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No. 824

COMBINED BEAM COLUMN STRESSES OF ALUMINUM-ALLOY CHANNEL SECTIONS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

The results of tests of 65 specimens of aluminum-alloy channel sections are graphed for stresses due to axial and bending loads as functions of the ratio of length of specimen to its radius of gyration, and from these data a suggested design chart is derived that is suitable for ready use.

INTRODUCTION

As far as is known, there is no completely satisfactory theory in existence for the combined loading of structural members common to aircraft construction; hence, for purposes of design, recourse must be had to tests for a given type of member made in the laboratory.

The tests reported in this paper were carried out in the Engineering laboratories of the University of Maryland under the supervision of Dr. John E. Younger, and the funds and specimens were supplied by the National Advisory Committee for Aeronautics.

SPECIMENS

The specimens tested were extruded 24 S-T aluminum-alloy channel sections 1.0 inch wide and 0.055 inch thick with the legs, or flanges, varying from approximately 0.300 inch to 1.000 inch in depth. (See fig. 1.)

The specimens were produced by the Aluminum Company of America, according to the following specifications:

1. The material shall be the Aluminum Company of America 24S-T aluminum alloy and shall conform in all respects to Navy Aeronautical specification 46A9 (INT) of July 1, 1937, except that:

2. To the chemical composition in paragraph E-1 shall be added "chromium (maximum 0.25%)."

3. The words "excess of 0.00%, in the note in paragraph E-1 shall be changed to read "excess of 0.03%."

4. The material shall have the following minimum physical properties:

Tensile strength: 57,000 pounds per square inch,

Yield strength: 42,000 pounds per square inch,

Elongation: 12 percent.

APPARATUS AND TESTS

Construction of Testing Jig

In figure 2 is shown a photograph of the beam-column testing jig designed by the author and used for these tests. The column load is applied by means of a hydraulic jack and a hand pump, the jack being designed without packing for greater accuracy. The pressure is measured by means of a calibrated Bourdon-type pressure gage. The load is applied through horizontal knife edges to V-grooves in specially made end plates. The specimen is held so that its x-x centroidal axis will coincide with the load as applied through the knife edges. Holes are drilled at suitable intervals in the top of the supporting I-beam so that both the end-support knife edge and the load-applying knife edge can be adjusted to suit the lengths of the specimens tested.

The side loading is applied through two knife edges located at third points along the length of the specimen and supporting, by steel straps, a platform and harness arrangement so designed that the loads upon the platform will be evenly distributed between the two knife edges. The loading for these tests was accomplished by means of a number of 5-pound calibrated lead weights, as well as several 25-pound and 50-pound cast-iron weights, which were also calibrated against standard weights.

Calibration of the Machine

The two Bourdon-type pressure gages used to measure the column load were calibrated by means of a dead weight gage tester and calibration curves were prepared to use in correcting the recorded data.

The 5-pound lead weights used to apply the bending load were calibrated by means of an oil-damped balance to within 0.01 pound of 5 pounds. The harness and the knife edges were weighed separately.

Preparation of Specimens

After the lengths of the specimens were determined upon the basis of the ratios of lengths to radii of gyration, they were cut and the ends were accurately milled to size.

METHOD OF TESTING SPECIMENS

1. The specimen was placed flanges (or legs) down upon the two knife edges.

2. The adjustable knife edges were raised so that the neutral axis of the specimen was directly in line with the two horizontal knife edges.

3. The tailpiece and the hydraulic jack were then moved to the correct position for the length of the specimen and bolted securely to the supporting I-beam.

4. The end plates were placed over the ends of the specimen and a small amount of end load was applied by means of the hand pump.

5. The harness straps were then placed at predetermined loading points upon the specimen, the platform being supported by the harness straps.

6. A known side load was then produced by placing calibrated weights upon the platform, the platform and harness weights being known.

7. The specimen was then ready for testing, and the test was carried out by applying end load with the hydraulic jack until the hand of the pressure gage showed a drop of pressure, and no amount of increased pressure would cause a higher pressure reading. This point was recorded as the point of ultimate strength.

DISCUSSION OF RESULTS

A thin-wall, torsionally unstable, structural member of the type used in aircraft construction, of which the channel sections tested are a special case, can fail by either bending, twisting, local wrinkling, or combinations of these forms. The first two forms are classified "primary failures" in reference 1. The theoretical work was validated for practical purposes in reference 2. No assumption was made as to the type of failure that would occur, but the lengths of specimens tested were such that failure occurred through bending or twisting. The equation for primary failure of axially loaded colums, as given in reference 1, is:

$$f_{cr} = \frac{GJ}{I_p} + \frac{C_{BT}}{I_p}\frac{\pi^2 E}{L_o^2}$$

where E tension-compression modulus of elasticity

G shear modulus of elasticity $\left(\frac{E}{2(1 + \mu^2)}\right)$

μ Poisson's ratio for material

I_p polar moment of inertia of cross section about axis of rotation

L_o effective length of column

J torsion constant for section. The product GJ in torsion problems is analogous to product EI in bending problems.

C_{BT} torsion-bending constant, dependent upon location of axis of rotation and dimension of cross section

When the column is attached to a skin, as in a sheet-stringer combination, Lundquist (reference 1) adds the term:

$$\Delta f_{cr} = \frac{K_1 E t_s^3}{6(1 - \mu^2) d I_p} \frac{L^2}{n^2 \pi^2}$$

since the restraining effect of the skin is to increase the critical stress. Thus the critical stress becomes:

$$f_{cr} = \frac{\bar{G}J}{I_p} + \frac{C_{BT}}{I_p} \frac{n^2 \pi^2 \bar{E}}{L^2} + \frac{K_1 E t_s^3}{6(1 - \mu^2) d I_p} \frac{L^2}{n^2 \pi^2}$$

where $n = 1, 2, 3,$ etc., the number of half sine waves in a length L and a trial solution must be made to find which value gives the lowest critical stress. The effect of the side loading in the tests under discussion is to add a restraining term somewhat analogous to the foregoing, which increases the critical column stress, and also another term, which increases the tension stress concentration along the outer flanges of the channel and thus decreases the critical column stress. The exact form of these terms is omitted as beyond the scope of this report.

The tests in this series were extended so as to include both the column and the beam axis. Pure torsion failures of a definite nature occurred only with the A sections with a L/ρ ratio greater than 50, and under axial load only; but several of the A sections with side loading that was relatively small exhibited tendencies toward torsional failure as well as some of the B sections in the same range and a few of the C sections. None of the shallower sections exhibited clearly discernible torsional tendencies, failing as did most of the specimens tested in tension of the outer flanges.

Although the various sections tested are similar only in a general way, the custom of plotting the results of the same L/ρ ratio in the same curve has been justified often enough in this type of work to become standard procedure. The points for each section, however, are differentiated by different symbols and also given in table I.

Figures 3 through 8 show the test data plotted as functions of primary bending stress f_b (tension) and primary axial stress f_c (compression) for L/ρ ratios of 150, 130, 110, 90, 70, and 50. For each L/ρ ratio an average curve is drawn and the results of the six curves with all values below the test data are shown in figure 9 as a recommended design curve. From the curves of figures 3 to 8 the design charts of figures 10 and 11 are constructed, showing the relationship of R_c to R_b; R_c is the ratio of column stress at failure to the ultimate column stress of the member and R_b is the ratio of the primary bending stress at failure to the ultimate bending stress of the member. (See reference 4.) This chart gives the combined stress allowable for any combination of primary axial stress and primary bending stress for bending and torsional failure, respectively.

It is seen from the plotted data (figs. 3 to 8) that the curves split as they near the column axis. The upper branches of the curves shown correspond to the curves of reference 3 upon this same topic. The upper branches are for the specimens that failed in both primary and secondary pure bending. The lower branches are for those specimens that were to some degree influenced in their failure by the inherent torsional instability of the specimens, as described in the first part of this discussion. This result is borne out by the fact that all the failures of the top group were in pure bending; those of the lower branch contain some pure torsional failures, notably the A sections for L/ρ ratios of 70, 90, 110, and 130; and quite a few of the other specimens in this group exhibited tendencies toward this type of failure, although they ultimately failed in bending. If the upper branches of the curves are used for design, the results will correspond to the curves of reference 3 for the 2- by 0.1-inch thick channels tested under similar conditions. In this report, however, it was decided to use the lower branches of the curves as being the most conservative because there is at this time no clear-cut method of determining which type of failure will govern, the results probably depending upon initial eccentricities of loading. As far as is known by the author, only the right half of the design curves are suitable for other sizes of aluminum-alloy channel section, unless the section is known to be constrained to fail in bending only.

Considering the bending-failure curves obtained in reference 3 as well as those of this report, it is found that, whereas the equation

$$R_c + R_b = 1.0 \qquad (1)$$

holds as the upper limit for the interaction curve, the values drop as low as:

$$R_c^{0.5} + R_b = 1.0 \tag{2}$$

and it is recommended that equation (2) be used where conditions are such that the channels can be assumed constrained to fail in bending, as when used in certain types of sheet-stiffener combinations.

Where the foregoing assumption cannot be made and the member fails torsionally or with torsional effect, the relation has been found to be:

$$R_c^{1.5} + R_b = 1.0 \tag{3}$$

shown in figure 11, and recommended for use, although the values may run as high as the dotted curve shown. It is interesting to note that the compressive-stress ratio may run as high as 111 percent at a bending stress ratio of around 20 percent. This condition is caused by the stabilizing effect of the side load upon the critical stress (compressive) for torsional failure as mentioned earlier in this discussion. The sheet of a sheet-stiffener combination would give the same effect, but the exact magnitude of the restraint is beyond the scope of this report.

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Experimental Station,
College Park, Md., July 1941.

REFERENCES

1. Lundquist, Eugene E., and Fligg, Claude M.: A Theory for Primary Failure of Straight Centrally Loaded Columns. Rep. No. 582, NACA, 1937.

2. Niles, Alfred S.: Experimental Study of Torsional Column Failure. T.N. No. 733, NACA, 1939.

3. Gottlieb, R., Thompson, T. M., and Witt, E. C.: Combined Beam-Column Stresses of Aluminum-Alloy Channel Sections. T.N. No. 726, NACA, 1939.

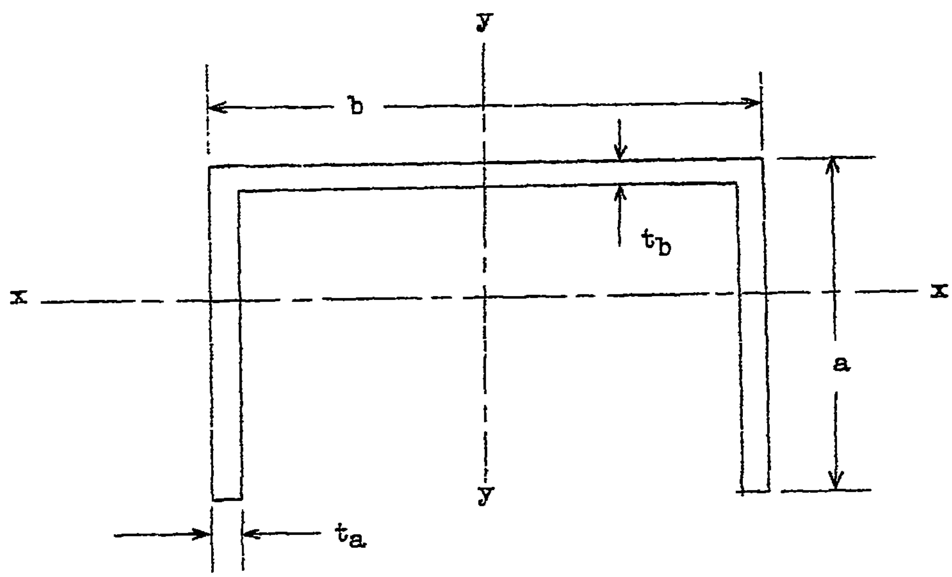
4. Anon.: Strength of Aircraft Elements - ANC-5. Army-Navy-Civil Committee on Aircraft Requirements. U.S. Govt. Printing Office, Oct. 1940.

TABLE I.- EXPERIMENTAL DATA FROM BEAM-COLUMN TESTS OF 24S-T ALUMINUM-ALLOY CHANNEL SECTIONS

Section	L/ρ	Column stress, f_c (lb/sq in.)	Primary bending stress, f_b (lb/sq in.)
A	150	1,600	0
A	150	0	72,800
E	150	1,810	0
E	150	0	64,900
E	150	2,400	28,200
E	150	1,145	42,100
E	150	1,900	38,800
C	150	2,840	12,000
C	150	2,840	0
C	150	1,290	32,000
A	130	4,890	0
A	130	0	82,300
A	130	2,720	42,700
A	130	6,100	10,800
C	130	4,320	27,800
A	110	5,500	0
A	110	8,750	10,300
A	110	6,250	22,800
A	110	4,500	40,100
A	110	0	79,800
E	110	9,250	0
E	110	0	74,900
E	110	3,430	41,300
C	110	5,800	16,200
C	110	3,950	38,200
C	110	1,750	52,900
B	90	12,250	0
B	90	12,500	0
B	90	10,000	15,600
B	90	8,750	21,300
A	90	6,880	0
A	90	6,360	17,400
A	90	0	84,500
A	90	4,750	38,100
E	90	13,400	0
E	90	0	84,500
C	90	5,875	0
C	90	7,700	20,600
C	90	6,050	39,900
B	70	10,800	11,700

TABLE I.- (Continued)

Section	L/ρ	Column stress, f_c (lb/sq in.)	Primary bending stress, f_b (lb/sq in.)
A	70	8,930	0
A	70	0	88,200
A	70	8,970	24,000
A	70	9,900	8,750
D	70	9,910	18,800
D	70	4,200	53,800
D	70	10,300	0
E	70	21,400	0
E	70	10,600	9,900
E	70	18,000	9,900
E	70	0	88,500
C	70	12,800	10,300
C	70	10,390	28,900
C	70	7,650	42,900
B	50	15,600	0
B	50	14,000	8,350
A	50	32,500	0
A	50	5,850	69,500
A	50	0	88,600
A	50	12,800	25,800
A	50	14,000	14,600
D	50	10,050	37,900
D	50	12,000	21,400
D	50	14,400	5,000



Section	A	B	C	D	E
a, in.	1.000	0.900	0.700	0.550	0.300
b, 1.000 inch; t_a, 0.055 inch; t_b, 0.055					
All dimensions ±0.0015 inch					

Figure 1.- Designation of sections.

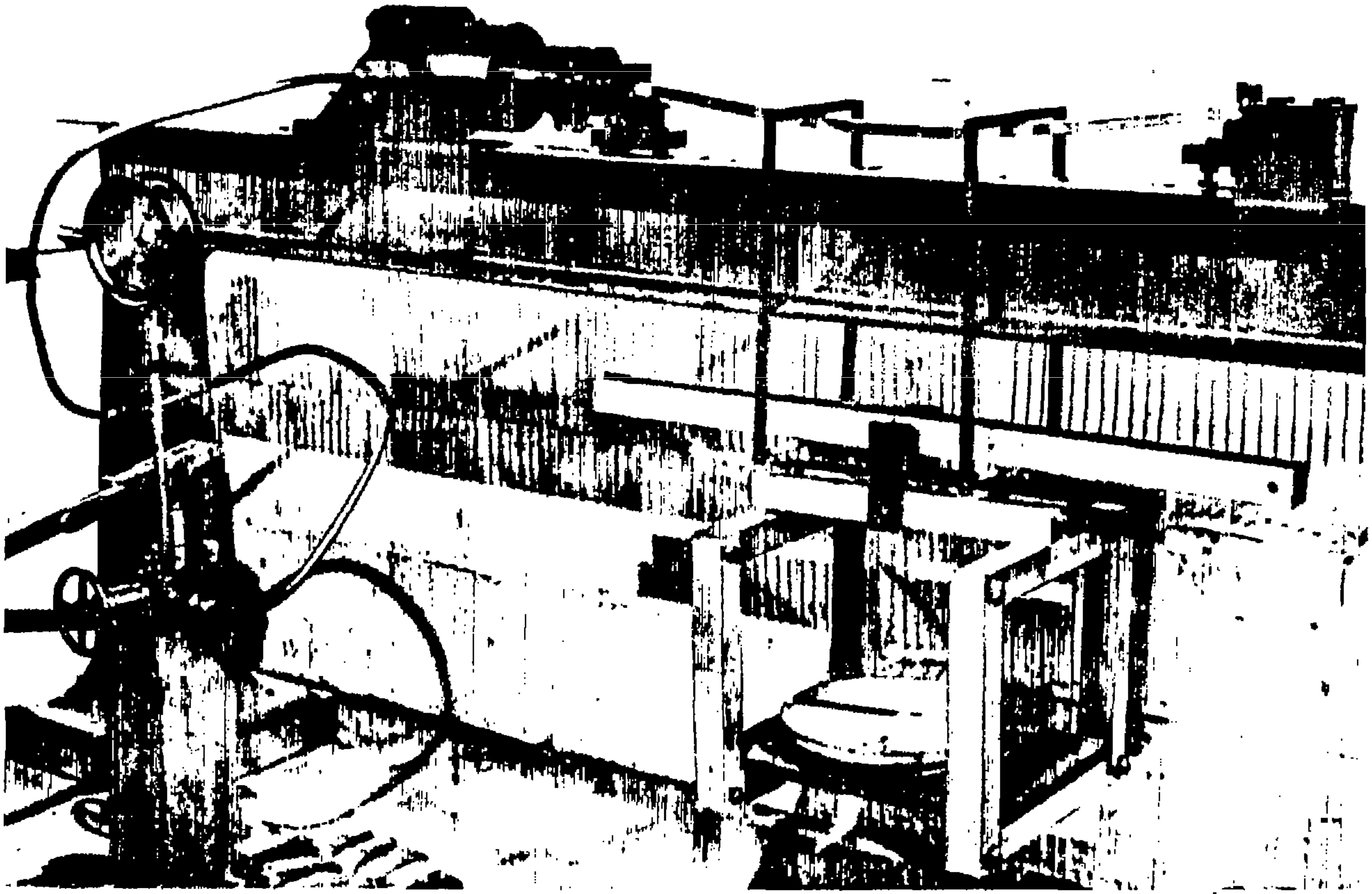


Figure 2.- Beam-column testing machine, showing one of the longest specimens tested ($L/\rho = 150$) failing by bending.

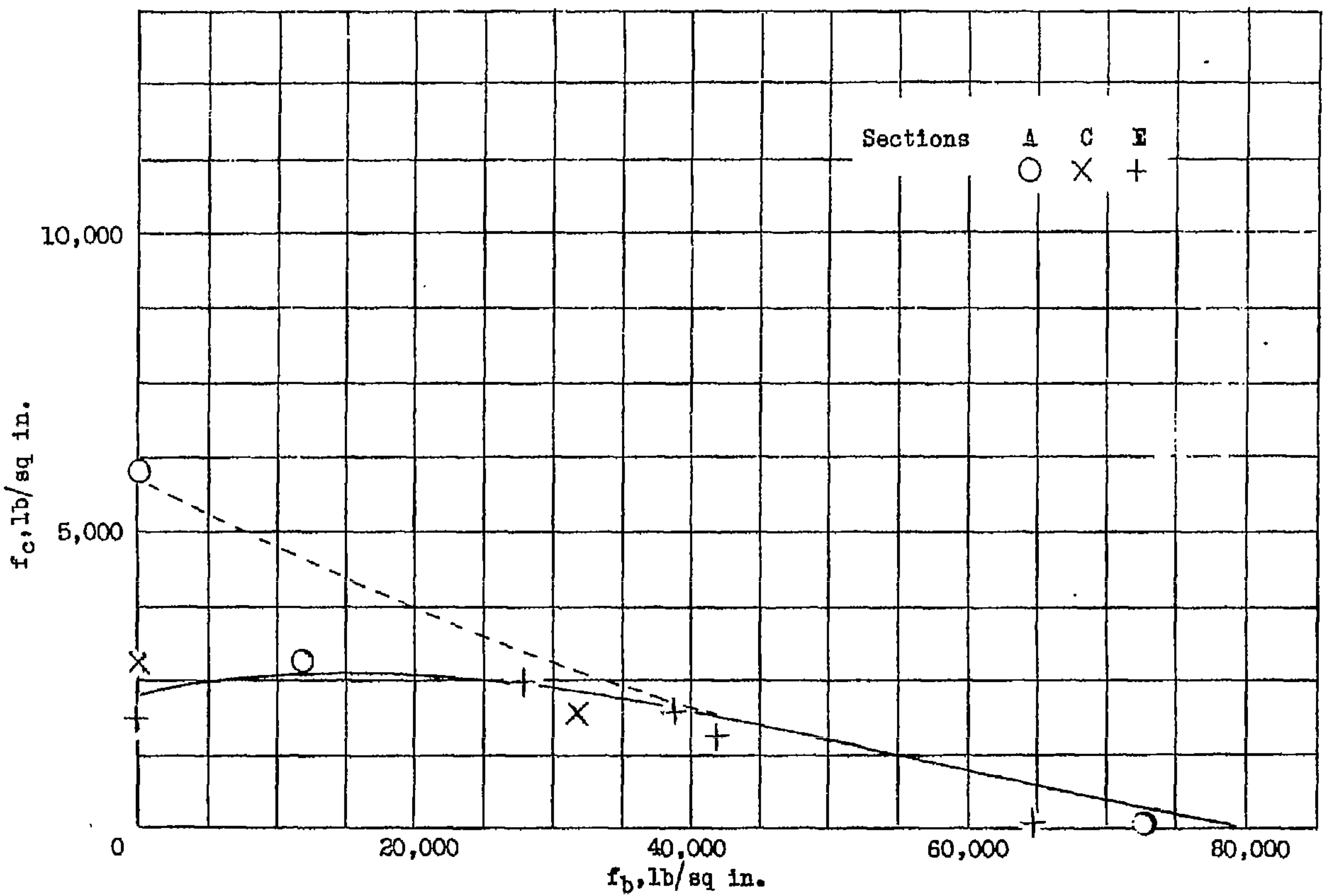


Figure 3.- Beam column tests of 24S-T aluminum-alloy channel sections, $L/\rho = 150$.

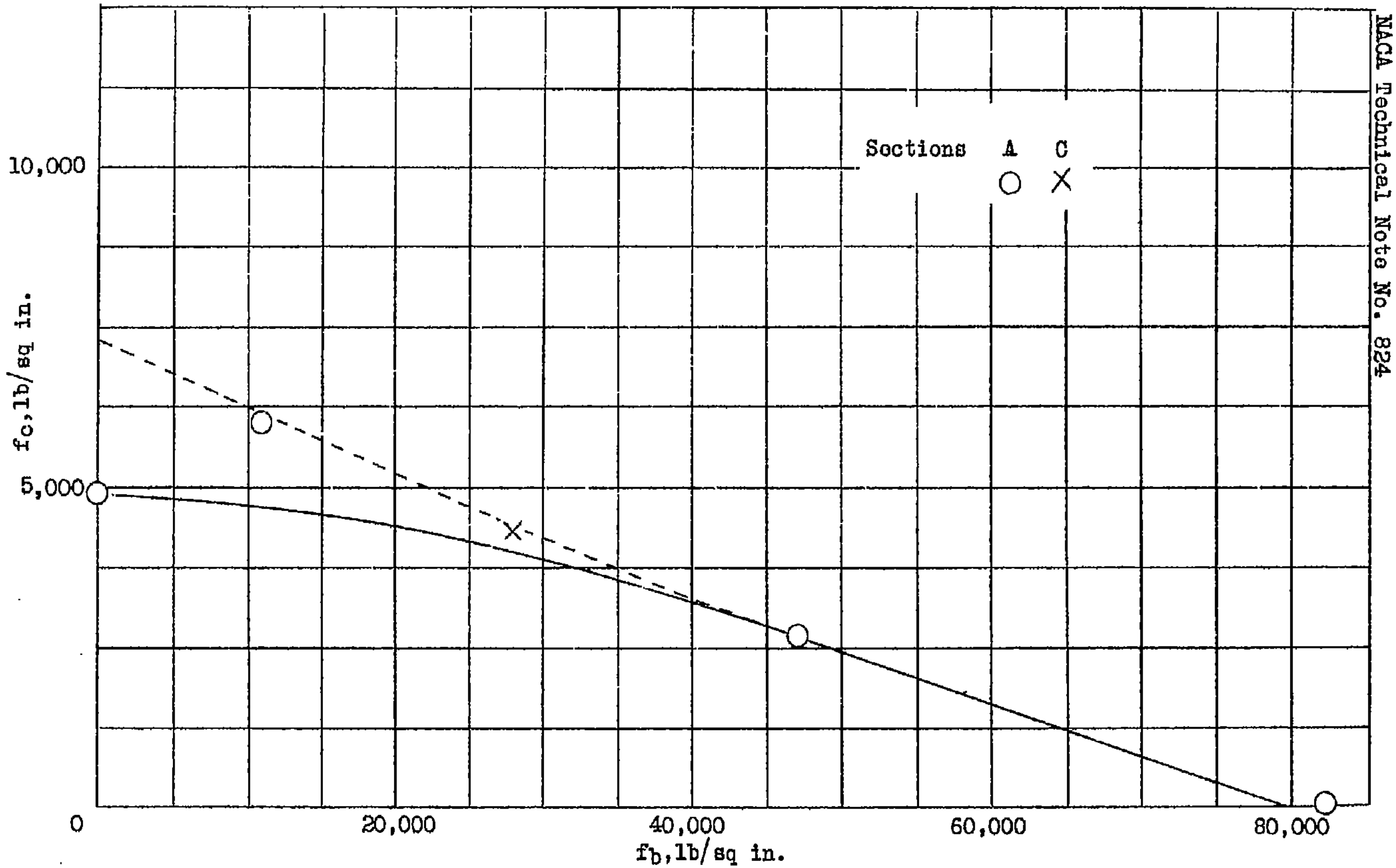


Figure 4.- Beam column tests of 24S-T aluminum-alloy channel sections, $L/\rho = 130$.

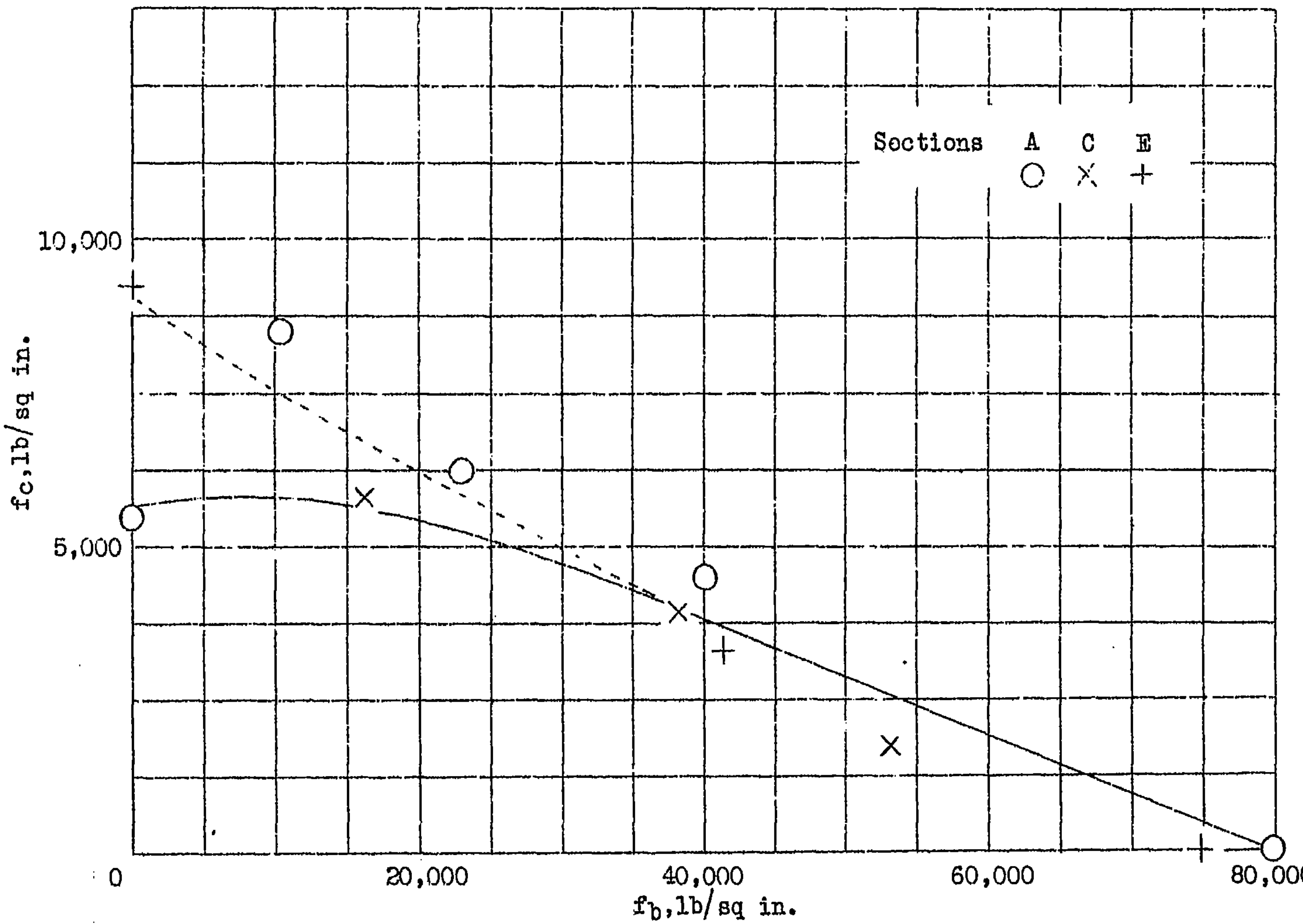


Figure 5.- Beam column tests of 24S-T aluminum-alloy channel sections, L/ρ = 110

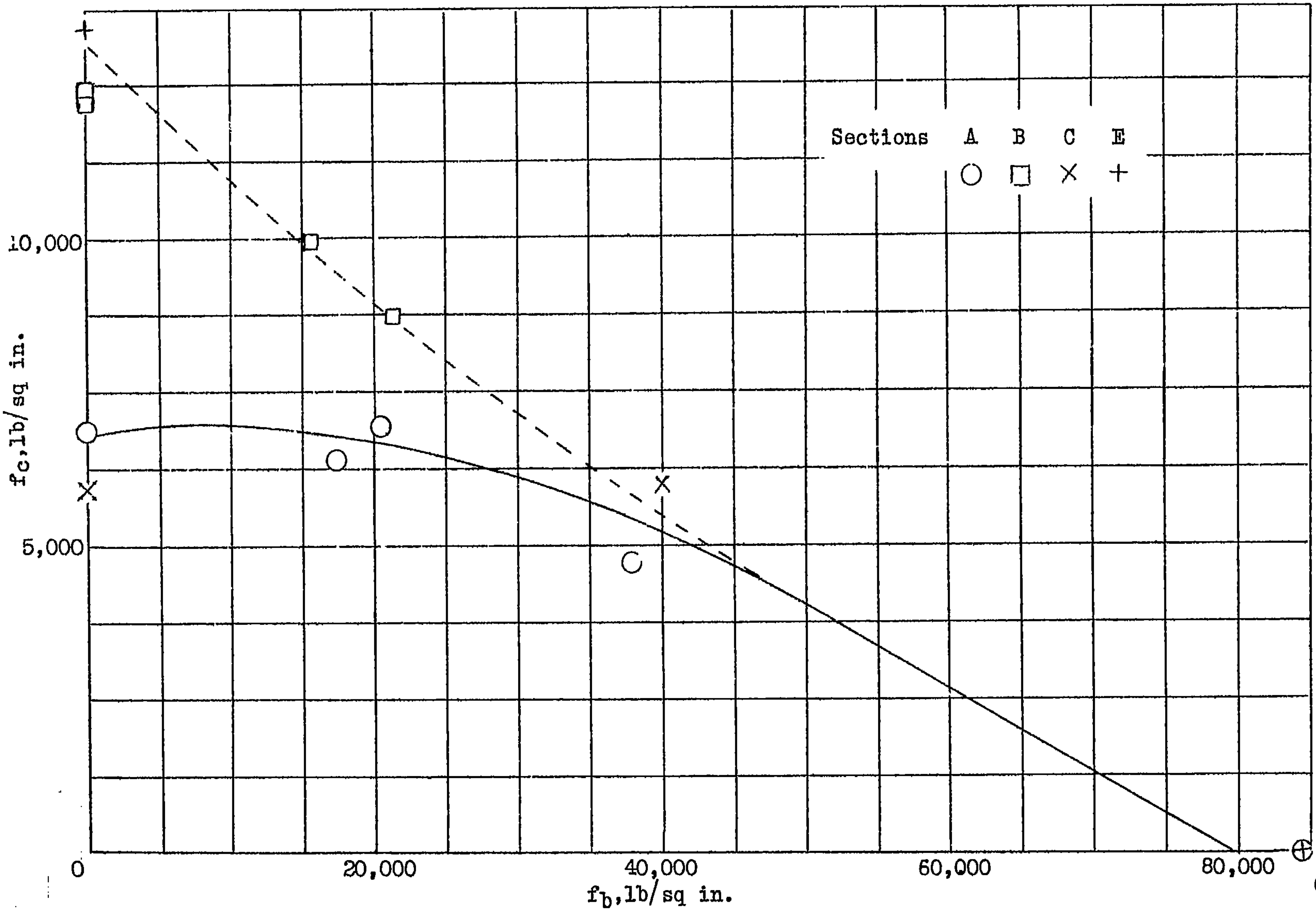


Figure 6.- Beam column tests of 24S-T aluminum-alloy channel sections, L/ρ = 90.

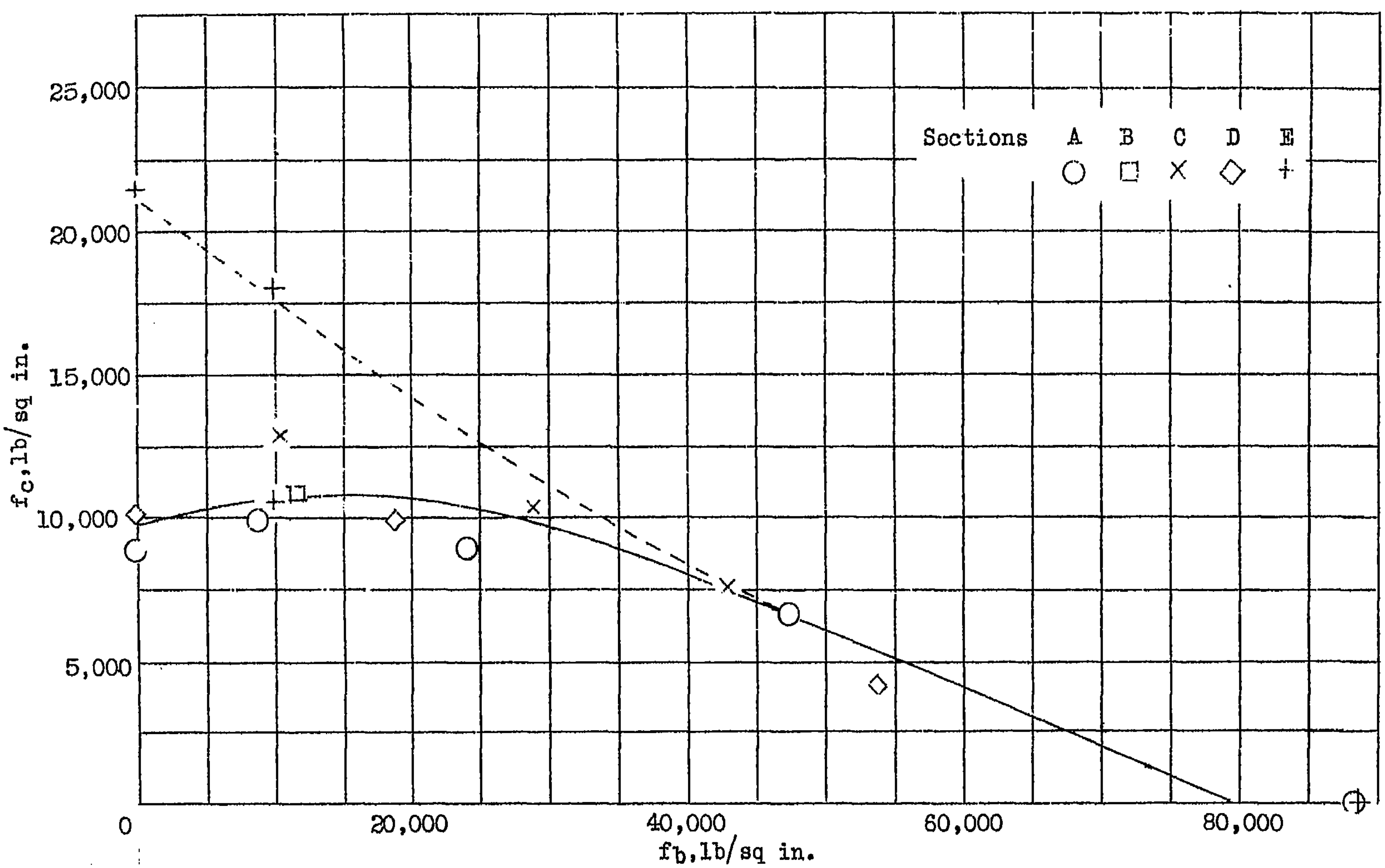


Figure 7.- Beam column tests of 24S-T aluminum-alloy channel sections, $L/\rho = 70$.

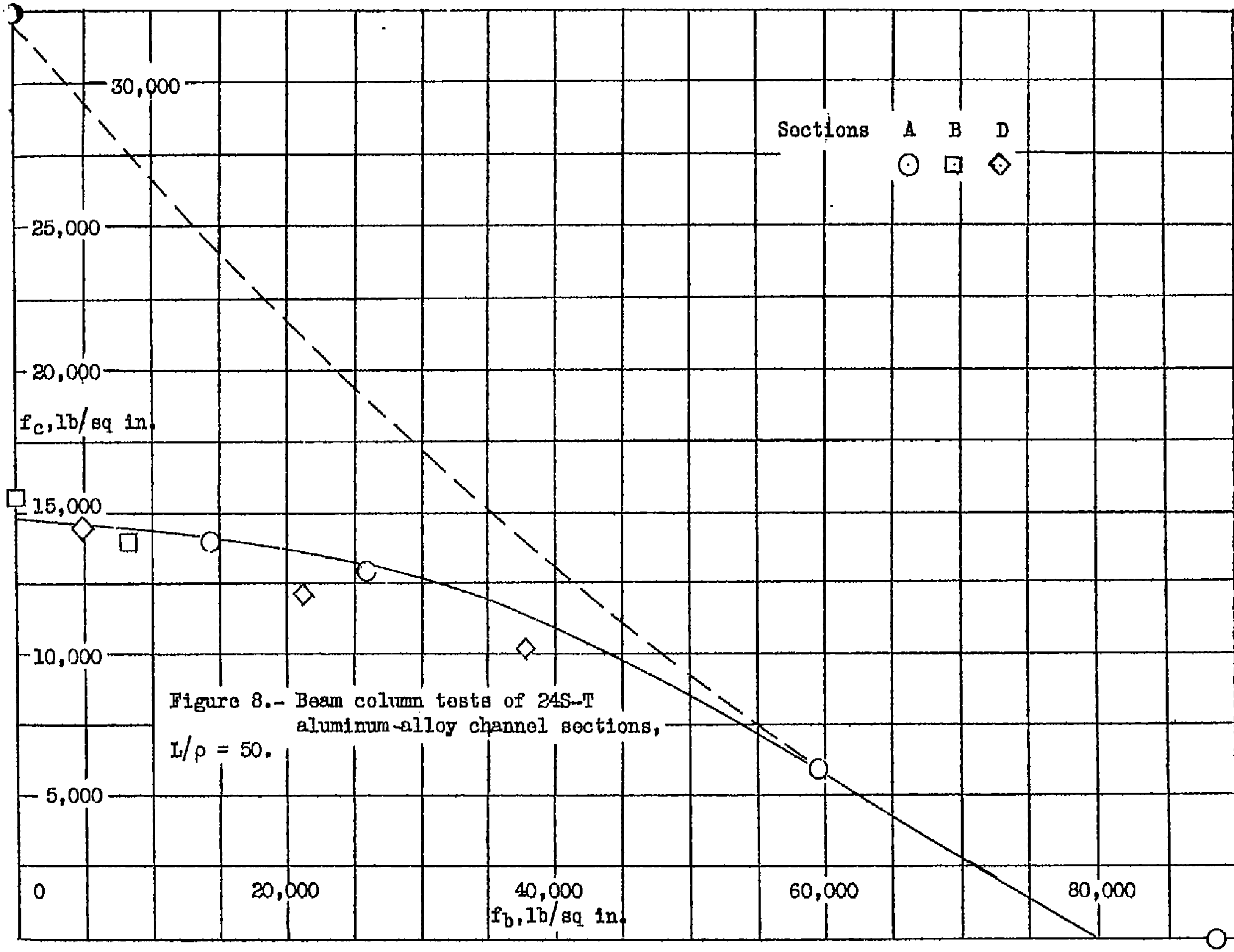


Figure 8.- Beam column tests of 24S-T aluminum-alloy channel sections, $L/\rho = 50$.

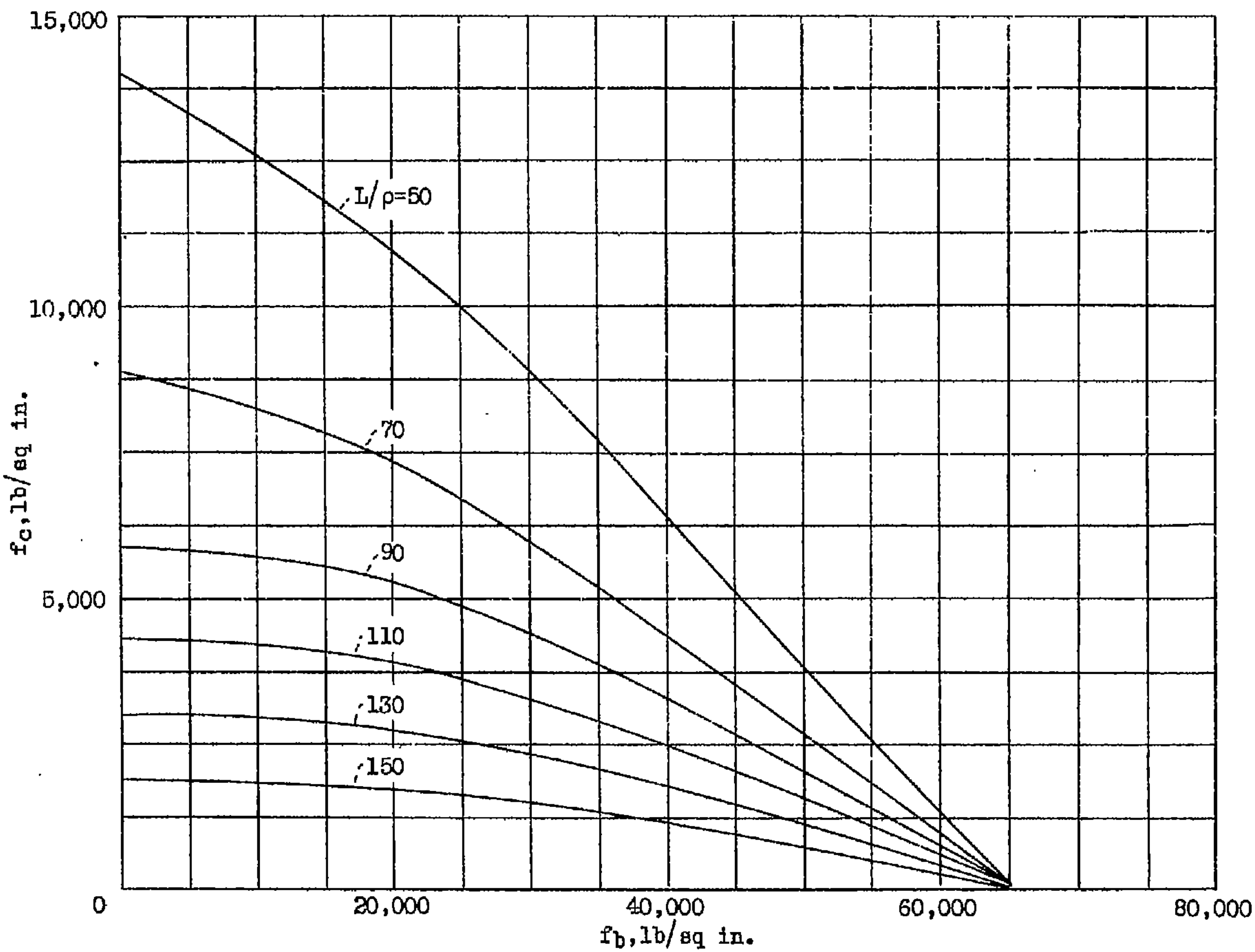


Figure 9.- Suggested design curves for 24S-T aluminum-alloy channel sections.

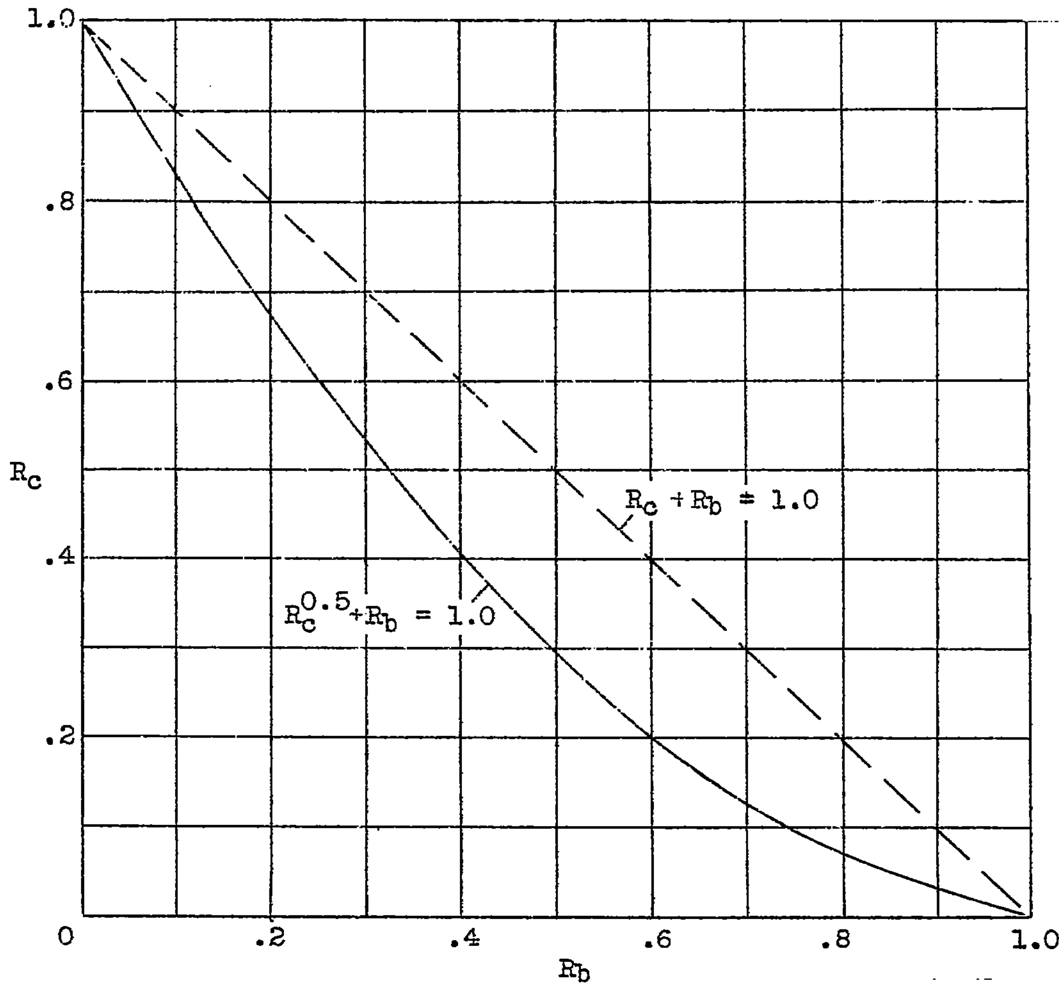


Figure 10.- Interaction curves for bending failure for 24S-T aluminum-alloy channel sections.

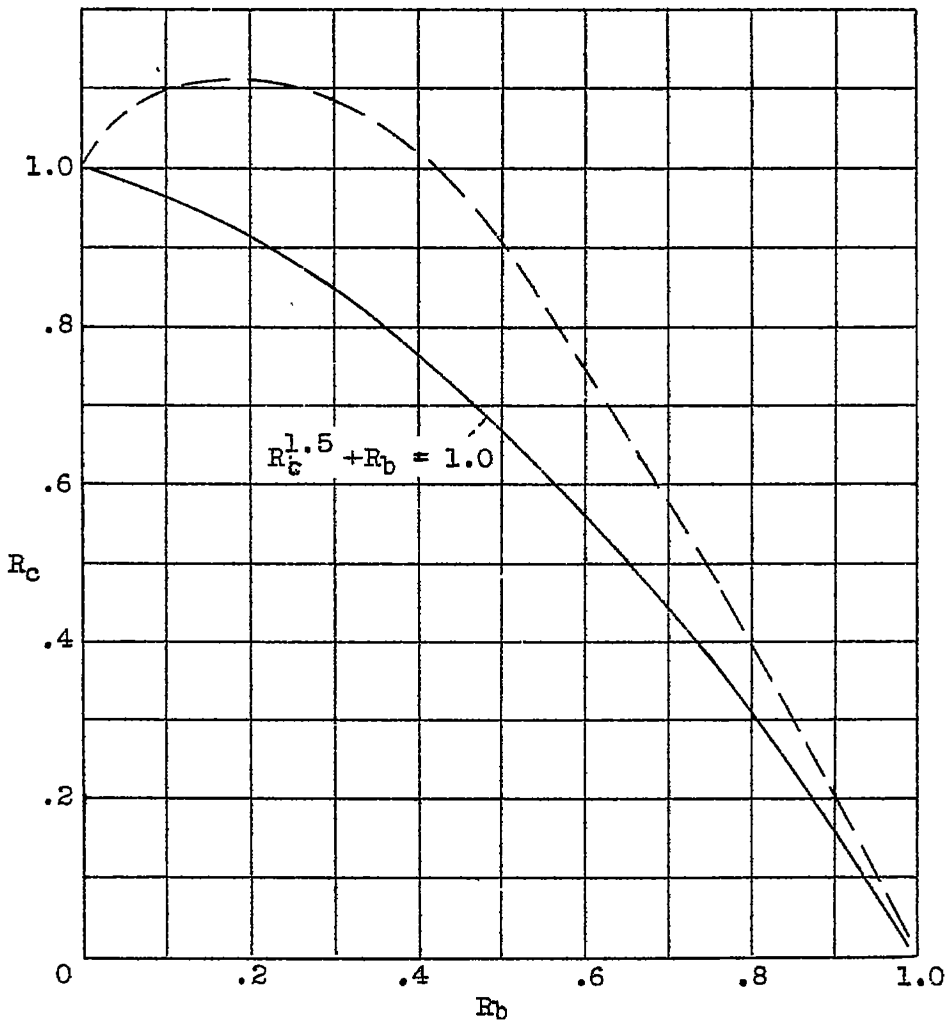


Figure 11.- Interaction curves for torsion failure for 24S-T aluminum-alloy channel sections.

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