NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1027

COLUMN STRENGTH OF ALUMINUM ALLOY 14S-T EXTRUDED SHAPES AND ROD

By J. R. Leary and Marshall Holt
Aluminum Company of America

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INTRODUCTION

Considerable interest is being shown in the use of aluminum alloy 14S-T in heavy-duty structural applications as well as in aircraft. This alloy, once considered primarily a forging alloy, is now being produced in a variety of forms, such as extruded shapes, rolled shapes, and alclad sheet and plate. With the expanding uses of this material it has seemed desirable to determine some of its structural characteristics, and one of the important items is column strength. The column test data presented herein have been obtained on extruded shapes and on rolled and drawn rod of this alloy.

OBJECT

It was the object of this investigation to determine the column strength of aluminum alloy 14S-T on the basis of tests of extruded shapes and rolled and drawn rod.

SPECIMENS AND METHOD OF TEST

Extruded shapes of 14S-T were selected to represent the following three thickness ranges covered by the specification:

Thickness range	Section
0.125 to 0.499 in.	$2\frac{1}{2}$- by $2\frac{1}{2}$- by 1/4-in. angle
0.500 to 0.749 in.	4- by 9/16-in. zee 5/8- by $2\frac{1}{4}$-in. bar
0.750 in. and over	1- by 2-in. bar

In addition, tests were made on 1-inch diameter rolled and drawn rod.

The nominal elements of these sections are:

Section	Dimensions (in.)	Die number	Nominal thickness (in.)	Area (sq in.)	Least radius of gyration (in.)
Angle	2½ by 2½ by 1/4	78-H	1/4	1.194	0.489
Zee	4 by 9/16	771-F	9/16	5.289	.675
Bar	5/8 by 2¼	22513-EG	5/8	1.406	.181
Bar	1 by 2	22513-EV	1	2.000	.289
Rod	1-in. diam.	Rolled-drawn	--	.785	.250

The column specimens tested are described in table I. The actual average area was determined for each specimen from the weight, length, and nominal specific gravity (0.101 lb per cu in.). The crookedness was obtained by inserting thickness gages between the specimen and a plane surface upon which it rested. The ratio of length to crookedness is greater than 1000 except for the four specimens cut from the 5/8- by 2¼-inch bar marked No. 16 and specimen 18-20 from the 1- by 2-inch bar. Experience has indicated that the strengths of the specimens with this ratio less than 1000 are significantly reduced by the crookedness. The original angle of twist was determined from measurements obtained by inserting thickness gages under one corner of an outstanding leg of the angle or one corner of the bar when the other three corners touched the surface plate. The ends of the specimens were finished flat and parallel by turning on an arbor in a lathe.

The tests, except those on the three shortest zee specimens, were made in an Amsler testing machine of 300,000-pound maximum capacity with intermediate load ranges of 30,000, 100,000, and 200,000 pounds (type 150 SZBDA, serial No. 5254). This machine is of the four-column type, and the guides on the movable head are adjustable to allow a minimum of lateral motion of the movable platen for the satisfactory operation of the machine. When testing the shorter specimens in the 300,000-pound capacity machine, the platens were protected by hardened steel disks 9 inches in diameter, the faces of which had been finished flat and parallel by precision grinding. The three shortest specimens of zee sections were tested in the 3,000,000-pound capacity Templin Precision Metal Working Machine (Baldwin-Southwark Shop Order No. 63430).

All specimens were tested as columns with flat ends. During each test on either machine the platens were fixed in position to prevent tipping, but before the test they were alined parallel within 0.0003 inch in 12 inches by means of special leveling rings. The platen in the lower head is supported by a pair of tapered rings which vary uniformly in thickness so that, by rotating one ring relative to the other and both rings relative to the lower head, this platen can be tipped and alined parallel to the upper platen.

The mechanical properties of the material are shown in table II. The tensile values given in all cases surpass the specified minimum properties for 14S-T extruded shapes for the particular thickness range. The compressive stress-strain relations, as determined by the movement of the platens during the tests of specimens of the full cross section, are shown in figure 1. It is recognized that the relative movement of the heads of the machine includes strains other than those in the specimen; so these curves have been corrected to give an initial slope equal to the nominal modulus of elasticity of the material, 10,600,000 psi. (See reference 1.)

RESULTS AND DISCUSSION

The results of the column tests are given in table I and figures 2, 3, 4, and 5. All specimens except the $2\frac{1}{2}$- by $2\frac{1}{2}$ by 1/4-inch angle failed by sidewise bending, and the test results, except for the angle, follow the Euler and tangent-modulus column curves fairly well. The equations of these curves are of the same form, the difference being in the interpretation of the term $\overline{E}$ which is the effective modulus of elasticity. The equation is:

$$\frac{P}{A} = \frac{\pi^2 \overline{E}}{\left(\frac{KL}{r}\right)^2} \qquad (1)$$

where

P total load, pounds

A cross-sectional area, square inches

$\bar{E}$ effective modulus of elasticity, pounds per square inch. Euler's interpretation for stresses in the elastic range uses $\bar{E}$ equal to the initial value, 10,600,000 psi. Engesser's interpretation for stresses above the elastic range uses an effective modulus which is less than the initial modulus and which varies with the stress. In this case the tangent modulus was taken as the effective modulus, and the compressive-stress-tangent-modulus relations are shown in figure 6.

K coefficient describing the end conditions, taken here as 0.5 (flat ends assumed equivalent to fixed ends)

L length of specimen, inches

r least radius of gyration, inches

The straight-line column curves obtained by the procedure outlined in reference 2 are shown in figures 2, 3, and 4 for the sections that failed by sidewise bending. The equation is of the form,

$$\frac{P}{A} = B - D\left(\frac{KL}{r}\right) \tag{2}$$

where

B intercept of the straight line on the axis of zero slenderness ratio

D slope of the straight line, such that the straight line is tangent to the Euler curve

and the other terms are as defined above. The relation between B and the compressive yield strength of the material is given in the above reference as:

$$B = CYS\left(1 + \frac{CYS}{200000}\right) \tag{3}$$

in which CYS is compressive yield strength, pounds per square inch. This equation is to be used only in the range of effective slenderness ratios up to that at the point of tangency of the straight line and Euler curves. Beyond the point of tangency the Euler curve is applicable.

The agreement between the test results and the combination of the straight line and the Euler curves indicates that the combination is probably satisfactory for the design of 14S-T structures for stresses less than the compressive yield strength. It will be noticed that the trends of the tangent modulus curves and of the data points in some cases suggest the possible use of an empirical curve of the parabolic type also but not to the same extent as in the case of 75S-T, which has a higher yield strength.

As noted above, some of the equal-leg angle specimens did not fail by sidewise bending. Instead, the shorter ones failed by a combination of sidewise bending and twisting about a longitudinal axis. On the basis of elastic action, the strengths of this latter group of specimens could be computed by the following equation:

$$p = \frac{P}{A} = \frac{\rho^2}{2\rho_o^2}\left[Q + T + \sqrt{(Q - T)^2 + 4\,QT\,\frac{x_o^2}{\rho^2}}\right] \text{ (reference 3) } (4)$$

where

$p = \frac{P}{A}$ average stress at failure, pounds per square inch

ρ polar radius of gyration about the shear center, inches

ρ_o polar radius of gyration about the centroid, inches

x_o distance between shear center and centroid, inches

Q Euler column strength for bending about the principal axis of maximum stiffness, pounds per square inch, computed by equation (1)

T column strength for pure twisting failure, pounds per square inch

Further explanation of some of the terms in equation (4) is given in appendix A.

The curve of equation (4) is shown in figure 5. The Euler curve for bending failure and the curve for combined elastic bending and twisting failure for $2\frac{1}{2}$- by $2\frac{1}{2}$- by 1/4-inch angles intersect at an effective slenderness ratio equal to about 50. On the basis of elastic action, it would, therefore, be expected that the specimens longer than this would fail by bending and shorter ones would fail by combined bending and twisting.

It is seen in figure 5 that the test results in the region where combined bending and twisting failures occur are above the elastic limit stress and that the data points lie somewhat below the computed curve based on elastic action. In the case of bending failures, inelastic action can be taken care of by using the tangent modulus as the effective modulus in the Euler equation. The case of twisting failures is not so simple because of the biaxial stress conditions in the twisting problem. The use of the tangent modulus in equation (4) leads to a computed curve that lies below the test results. Better agreement with the test results would, therefore, be obtained by using an effective modulus between the tangent modulus and the initial modulus. An effective modulus that results in reasonably good agreement with the test data can be obtained from either of the following relations:

$$\bar{E} = E\sqrt{\frac{E'}{E}} = \sqrt{EE'} \qquad (5)$$

$$\bar{E}_1 = E\sqrt[3]{\frac{E'}{E}} = \sqrt[3]{E^2E'} \qquad (6)$$

where

$\bar{E}$, $\bar{E}_1$ effective modulus, pounds per square inch

E initial modulus, pounds per square inch

E' tangent modulus, pounds per square inch

The use of equation (6) results in a slightly higher computed curve.

The compressive stress-tangent modulus curve for these angle specimens and the effective modulus defined by equation

(5) are shown in figure 7. The compressive stress-strain curve determined on a specimen cut from the angle is shown in figure 8.

An approximate method, which is much simpler, for computing the strength of equal-leg angles which fail by twisting considers each of the outstanding legs as a flat plate with one longitudinal edge simply supported and the other free. The ultimate strength of the angle is assumed equal to the buckling strength of the plate. Actually, there may be a a slight restraint along the supported edge of the plate because of the bulk of material at the junction of the two legs, but in comparison with complete fixation any restraint from this source is undoubtedly slight. On the basis of elastic action, the critical buckling stress is given by the equation,

$$\sigma = k \frac{E}{(1 - \mu^2)} \left(\frac{t}{b} \right)^2 \quad \text{(reference 4)} \qquad (7)$$

where

σ average stress at failure, pounds per square inch

k factor depending on length-width ratio of the plate and the conditions along the edges and ends

E modulus of elasticity, pounds per square inch

μ Poisson's ratio

t thickness of plate, inches

b width of plate, inches

In these tests the condition of the loaded edges of the individual legs was practically equivalent to fixed ends since the individual legs were machined flat and bore on the platens as columns with flat ends. Thus the value of k for use in equation (7) for computing the twisting strength of equal-leg angles can be obtained from the equation,

$$k = \frac{\mu^2}{12} \left[\frac{4}{\left(\frac{L}{b} \right)^2} + 0.406 \right] \quad \text{(reference 5)} \qquad (8)$$

Two sets of curves of buckling strength computed by means of equations (7) and (8) are shown in figure 9. In one set the ratio of b/t was taken equal to 10, which is the ratio of the full width of leg to the thickness, and in the other set the ratio was taken equal to 9, which is the ratio of the outstanding width to the thickness. As is the case of equation (4), the combination with the Euler curve indicates that specimens shorter than about KL/r equal to 50 would fail by combined bending and twisting. In this region the data points lie between the two computed curves based on the effective modulus defined by equation (5).

Kollbrunner (reference 6) employed this method of analysis with his data from column tests on equal-leg angles and used the following relation for the effective modulus,

$$\bar{E}_2 = E\left(\frac{\tau + \sqrt{\tau}}{2}\right)$$

$$\tau = \frac{E''}{E} = \frac{4\frac{E'}{E}}{\left(1 + \sqrt{\frac{E'}{E}}\right)^2} \qquad (9)$$

where

$\bar{E}_2$ effective modulus, pounds per square inch

E initial modulus, pounds per square inch

E'' double modulus, pounds per square inch

E' tangent modulus, pounds per square inch

τ ratio of double modulus to initial modulus

This relation for effective modulus was tried out with the data in figures 5 and 9, but it gave no better agreement with the data than the simple expression of equation (5).

An even simpler approximate method for computing the buckling strength of an outstanding plate is described in the Structural Aluminum Handbook published by Aluminum Company of America (1945). An equivalent slenderness ratio is obtained for the particular width-thickness ratio and the buckling strength then determined from a column curve for the material. The dotted horizontal line in figure 9 was thus determined, and it is apparent that the Handbook method is on the conservative side.

In order to avoid the twisting type of failure or buckling of the legs at stresses below the tangent-modulus column curve for bending failures, the width-thickness ratio of the legs would need to be about 7 or less.

CONCLUSIONS

The following conclusions concerning the column strength of extruded 14S-T shapes and rolled and drawn rod have been drawn from the data and discussion presented in this report.

1. There is good agreement between the test data and the combination of Euler and tangent-modulus column curves (equation (1)) for specimens that fail by sidewise bending, the coefficient of end restraint, K, of the specimens tested as columns with flat ends being taken equal to 0.50.

2. For the purpose of design of straight, axially loaded columns that fail by sidewise bending and not by twisting or local buckling, the combination of the Euler curve and a straight line tangent to it (equations (1) and (2)) should be satisfactory for ultimate column strengths less than the compressive yield strength.

3. Single-member columns consisting of equal-leg angles of 14S-T and having a width-thickness ratio of the legs equal to 10 are subject to failure by combined bending and twisting about a longitudinal axis at an average stress less than that computed for failure by bending about the axis of least stiffness when the effective slenderness ratios (KL/r) are less than about 50.

4. In order to avoid the twisting type of failure or buckling of the legs at stresses below the tangent-modulus column curves for bending failures, the width-thickness ratio based on the outstanding width of the legs would need to be about 7 or less.

5. There is good agreement between the test results from the equal-leg angle specimens and the curve of equation (4) for the combination bending and twisting type of failure when

the effective modulus is as defined by equation (5) or (6). The use of the tangent modulus as the effective modulus gives a computed curve somewhat below the data points.

6. For a simple approximate method of computing the column strength of equal-leg angles, equations (7) and (8) from the theory of flat plates can be used. The effective moduli defined by equations (5) and (6) give satisfactory agreement with the data for column strengths above the elastic stress range. The computed strengths are conservative when the full width is used in determining the width-thickness ratio.

7. The approximate method for computing the buckling strengths of outstanding plates as given in the Structural Aluminum Handbook results in conservative computed strengths for equal-leg angles.

Aluminum Research Laboratories,
Aluminum Company of America,
New Kensington, Penna., July 5, 1945.

APPENDIX A

Further explanation of some of the terms in equation (4):

$$T = \frac{GC}{I_p} + \frac{n^2\pi^2 E}{L^2 I_p}\,\Gamma \qquad (10)$$

where

G modulus of elasticity in shear, psi

C torsion factor, in.^{4} (sometimes designated as J)

I_p polar moment of inertia of the cross section with respect to the shear center, in.^{4}

n number of half-waves in the configuration of the deformed member

Γ torsion-bending factor, in.^{6} (variously designated C_{BT} or C_{BD})

L length of the member, in.

$$G = \frac{E}{2(1 + \mu)} \tag{11}$$

where

μ Poisson's ratio; for aluminum alloys the value is usually taken as one-third.

$$C = \frac{2}{3} dt^3 - 0.210t^4 + 0.164\delta^4 \tag{12}$$ [1]

where

d length of leg, b, minus one-half the thickness of leg, in.

t thickness of leg, in.

δ diameter of largest circle that can be drawn within the cross section at the heel of the angle, in.

$$\Gamma = \frac{1}{18} d^3t^3 \tag{13}$$

The shear center of an equal-leg angle is in the heel of the angle at the intersection of the center lines of the two legs. If the effects of the fillet and roundings are neglected, it follows that:

$$x_o = \frac{d}{2\sqrt{2}} \tag{14}$$

By definition it follows that

$$I_p = I_x + I_y + Ax_o^2 \tag{15}$$

$$\rho^2 = r_x^2 + r_y^2 + x_o^2 \tag{16}$$

[1]Developed from equation (21) of reference 7.

where

I_x, I_y moments of inertia about a pair of perpendicular axes, in.[4]

A cross-sectional area, sq. in.

r_x, r_y radii of gyration about a pair of perpendicular axes, in.[4]

It should be pointed out that equations (4) and (10) are valid for any cross section having one axis of symmetry. The values of the terms as defined by equations (12), (13), and (14) are limited to equal-leg angles.

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TABLE I

DESCRIPTION OF SPECIMENS AND RESULTS OF TESTS

COLUMN TESTS ON 14S-T

[Specimens tested as columns with flat ends]

Specimen number	Length, L (in.)	Weight (lb)	Actual area, A (sq in.)[1]	Effective slenderness ratio, KL/r [2]	Measured crookedness (in.)[3] e_1	Measured crookedness (in.)[3] e_2	Ratio L/e_1	Ratio L/e_2	Measured initial twist (rad per ft of length)	Maximum load, P (lb)	Column strength, P/A (psi)
2-1/2 x 2-1/2 x 1/4 in. angle, r = 0.489 in.											
6-10	9.81	1.19	1.202	10.0	0.003	--	3,270	--	0.0064	65,350	54,350
6-20	19.62	2.38	1.203	20.1	.004	--	4,405	--	.0034	59,000	49,050
4-29	29.44	3.51	1.183	30.1	.006	--	4,907	--	.0013	53,800	45,500
6-39	39.31	4.78	1.206	40.2	.004	--	9,828	--	.0035	53,050	44,000
5-49	49.00	5.93	1.201	50.1	.008	--	6,125	--	.0037	45,100	37,550
6-59	58.87	7.19	1.212	60.2	.010	--	5,887	--	.0078	33,350	27,500
5-78	78.56	9.42	1.190	80.5	.031	--	2,537	--	.0004	18,350	15,400
4-98	98.00	11.68	1.182	100.2	.010	--	9,800	--	.0016	12,090	10,250
4 x 9/16 in. zee, r = 0.675 in.											
8-7	6.81	3.64	5.303	5.0	--	--	--	--	0.0010	375,200	70,750
7-11	11.40	6.10	5.308	8.5	0.005	--	1,220	--	.0096	356,800	67,200
7-27	27.12	14.54	5.319	20.1	.010	0.006	1,400	2,425	.0091	303,200	57,000
10-41	40.76	22.50	5.476	30.2	.015	.004	2,717	10,190	.0014	281,000	51,300
7-54	54.44	29.23	5.327	40.3	.010	.022	5,444	2,474	.0027	247,400	46,450
8-61	60.76	32.43	5.295	45.0	.010	.004	6,076	16,190	.0005	230,000	43,450
8-82	81.68	44.00	5.344	60.5	.018	.018	4,538	4,538	.0010	142,500	26,650
10-108	108.56	58.50	5.346	80.4	.004	.005	14,625	11,700	.0010	84,800	15,850
5/8 x 2-1/4 in. bar, r = 0.181 in.											
16-4	3.76	0.54	1.417	10.4	0.005	--	751	--	--	109,300	77,100
16-6	5.52	.80	1.429	15.3	.015	--	368	--	--	95,500	66,800
16-7	7.33	1.05	1.412	20.3	.025	--	293	--	--	91,500	64,800
16-9	9.09	1.30	1.411	25.2	.010	--	908	--	--	88,000	62,400
15-16	16.40	2.38	1.431	45.4	.005	--	3,280	--	0.0037	67,400	47,700
15-18	18.15	2.63	1.429	50.2	.014	--	1,296	--	.0082	59,500	41,650
15-22	21.80	3.16	1.430	60.4	.012	--	1,817	--	.0061	41,500	29,000
15-29	29.04	4.20	1.426	80.4	.009	--	3,227	--	.0033	23,400	16,410
1 x 2 in. bar, r = 0.289 in.											
18-6	5.87	1.19	1.939	10.2	0.004	--	1,468	--	--	145,000	72,540
18-9	8.80	1.78	1.995	15.2	.007	--	1,257	--	--	131,400	65,860
18-12	11.65	2.36	1.998	20.2	.010	--	1,164	--	--	126,500	63,310
17-14	14.50	2.99	2.034	25.1	.012	--	1,208	--	0.0096	128,800	63,320
18-17	17.39	3.53	2.002	30.1	.008	--	2,174	--	.0052	113,000	56,440
18-20	20.37	4.13	2.000	35.3	.030	--	679	--	--	104,300	52,150
18-23	23.48	4.76	1.999	40.7	.005	--	4,696	--	.0026	94,500	47,270
18-26	26.10	5.39	1.999	45.2	.009	--	2,900	--	.0041	89,000	44,520
18-29	28.92	5.84	1.991	50.1	.012	--	2,410	--	.0052	76,400	38,370
17-35	34.69	7.07	2.010	60.1	.025	--	1,388	--	--	58,000	28,860
17-46	46.48	9.44	2.003	80.5	.030	--	1,549	--	--	32,000	15,980
17-57	56.80	11.52	2.000	98.4	.008	--	7,100	--	--	20,700	10,350
1-in. diameter rod, r = 0.250 in.											
2-5	5.00	0.41	0.794	10.0	--	--	--	--	--	54,750	68,950
2-10	10.00	.80	.784	20.0	--	--	--	--	--	48,700	61,350
2-15	14.97	1.19	.788	29.9	--	--	--	--	--	45,400	57,600
1-20	19.94	1.60	.796	39.9	--	--	--	--	--	41,400	52,000
2-25	24.94	1.98	.788	49.9	--	--	--	--	--	31,800	40,350
2-30	29.96	2.38	.788	59.9	--	--	--	--	--	22,850	29,000
1-40	39.96	3.20	.794	79.9	--	--	--	--	--	13,000	16,350
1-50	49.13	3.93	.794	98.3	--	--	--	--	--	8,600	10,850

[1]Computed from the length and weight of the specimen and the nominal specific gravity of the material.

[2]Specimens tested as columns with flat ends, K taken as 0.5.

[3]For the zee, e_1 = crookedness in plane parallel to the flanges; for other sections, e_1 = crookedness in plane of least stiffness; for the zee, e_2 = crookedness in plane parallel to the web.

TABLE II.- MECHANICAL PROPERTIES OF MATERIAL, INVESTIGATION OF COLUMN STRENGTH OF 14 S-T

Section	Dimensions (in.)	Tensile strength (psi)	Tensile yield strength (set = 0.2%) (psi)	Elongation in 2 in. (percent)	Type of tensile specimen[1]	Compressive yield strength (set = 0.2%) (psi)	Type of compressive specimen
Extruded bar	5/8 x $2\frac{1}{4}$	75,900	68,000	13.0	1/2 in. round	[2]66,900	Full section
Extruded zee	4 x 9/16	65,860	60,500	12.0	1/2 in. round	[2]59,800	Full section
Extruded bar	1 x 2	75,900	67,500	11.00	1/2 in. round	[2]65,600	Full section
Rolled and drawn rod	1 diameter	69,900	62,250	13.0	1/2 in. round	[2]64,500	Full section
Extruded angle	$2\frac{1}{2}$x$2\frac{1}{2}$x1/4	62,400	56,300	10.0	1/2 in. wide, full thickness	[3]57,100	5/8 in. wide, full thickness

[1]Specimens in accordance with ASTM Standard Methods of Tension Testing of Metallic Materials (E8-42).

[2]Determined from stress-strain curves shown in fig. 1.

[3]Determined from stress-strain curve shown in fig. 8.

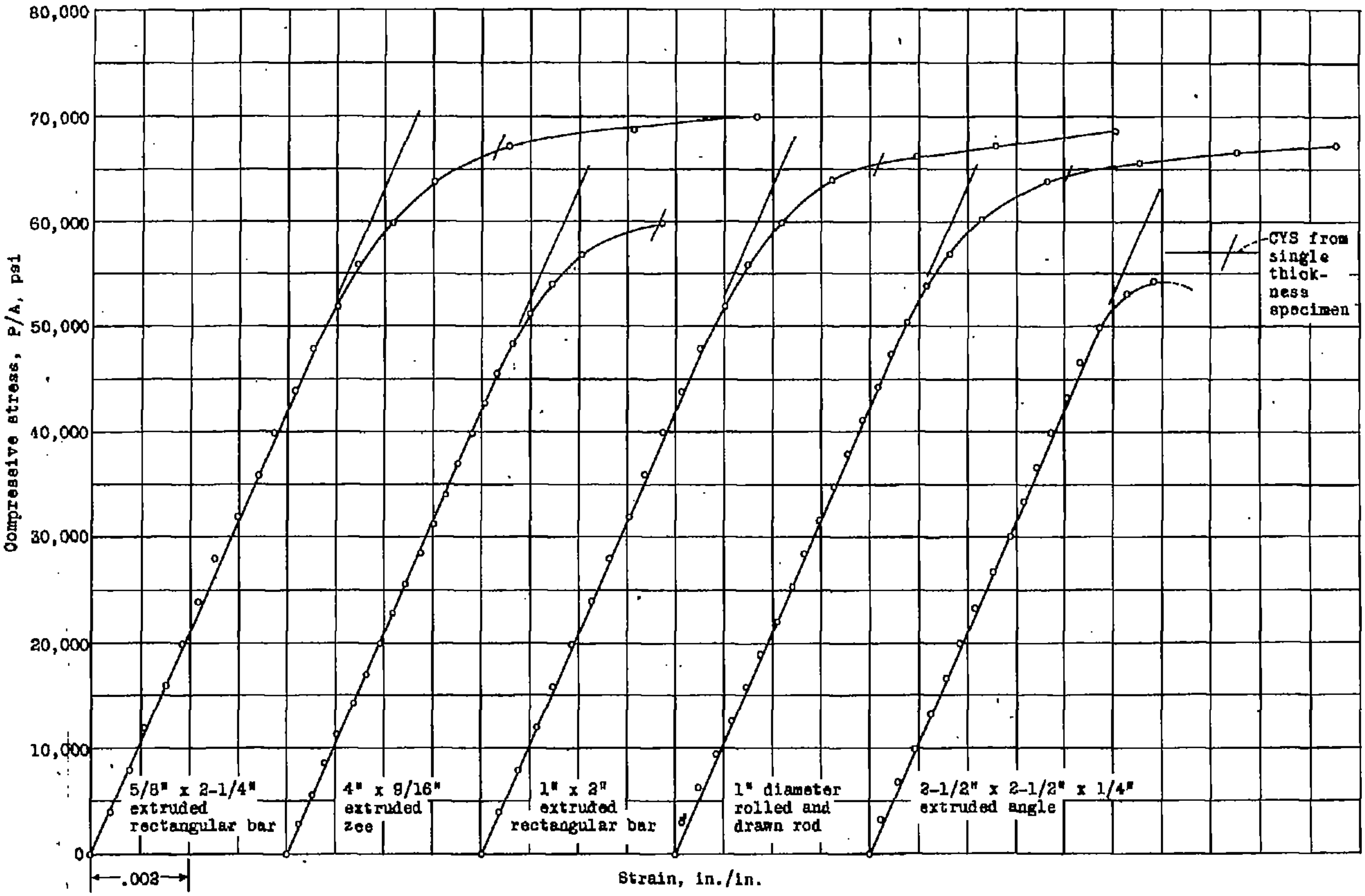

Figure 1.- Compressive stress-strain curves, 14S-T. Strains obtained from measured relative movement of the testing machine platens; corrected to give an initial slope of 10,600,000 psi.

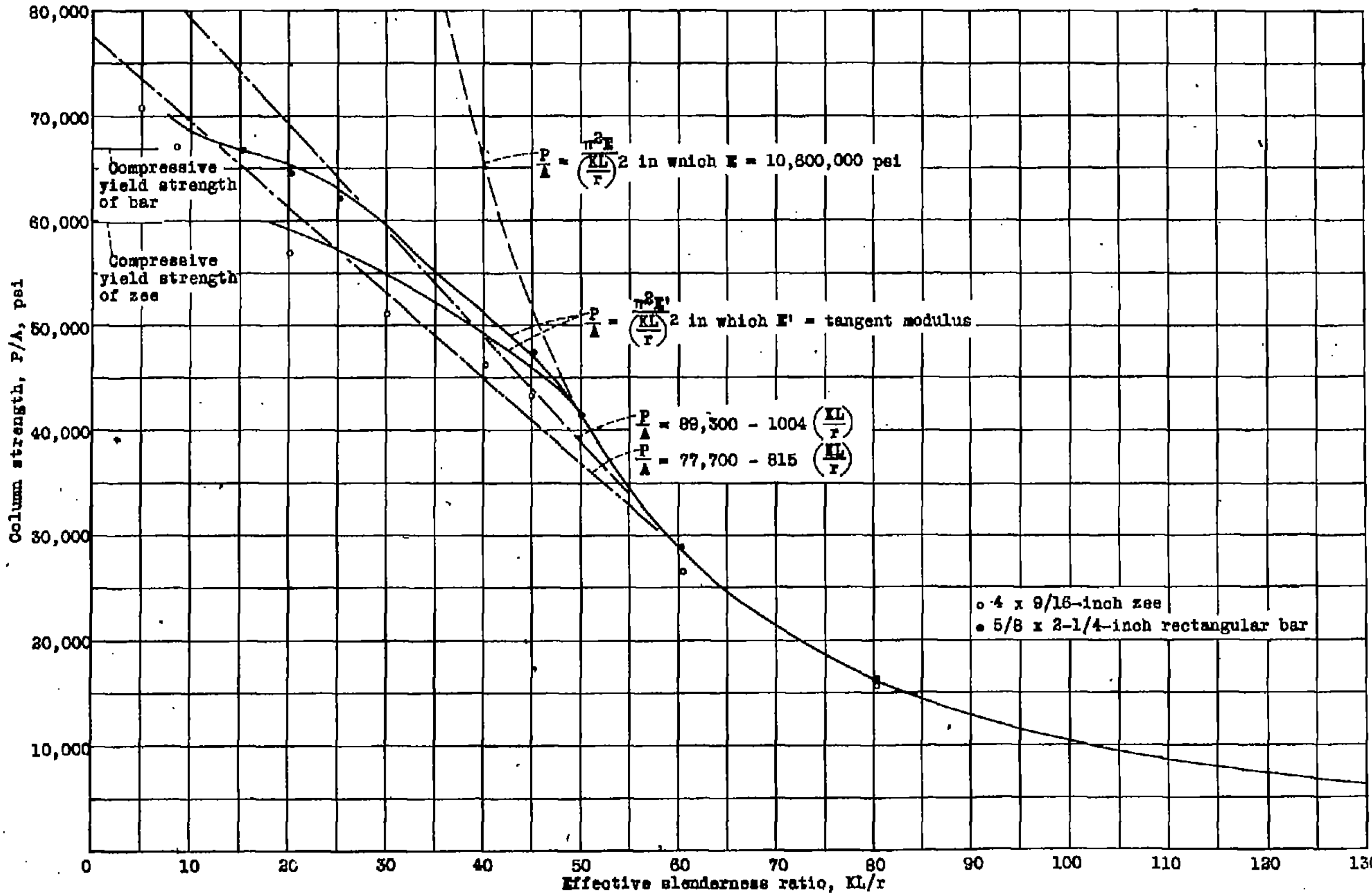

Figure 2.- Column strength of extruded 14S-T. Specimens tested as columns with flat ends, K taken as 0.50.

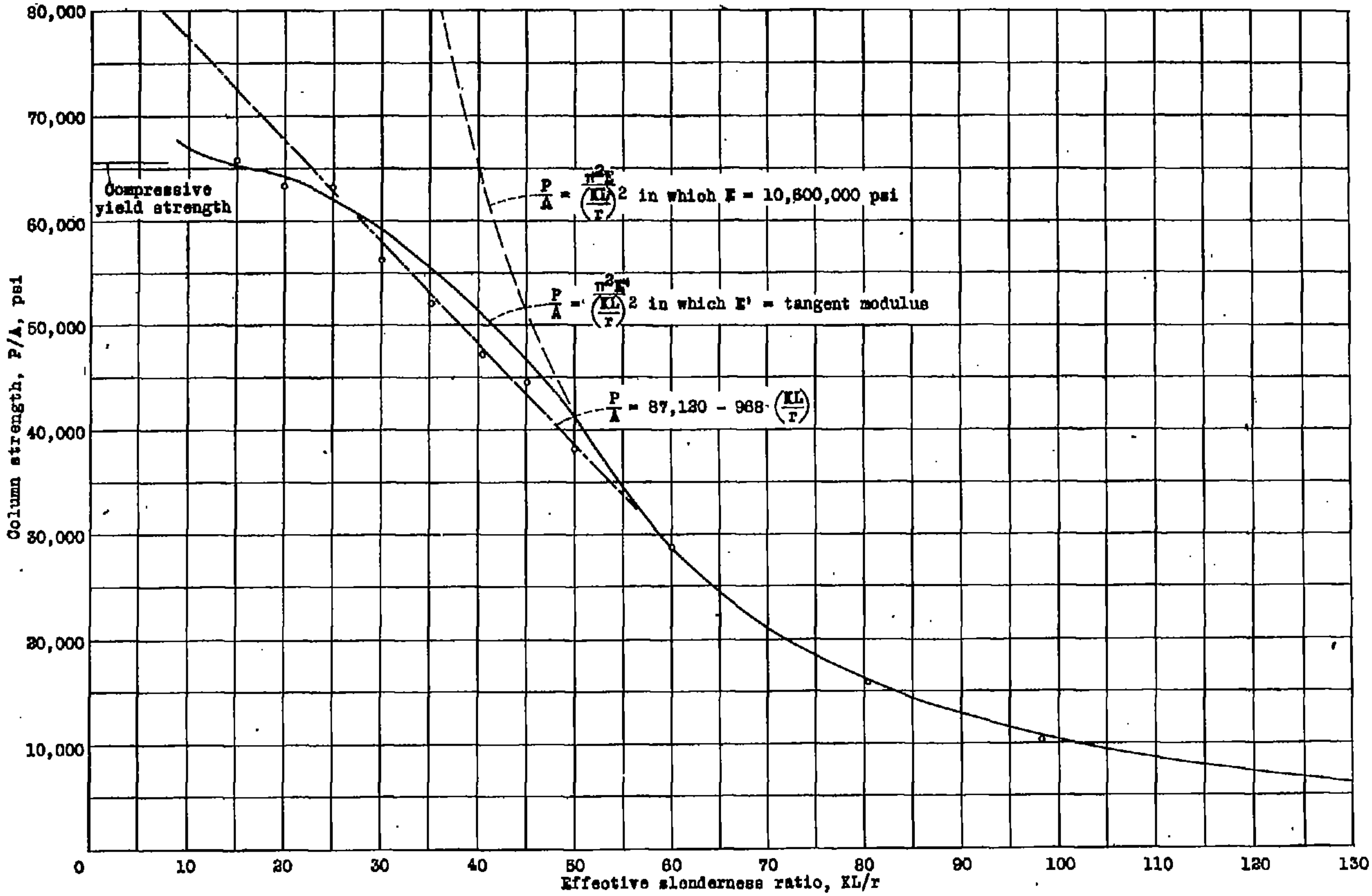

Figure 3.- Column strength of extruded 14S-T. 1 x 2-inch rectangular bar. Specimens tested as columns with flat ends, K taken as 0.50.

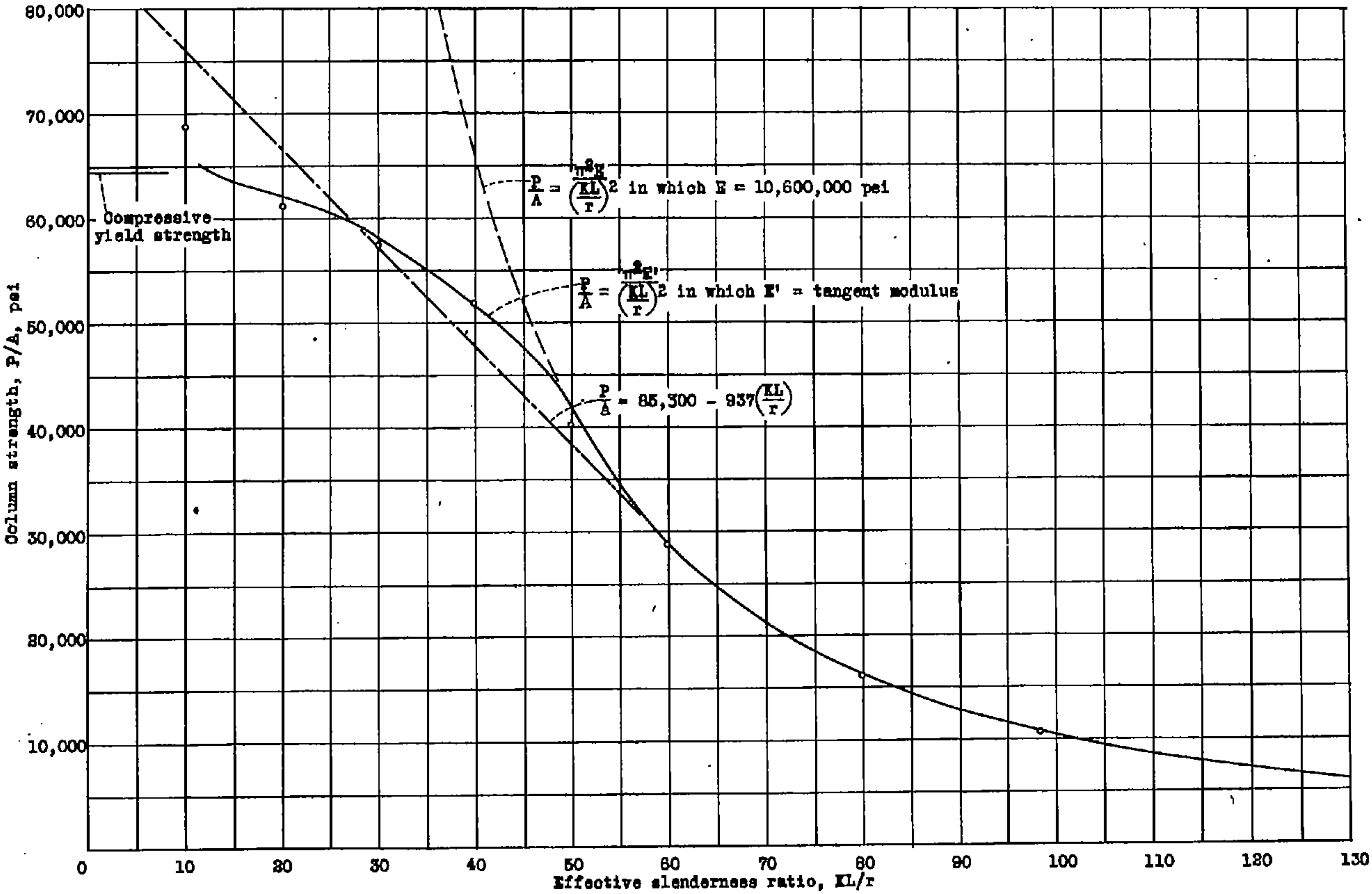

Figure 4.- Column strength of rolled and drawn 14S-T. 1-inch diameter round rod. Specimens tested as columns with flat ends, K taken as 0.50.

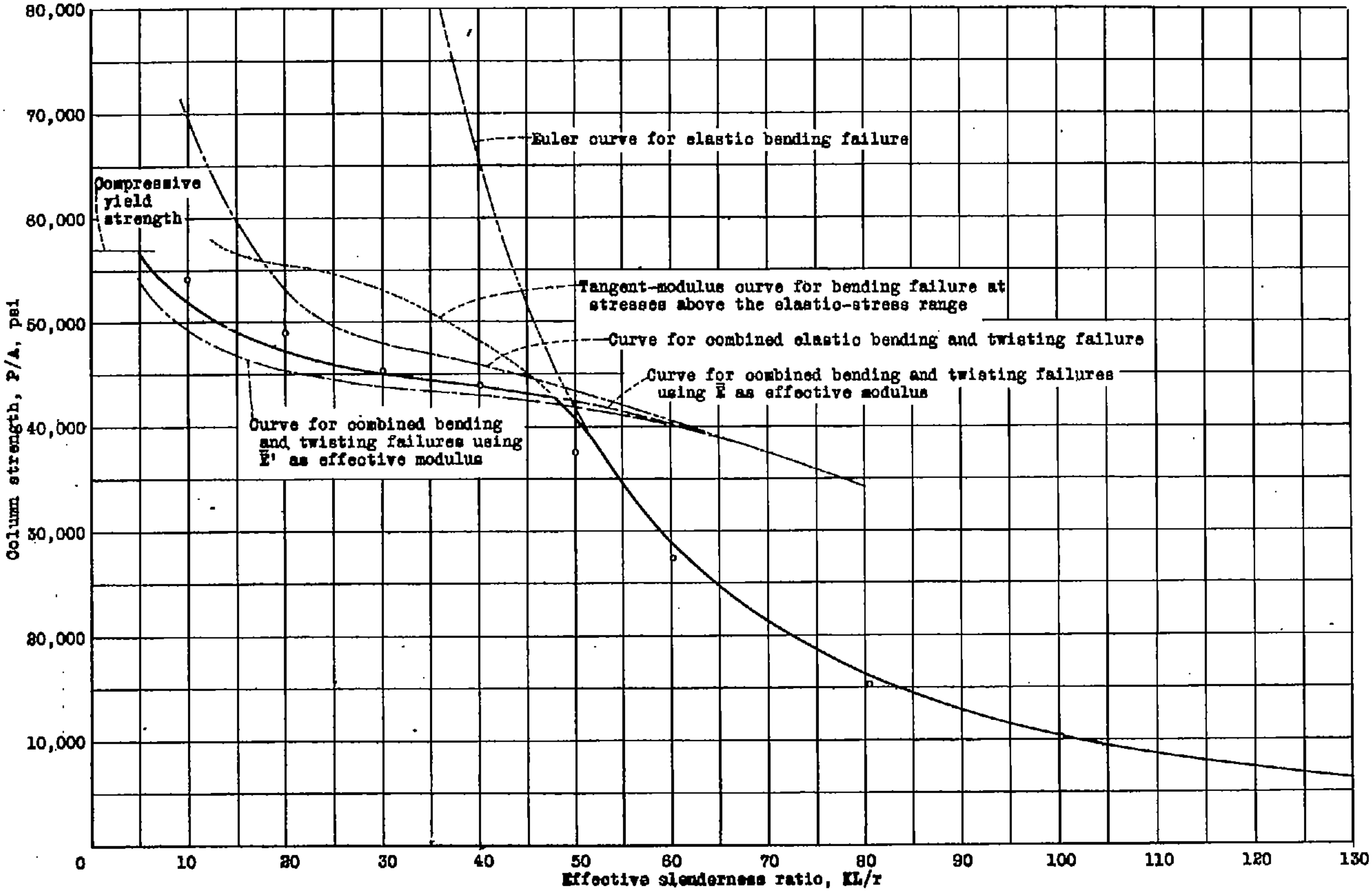

Figure 5.- Column strength of 2-1/2 x 2-1/2 x 1/4-inch angle, 14S-T. Specimens tested as columns with flat ends, K taken as 0.50.

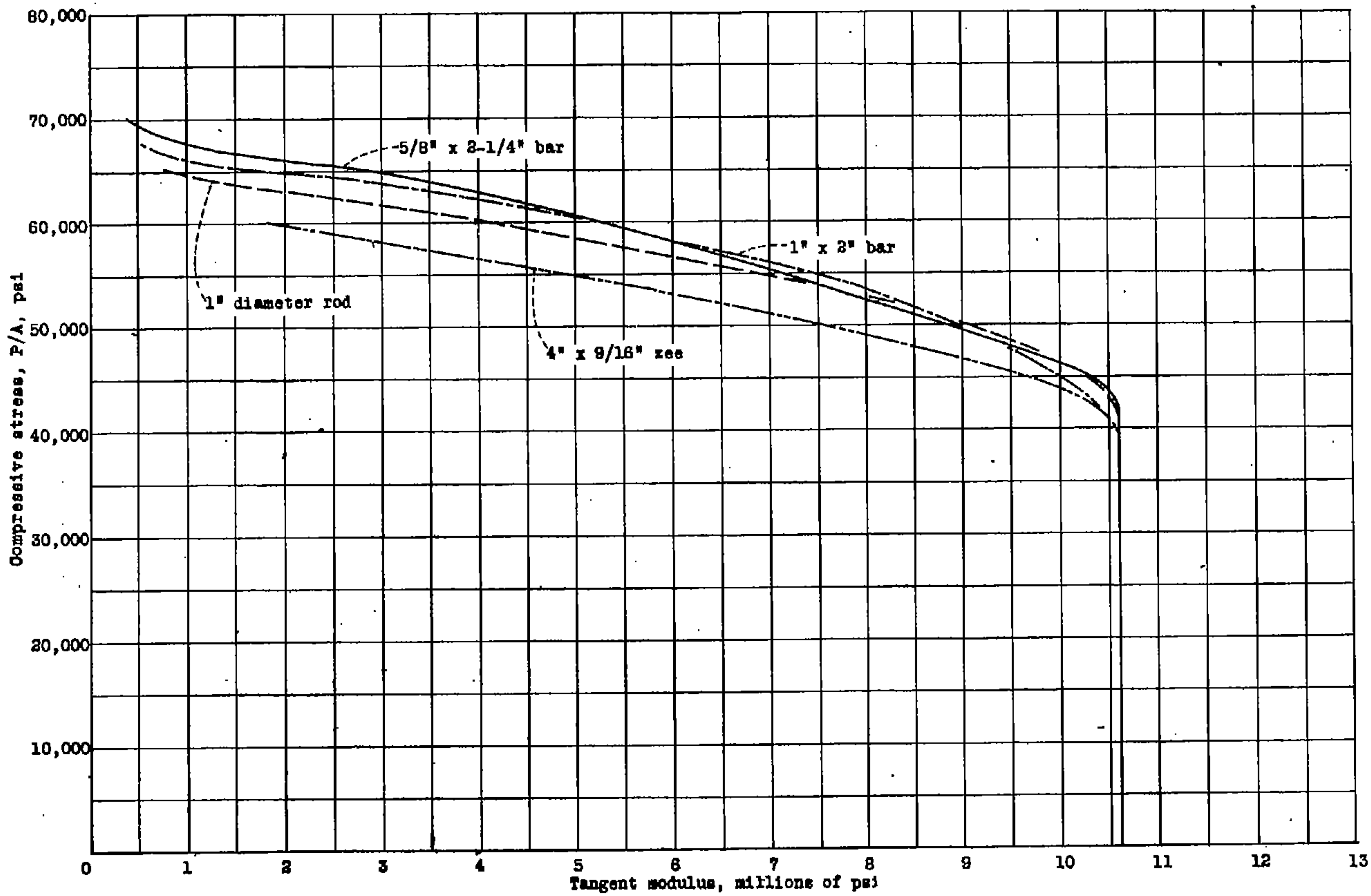

Figure 6.- Compressive stress-tangent modulus curves, 14S-T.

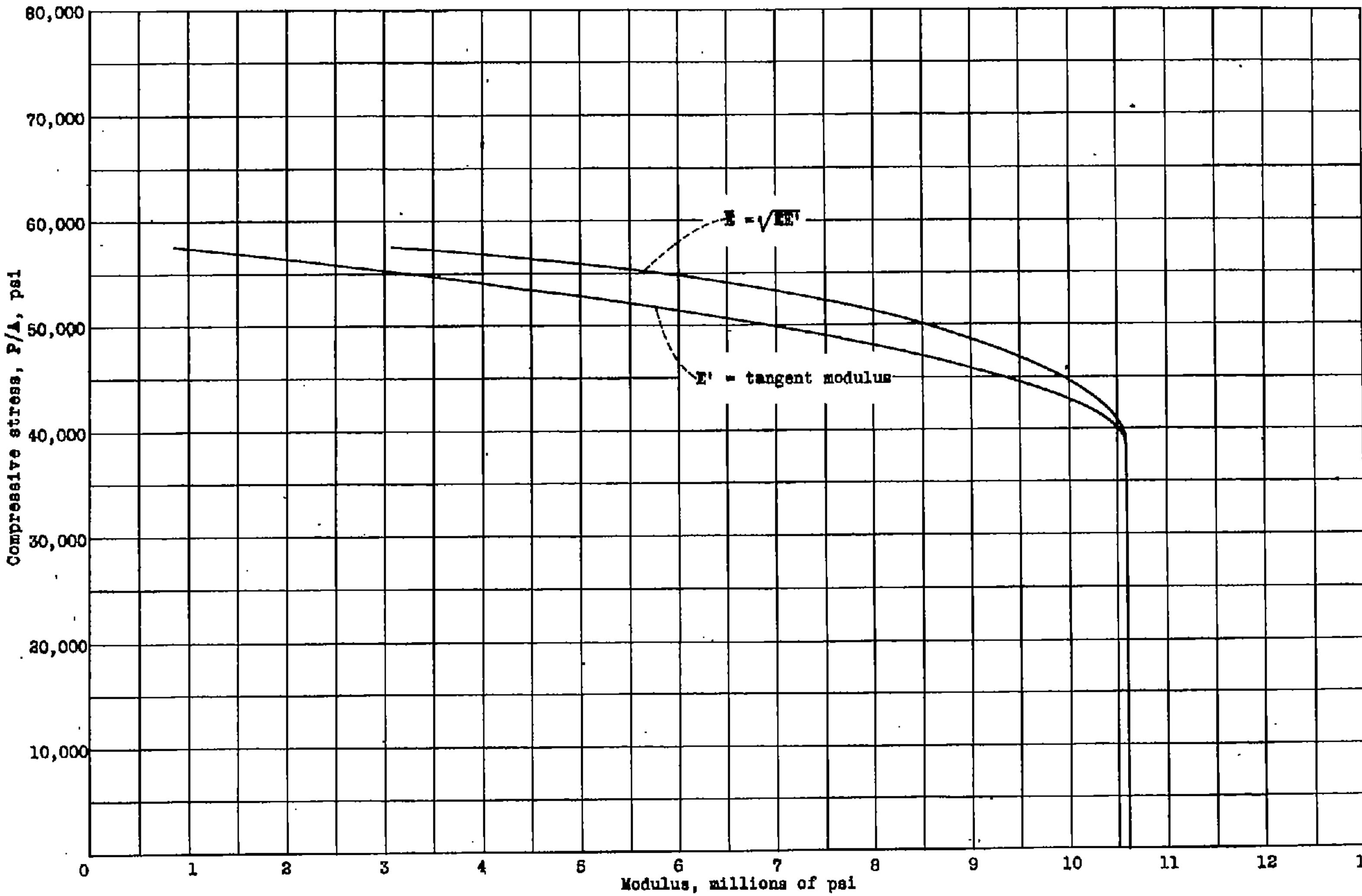

Figure 7.- Compressive stress-modulus curves. Relations derived from compressive stress-strain curve for 2-1/2 x 2-1/2 x 1/4-inch extruded 14S-T angle. Compressive specimen-5/8-inch wide × full thickness. Strains measured with Huggenberger tensometer.

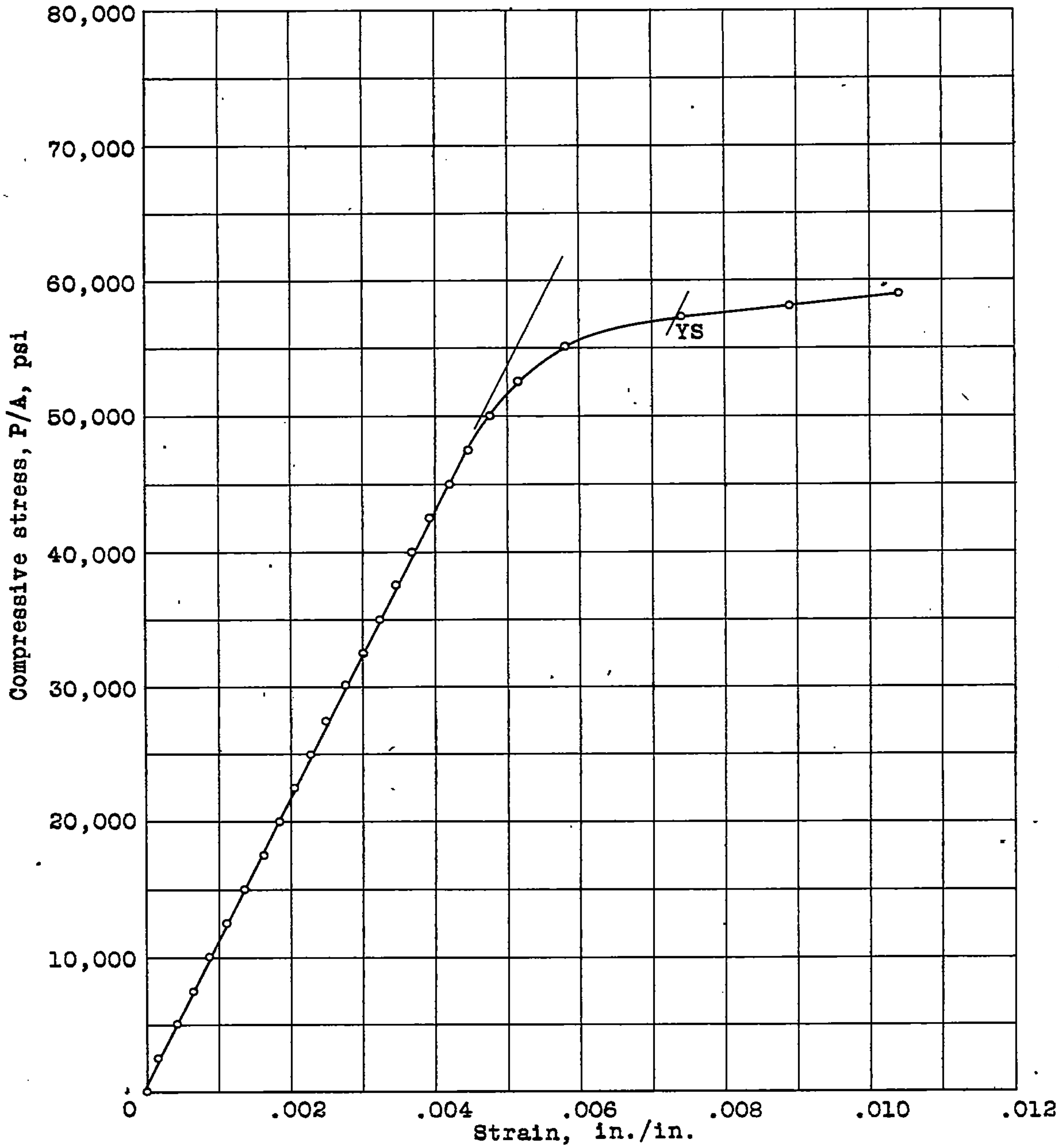

Figure 8.- Compressive stress-strain curve, 14S-T. 2-1/2 x 2-1/2 x 1/4-inch extruded angle. Compressive specimen 5/8-inch wide x full thickness. Strains measured with Huggenberger tensometers, gage length = 0.50-inch.

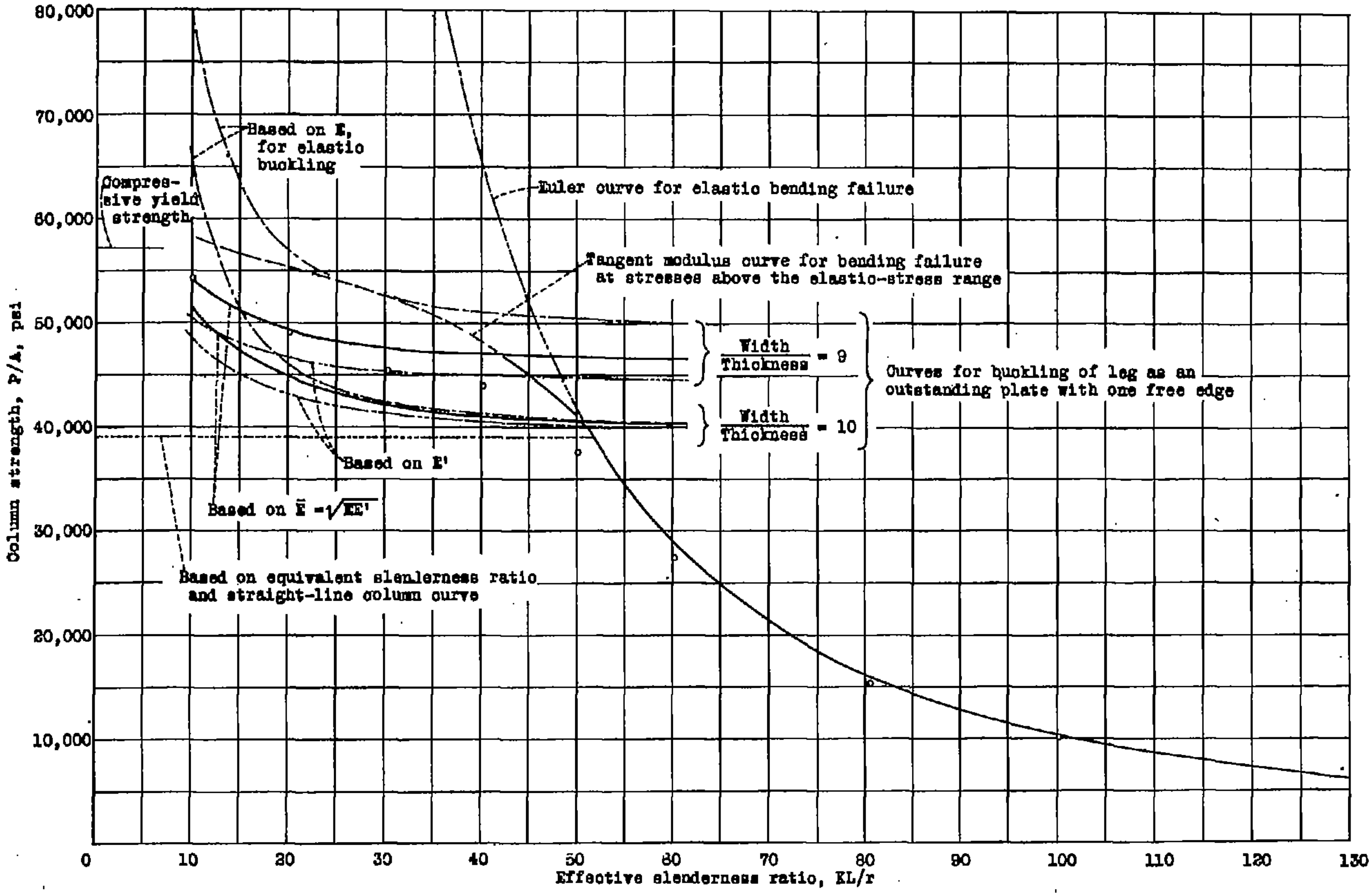

Figure 9.- Column strength of 2-1/2 x 2-1/2 x 1/4-inch angle, extruded 14S-T. Tested as a column with flat ends, K taken as 0.50.