

LONGITUDINALLY STIFFENED THIN-WALLED PLYWOOD CYLINDERS IN AXIAL COMPRESSION

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**UNITED STATES DEPARTMENT OF AGRICULTURE
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LONGITUDINALLY STIFFENED THIN-WALLED PLYWOOD

CYLINDERS IN AXIAL COMPRESSION¹

By EDWARD W. KUENZI, Engineer
and
C. B. NORRIS, Engineer

Summary

Results are presented on tests of 1,050 specimens of longitudinally stiffened thin-walled plywood cylinders in axial compression. The specimens were cylindrical shells of thin plywood (approximately 0.05 inch thick) 18 inches in diameter with inner longitudinal stiffeners of veneer, plywood, or solid wood. The stiffener thicknesses varied from 1/48 inch to 1 inch, the spacings between stiffeners from 1/4 inch to 6 inches, and the number of stiffeners from 9 to 28.

The test data indicate that the average shell buckles at the critical stress of a complete unstiffened cylinder, provided the spacing between its stiffeners is not too small and the stiffeners are sufficiently rigid. If the stiffeners are more closely spaced and sufficiently rigid, the buckling stress of the shell is greater than that of an unstiffened cylinder. No theory is presented regarding specimens with closely spaced, rigid stiffeners.

Most of the failures occurred when the shell buckled. A few specimens having heavy stiffeners sustained loads subsequent to buckling of the shell and finally failed because of general instability. No theory is presented regarding the load at which general instability may occur.

When the efficiency (ratio of load to weight) of stiffened shells was compared to that of unstiffened shells, it was found that an unstiffened shell having the same weight and curvature but greater thickness than the stiffened shell would theoretically buckle at the same, or greater, loads as the stiffened shell. This was particularly true if the stiffeners were heavy, in which case an unstiffened shell of the same weight was theoretically capable of supporting two to three times the initial buckling load of a stiffened shell.

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Introduction

At the time this work was begun at the Forest Products Laboratory (July 1943), it was thought that more information on the behavior of longitudinally stiffened shells in axial compression was needed for the design of aircraft structures. Previous work at the Forest Products Laboratory on unstiffened shells showed that plywood is particularly useful in the experimental determination of the buckling stresses of shell structures, since it is smooth and can be made thicker than metal shells of the same size and still exhibit buckling. Accordingly, plywood was used in the extensive series of specimens included in the work covered by this report.

A theoretical analysis applicable to a stiffened structure of this type should include the behavior of plates supported at the edges by stiffeners that are not rigid but that can bend and twist, but as an analysis of this sort would be exceedingly complicated,² it was not included in the work covered by this report.

Description of Specimens

The specimens were circular shells of plywood 18 inches in diameter having stiffeners glued to their inner surfaces. All stiffeners were placed with their length parallel to the axis of the cylinder and were equally spaced around the circumference of the shell. The stiffeners were of three types, veneer, plywood, and solid wood. Tables 1 (cols. 15 to 17) and 2 (cols. 14 to 16) give the size and number (col. 3) of stiffeners for each specimen.

The plywood was made of yellow-poplar or yellow birch veneers of aircraft grade, rotary cut at the Forest Products Laboratory. All of the plywood was made by bonding the veneers with film glue set in a standard hot-plate veneer press. The two ends of the flat sheet that were to be later joined to form the circular shell were scarfed. The stiffeners of veneer and those of solid wood were then placed with their grain directions parallel to the axis of the shell and were glued to the plywood in a hot-plate press. The sheet was finally bent to cylindrical form, and the scarf joint was glued with a thermosetting synthetic-resin glue.

The plywood stiffeners were made of three plies, of which the face plies were 1/32 inch thick with their grain in the circumferential direction, and the core ply was 1/16 inch thick with its grain in the axial direction. They were bag molded to the curvature of the shell and finally glued to the shell by internal bag molding in a female mold.

²Timoshenko, S. "Theory of Elastic Stability," p. 337, 1936.
Chwalla, E. Ingenieur-Archiv, vol. 5, p. 54, 1934.

The ends of specimens having stiffeners $1/8$ inch thick or less were cut square and true in a turning lathe. Those of specimens having thicker stiffeners were cut by placing the specimen on a mandrel and rotating it into a fine-toothed, circular, cross-cut saw.

A stiffened plywood shell in which the face grain of the plywood is in the circumferential direction and the grain of the stiffeners in an axial direction will develop internal stresses if its moisture content is increased. Because the stiffeners do not expand so much in the axial direction of the shell as does the plywood shell, the shell is subjected to compression and the stiffeners to tension. If the change in moisture content is great enough, the compression in the shell will cause it to buckle between the stiffeners. Since a thin stiffener is stretched more easily than a heavy one, buckles in the plywood shell between stiffeners will not be so likely to appear in a shell having light stiffeners. Also, if the stiffeners are made of the same plywood construction as that of the plywood shell, they will expand by the same amount as the shell and no stresses due to the expansion will occur.

Since the stiffeners were bonded to the shell by means of heat and pressure, the shell and the stiffeners were quite dry immediately after manufacture. An attempt was made to condition all specimens to a constant weight in a controlled atmosphere of 64 percent relative humidity at a temperature of 75° F. Buckles in the plywood shell then appeared between the stiffeners that were $3/8$ inch, $1/2$ inch, and 1 inch thick. The plywood of specimens having lighter stiffeners did not buckle. In order that smooth specimens could be tested, those that did buckle under conditioning were placed in a dry kiln until they became smooth, when they were tested immediately.

Coupons of flat plywood were made of material cut from portions of the log adjacent to the portions used in making the corresponding cylindrical shell or corresponding plywood stiffener.

Coupons of stiffeners thicker than $1/8$ inch were cut from the ends of the stiffeners prior to gluing the stiffeners to the plywood shell.

Coupons of stiffeners of veneer were made of veneers cut from portions of the log adjacent to the portions used in making the stiffeners. These were prepared for testing in compression by gluing together six 1- by 4-inch pieces. The pieces were not glued over their entire surface but were only glued for a distance of $1/2$ inch from each end. The resulting compression specimen was made up of six veneers having their ends glued together. Thus end failures during test were prevented.

Each of the coupons received the same conditioning before test as that of the corresponding stiffened cylinder.

Methods of Testing

All of the stiffened plywood cylinders, except those having 19 or 28 stiffeners 1/2 by 1 inch in cross section, were tested in a hydraulic testing machine. Those excepted, being heavier specimens, were tested in a screw-operated testing machine of 1,000,000-pound capacity.

The ends of each cylinder were fitted with external plywood rings, lightly clamped around the specimen. The purpose of these rings was to hold the shell to its circular shape.

With the exception of the heavy specimens having 19 or 28 stiffeners 1/2 by 1 inch in cross section, the cylinders, with end rings attached, were placed on a flat machined steel plate that rested on a spherical bearing on the bottom head of the testing machine. The top of the shell was allowed to bear on the machined surface of the upper head of the testing machine. A small initial load was applied. The bottom plate was then adjusted by tapping on its corners with a mallet. If the bearing was uniform, the initial load was sustained. If the bearing was not uniform, the load dropped. Then load was applied again and the bottom plate tapped. This procedure was continued until no drop in initial load occurred. Screw jacks in the form of bolts were then placed under the corners of the lower bearing plate to prevent its tilting during the test. The load was applied until failure occurred.

The heavy specimens were tested in the same manner except that no spherical bearing was used. The ends of these specimens were brought to bear uniformly by using paper shims.

Methods used to test the coupons are described in detail in the appendix of this report.

Computation of Results

In order to compare the buckling stress of a stiffened shell to the theoretical buckling stress of an unstiffened shell the buckling constant k was computed for each specimen.

The buckling stress of a long plywood cylinder under axial compression is given by the formula:³

$$p = k E_L \frac{h}{r}$$

where E_L = modulus of elasticity of the veneers of the plywood, measured parallel to the grain.

h = thickness of plywood.

r = radius of curvature of cylinder.

³This is formula (1) of Forest Products Laboratory Report No. 1322.

If p_p and p_s denote the stress in the plywood shell and the stress in the stiffeners, respectively, and if it is assumed that deformations in the plywood shell and stiffeners are equal until buckling occurs,

$$p_p = \frac{PE_p}{E_s A_s + E_p A_p} \quad (1) \quad \begin{array}{l} \text{(col. 20, table 1)} \\ \text{(col. 19, table 2)} \end{array}$$

$$\text{and } p_s = \frac{PE_s}{E_s A_s + E_p A_p} \quad (2) \quad \begin{array}{l} \text{(col. 21, table 1)} \\ \text{(col. 20, table 2)} \end{array}$$

where P = load on the specimen.

E_s = compressive modulus of elasticity of the stiffener in the axial direction.

E_p = compressive modulus of elasticity of the plywood in the axial direction.

A_p = cross-sectional area of plywood shell.

A_s = sum of cross-sectional areas of the stiffeners.

Values of E_s and E_p were determined from compression tests of coupons.

Then a value of k for any specimen can be found by the formula

$$k = \frac{p_p r}{E_L h} \quad (3) \quad \begin{array}{l} \text{(col. 22, table 1)} \\ \text{(col. 21, table 2)} \end{array}$$

Values of E_L were determined from bending tests of coupons, and values of p_p from equation (1).

If the specimen is so short that $\frac{l}{r} z < 1.5$, the buckling constant will be higher than for a long specimen. In this inequality

l = length of specimen.

$$z = \left(\frac{E_2}{E_1} \right)^{1/4}, \text{ where}$$

E_1 = bending modulus of elasticity of the plywood in the axial direction.

E_2 = bending modulus of elasticity of the plywood in the circumferential direction.

The effect of length on the buckling stress of unstiffened cylinders is discussed in Forest Products Laboratory Report No. 1514 (revised). The curve of that report showing $\frac{k}{k_p}$ for values of $\left(\frac{l}{r} z \right)$ is repeated as figure 1 in this

report. In order to compare values of buckling constants for short specimens, k_D was computed by dividing the value of k as determined by formula 3 by the ratio of $\frac{k}{k_D}$ for the corresponding value of $\frac{l}{r}$ given by figure 1. The only short specimens were several of those having Sitka spruce stiffeners. Data for these are given in table 1.

In order to obtain a comparison with unstiffened shells of the same weight, the buckling stresses and buckling loads of equivalent unstiffened cylinders were computed by the following formulas:

$$p_p \text{ equiv.} = 0.115 E_L \frac{(A_s + A_p)}{2\pi r^2} \quad (4) \quad \begin{array}{l} \text{(col. 25, table 1)} \\ \text{(col. 23, table 2)} \end{array}$$

$$P \text{ equiv.} = 0.115 E_L \frac{(A_s + A_p)^2}{2\pi r^2} \quad (5) \quad \begin{array}{l} \text{(col. 26, table 1)} \\ \text{(col. 24, table 2)} \end{array}$$

These formulas are obtained from formula (1) of Forest Products Laboratory Report No. 1322. They assume that the stiffeners are replaced by material added to the original shell so that the cross-sectional area is the same as that of the total area of the stiffened specimen. Thus the equivalent

thickness is $\frac{A_s + A_p}{2\pi r}$. The mean radius of curvature is assumed to be the same as that of the stiffened shell. The modulus of elasticity E_L is also assumed to be that of the stiffened shell. The constant $k = 0.115$ is that obtained from Forest Products Laboratory Report No. 1322 for all plywood having values of $\frac{E_1}{E_1 + E_2}$ greater than 0.20 but less than 0.80.

Presentation of Results

The results of the tests are presented in tabular and graphical form.

Table 1 contains the data obtained from tests of cylinders of yellow-poplar plywood stiffened with Sitka spruce stiffeners. Table 2 contains the data from tests of yellow birch plywood cylinders stiffened with yellow birch veneer, plywood, or solid-wood stiffeners. The values presented are averages of observed and computed values of groups of specimens. In addition to information relating to dimensions of the specimens, buckling loads, and the like, the tables contain the computed shell and stiffener stresses, the buckling constant k , the computed stresses of an equivalent unstiffened cylinder, ratios of the buckling load of an equivalent cylinder to that of the stiffened specimen, and compressive proportional-limit stresses of the shell and stiffener material. The computed values were obtained by using the formulas previously presented. They were computed for each specimen and then averaged, thus the tabulated values will not necessarily be obtained exactly if average observed values are used in the computations.

Graphs showing the buckling constant plotted against the parameter $\frac{s^2}{hrz}$, where s is the space between the stiffeners, are presented in figures 2, 3, 4, 5, 6, 7, and 8. Figure 2 shows the constant k_{xy} for yellow-poplar plywood cylinders stiffened with Sitka spruce stiffeners. Figures 3 to 8 show the constant k for yellow birch plywood cylinders stiffened with 1/48-inch veneers, 1/32-inch veneers, 1/24-inch veneers, 1/16-inch veneers, 1/8-inch plywood, and 1/4- by 3/8-inch, 1/2, by 1/2-inch, and 1/2- by 1-inch birch stiffeners, respectively.

Figure 9 shows frequency-distribution curves for the buckling constants of the stiffened yellow birch plywood cylinders in compression. The number of occurrences of values of k are plotted versus the values of k for each different size of stiffener, and for all stiffeners.

Discussion of Results

Behavior of Specimens Under Test

The plywood of all of the specimens buckled between the stiffeners. This buckling occurred suddenly and involved most of the shell.

If the stiffeners were less than 1/8 inch thick the stiffener also buckled and additional compressing in the testing machine increased the depth of the buckles until failure appeared in the plywood or stiffeners or both. The load after initial buckling continued to decrease as further compression occurred.

The specimens having heavier stiffeners exhibited buckles between the stiffeners; but it was not always apparent whether the buckles grew and involved the stiffeners, because the failure was of an explosive kind that shattered the entire specimen. Compression failures were found in several of the stiffeners. Some of the specimens with heavy stiffeners carried loads greater than the load at which initial buckling occurred. The performance after initial buckling, see figures 10 and 11, was an increase in the depth of the initial buckles and also the formation of larger buckles involving several stiffeners (figs. 12 and 13). Failure occurred by a tearing of the plywood at the stiffener or by a breaking of several stiffeners.

Discussion of Data

The cylindrical shell between the stiffeners will tend to buckle in a manner similar to that of a complete cylinder as described in Forest Products Laboratory Report No. 1322-A, but the buckling will be restrained by the presence of the stiffeners. If the spacing between the stiffeners is sufficiently great to allow the formation of complete natural buckles, the critical stress will be equal to that of a complete cylinder, as is given by Report No. 1322. For more closely spaced stiffeners, an increase in critical stress might be expected.

The following discussion of the expected increase is based on the curves shown in figure 14, which is a reproduction of figures 10 to 13, inclusive, of Report No. 1322-A. The ordinates of these curves are proportional to the critical stresses, and the abscissas ξ are proportionate amplitudes of the buckles. It is assumed in Report No. 1322-A that the plywood shells are not perfect cylinders, but were originally buckled, and that the amplitudes of the original buckles are proportional to ξ_0 . A family of curves is drawn in each graph, each curve of which represents a certain size of buckle and is designated by a particular value of

$$\eta = 4\pi \frac{hr}{b^2},$$

in which b is the width of the buckle, h is the thickness of the plywood, and r is the radius of the cylinder. The critical stress associated with each value of η is the minimum value of the stress indicated by the corresponding curve. Four different families of curves are shown, one for each of four values of ξ_0 .

It is evident from these four families of curves that the critical stress of complete cylinders of the plywood for which the curves were drawn, is given by $\frac{pr}{E_L h} = 0.095$, since this is the minimum value of the envelopes of the families of curves; that is, the critical stress of a complete cylinder is independent of the original amplitude, ξ_0 , of the buckles. The value of η associated with the critical stress is 0.35 in all of these families, since this value yields a minimum, and the width of the natural buckle is, therefore, given by $0.35 = 4\pi \frac{hr}{b^2}$.

Now, if the space between the stiffeners, s , is greater than the value of b given by this equation, there should be room for natural buckles to form between the stiffeners, and the critical stress will be that of an unstiffened cylinder. However, if the space between the stiffeners is less than b , the size of the buckles will be limited, η will have a value greater than 0.35, and the critical stress will be given by the minimum value of $\frac{pr}{E_L h}$ determined on the curve associated with this greater value of η . An examination of the four families of curves shown in figure 14 indicates that a considerable increase of critical stress may be expected if the original amplitude of the buckles, ξ_0 , is small but practically no increase if ξ_0 is large.

This discussion indicates that the effect of stiffener spacing can best be shown by plotting $k = \frac{pr}{E_L h}$ against the parameter $\frac{s^2}{hr}$. Such plots indicated that this parameter should be divided by the aspect ratio $z = \left(\frac{E_2}{E_1}\right)^{1/4}$; therefore, the parameter $\frac{s^2}{hrz}$ was employed in figures 2 to 8, inclusive.

These figures indicate that, with the exception of the cylinders stiffened with the 1/8-inch plywood stiffeners, very little increase in the critical stress was obtained by the use of stiffeners except for very close spacings. It seems probable that the differential swelling between the wood stiffeners and the plywood cylinders caused original waves of sufficient amplitude to yield this result. The plywood stiffeners were of the same construction as the plywood of the cylinders, and, therefore, differential swelling did not occur. It is possible, also, that the lighter stiffeners did not limit the buckle size as sharply as the heavy stiffeners.

The ordinates of figures 2 to 8, inclusive, are values of $k = \frac{pr}{E_L h}$ corrected by means of figure 1 to the proper values for long cylinders. Thus for large values of $\frac{s^2}{hr^2}$, the values of k should agree with values for unstiffened cylinders. The agreement obtained is shown by comparing the position of the plotted points with the short horizontal lines drawn in the figures. These lines are drawn at positions indicating the values for unstiffened cylinders as obtained from Report No. 1322. The agreement is shown more clearly by the frequency curves of figure 9. The value of k for unstiffened cylinders is 0.115.

The variation in the experimental results can be expected to be large because of the presence of small local imperfections in the cylinders tested. This matter is discussed in Reports Nos. 1322, 1322-A, and 1322-B.

A comparison was made between the critical loads obtained from the tests of the stiffened cylinders and critical loads computed for unstiffened cylinders of the same weights as the stiffened ones. The critical loads of the unstiffened cylinders were computed according to equation (5). In this computation a value of k of 0.115 was employed as a good average value for the types of plywood that would normally be used. The last column of tables 1 and 2 gives the ratios of the critical loads of the unstiffened cylinders to those of the stiffened cylinders. Average values of these ratios, taken from table 2, for cylinders stiffened with stiffeners of different depths are as follows:

Stiffener depth-in.	1/48	1/32	1/24	1/16	1/8	3/8	1/2	1
Average values of ratios	0.93	1.04	1.12	1.24	1.55	1.69	2.30	2.21

These average values indicate that higher critical loads can, in general, be obtained by the use of unstiffened cylinders than by the use of stiffened cylinders. The plywood of which the stiffened cylinders were made was of 1:2:1 construction (core twice as thick as one of the faces) with face grain circumferential. The slight advantage over unstiffened cylinders of the cylinders stiffened with stiffeners 1/48 inch deep, is probably similar to the advantage over cylinders of 1:2:1 construction of cylinders made of plywood for which the stiffness in the axial direction is equal to that in the circumferential direction.

Conclusions

The buckling stress of the curved sheet between the stiffeners of a stiffened thin-walled plywood cylinder may be taken to be the same as that of the same cylinder without stiffeners. If the stiffeners are very closely spaced the value of the stress determined by the method described in this report will be conservative.

An unstiffened cylinder of the same weight and curvature and, therefore, of a greater thickness than the stiffened cylinder, will in general, buckle at a load equal to or greater than that applied to the stiffened cylinder.

APPENDIX

Testing of Minor Coupons

Bending Specimens

Bending specimens 1 inch wide were tested on a span length 48 or more times the thickness of the specimen for face-grain directions parallel to the span and 24 or more times the thickness for face-grain directions perpendicular to the span, so that the necessity of correcting the deflection for transverse shearing deformations was eliminated. The ends of the specimens rested on supports rounded to about 1/16-inch radius. The load was applied through a 1/4-inch-diameter bar placed at the center of the span. Specimens having their face-grain directions parallel to the span were tested on an apparatus that measured the load by means of a platform scale reading to 1/100 pound. The rate of loading and driving force was obtained from a testing machine on which the scale was mounted. Specimens having their face-grain direction perpendicular to the span were tested on an apparatus that used water as a load. The load increments could be measured to 10 grams.

Load-deflection curves were plotted as the test was run. Immediately after testing, a sample was cut from the specimen for moisture-content determination. Properties computed from test data were the modulus of elasticity and moisture content.

Compression Specimens

The plywood compression specimens were 1 inch wide and 4 inches long with the face-grain direction oriented the same with respect to the direction of the applied load as it was to the corresponding part of the cylindrical shell. Because of the thinness of the specimen, an apparatus consisting of thin spring fingers was used to give lateral support. The deformation was

measured over a 2-inch gage length with a Marten's mirror apparatus. Load-deformation data were recorded as the test was made. Properties computed from the test data were the modulus of elasticity, the compressive stress at proportional-limit load, the compressive strength, and the moisture content.

The stiffener compression specimens were 4 inches long. The veneer stiffener specimens were made as described in "Description of Specimens." They were tested in the same apparatus as were the plywood coupons. Coupons of the heavy stiffeners were tested without the lateral-support apparatus.

Table 2. ¹ Effects of different concentrations of the growth regulator on the growth of the plants.

[illegible]

Table 2.--2000 yellow perch *perca flavescens* and white perch *morone americana* in the Chesapeake Bay and Potomac River, Maryland, 1999-2000. (continued)

[illegible]

Table 2.—Stiffness of yellow birch plywood in axial compression — yellow birch plyforms (continued)

Spec. length of ply, in.	Number of stiffeners	Span between stiffeners, in.	Buckling load, lb.	Modulus of elasticity, lb./sq. in.	Shell				Stiffener				Shell stress at buckling, lb./sq. in.	Stiffener stress at buckling, lb./sq. in.	$\frac{E}{E_s}$	Equivalent stress at buckling, lb./sq. in.	P equiv., lb.
					Thick-ness, in.	Radius of curvature, in.	Area, sq. in.	Modulus of elasticity, lb./sq. in.	Depth, in.	Area, sq. in.	Modulus of elasticity, lb./sq. in.	Stress, lb./sq. in.					
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
206	24	4	4,100	4,100	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
207	24	4	4,200	4,200	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
208	24	4	4,300	4,300	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
209	24	4	4,400	4,400	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
210	24	4	4,500	4,500	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
211	24	4	4,600	4,600	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
212	24	4	4,700	4,700	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
213	24	4	4,800	4,800	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
214	24	4	4,900	4,900	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
215	24	4	5,000	5,000	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
216	24	4	5,100	5,100	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
217	24	4	5,200	5,200	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
218	24	4	5,300	5,300	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
219	24	4	5,400	5,400	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
220	24	4	5,500	5,500	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
221	24	4	5,600	5,600	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
222	24	4	5,700	5,700	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
223	24	4	5,800	5,800	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
224	24	4	5,900	5,900	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
225	24	4	6,000	6,000	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
226	24	4	6,100	6,100	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
227	24	4	6,200	6,200	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
228	24	4	6,300	6,300	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
229	24	4	6,400	6,400	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
230	24	4	6,500	6,500	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
231	24	4	6,600	6,600	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
232	24	4	6,700	6,700	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
233	24	4	6,800	6,800	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
234	24	4	6,900	6,900	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
235	24	4	7,000	7,000	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
236	24	4	7,100	7,100	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
237	24	4	7,200	7,200	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
238	24	4	7,300	7,300	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
239	24	4	7,400	7,400	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
240	24	4	7,500	7,500	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
241	24	4	7,600	7,600	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
242	24	4	7,700	7,700	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
243	24	4	7,800	7,800	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
244	24	4	7,900	7,900	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
245	24	4	8,000	8,000	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
246	24	4	8,100	8,100	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
247	24	4	8,200	8,200	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
248	24	4	8,300	8,300	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
249	24	4	8,400	8,400	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
250	24	4	8,500	8,500	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
251	24	4	8,600	8,600	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
252	24	4	8,700	8,700	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
253	24	4	8,800	8,800	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
254	24	4	8,900	8,900	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334
255	24	4	9,000	9,000	0.037	3.11	2,119	7.8	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334	1,334

Improved of four plies of 1/16-inch yellow birch veneer; grain direction of face ply circumferential, grain of core ply axial, same equivalent to three-ply lami construction.

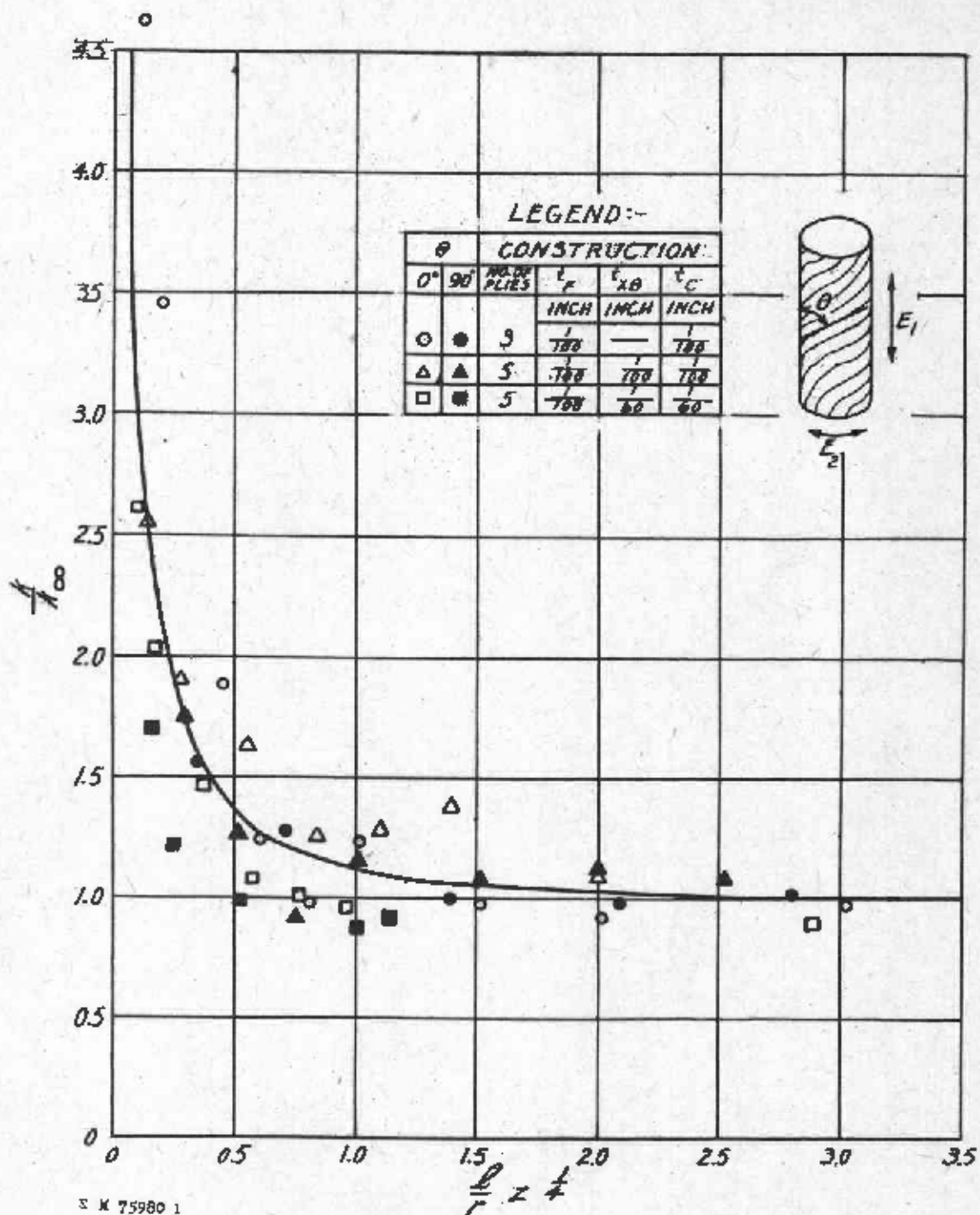
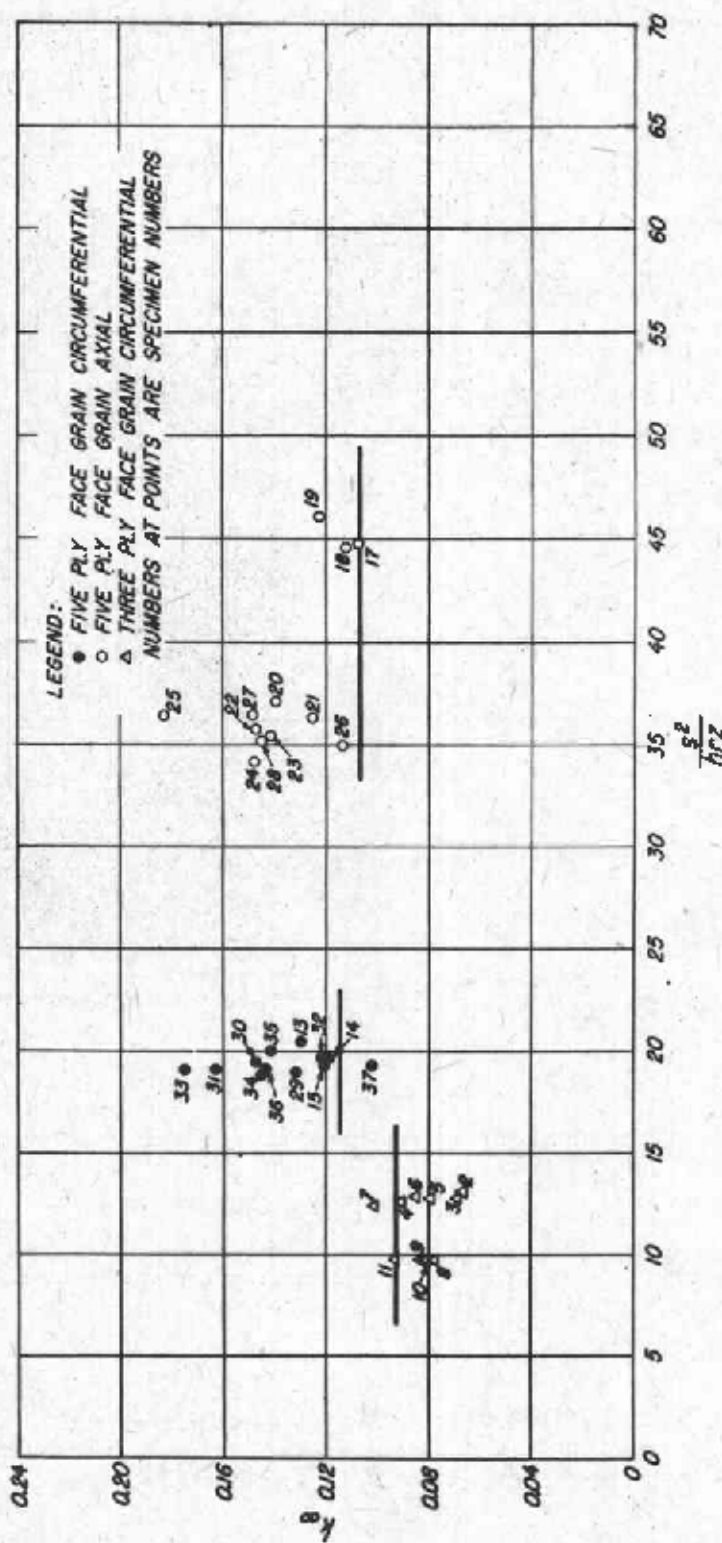


Figure 1.--The effect of length of specimen on the buckling constant for thin plywood cylinders in axial compression. Each point represents three test specimens.



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Figure 2.--Buckling constants for yellow-poplar plywood cylinders having 8thm spruce stiffeners.

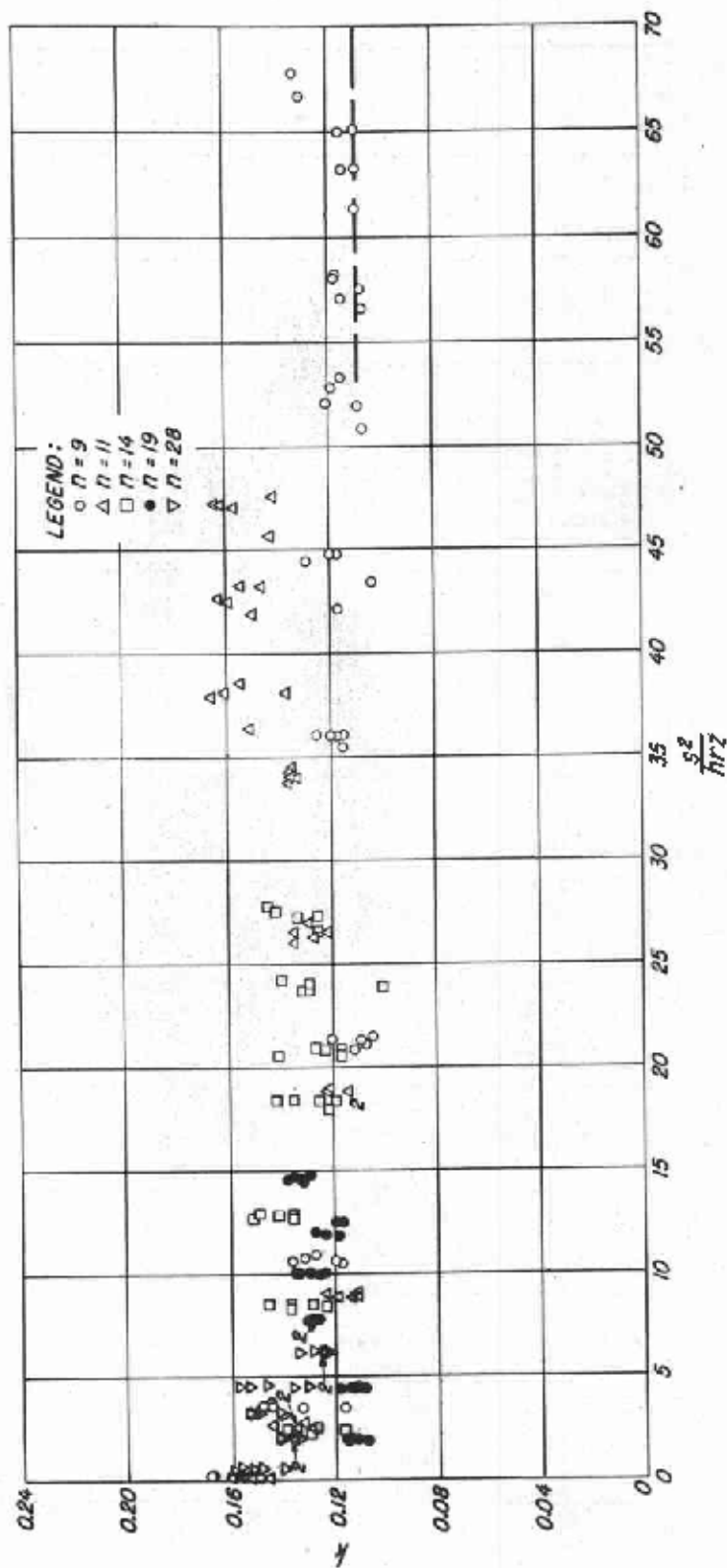


Figure 3.--Buckling constants for yellow birch plywood cylinders having yellow birch stiffeners 1/48 inch thick.

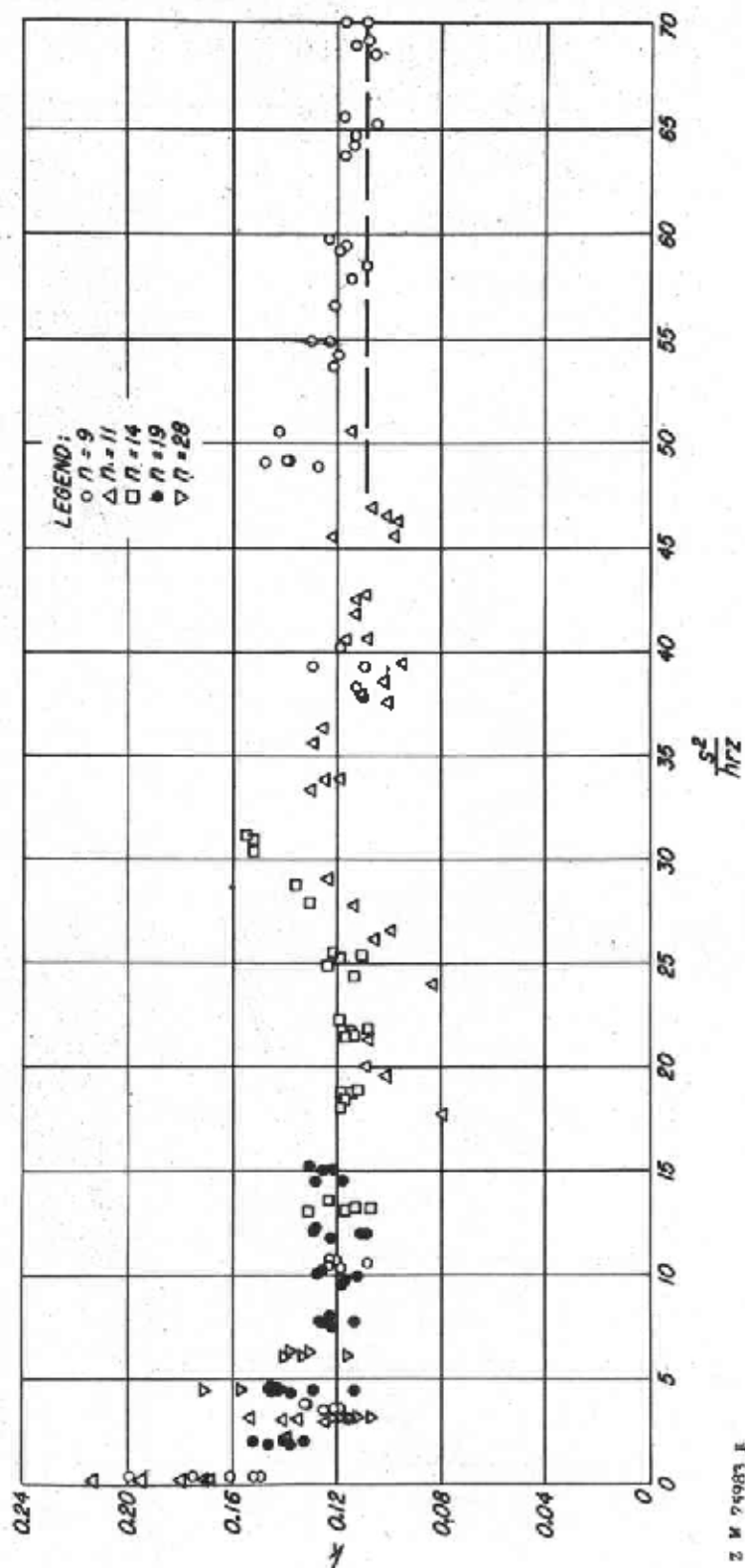


Figure 4.--Buckling constants for yellow birch plywood cylinders having yellow birch stiffeners 1/32 inch thick.

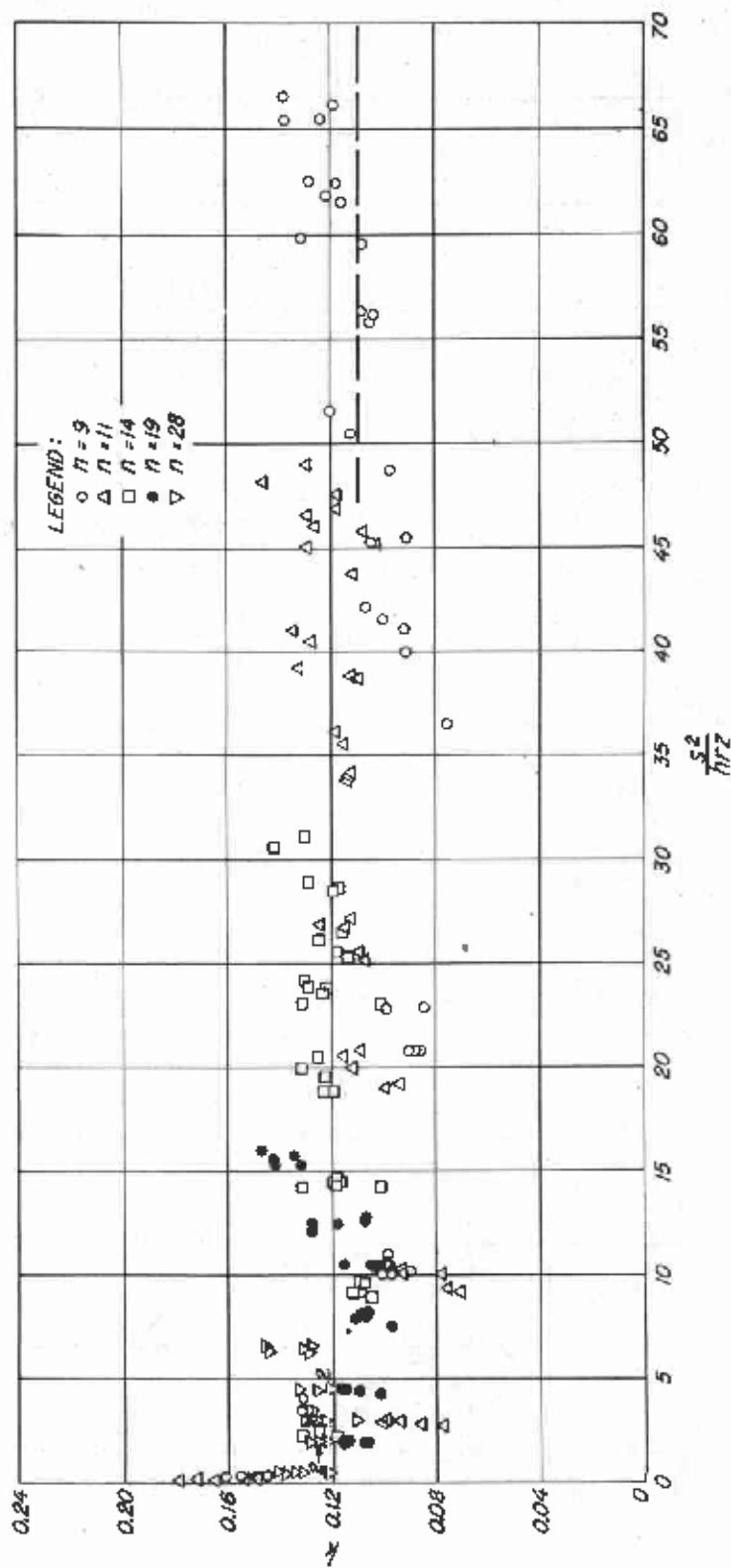
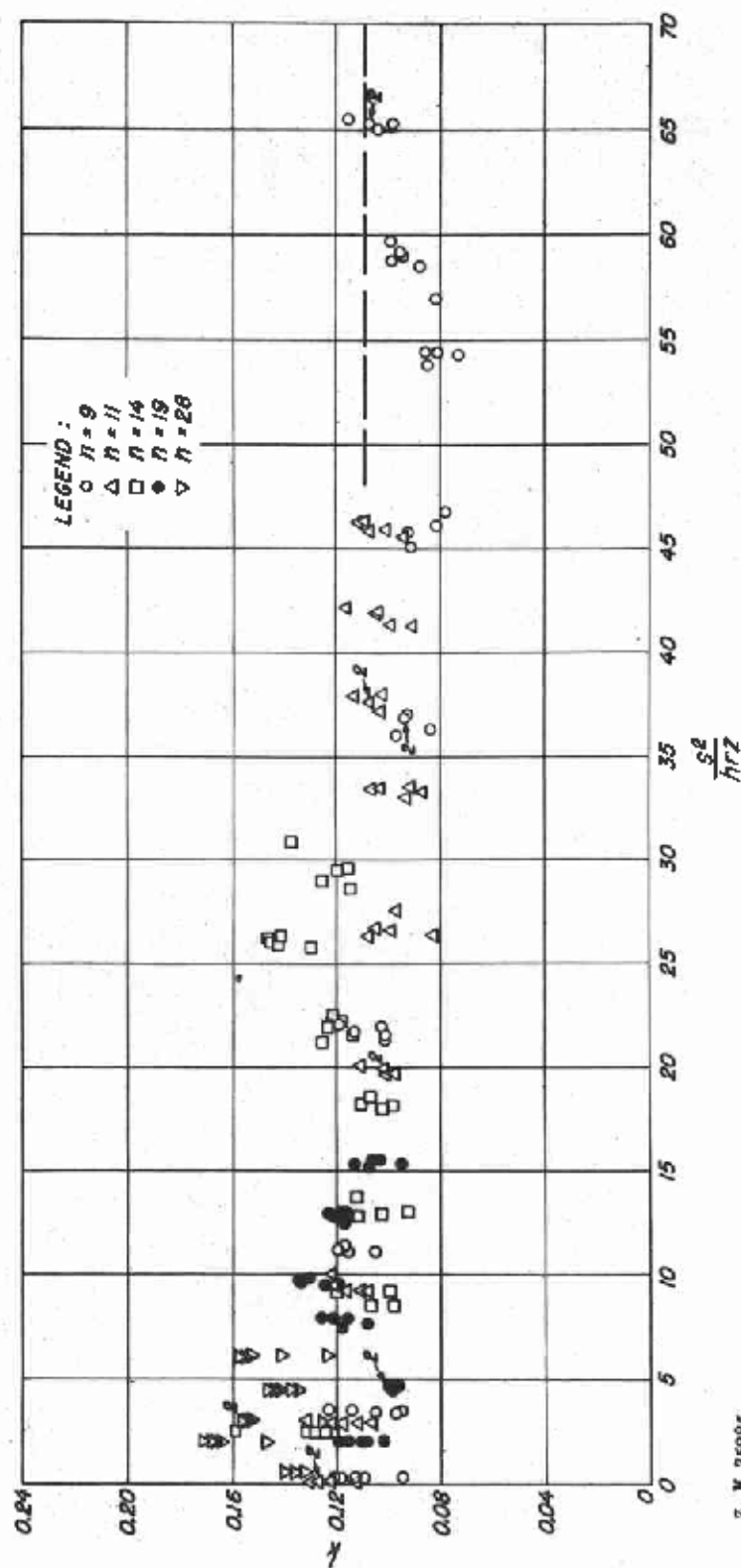


Figure 5.--Buckling constants for yellow birch plywood cylinders having yellow birch stiffeners 1/24 inch thick.



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Figure 6.--Buckling constants for yellow birch plywood cylinders having yellow birch stiffeners 1/16 inch thick.

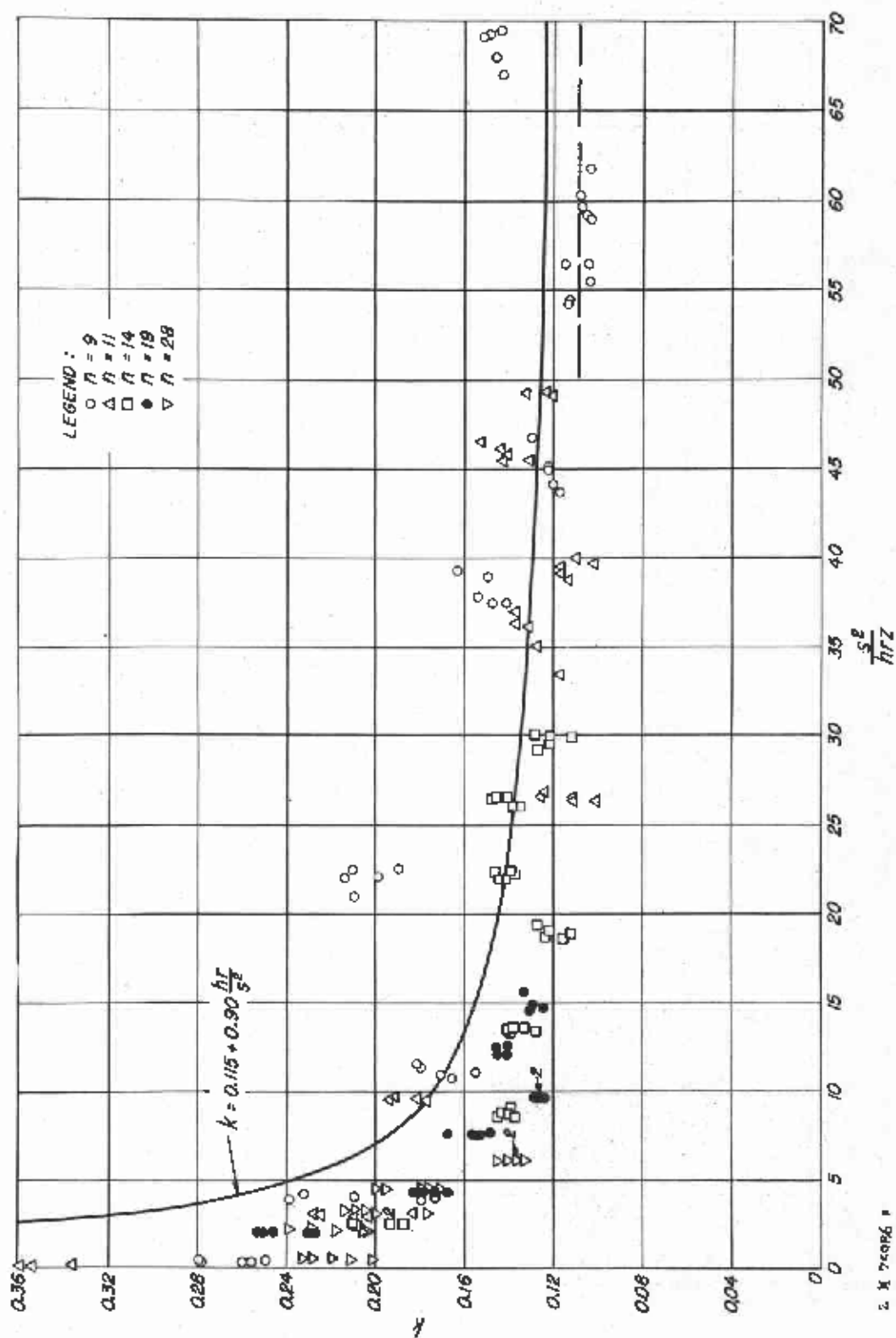


Figure 7.--Buckling constants for yellow birch plywood cylinders having yellow birch plywood stiffeners 1/8 inch thick.

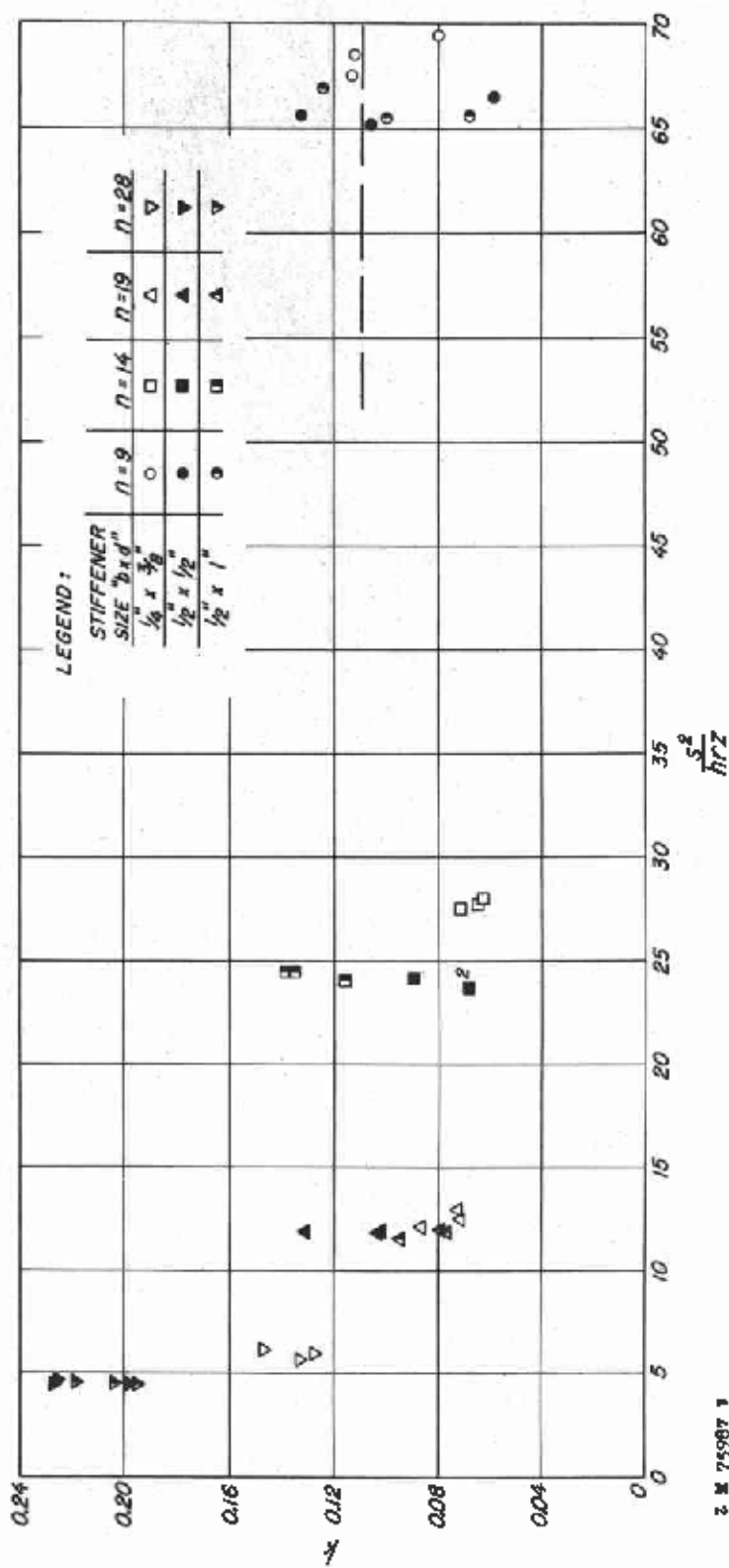
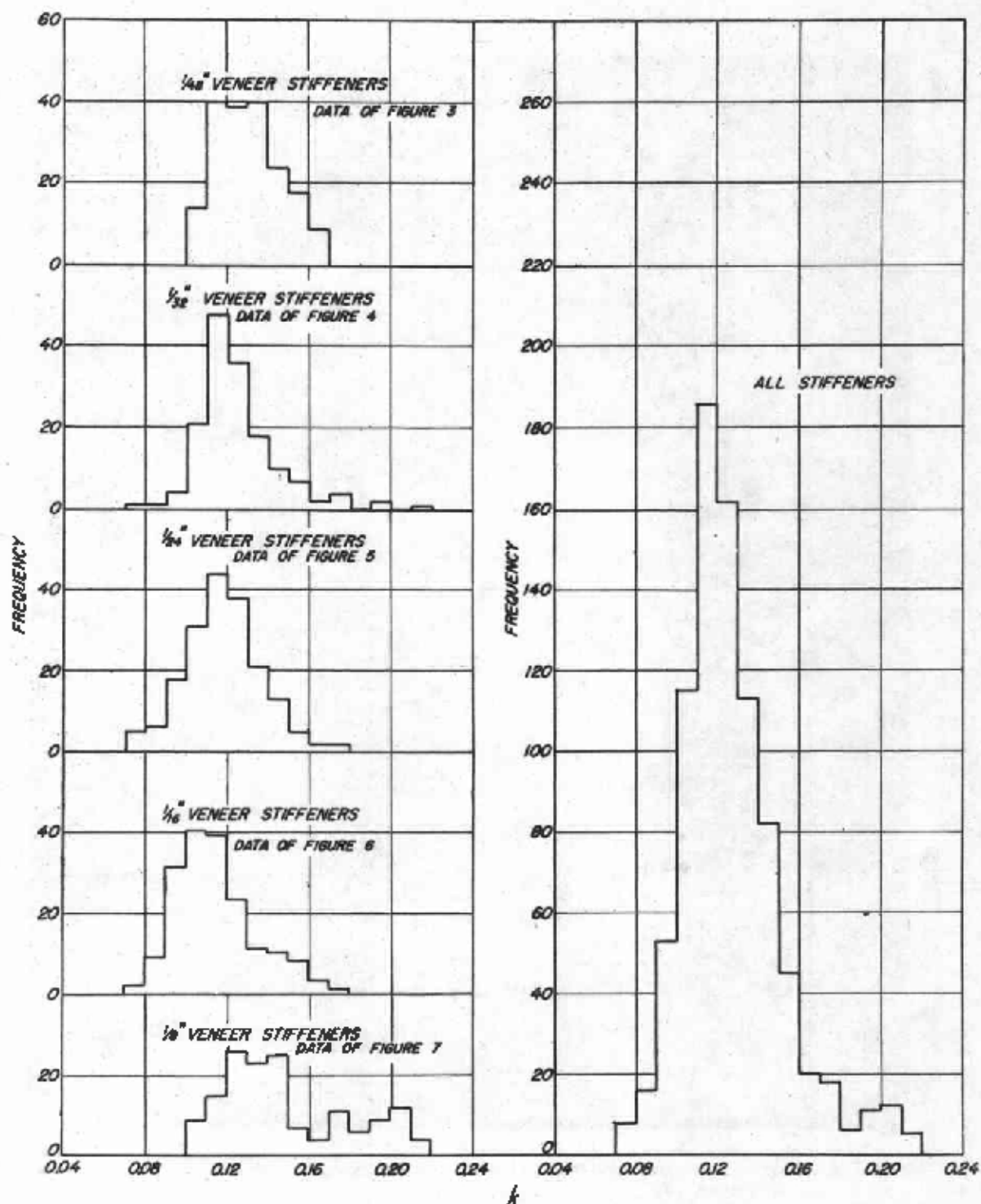


Figure 8.--Buckling constants for yellow birch plywood cylinders having heavy yellow birch stiffeners.



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Figure 9.--Distribution of buckling constants for stiffened yellow birch plywood cylinders in compression.

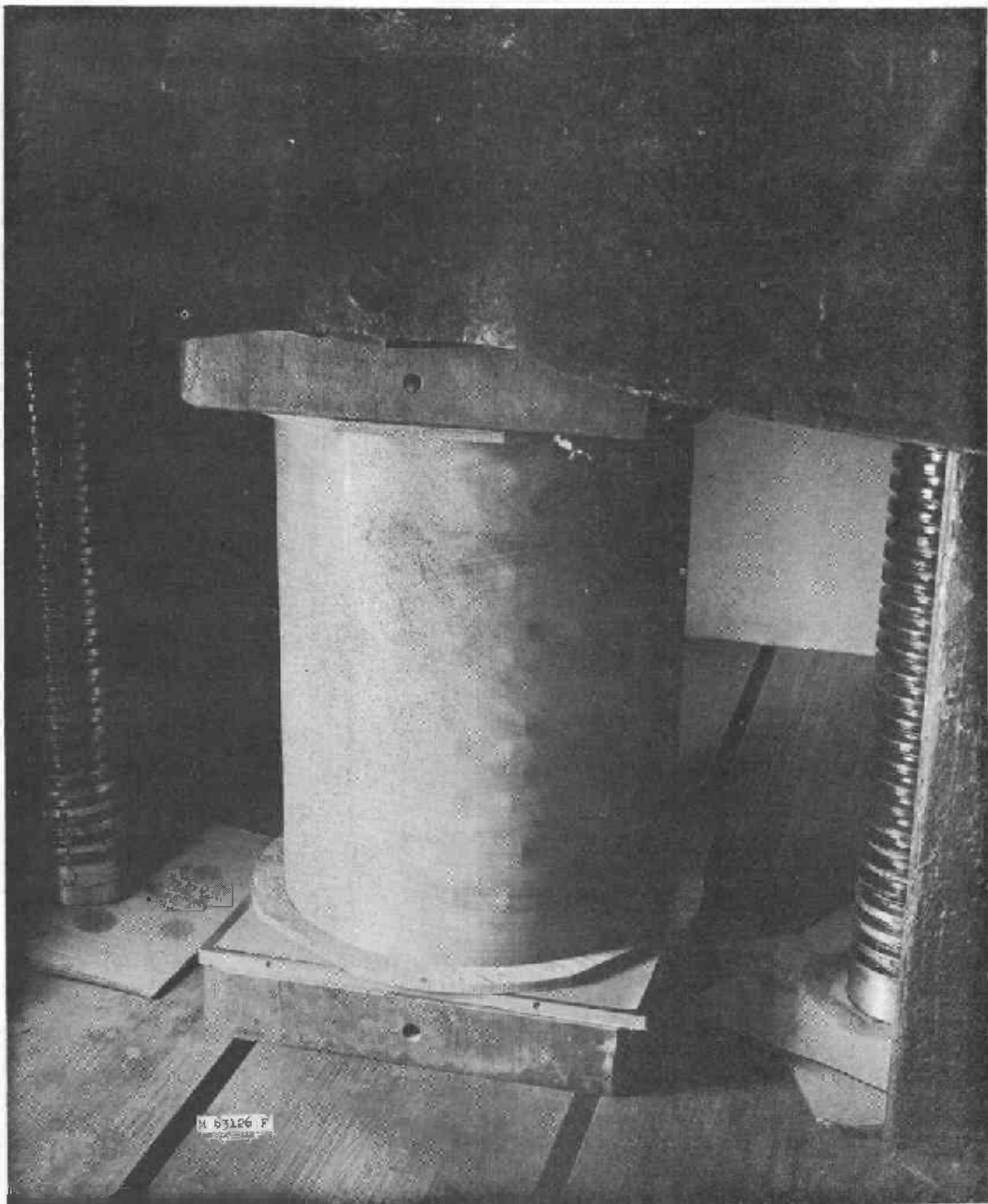


Figure 10.--Initial buckling of a plywood cylinder having
nineteen 1- by 1/2-inch stiffeners.

Z M 77256 F

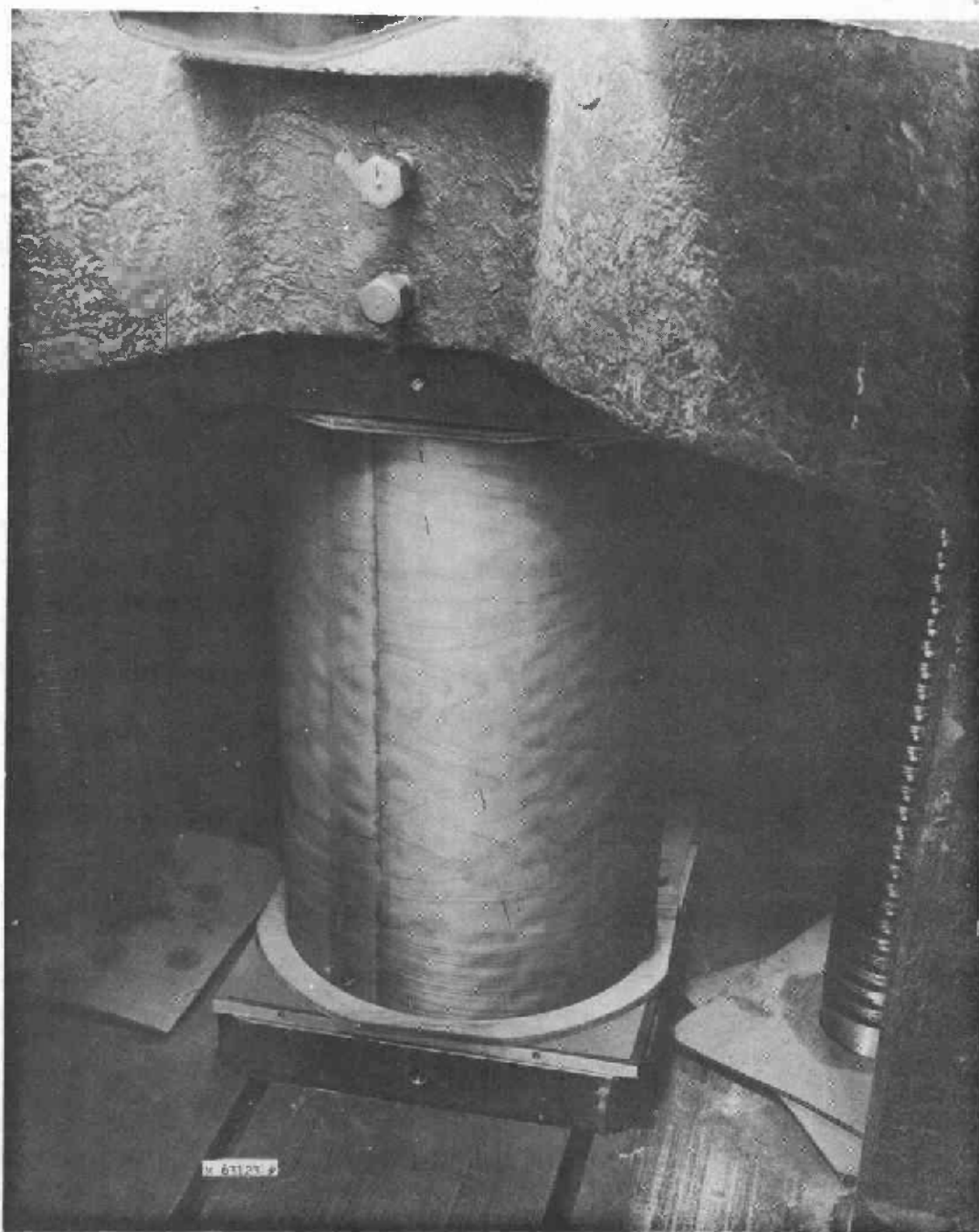


Figure 11.--Initial buckling of a plywood cylinder having twenty-eight 1- by 1/2-inch stiffeners.

Z N 77257 F

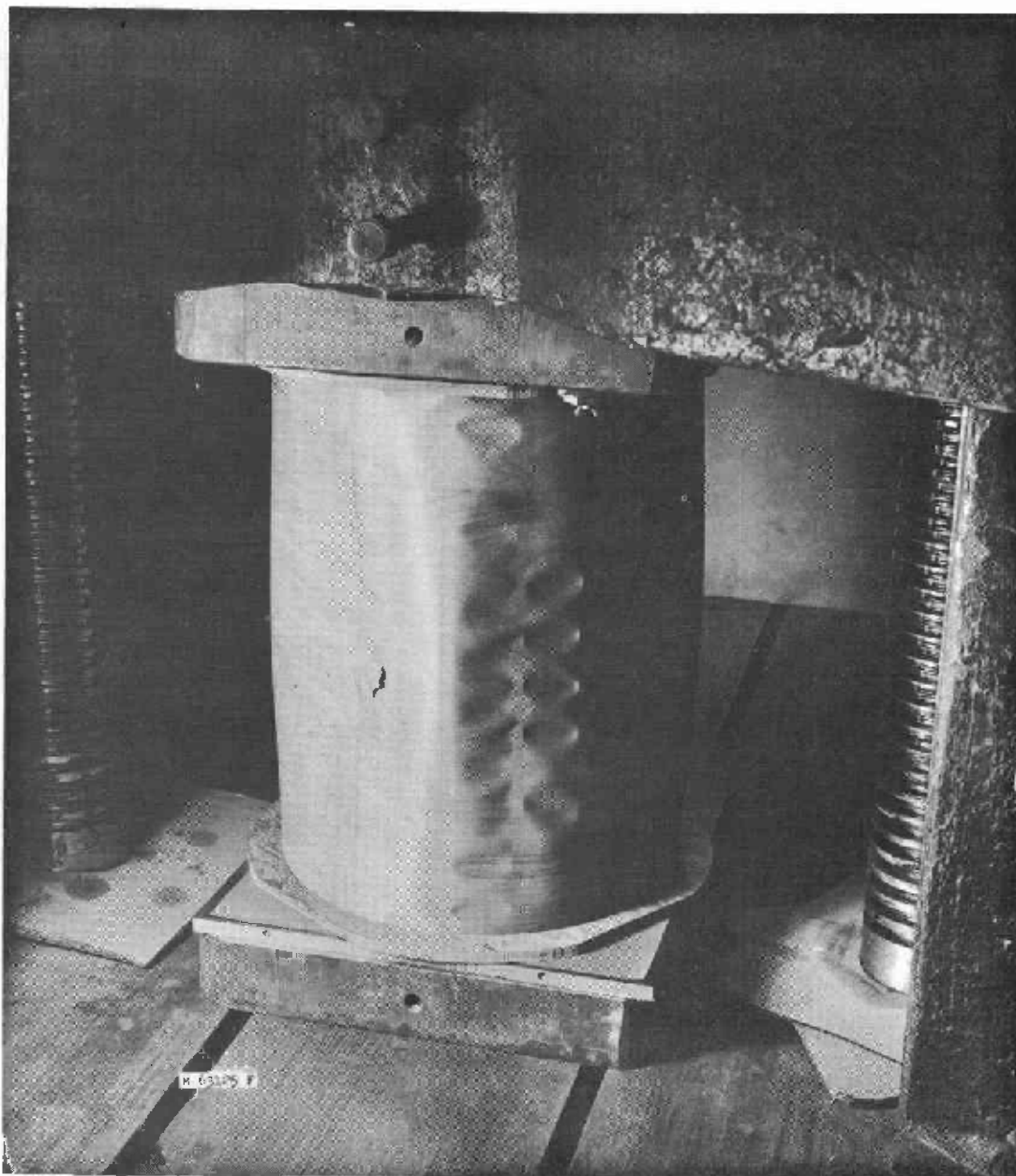


Figure 12.--Failure of specimen shown in figure 10. Note the appearance of large buckles.

2 M 77258 F

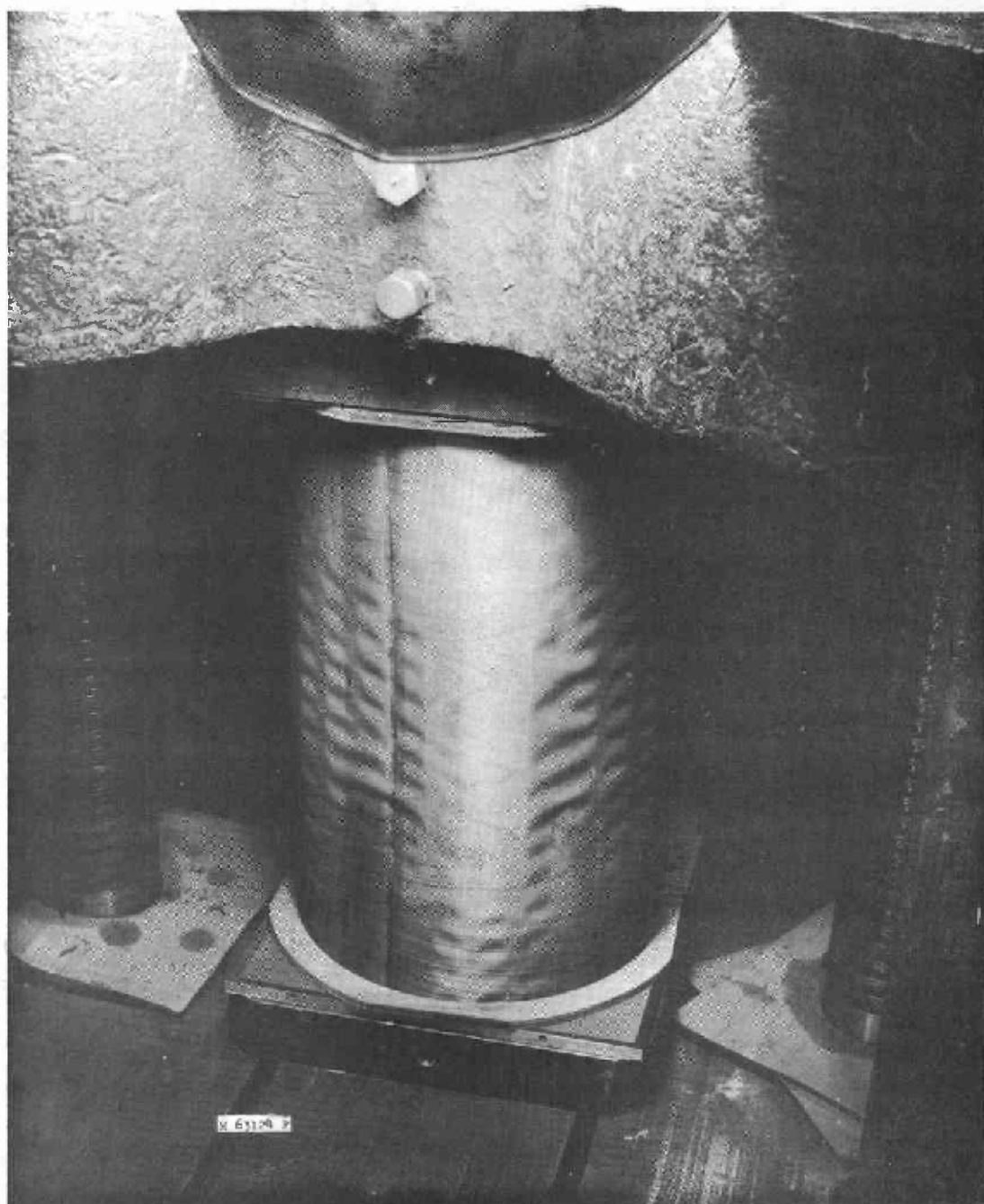


Figure 13.--Failure of specimen shown in figure 11. Note the appearance of large buckles.

2 M 77259 F

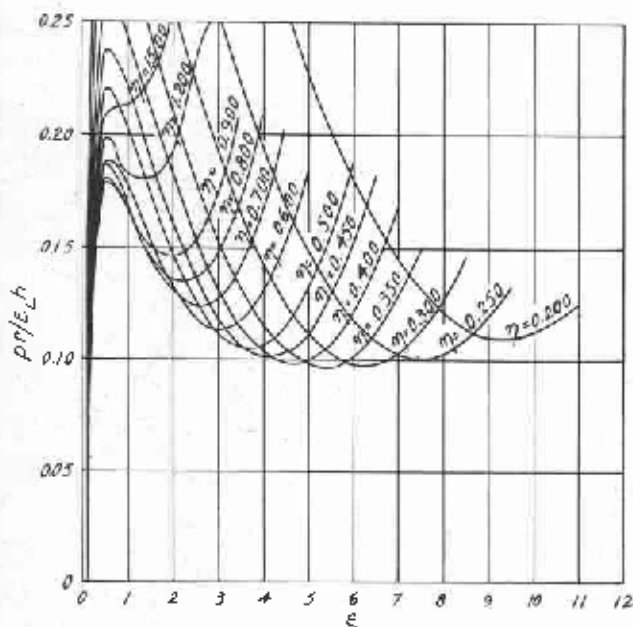


Figure 10.—Three-ply (1:2:1) cylinder. Face plies axial. $\xi_0 = 0.1$.

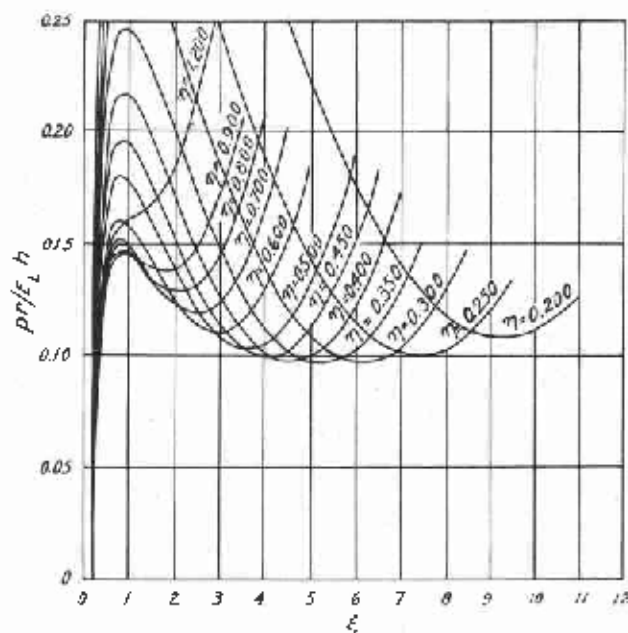


Figure 11.—Three-ply (1:2:1) cylinder. Face plies axial. $\xi_0 = 0.2$.

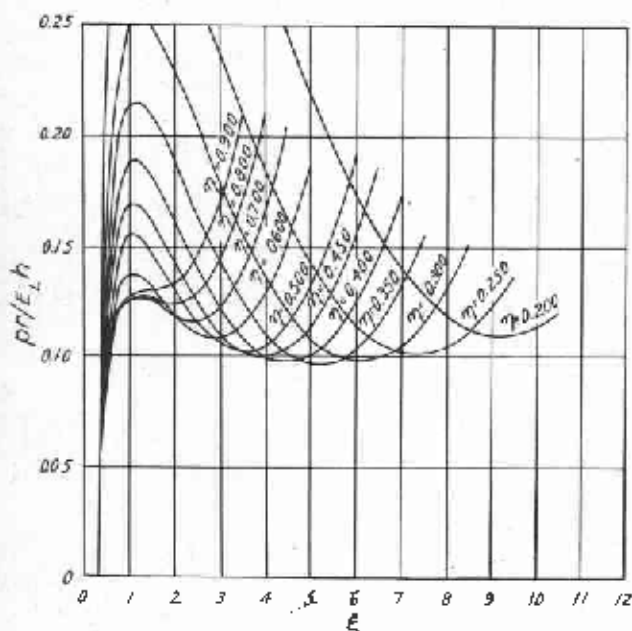


Figure 12.—Three-ply (1:2:1) cylinder. Face plies axial. $\xi_0 = 0.3$.

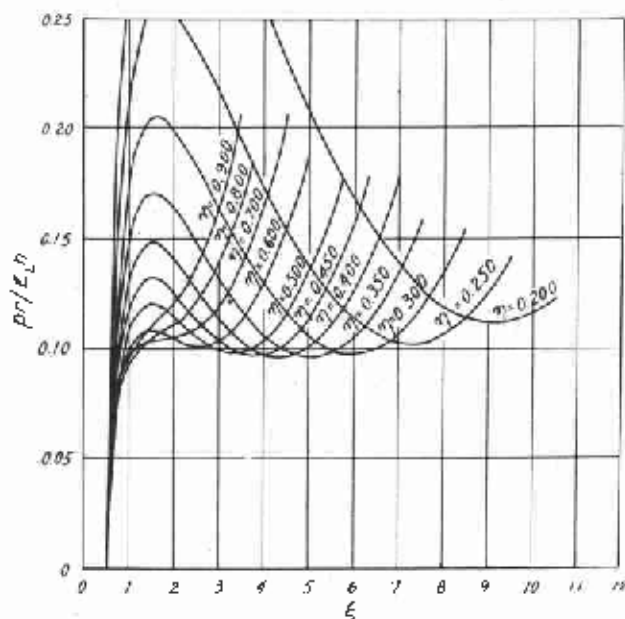


Figure 13.—Three-ply (1:2:1) cylinder. Face plies axial. $\xi_0 = 0.5$.

Figure 14.—A reproduction of figures 10-13 of Forest Products Laboratory Report No. 1322-A.