.00	0	33.94	35.3	243	35.3	243	3800	26	35.0	241
		.058	.147	.384	.975	.081	.523	.00787	.1405	1.00	0	33.94	34.7	239	35.3	243	3800	26	35.0	241
Boron/epoxy-aluminum	2	0.057	0.145	0.405	1.029	0.083	0.535	0.00773	0.1380	0.81	0.19	31.26	62.8	433	66.1	456	3340	23	63.6	439
		.057	.145	.406	1.031	.083	.535	.00752	.1343	.80	.20	31.25	62.8	433	65.7	453	3310	23	63.2	436
	4	0.056	0.142	0.427	1.085	0.085	0.548	0.00749	0.1338	0.63	0.37	29.90	90.8	626	95.8	661	2950	19	90.0	621
		.056	.142	.427	1.085	.085	.548	.00751	.1341	.63	.37	28.89	90.5	624	95.9	661	2950	19	90.0	621
	6	0.057	0.145	0.447	1.135	0.090	0.581	0.00754	0.1346	0.44	0.56	28.75	114.1	787	125.6	866	2520	17	114.2	787
		.056	.142	.447	1.135	.089	.574	.00736	.1314	.45	.55	28.78	117.6	811	126.0	869	2540	18	114.6	790
	8	0.058	0.147	0.468	1.189	0.096	0.619	0.00749	0.1338	0.26	0.74	27.81	134.3	926	151.8	1047	1930	13	131.2	905
		.061	.155	.464	1.179	.101	.652	.00785	.1402	.27	.73	27.88	133.3	919	148.0	1020	1950	13	128.5	886
	10	0.057	0.145	0.489	1.242	0.098	0.632	0.00730	0.1304	0.09	0.91	27.19	162.0	1117	187.7	1294	1620	11	152.4	1051
		.059	.150	.487	1.237	.101	.652	.00749	.1338	.10	.90	27.11	155.2	1070	186.0	1282	1650	13	151.8	1047
All boron/epoxy	11	0.053	0.135	0.509	1.293	0.094	0.606	0.00704	0.1257	0	1.00	26.68	169.9	1171	222.8	1536	1610	11	174.5	1203
		.053	.135	.508	1.290	.093	.600	.00693	.1238	0	1.00	26.74	182.9	1261	221.7	1529	1610	11	173.8	1198

[a] Calculated by using rule of mixtures (see eq. (2)), where G_{Al} = 3800 ksi (26 GN/m^2) and $G_{L,T}$ was obtained from figure 12.

TABLE III.- RESULTS OF RESIDUAL THERMAL[a]-STRESS CALCULATIONS FOR BORON/EPOXY-ALUMINUM COMPOSITES

Number of plies of boron/epoxy	K	E_b		E_e		$E_{b/e}$		E_{Al}		α_b		α_e		$\alpha_{b/e}$		α_{Al}		$\sigma_{r,Al}$ (b)		$\sigma_{r,b/e}$	
		ksi	GN/m²	ksi	GN/m²	ksi	GN/m²	ksi	GN/m²	per °F	per K	per °F	per K	per °F	per K	per °F	per K	ksi	MN/m²	ksi	MN/m²
2	0.55	60 000	414	500	3.4	33 200	229	10 000	69	2.7×10^{-6}	4.9×10^{-6}	16.0×10^{-6}	28.8×10^{-6}	2.8×10^{-6}	5.0×10^{-6}	13.6×10^{-6}	24.5×10^{-6}	-13.0	-89.6	54.2	373.7
4	.58	60 000	414	500	3.4	35 000	241	10 000	69	2.7	4.9	16.0	28.8	2.7	4.9	13.6	24.5	-20.0	-137.9	32.6	224.8
6	.58	60 000	414	500	3.4	35 000	241	10 000	69	2.7	4.9	16.0	28.8	2.7	4.9	13.6	24.5	-23.8	-164.1	19.4	133.8
8	.53	60 000	414	500	3.4	32 000	221	10 000	69	2.7	4.9	16.0	28.8	2.8	5.0	13.6	24.5	-26.6	-183.4	8.4	57.9
10	.56	60 000	414	500	3.4	33 800	233	10 000	69	2.7	4.9	16.0	28.8	2.8	5.0	13.6	24.5	-28.4	-195.8	3.2	22.1

[a] Temperature change from curing to room temperature was 270° F (150 K).

[b] Negative values indicate tension.

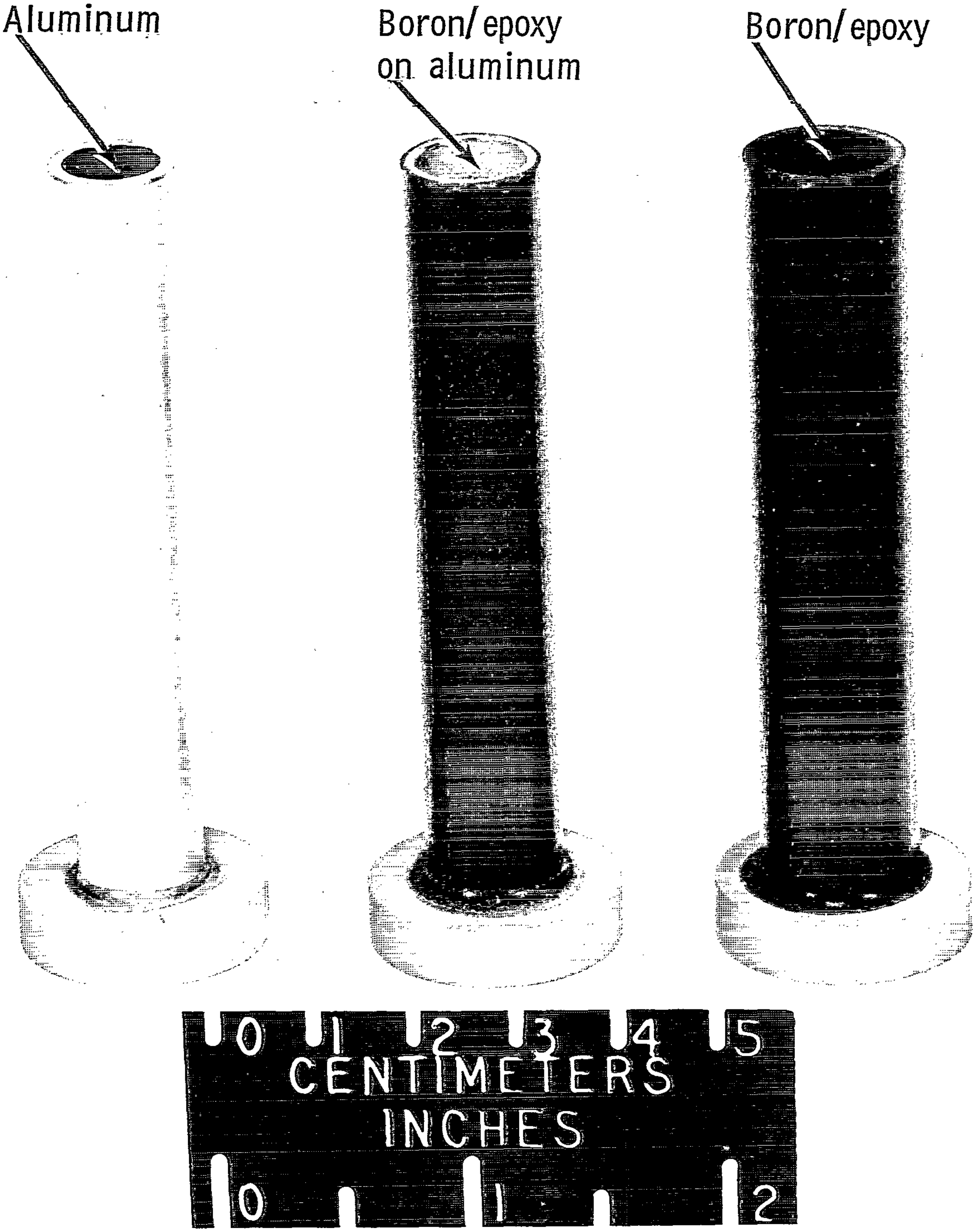
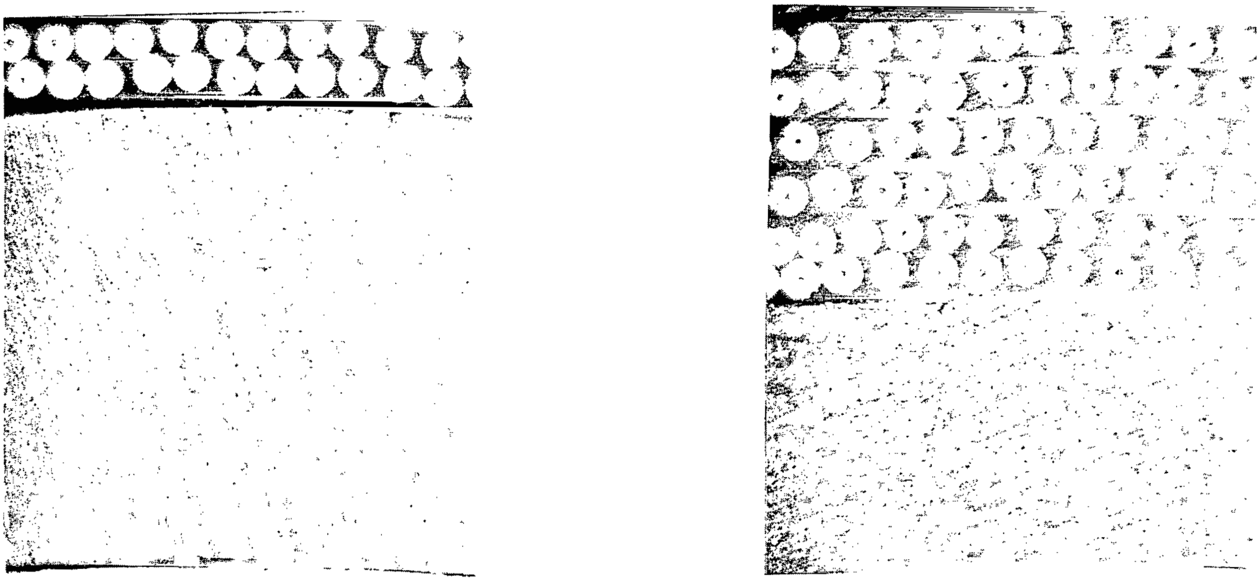
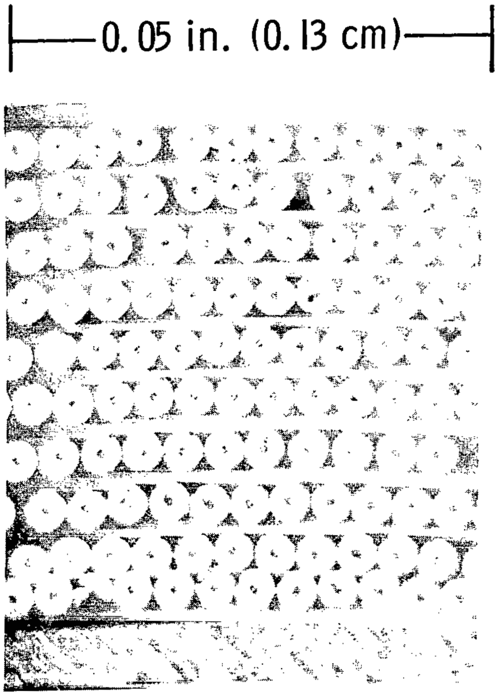

Aluminum
Boron/epoxy on aluminum
Boron/epoxy
0 1 2 3 4 5
CENTIMETERS
INCHES
0 1 2

Figure 1.- Typical tubular specimens designed for crushing failure. L-69-631



(a) Two plies of boron/epoxy on aluminum.

(b) Six plies of boron/epoxy on aluminum.



(c) Ten plies of boron/epoxy on aluminum.

L-70-1660

Figure 2.- Photomicrographs of typical cross sections of boron/epoxy-aluminum composites.

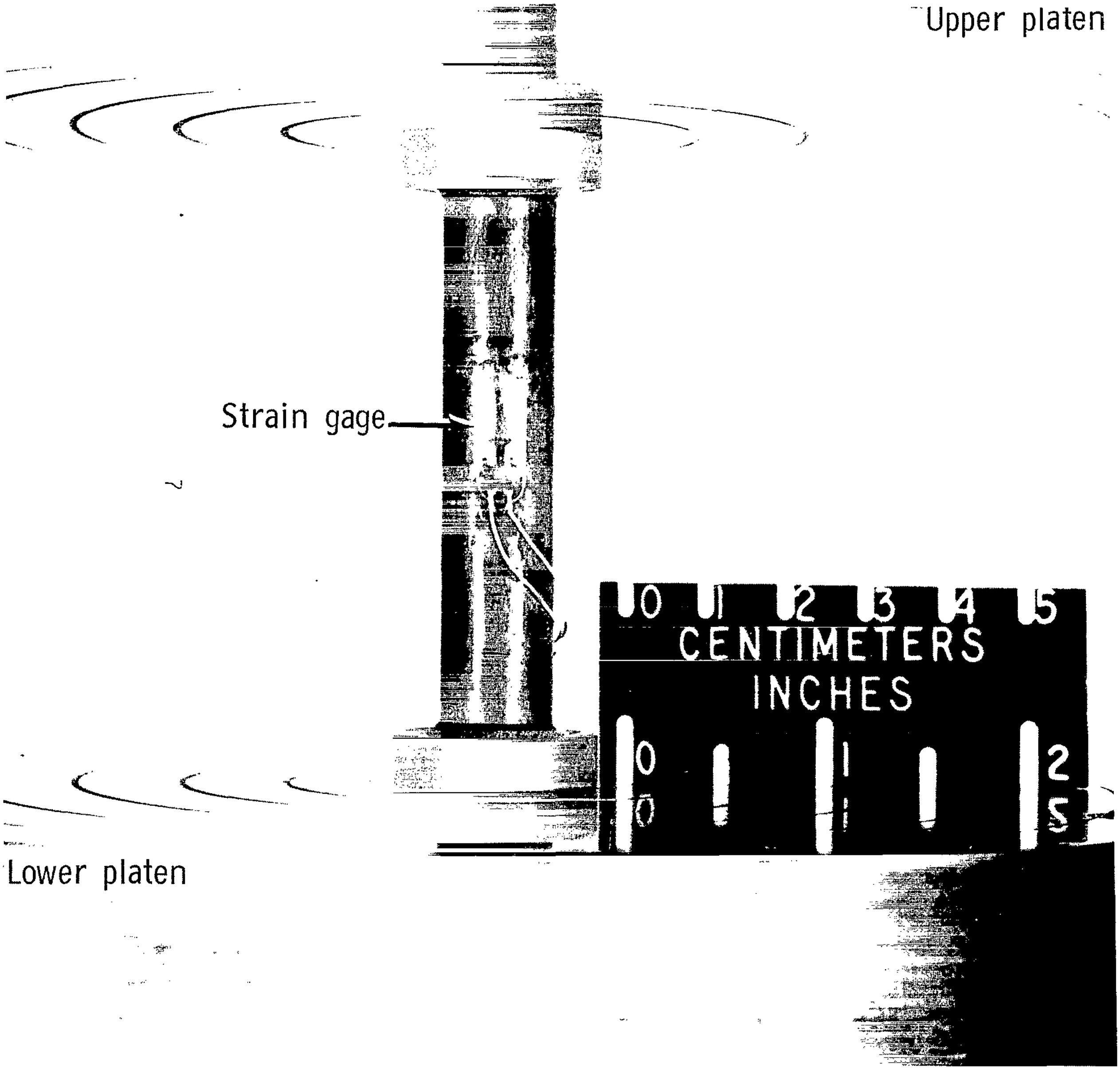

Upper platen
Strain gage
Lower platen
0 1 2 3 4 5
CENTIMETERS
INCHES
0 1 2

Figure 3.- Test setup for crushing test. L-68-4126

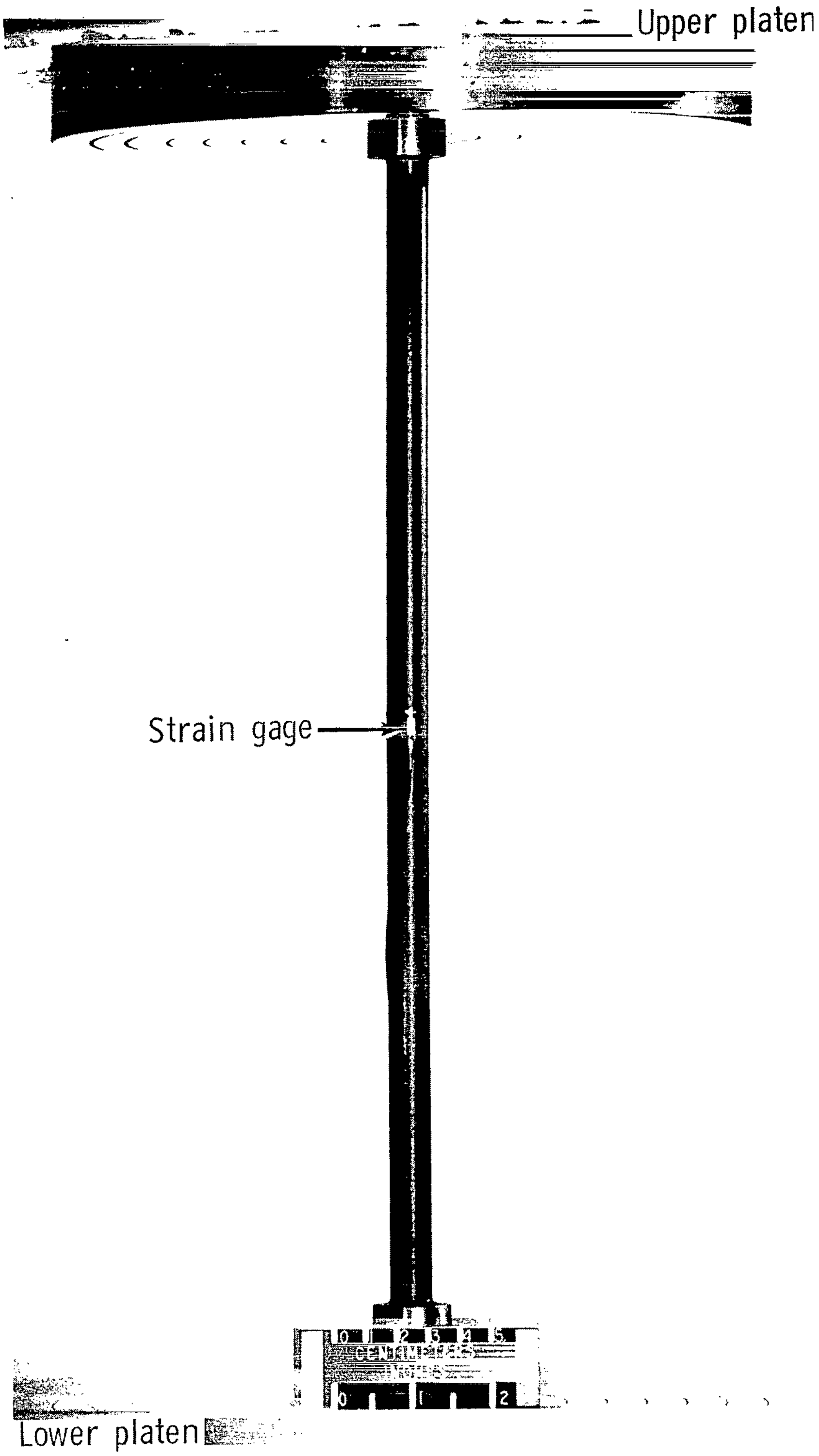

Upper platen
Strain gage
CENTIMETERS
INCHES
Lower platen

Figure 4.- Test setup for column-buckling test. L-69-4003

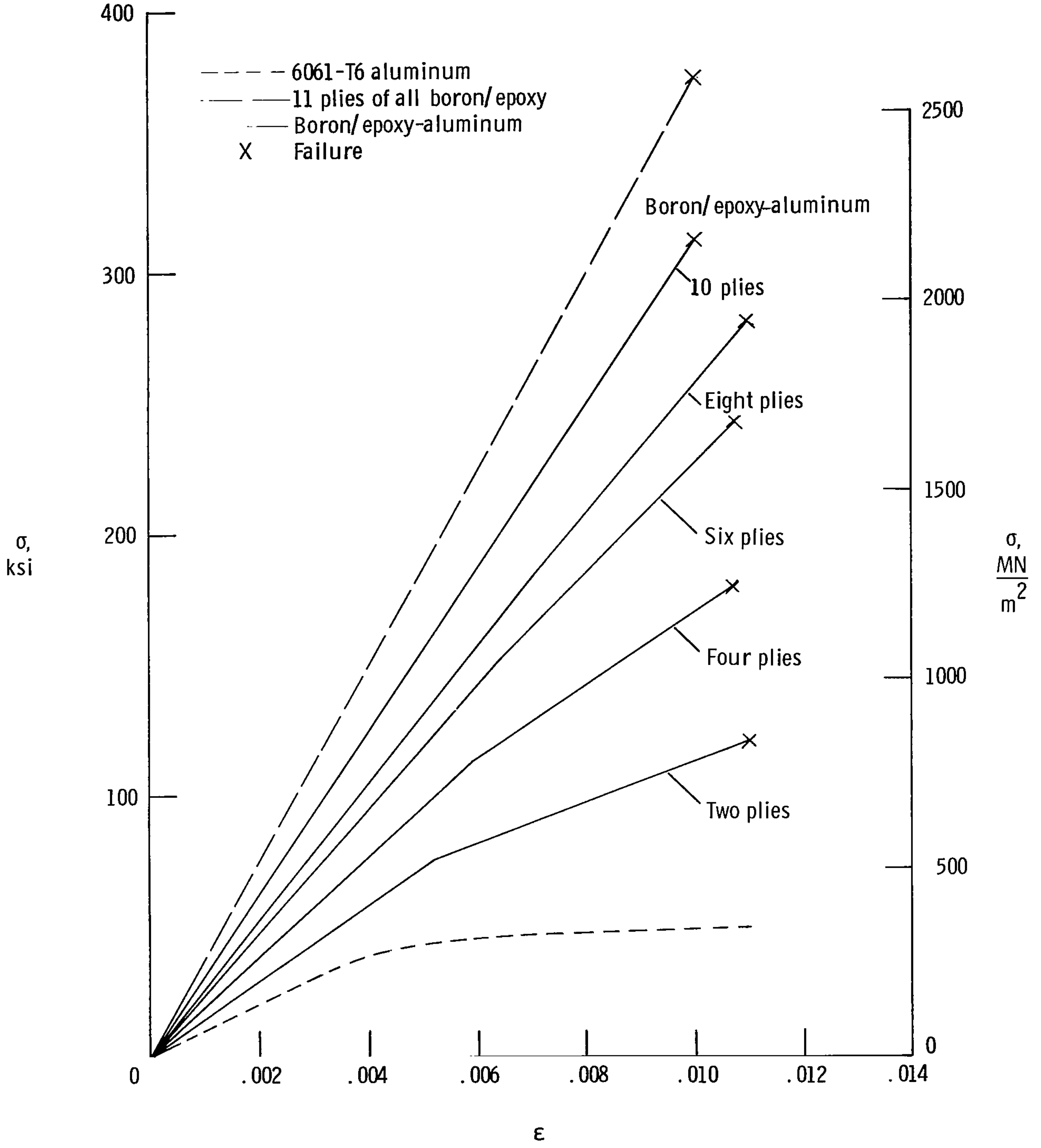


Figure 5.- Compressive stress-strain curves for tubes of aluminum, various amounts of boron/epoxy on aluminum, and boron/epoxy.

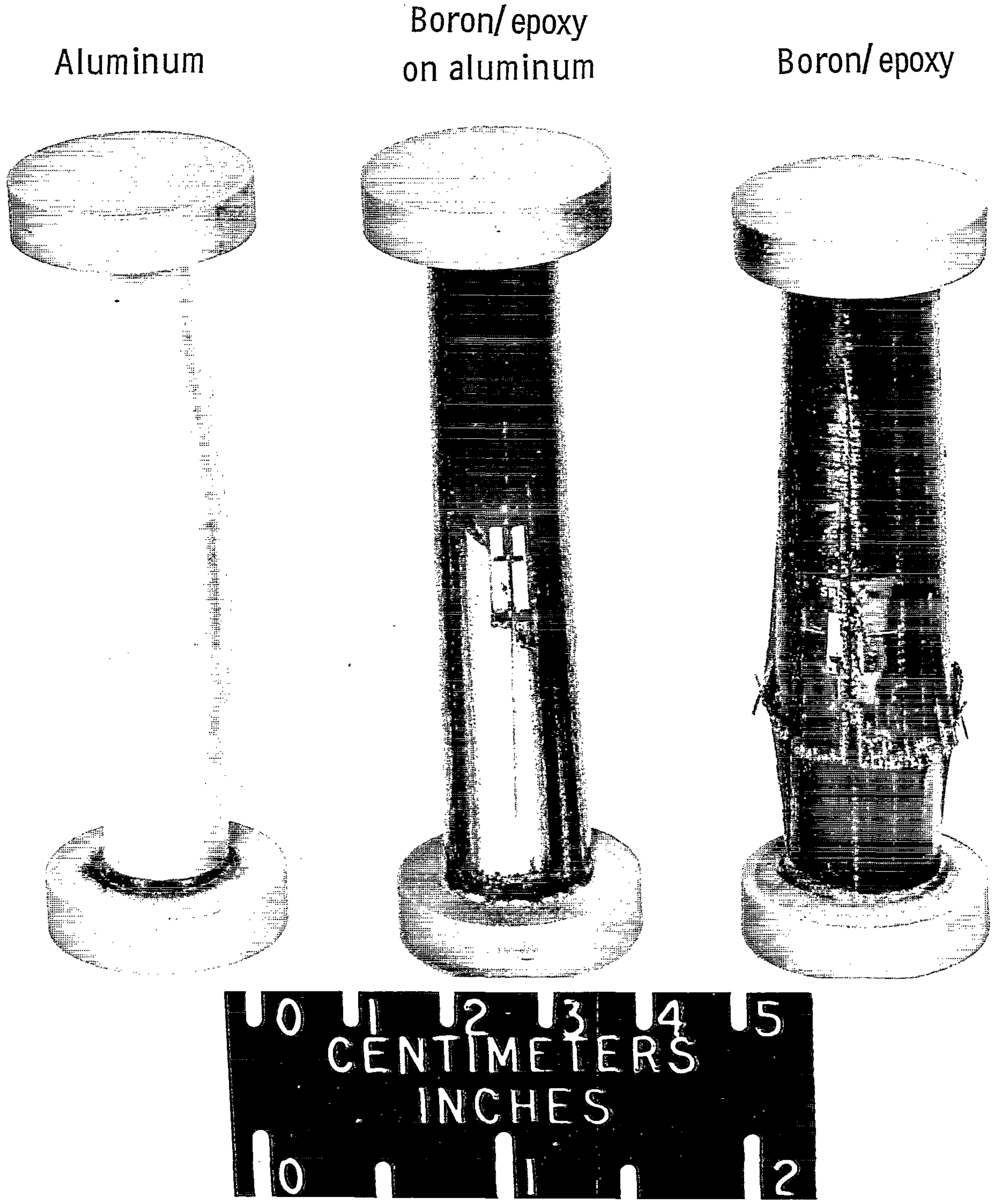

Aluminum
Boron/epoxy on aluminum
Boron/epoxy
0 1 2 3 4 5
CENTIMETERS
INCHES
0 1 2

Figure 6.- Typical failures of crushing specimens.

L-69-630

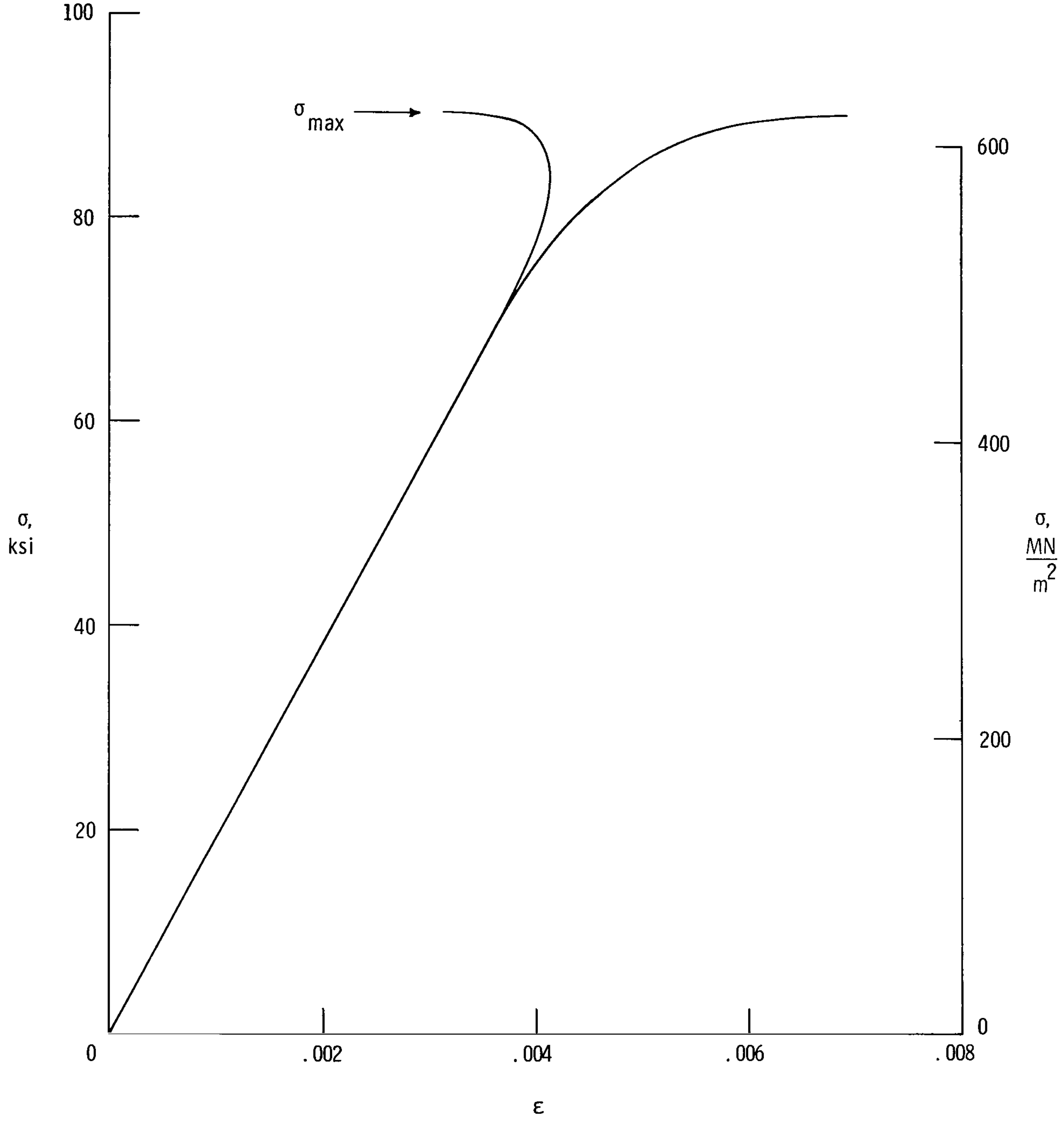
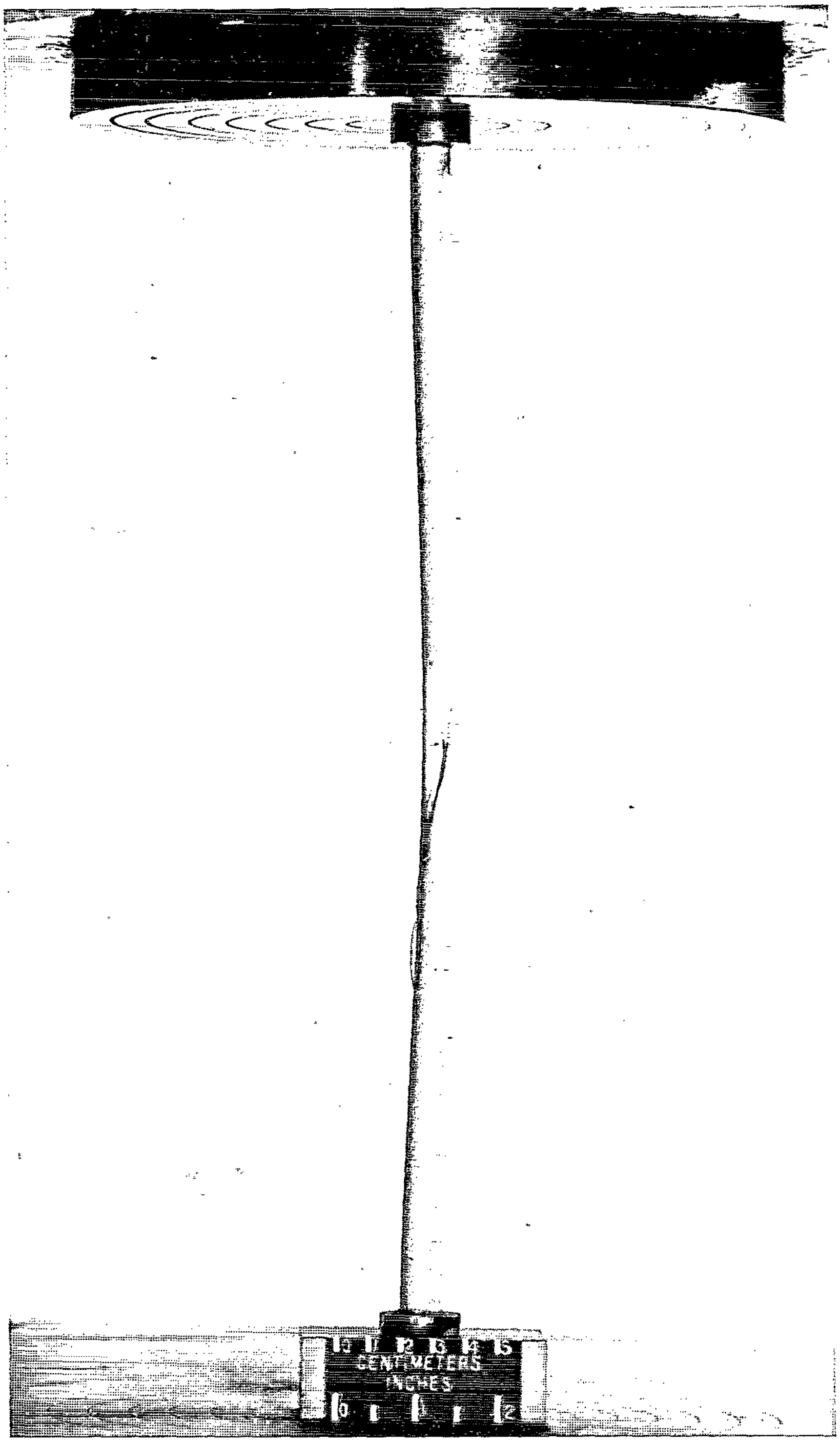


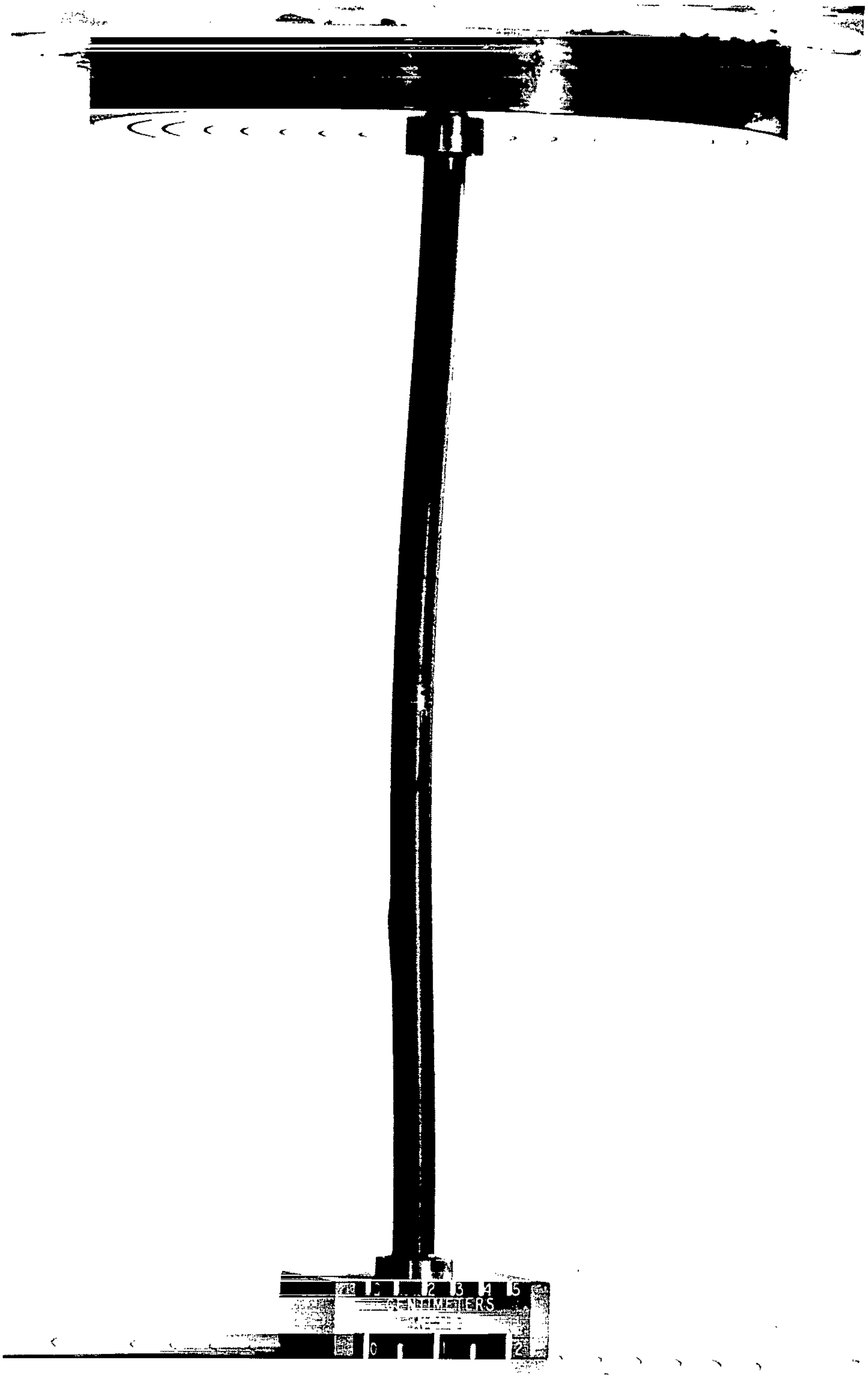
Figure 7.- Typical stress-strain behavior for a four-ply boron/epoxy-aluminum column as obtained from diametrically opposite strain gages.


10 11 12 13 14 15
CENTIMETERS
INCHES
0 1 2

(a) 6061-T6 aluminum.

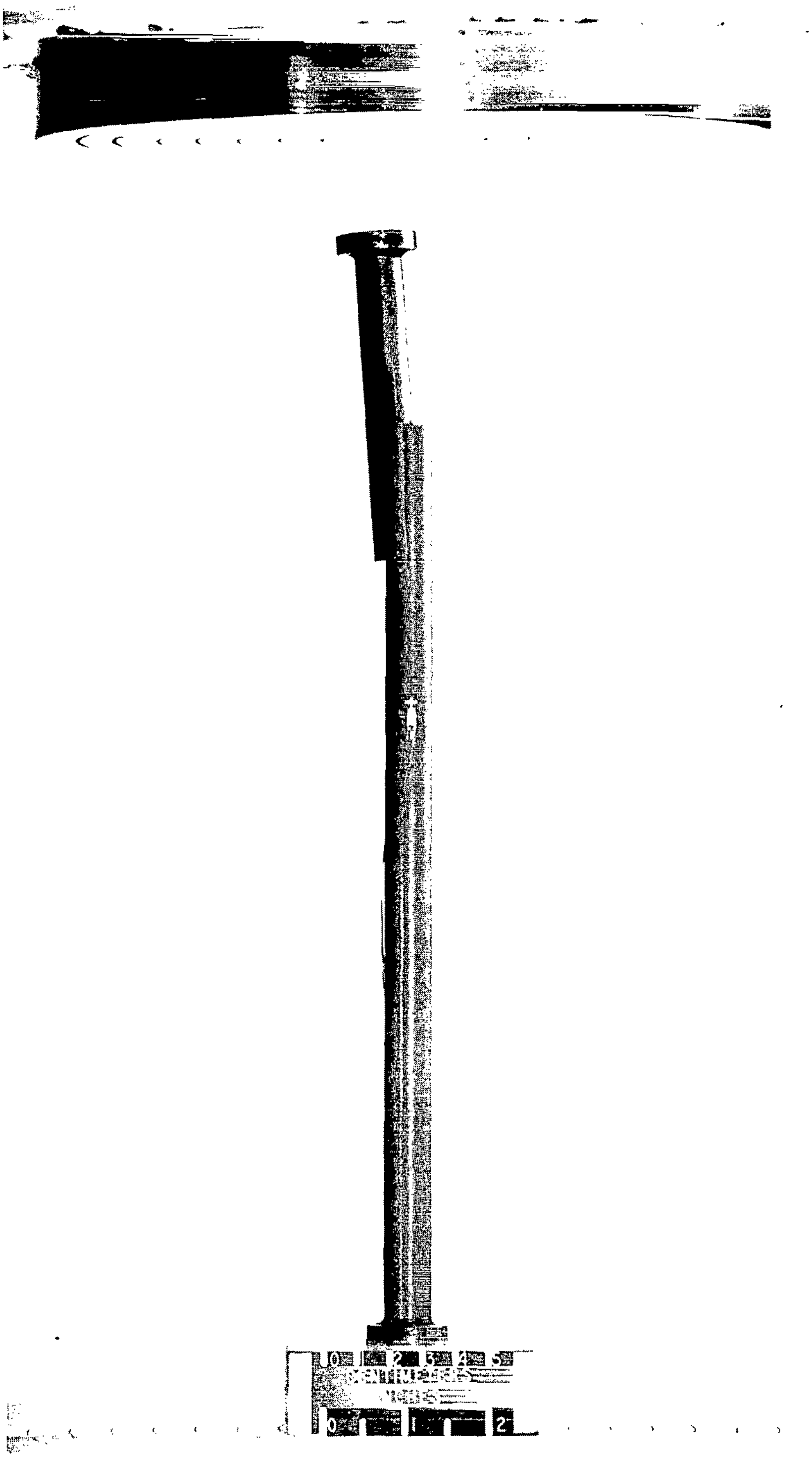
L-69-4005

Figure 8.- Typical failure of 15-inch (38-cm) tubular columns.


0
1
2
3
4
5
CENTIMETERS
0
1
2

(b) Four plies of boron/epoxy on aluminum. L-69-4001

Figure 8.- Continued.


0 1 2 3 4 5
CENTIMETERS
INCHES
0 1 2

(c) Eleven plies of boron/epoxy. L-69-4004

Figure 8.- Concluded.

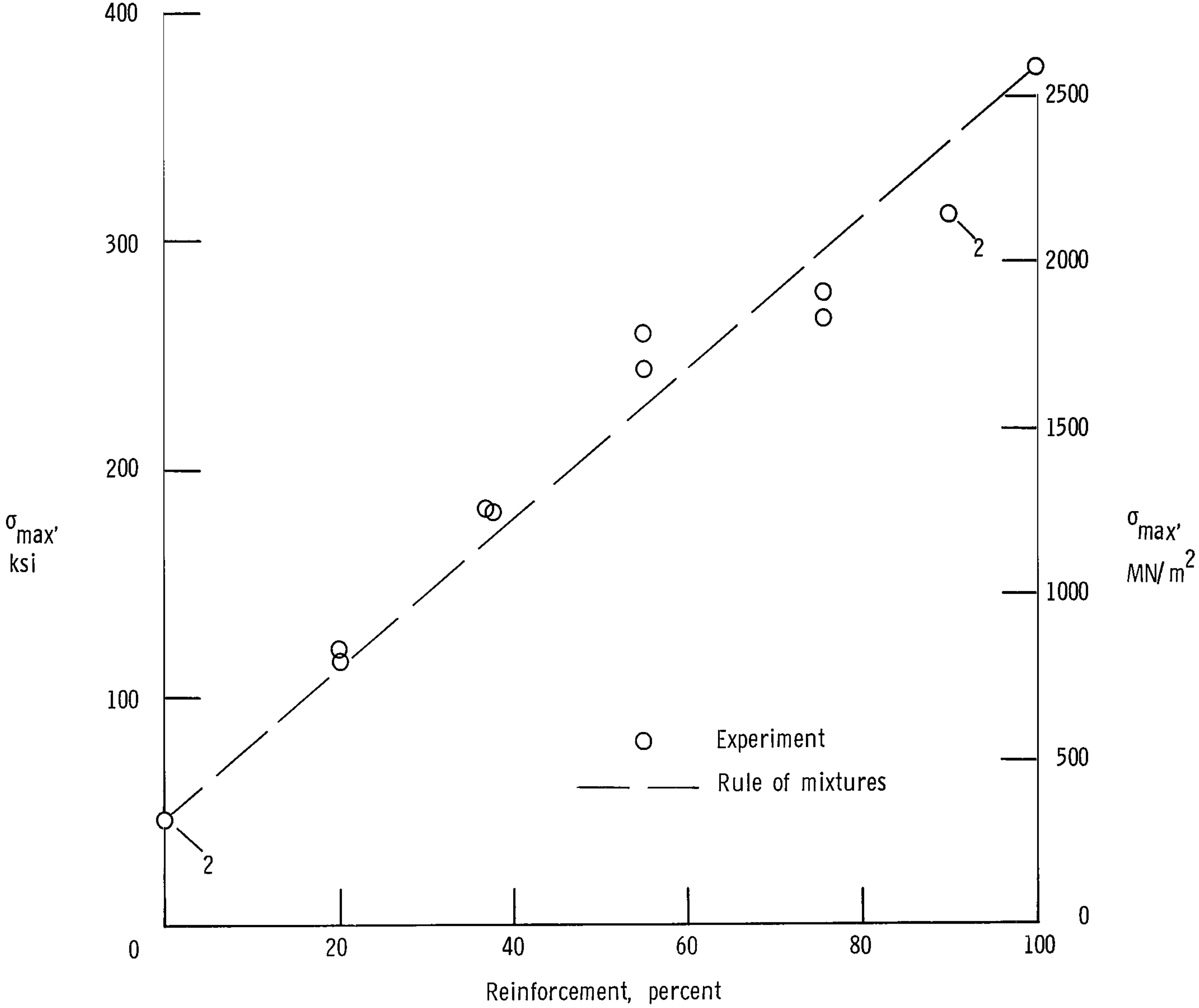


Figure 9.- Effect of various amounts of boron/epoxy reinforcement on compressive strength of aluminum tubes. (All tubes are approximately equal in mass.)

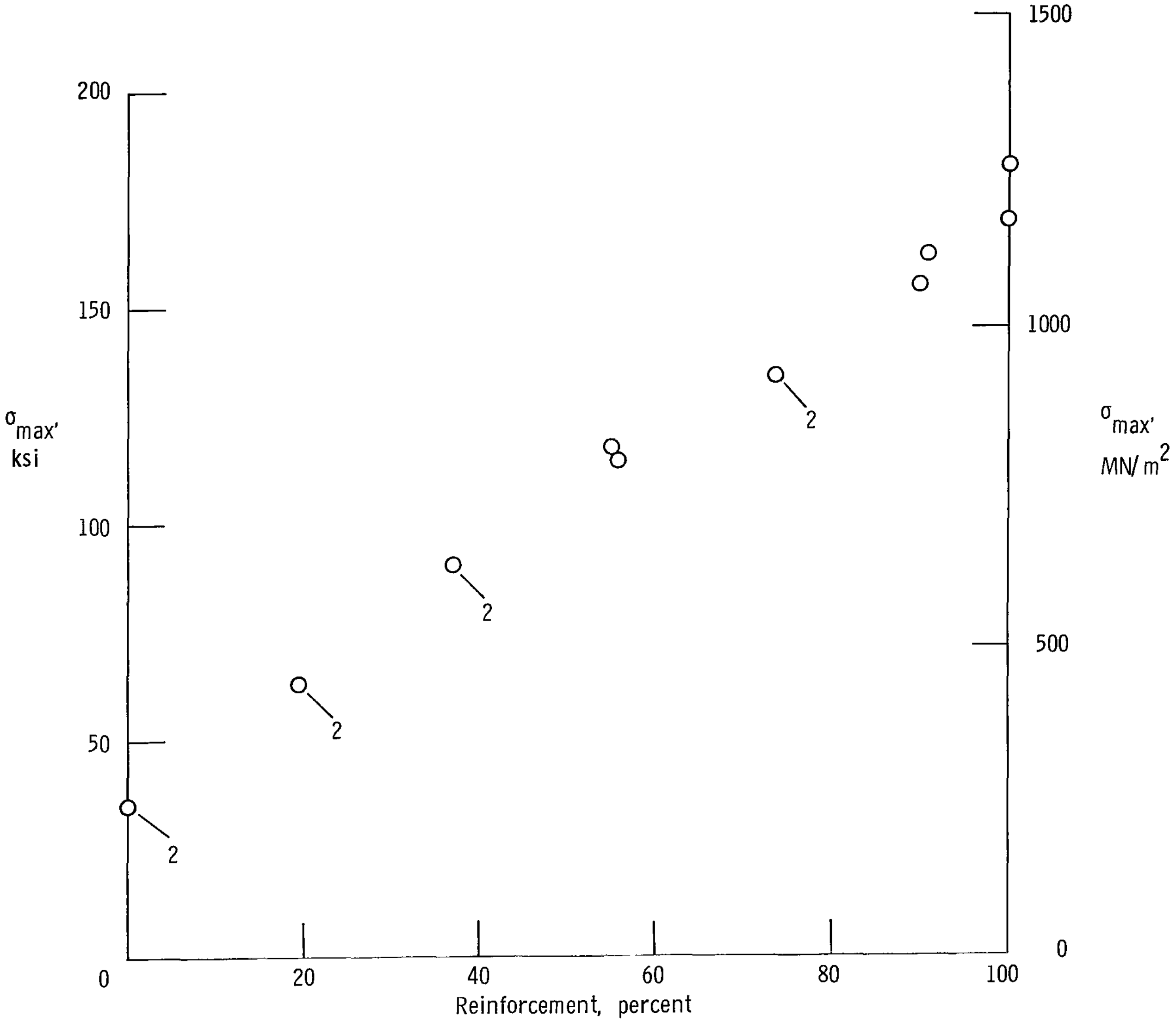


Figure 10.- Effect of various amounts of boron/epoxy reinforcement on buckling strength of 15-inch (38-cm) aluminum tubular columns. (All tubes are approximately equal in mass.)

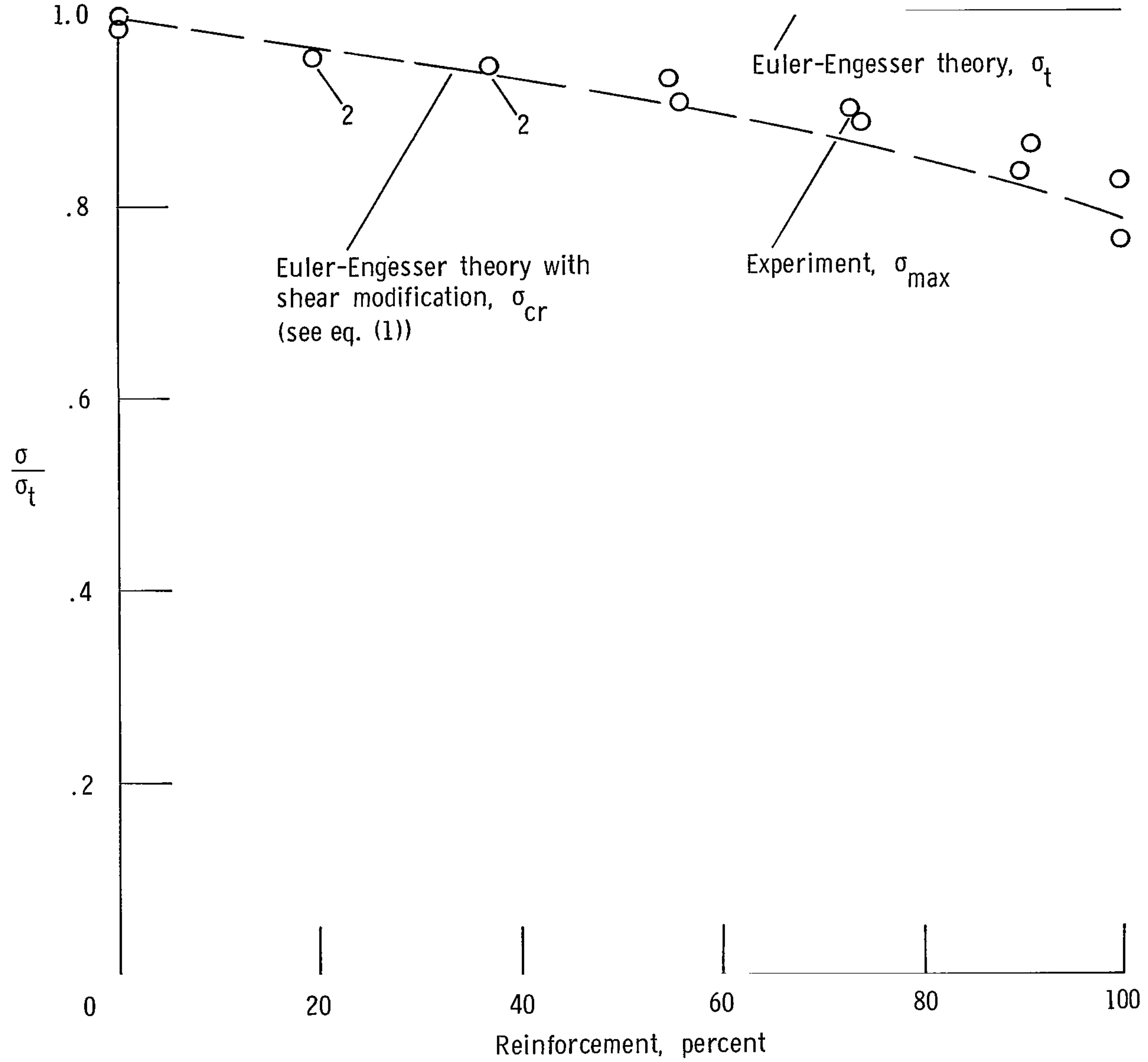


Figure 11.- Comparison of experimental and calculated buckling stress for 15-inch (38-cm) columns with various amounts of boron/epoxy reinforcement.

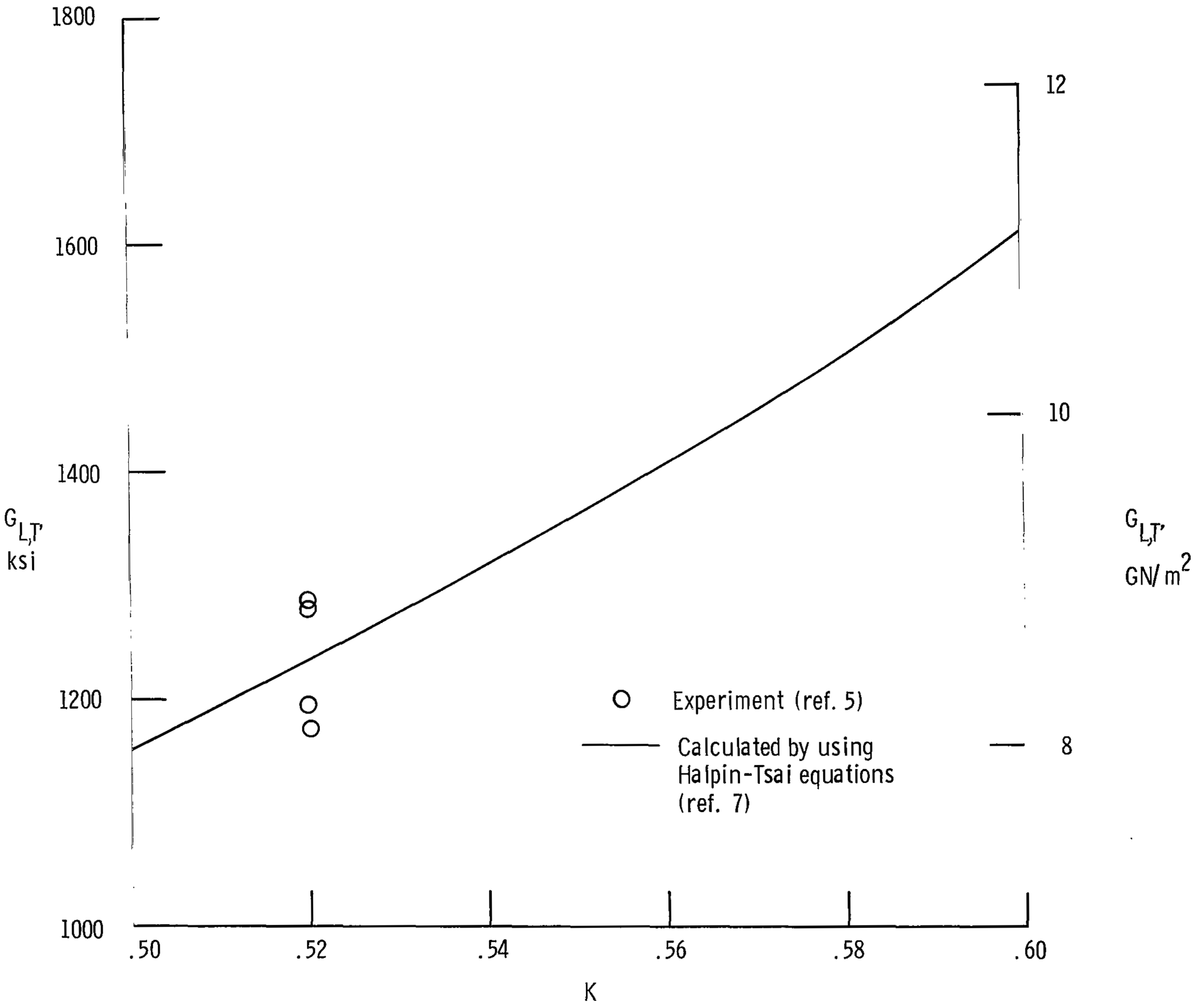


Figure 12.- Variation of shear modulus as a function of volume fraction of boron for a unidirectional boron/epoxy composite.

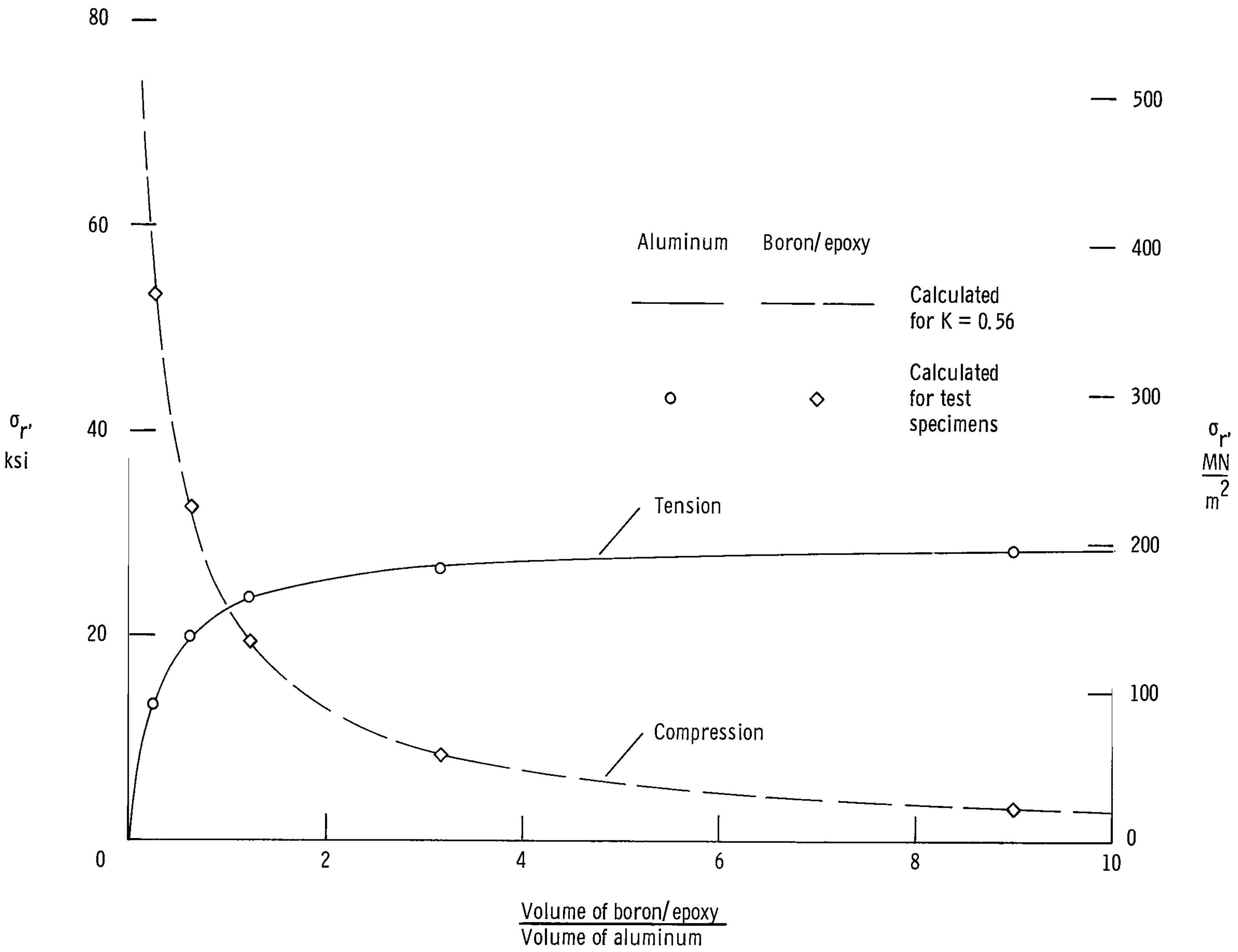


Figure 13.- Calculated residual thermal stresses in boron/epoxy and aluminum for various ratios of boron/epoxy volume to aluminum volume.

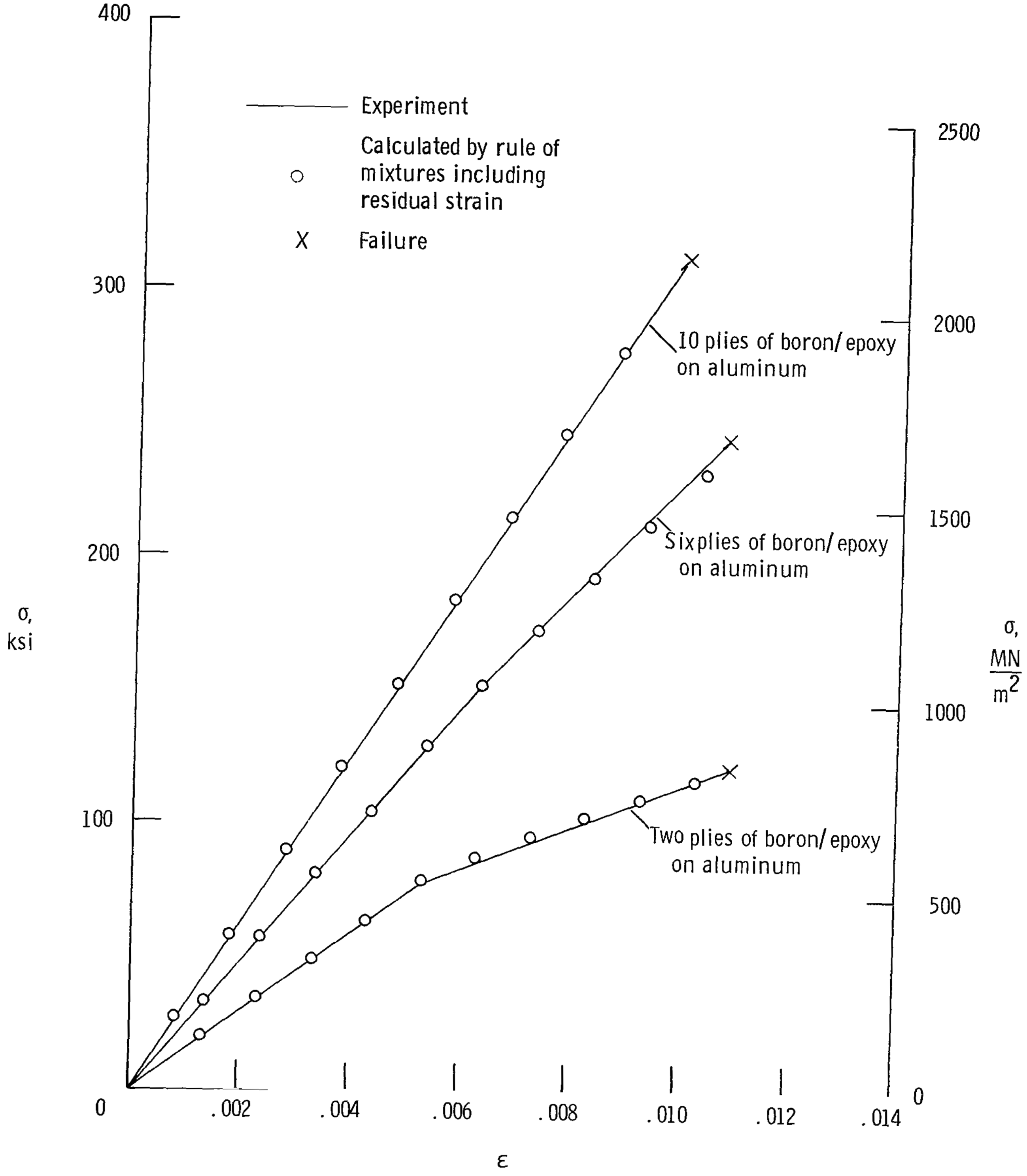


Figure 14.- Calculated and experimental compressive stress-strain curves for boron/epoxy-aluminum tubes.

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