Supplement to

# DESIGN OF PLYWOOD WEBS IN BOX BEAMS

## BUCKLING IN SHEAR WEBS OF BOX AND I BEAMS AND THE EFFECT UPON DESIGN CRITERIA

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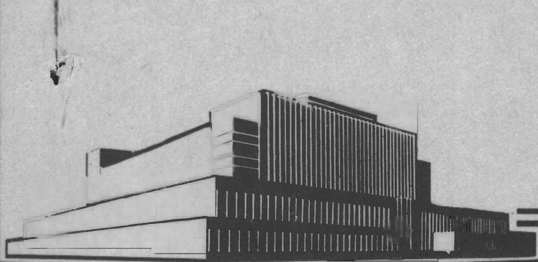

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UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE
In Cooperation with the University of Wisconsin

# BUCKLING IN SHEAR WEBS OF BOX AND I-BEAMS AND THE EFFECT UPON DESIGN CRITERIA[1]

By

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## Summary

Evidence from tests of built-up box and I-beams is that the theoretical buckling curve for plywood webs in shear, as shown in figure 2-19 of the "ANC[3] Handbook on the Design of Wood Aircraft Structures," July 1942, applies reasonably well for values of $\frac{a}{a_o}$ greater than about 1.6. When $\frac{a}{a_o}$ is small, buckles are likely to form at loads considerably lower than those indicated by the theory. Structural damage to the plywood results from buckles occurring in the lower range of $\frac{a}{a_o}$ when the proportional limit stress in compression for plywood is less than the buckling stress.

A curve (fig. 17)[4] is presented from which it is possible to estimate the shear stress which may produce buckling. This figure also shows the curves of figure 4 of Forest Products Laboratory Report No. 1318.

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[1]Original report dated October 1943. This report was one of a series of progress reports prepared by the Forest Products Laboratory to further the nation's war effort. Results here reported are preliminary and may be revised as additional data become available.

[2]Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

[3]Army-Navy-Civil Committee on Aircraft Design Criteria.

[4]The figures and tables in this supplement are numbered consecutively with those of Reports 1318 and 1318-A.

## Introduction

This study was undertaken to determine the buckling characteristics of shear webs of box and I-beams and to ascertain the correlation between experimental buckling stresses and theoretical values as represented by the buckling curve of figure 2-19 of the ANC Handbook.

The observations on buckling and the data herein presented were obtained from a study of tests of box and I-beams differing in panel dimensions, in web thickness, and in direction of face grain.

Forest Products Laboratory Reports Nos. 1318, "Design of Plywood Webs for Box Beams," and 1318-A, "Stiffeners in Box Beams and Details of Design," present details of beams 2A to 63 and methods of testing not included in this report.

## Notation

The following symbols, ANC whenever possible, are used in this report:

$a$ = the length of the short side of the panel (the distance between flanges or between stiffeners, whichever is smaller) in inches.

$a_o$ = the width of a hypothetical panel of length b, which will buckle at a shearing stress of $F_{s\theta}$, in inches.

$b$ = the length of the long side of the panel in inches.

$E_L$ = modulus of elasticity of wood in the direction parallel to the grain, in pounds per square inch.

$f_{s_{cr}}$ = calculated unit shear stress, in pounds per square inch, at buckling load $= \frac{P_{cr}Q}{2It}$

$F_{s\theta}$ = allowable (ultimate) stress for plywood in shear, in pounds per square inch, where $\theta$ is the angle of the face plies from the axis of the beam.

$I$ = moment of inertia[5] of the cross section of the beam about its neutral axis in inches$^4$.

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[5]The area of the webs was transformed by using the modular ratio of 1/4 (ANC Handbook, sec. 3.1151) both in locating the neutral axis and in calculating I and Q.

$P_{cr}$ = load on the beam, at buckling, in pounds.

$Q$ = static moment[5] of the area external to the shear section about the neutral axis in inches$^3$.

$t$ = total thickness of webs in inches.

$t_w$ = thickness of thinner web in inches.

## Description of Beams

The beams were all 10-1/2 feet long, from 4-1/16 to 5-1/2 inches wide, and from 9 to 32-1/2 inches in height. Webs of 3-ply yellow-poplar plywood varied in thickness from 1/16 to 1/4 inch with the grain of the plies making an angle of $\pm 45°$ with the horizontal axis of the beam. Ply-thickness ratios were 1:2:1 for all beams with the exception of beam 56 which had a 1:1:1 ratio. Plywood was manufactured at the Laboratory from commercial veneers for box beams 2A to 63, inclusive. The webs of the remainder of the beams were of commercial aircraft-grade plywood. Flanges were of Sitka spruce, laminated in nearly all tension flanges and in the majority of compression flanges. Solid and built-up load blocks, reaction blocks, and stiffeners were used. Tego No. 2 film was used to fabricate the plywood; Plaskon 250-2, a cold-setting urea-formaldehyde resin glue, was used for all assembly gluing.

## Marking and Matching

Minor specimens representative of the material of the webs of beams 2A to 63, inclusive, were obtained from companion panels fabricated at the same time as the webs. Minors for the webs of the remaining beams were obtained from each sheet of the commercial aircraft plywood used.

Minor test specimens were prepared from the ends of all Sitka spruce planks. Minor tests were made prior to final selection for flanges.

## Methods of Tests

The box and I-beams were tested in a 200,000-pound screw-type testing machine by loading at the third points of a simply supported 10-foot span. Load was applied at ASTM standard rates in predetermined increments. Loading was stopped during the early stages of each test while strains and deflections were observed.

The flatness of the panels was checked at each increment of load, and the first visible sign of buckling was noted. The load at which buckling first occurred was determined by one or more of the following observations: Placing a straight edge against the panels and observing deformations, a sudden increase in the rate of deflection of the beam, or a sudden increase in rate of web deformation in the vertical, inclined, or horizontal direction as disclosed by strain measurements.

All dials and gages were removed when the beam gave signs of approaching failure. From this time until failure, the load was applied continuously. Centerline deflections and the corresponding loads were the only readings taken during this stage of the tests.

Tests of the minor specimens for the flanges consisted of toughness, static bending, and compression. Moisture content at time of test and specific gravity were also determined.

Tests of the minor specimens for the webs included static bending, compression, and tension, made both parallel and perpendicular to the face grain of the material. A plate deflection test for the determination of modulus of rigidity was run in most instances. Minor specimens were stored with the beams until time of test and tested simultaneously with the beam whenever possible. Thus, the moisture content as determined from the minors represented the condition of the corresponding beam at time of test.

## Presentation of Data

Data obtained from these tests are presented in table 3. Columns 2 to 13 present dimensional data for the beams and other tails of importance. Column 4 shows the direction of grain; (+) indicates that the diagonal tensile stress was parallel to the grain in the face plies, and (-) indicates that the diagonal tensile stress was perpendicular to the grain in the face plies.

The type of beam cross section is indicated in column 6. Beams 8-S, 12-S, and 13-S were modified from the normal box cross section, and the widths of the flanges were increased by gluing to the outer faces of the webs strips of spruce, 1/2 inch wide having depths equal to those of the flanges. Beams of I section, 1-I to 6-I, were constructed by gluing flanges, stiffeners, load blocks, and reaction blocks to opposite faces of a single plywood web. Defects developed in the flanges of beams 8, 9, 21, and 45; they were modified, before testing to destruction, by gluing cap strips to the flanges.

The modulus of elasticity of the wood parallel to the grain ($E_L$) and the plywood ultimate shear values ($F_{s\theta}$), tabulated in columns 18 and 19, were calculated from averaged plywood minor test data. These values were arithmetic means obtained for each thickness of plywood from each source. Sample calculations on pages 4 to 7, inclusive, of Forest Products Laboratory Report 1318 show the methods used.

The change in the slope of the load-deflection curve of a beam due to buckling is illustrated in figure 13. This is typical of the majority of beams in which buckling occurred. When the buckle load was low and the straight line portion of the curve before buckling was short, the break in the curve sometimes could not be detected.

The values of $\frac{a}{a_o}$ and $\frac{f_{s_{cr}}}{F_{s\theta}}$ for each of the tests, and the theoretical buckling curve, are plotted in figure 16. An empirical curve for $\frac{a}{a_o}$ values of less than 2.4 is shown as a dotted line in this figure.

## Formation and Development of Buckles

The formation and development of buckles in the webs was observed during the testing of the beams. Regardless of the shape or position of the panel or of the thickness of plywood, ridges or valleys of the buckles appeared first on 45° lines usually extending to those corners of the panel at which, by reason of the direction of the shearing forces, the plywood was subjected to tensile stress. In panels not square, the buckles were observed to form first with an inclination of about 45°, later changing so as to approach the diagonal of the panel. This tendency, eventually to form a single diagonal buckle, was apparent even in panels in which the a/b ratio was far from unity and in which several buckles formed at first. Only in panels in which the shorter side was horizontal was there any noticeable tendency for multiple buckles to remain. Figure 14 illustrates a dual buckle pattern just prior to failure in a rectangular panel (beam 22), and figure 15 shows a single buckle in a square panel (beam 16-S).

## Analysis of Results

The full-line curve in figure 16 shows the theoretical unit stress at which buckling may be expected and is based upon the assumption that the edges are simply supported. Similar curves for clamped edges would be higher. As shown by the plotted points representing test results, most webs with values of $\frac{a}{a_o}$ larger than 1.6 buckled at stresses greater than those indicated by the curve. This is to be expected, for the edges of the panels were restrained either by gluing to the flanges and stiffeners or by continuity. A fully clamped condition is difficult to obtain, however, and a small reduction in edge fixity has a large influence on the panel behavior. The buckling constants for simply supported edges were used in determining $a_o$ for each web. The conditions at the edges of the panels in the webs of the box and I-beams were between simply supported and clamped, but comparison indicates that conditions in these beams more closely approximated those of simply supported edges than clamped.

Webs with $\frac{a}{a_o}$ less than 1.6 showed a tendency to buckle at unit stresses lower than those indicated by the theoretical curve. This phenomenon is similar to that observed in column tests and may be explained by the fact that, due to eccentricity of loading, initial deviation from a perfect plane, and variability of material, the plywood reached its proportional limit before reaching the buckling stress represented by the theoretical curve. Buckles occurring in webs with $\frac{a}{a_o}$ less than 1.2 often damaged the material and were therefore termed inelastic buckles. Buckles which formed in webs with $\frac{a}{a_o}$ greater than 2.2 are termed elastic buckles, inasmuch as the material was not damaged until loading approached the ultimate stress. A transition stage between values of $\frac{a}{a_o}$ equal to 1.2 and 2.2 existed where both types of buckling occurred.

The buckling curve represented by the dotted line in figure 16 is drawn below the buckling stress ratio ($f_{s_{cr}}/F_{s45°}$) of most of the test beams and is tangent to the theoretical buckling curve at about $\frac{a}{a_o} = 2.4$. The relation of buckling stress to panel dimensions (a/b ratio) does not appear to be sufficiently well defined to justify more than the single curve.

Figure 17 shows the ultimate stress ratio ($F_s/F_{s\theta}$) curves, presented in figure 4 of the original report, and the buckling curve. This buckling curve is the dotted empirical curve of figure 16 for values of $\frac{a}{a_o}$ less than 2.4 and the theoretical curve for values of $\frac{a}{a_o}$ greater than 2.4.

## Conclusions

Buckles forming in the web of a beam take an angle at the beginning of their formation of about 45°, usually changing angle with increasing load to approach a position between diagonally opposite corners of the panels. Several buckles may begin to form in a panel but tend to merge with increasing load, so that at failure only one or at most two buckles remain. Buckles in webs may be of two kinds depending upon the $\frac{a}{a_o}$ ratio. For webs with large $\frac{a}{a_o}$ ratios, buckling in its early stages is elastic and is not harmful to the material. Webs with small values of the ratio $\frac{a}{a_o}$ may be harmed as soon as buckling occurs. Care should be exercised to avoid the use of webs that may be damaged by buckling before the limit or yield stress is reached. Figure 17 is presented from which the lower limit of the buckling stress can be obtained. This figure shows also the ultimate curves of figure 4 of Report 1318.

Table 3.--Buckling loads and computed stresses for box and I beams.[1]

| Beam No. | Nominal depth of beam | Nominal width of beam | Web grain[2] | Nominal plywood thickness | Type of beam | t both webs | $t_w$ thinner web | I | Q | a vertical or horizontal | b | a/b | P critical | $f_{s_{cr}}$ in web | Elastic buckle | Inelastic buckle | $E_L$ average from minors | $F_{s\theta}$ average from minors | $a/a_0$ | $\frac{f_{s_{cr}}}{F_{s\theta}}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Construction details | | | | | | | | | Panel information | | | Critical buckling | | Probable type of buckle | | Calculations | | | |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) | (21) |
| | Inches | Inches | | Inch | | Inch | Inch | $Inches^4$ | $Inches^3$ | Inches | Inches | | Pounds | Pounds per square inch | | | 1,000 pounds per square inch | Pounds per square inch | | |
| 2A | 12 | 4-1/4 | - | 1/8 | Box | 0.230 | 0.112 | 332.0 | 30.28 | 9.31v | 40.00 | 0.233 | 4,000 | 795 | x | | 1,540 | 3,410 | 2.12 | 0.233 |
| 2B | 12 | 4-1/4 | - | 1/8 | " | .271 | .134 | 317.1 | 29.98 | 9.27v | 34.50 | .269 | 6,000 | 1,050 | x | | 1,540 | 3,410 | 1.75 | .308 |
| 3A | 12 | 4-1/4 | + | 1/8 | " | .250 | .125 | 322.1 | 30.32 | 9.30v | 40.00 | .233 | 2,200 | 415 | x | | 1,540 | 3,560 | 3.63 | .116 |
| 3B | 12 | 4-1/4 | + | 1/8 | " | .250 | .125 | 322.0 | 30.42 | 9.25v | 34.50 | .268 | 2,300 | 435 | x | | 1,540 | 3,560 | 3.60 | .122 |
| 4A | 12 | 4-1/6 | - | 1/12 | " | .173 | .085 | 250.2 | 22.86 | 10.02v | 40.00 | .251 | 2,100 | 555 | x | | 1,760 | 3,620 | 2.89 | .152 |
| 4B | 12 | 4-1/6 | - | 1/12 | " | .174 | .086 | 247.8 | 22.72 | 9.98v | 34.50 | .289 | 2,200 | 580 | x | | 1,760 | 3,620 | 2.82 | .160 |
| 7 | 12 | 4-1/4 | + | 1/8 | " | .257 | .128 | 297.1 | 28.21 | 5.63h | 9.21 | .611 | 9,000 | 1,660 | x | | 1,540 | 3,560 | 1.98 | .467 |
| 8 | 12 | 4-1/4 | + | 1/8 | " | .258 | .128 | 300.7 | 28.36 | 9.29v | 11.63 | .799 | 4,500 | 825 | x | | 1,540 | 3,560 | 3.05 | .231 |
| 8 modified | 12 | 4-1/4 | + | 1/8 | " | .258 | .128 | 638.4 | 54.69 | 9.29v | 11.63 | .799 | 5,000 | 830 | x | | 1,540 | 3,560 | 3.05 | .233 |
| 9 modified | 12 | 4-1/4 | + | 1/8 | " | .263 | .131 | 402.0 | 36.88 | 3.75h | 9.27 | .405 | 12,000 | 2,090 | x | | 1,540 | 3,560 | 1.36 | .587 |
| 10 | 12 | 4-1/4 | - | 1/8 | " | .255 | .125 | 404.6 | 37.12 | 3.75h | 9.26 | .405 | 17,000 | 3,060 | | x | 1,540 | 3,410 | 0.72 | .897 |
| 11 | 12 | 4-1/6 | + | 1/12 | " | .178 | .086 | 235.1 | 21.57 | 5.81h | 9.99 | .582 | 2,500 | 645 | x | | 1,760 | 3,610 | 2.95 | .179 |
| 12 | 12 | 4-1/6 | + | 1/12 | " | .175 | .085 | 238.2 | 21.83 | 9.99v | 10.63 | .940 | 2,000 | 525 | x | | 1,760 | 3,610 | 4.31 | .145 |
| 13 | 12 | 4-1/8 | + | 1/16 | " | .118 | .056 | 192.5 | 17.24 | 10.49v | 35.75 | .293 | 200 | 75 | x | | 1,770 | 3,380 | 8.26 | .022 |
| 14 | 12 | 4-1/8 | - | 1/16 | " | .106 | .052 | 189.2 | 16.90 | 10.53v | 35.75 | .295 | 750 | 315 | x | | 1,770 | 3,720 | 4.94 | .085 |
| 15 | 12 | 4-1/8 | + | 1/16 | " | .113 | .055 | 189.6 | 16.97 | 10.51v | 11.75 | .894 | 800 | 320 | x | | 1,770 | 3,380 | 7.01 | .095 |
| 16 | 12 | 4-1/8 | - | 1/16 | " | .114 | .054 | 187.3 | 16.74 | 10.53v | 11.75 | .896 | 1,750 | 685 | x | | 1,770 | 3,720 | 3.28 | .184 |
| 17 | 12 | 4-1/8 | + | 1/16 | " | .117 | .057 | 190.3 | 17.02 | 8.75h | 10.52 | .832 | 1,000 | 380 | x | | 1,770 | 3,380 | 5.80 | .112 |
| 18 | 12 | 4-1/8 | - | 1/16 | " | .117 | .054 | 193.0 | 17.21 | 8.75h | 10.55 | .829 | 2,500 | 950 | x | | 1,770 | 3,720 | 2.91 | .255 |
| 19 | 12 | 4-1/8 | + | 1/16 | " | .118 | .059 | 184.6 | 16.50 | 3.75h | 10.55 | .355 | 3,500 | 1,320 | x | | 1,770 | 3,380 | 2.78 | .391 |
| 20 | 12 | 4-1/8 | - | 1/16 | " | .113 | .055 | 184.7 | 16.50 | 3.75h | 10.55 | .355 | 4,500 | 1,780 | x | | 1,770 | 3,720 | 1.63 | .479 |
| 21 | 12 | 4-1/8 | + | 1/16 | " | .124 | .059 | 192.3 | 17.21 | 3.75h | 10.51 | .357 | 1,500 | 540 | x | | 1,770 | 3,380 | 2.78 | .160 |
| 21 modified | 12 | 4-1/8 | + | 1/16 | " | .124 | .059 | 285.3 | 24.72 | 3.75h | 10.51 | .357 | 3,500 | 1,220 | x | | 1,770 | 3,380 | 2.78 | .361 |
| 22 | 12 | 4-1/8 | - | 1/16 | " | .119 | .059 | 190.9 | 17.08 | 3.75h | 10.51 | .357 | 3,500 | 1,320 | | x | 1,770 | 3,720 | 1.52 | .355 |
| 30 | 12 | 4-1/4 | - | 1/8 | " | .220 | .108 | 316.5 | 30.00 | 9.13v | 11.63 | .785 | 7,000 | 1,510 | x | | 1,710 | 3,410 | 1.51 | .443 |
| 31 | 12 | 4-1/4 | + | 1/8 | " | .216 | .108 | 318.5 | 30.18 | 9.14v | 35.75 | .256 | 1,500 | 330 | x | | 1,710 | 3,370 | 3.81 | .098 |
| 32 | 12 | 4-1/4 | + | 1/8 | " | .230 | .112 | 316.6 | 30.02 | 5.63h | 9.13 | .617 | 4,000 | 825 | x | | 1,710 | 3,370 | 2.09 | .245 |
| 33 | 12 | 4-1/4 | + | 1/8 | " | .229 | .109 | 319.5 | 30.23 | 4.88h | 9.15 | .533 | 6,000 | 1,240 | x | | 1,710 | 3,370 | 1.90 | .368 |
| 34 | 12 | 4-1/4 | - | 1/8 | " | .239 | .119 | 318.8 | 30.16 | 4.88h | 9.16 | .533 | 10,000 | 1,980 | | x | 1,710 | 3,410 | 0.88 | .581 |
| 37 | 12 | 4-1/4 | + | 1/8 | " | .235 | .117 | 322.3 | 30.45 | 3.75h | 9.16 | .409 | 9,000 | 1,810 | x | | 1,710 | 3,370 | 1.40 | .537 |
| 38 | 12 | 4-1/4 | - | 1/8 | " | .233 | .115 | 311.3 | 29.51 | 3.75h | 9.13 | .411 | 11,000 | 2,240 | | x | 1,710 | 3,410 | 0.74 | .657 |
| 40 | 13-1/2 | 4-1/2 | - | 1/4 | " | .460 | .230 | 687.2 | 63.42 | 7.54v | 35.75 | .211 | 28,000 | 2,810 | | x | 1,710 | 3,550 | 0.82 | .792 |
| 41 | 13-1/2 | 4-1/2 | + | 1/4 | " | .468 | .234 | 686.6 | 63.37 | 7.54v | 35.75 | .211 | 16,000 | 1,580 | x | | 1,710 | 3,560 | 1.50 | .444 |
| 43 | 13-1/2 | 4-1/2 | + | 1/4 | " | .439 | .216 | 673.7 | 62.33 | 7.50v | 10.88 | .689 | 19,000 | 2,000 | x | | 1,710 | 3,560 | 1.44 | .562 |
| 45 modified | 13-1/2 | 4-1/2 | - | 1/4 | " | .475 | .232 | 913.1 | 76.59 | 5.44h | 7.52 | .723 | 30,000 | 2,650 | | x | 1,710 | 3,550 | 0.47 | .747 |
| 50 | 18 | 4-1/4 | - | 1/8 | " | .243 | .121 | 817.7 | 50.24 | 5.63h | 14.97 | .376 | 15,000 | 1,900 | | x | 1,710 | 3,410 | 1.07 | .558 |
| 51 | 18 | 4-1/4 | + | 1/8 | " | .228 | .110 | 826.2 | 50.67 | 4.88h | 14.97 | .326 | 6,000 | 810 | x | | 1,710 | 3,370 | 1.98 | .240 |
| 52 | 18 | 4-1/4 | + | 1/8 | " | .238 | .118 | 820.1 | 50.30 | 10.88h | 14.99 | .726 | 3,000 | 385 | x | | 1,710 | 3,370 | 3.75 | .114 |
| 53 | 18 | 4-1/4 | - | 1/8 | " | .229 | .111 | 836.3 | 51.41 | 10.88h | 14.90 | .730 | 8,000 | 1,070 | x | | 1,710 | 3,410 | 1.83 | .314 |
| 54 | 18 | 4-1/4 | - | 1/8 | " | .219 | .109 | 808.7 | 49.70 | 14.96v | 35.75 | .418 | 4,000 | 560 | x | | 1,710 | 3,410 | 3.11 | .164 |
| 56 | 18 | 4-3/8 | - | 3/16 | " | .347 | .173 | 820.3 | 50.74 | 3.75h | 14.96 | .251 | 34,000 | 3,030 | | x | 1,690 | 3,400 | 0.52 | .891 |
| 60 | 18 | 5-1/2 | - | 1/4 | " | .476 | .234 | 1485.5 | 95.51 | 13.25v | 34.75 | .381 | 22,000 | 1,480 | | x | 1,710 | 3,550 | 1.34 | .417 |
| 61 | 18 | 5-1/2 | + | 1/4 | " | .449 | .224 | 1486.5 | 95.39 | 13.27v | 34.75 | .382 | 8,000 | 570 | x | | 1,710 | 3,560 | 2.69 | .160 |
| 62 | 18 | 5-1/2 | + | 1/4 | " | .455 | .227 | 1473.3 | 94.59 | 11.25h | 13.27 | .848 | 16,000 | 1,130 | x | | 1,710 | 3,560 | 1.93 | .317 |
| 63 | 18 | 5-1/2 | - | 1/4 | " | .467 | .232 | 1477.7 | 94.88 | 11.25h | 13.27 | .848 | 40,000 | 2,750 | | x | 1,710 | 3,550 | 0.84 | .775 |
| 6-D | 12 | 4-1/4 | - | 1/8 | " | .227 | .113 | 291.6 | 27.57 | 5.13h | 9.26 | .554 | 11,000 | 2,290 | | x | 1,837 | 3,870 | 0.98 | .592 |
| 9-D | 12 | 4-1/4 | + | 1/8 | " | .228 | .114 | 291.0 | 27.54 | 3.13h | 9.25 | .338 | 12,000 | 2,490 | x | | 1,837 | 3,990 | 1.28 | .624 |
| 21-D | 12 | 4-1/8 | + | 1/16 | " | .124 | .062 | 187.8 | 16.85 | 3.13h | 10.50 | .298 | 1,600 | 580 | x | | 1,588 | 3,350 | 2.34 | .173 |
| 50-D | 18-1/2 | 4-1/4 | - | 1/8 | " | .220 | .110 | 1013.4 | 60.99 | 4.88h | 14.97 | .326 | 21,000 | 2,870 | | x | 1,837 | 3,870 | 1.07 | .742 |
| 60-D | 18 | 5-1/2 | - | 1/4 | " | .492 | .246 | 1484.7 | 95.63 | 13.22v | 34.75 | .381 | 24,000 | 1,570 | | x | 1,713 | 3,750 | 1.30 | .419 |
| 63-D | 18 | 5-1/2 | - | 1/4 | " | .492 | .246 | 1481.4 | 95.32 | 12.25h | 13.24 | .925 | 40,900 | 2,670 | | x | 1,713 | 3,750 | 0.81 | .712 |
| 1-S | 17 | 5-1/2 | - | 1/4 | " | .486 | .243 | 1539.7 | 111.09 | 10.11v | 11.00 | .920 | 48,000 | 3,560 | | x | 1,713 | 3,750 | 0.67 | .950 |
| 2-S | 12 | 4-1/4 | - | 1/8 | " | .228 | .114 | 330.8 | 32.38 | 8.33v | 8.38 | .994 | 10,000 | 2.150 | | x | 1,837 | 3,870 | 1.10 | .556 |
| 3-S | 9 | 4-1/6 | - | 1/12 | " | .144 | .072 | 106.1 | 13.16 | 7.22v | 7.25 | .996 | 2,600 | 1,120 | | x | 1,633 | 3,340 | 1.49 | .335 |
| 4-S | 15-1/2 | 4-1/2 | + | 1/4 | " | .492 | .246 | 778.7 | 58.97 | 11.00h | 11.01 | 1.000 | 20,000 | 1,540 | x | | 1,713 | 3,980 | 1.74 | .387 |
| 5-S | 12-1/2 | 4-1/6 | - | 1/12 | " | .146 | .073 | 171.4 | 14.74 | 11.18v | 11.25 | 0.994 | 2,600 | 770 | x | | 1,633 | 3,340 | 2.28 | .230 |
| 6-S | 10 | 4-1/4 | + | 1/8 | " | .240 | .120 | 133.5 | 14.80 | 8.25h | 8.36 | .987 | 2,600 | 600 | x | | 1,837 | 3,990 | 2.60 | .150 |
| 7-S | 12 | 4-1/4 | + | 1/8 | " | .238 | .119 | 208.6 | 19.11 | 10.22v | 10.25 | .998 | 2,500 | 480 | x | | 1,837 | 3,990 | 3.23 | .120 |
| 8-S | 10-1/4 | 5-1/6 | + | 1/12 | Modified box | .130 | .065 | 135.7 | 14.17 | 9.07v | 9.13 | .994 | 600 | 240 | x | | 1,633 | 3,410 | 5.16 | .072 |
| 9-S | 14 | 4-1/2 | + | 1/4 | box | .492 | .246 | 601.2 | 51.24 | 9.36v | 15.63 | .599 | 21,000 | 1,820 | x | | 1,713 | 3,980 | 1.72 | .457 |
| 10-S | 9-1/2 | 4-1/8 | - | 1/16 | " | .120 | .060 | 99.7 | 11.42 | 4.88h | 8.11 | .602 | 3,000 | 1,430 | x | | 1,588 | 3,590 | 1.77 | .400 |
| 11-S | 12-1/4 | 4-1/8 | + | 1/16 | " | .118 | .059 | 170.0 | 14.97 | 2.19h | 10.81 | .203 | 3,500 | 1,310 | x | | 1,588 | 3,350 | 1.73 | .391 |
| 12-S | 10-7/8 | 5-1/6 | - | 1/12 | Modified box | .130 | .065 | 153.9 | 15.08 | 9.71v | 16.25 | .597 | 1,400 | 530 | x | | 1,633 | 3,340 | 3.10 | .159 |
| 13-S | 9-1/4 | 5-1/6 | + | 1/12 | " | .144 | .072 | 118.1 | 13.94 | 4.75h | 7.83 | .607 | 2,000 | 820 | x | | 1,633 | 3,410 | 2.83 | .240 |
| 14-S | 17-5/8 | 4-1/8 | + | 1/16 | Box | .120 | .060 | 360.2 | 21.63 | 3.25h | 16.33 | .199 | 3,000 | 750 | x | | 1,588 | 3,350 | 2.53 | .224 |
| 16-S | 32-1/2 | 4-1/8 | - | 1/16 | " | .112 | .056 | 1097.5 | 35.49 | 31.49v | 31.50 | 1.000 | 1,000 | 145 | x | | 1,588 | 3,590 | 8.76 | .040 |
| 1-I | 13-1/2 | 4-1/4 | - | 1/4 | I | ---- | .246 | 440.3 | 37.30 | 10.03v | 10.06 | 0.998 | 18,000 | 3,100 | | x | 1,713 | 3,750 | 0.63 | .827 |
| 2-I | 10-3/4 | 4-1/4 | + | 1/4 | " | ---- | .246 | 168.1 | 17.48 | 8.79v | 22.19 | .396 | 9,000 | 1,900 | x | | 1,713 | 3,980 | 1.71 | .477 |
| 3-I | 14-7/8 | 4-1/4 | + | 1/4 | " | ---- | .246 | 414.0 | 30.64 | 10.00h | 12.56 | .797 | 10,000 | 1,500 | x | | 1,713 | 3,980 | 1.73 | .377 |
| 4-I | 16-3/4 | 4-1/4 | + | 1/4 | " | ---- | .243 | 424.3 | 27.43 | 15.01v | 18.75 | .801 | 5,000 | 670 | x | | 1,713 | 3,980 | 2.62 | .168 |
| 5-I | 11-3/8 | 4-1/16 | - | 1/16 | " | ---- | .062 | 119.6 | 11.03 | 8.31h | 10.41 | .798 | 600 | 450 | x | | 1,588 | 3,590 | 2.51 | .125 |
| 6-I | 10-1/6 | 4-1/12 | + | 1/12 | " | ---- | .074 | 88.8 | 9.38 | 9.04v | 9.06 | .998 | 600 | 430 | x | | 1,633 | 3,410 | 4.51 | .126 |

[1]Beams were tested under third point loading over a 10-foot span; flanges were Sitka spruce; webs were three-ply yellowpoplar with grain at 45 degrees to the direction of the span; ply thickness ratios were 1:2:1, excepting beam 56 which was 1:1:1.

[2]+ indicates that the diagonal tensile stress was parallel to the grain in the face plies.
- indicates that the diagonal tensile stress was perpendicular to the grain in the face plies.

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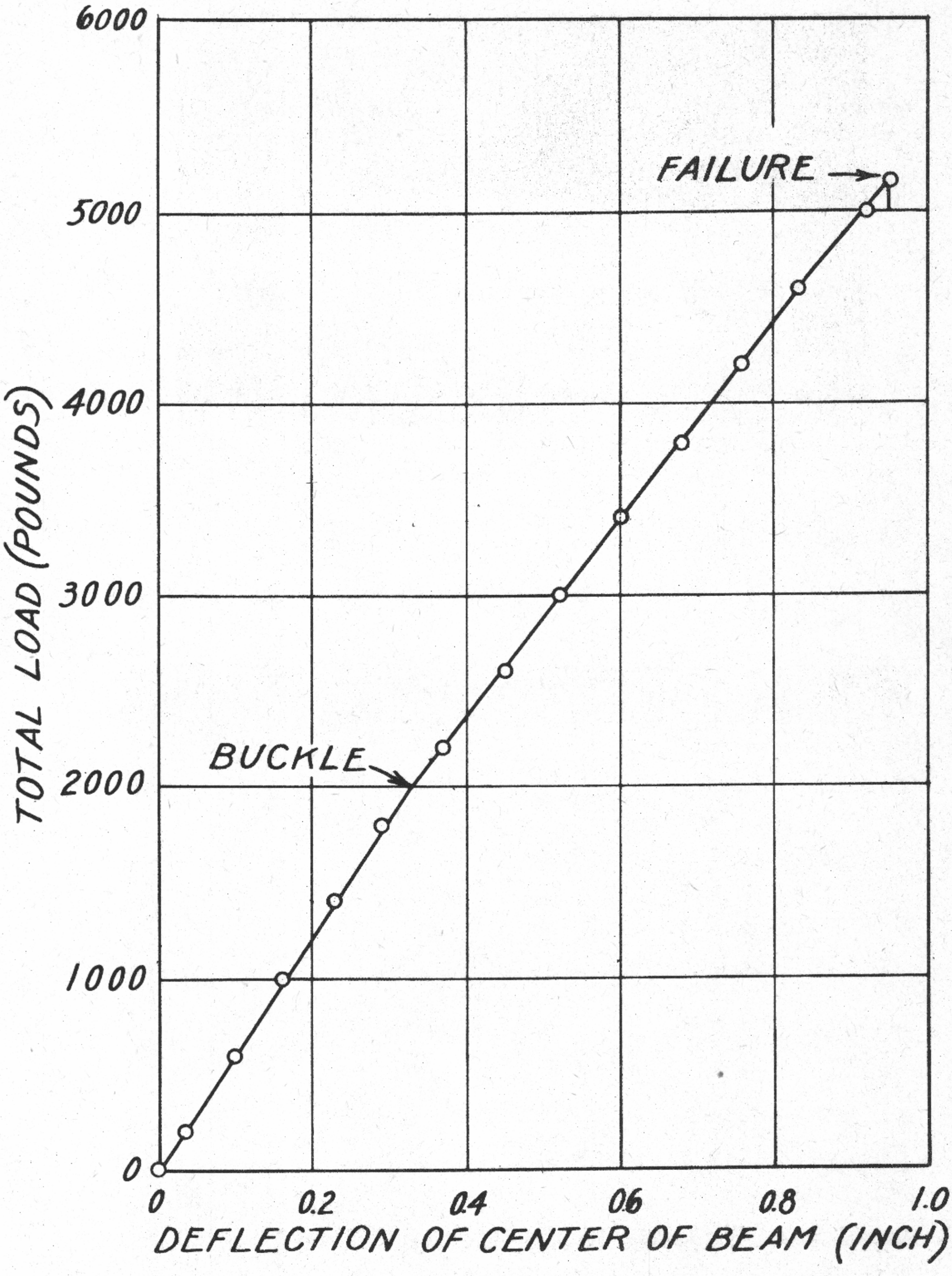


Figure 13.--Load-deflection curve for box beam 13-S, loaded at third points, showing typical break in curve at elastic buckle load.

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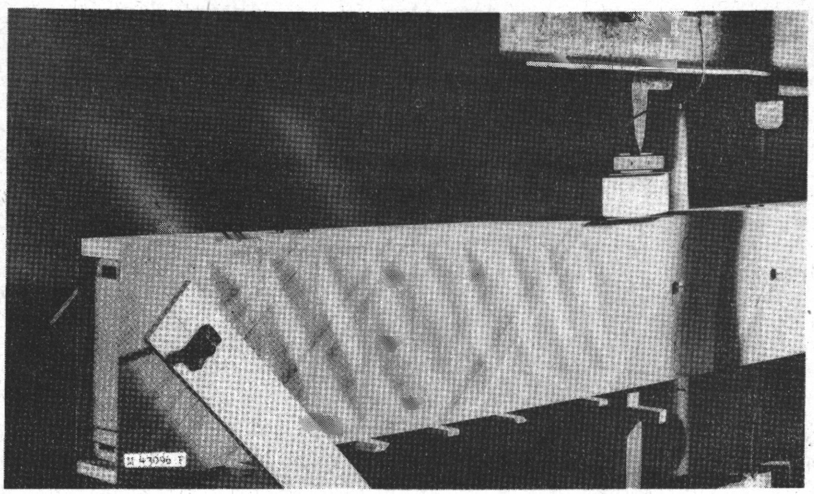


Figure 14.--Box beam 22 under load showing extent of buckling in web preceding failure of the beam.

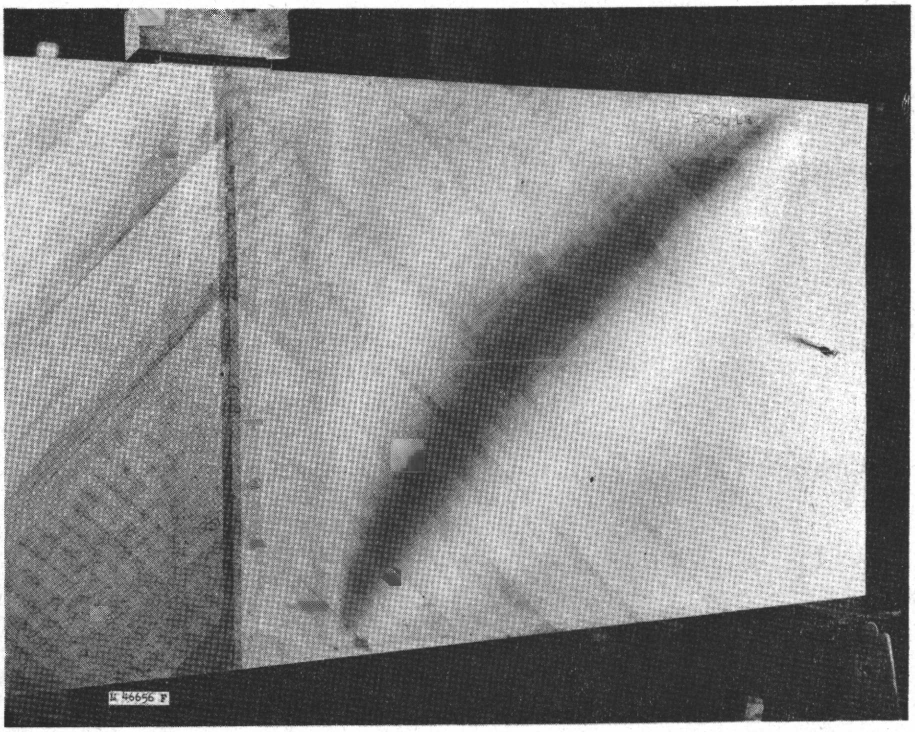


Figure 15.--Box beam 16-S under 5,000-pound load showing typical buckle formation in a square panel.

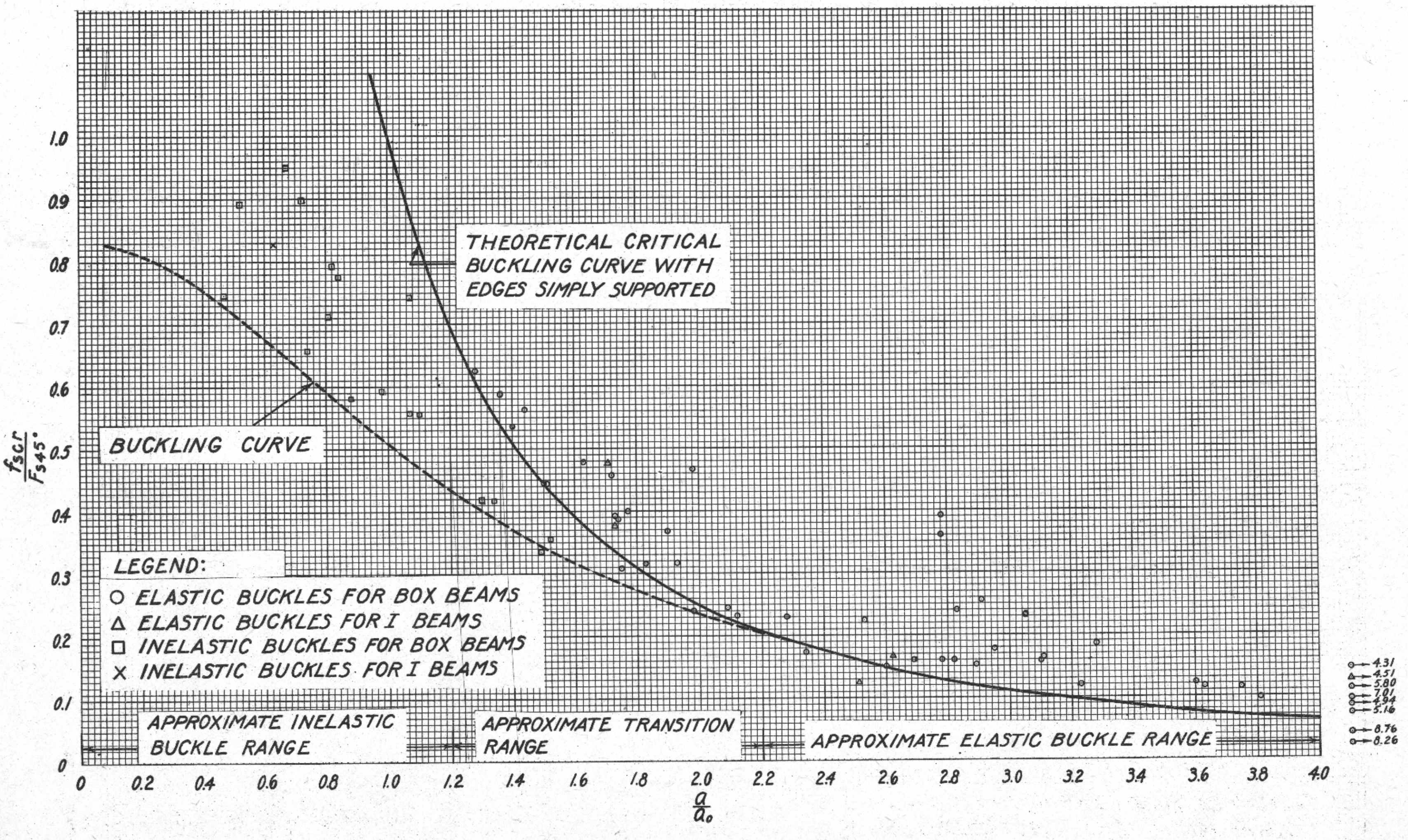


Figure 16.--Buckling stresses in shear webs of box and I beams.

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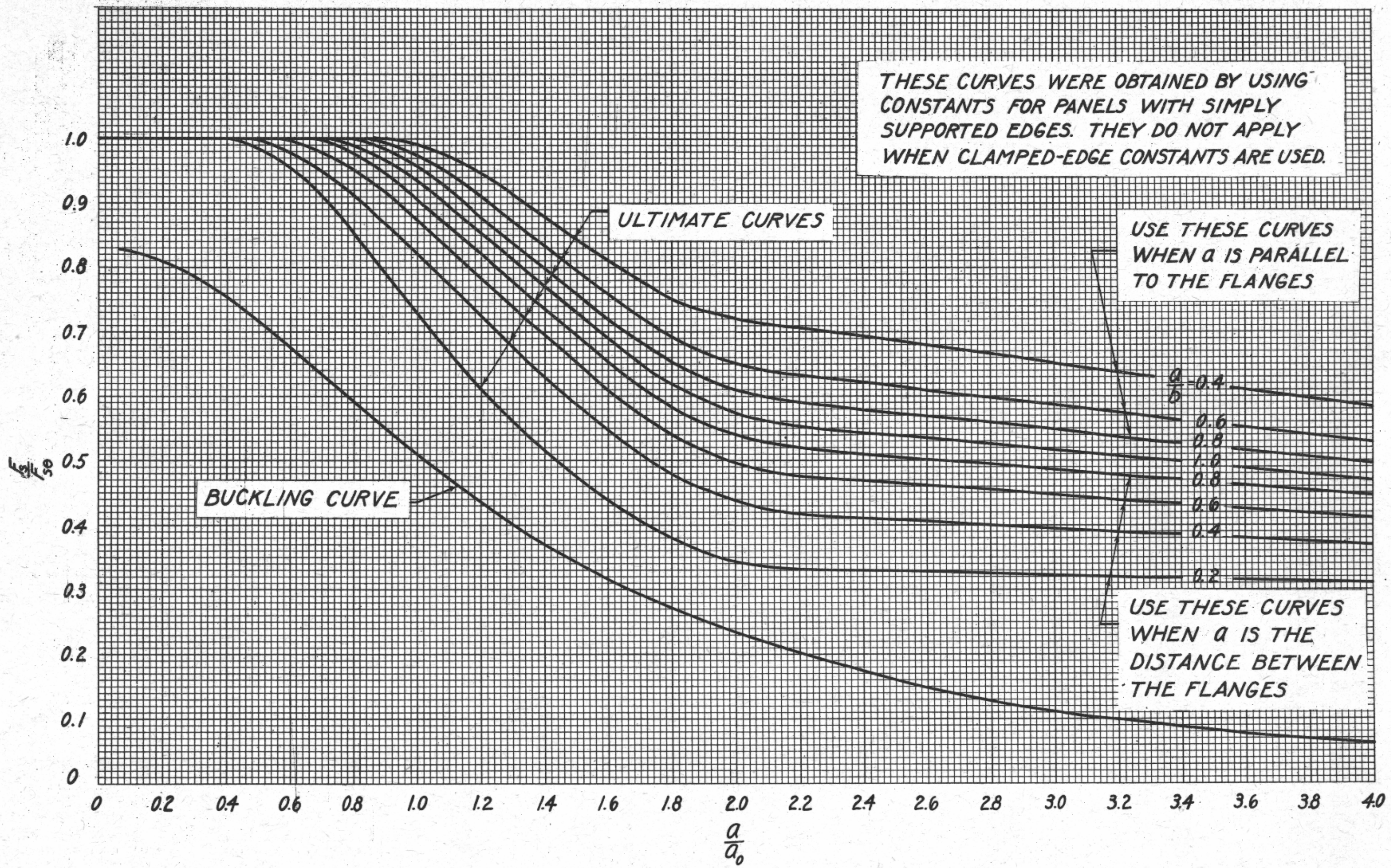


Figure 17.--Allowable ultimate stress and probable buckling stress for plywood webs in shear.

Z M 49085 F