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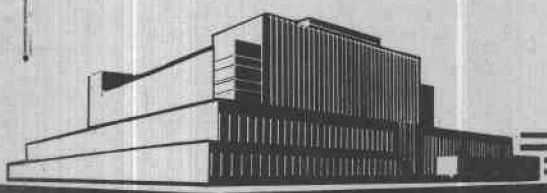

FOREST PRODUCTS LABORATORY
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UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE
In Cooperation with the University of Wisconsin

EFFECT OF LENGTH ON THE BUCKLING STRESSES OF THIN-WALLED, PLYWOOD CYLINDERS IN AXIAL COMPRESSION[1]

By

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Summary

This report presents the data and analysis of results of tests performed at the Forest Products Laboratory on short, thin-walled, plywood cylinders loaded in axial compression. The results of tests of long specimens, which have been presented in Forest Products Laboratory Report No. 1322-B, show that a cylinder having a length greater than its diameter exhibited buckling characteristics similar to those theoretically assumed to be correct for specimens of infinite length (Forest Products Laboratory Reports Nos. 1322 and 1322-A). This report presents an empirical design curve for plywood cylinders of lengths shorter than the diameters. This curve is to be used in conjunction with the design curves of Forest Products Laboratory Report No. 1322.

Description of Specimens

All specimens were of yellow birch or yellow-poplar plywood made of aircraft-grade veneers rotary cut at the Forest Products Laboratory. About

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[1] This progress report is one of a series prepared and distributed by the Forest Products Laboratory under U.S. Navy, Bureau of Aeronautics No. NBA-PO-NAer 00565, and Army Air Force No. AAF-PO-(33-038) 46-1189. Results here reported are preliminary and may be revised as additional data become available. Original report issued October 1944.

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

180 cylinders were tested, including plywood constructed with face-grain directions axial, circumferential, or at 45° to the axis of the specimen. Two diameters of cylinders were investigated, and lengths of specimens ranged from 1-1/2 times the diameter to 1/20 of the diameter. Three specimens were tested for each combination of length, diameter, construction, and orientation of grain.

Flat plates of plywood made of veneers cut adjacent to the veneers used in making the corresponding cylinders furnished material for minor specimens that were tested in bending, compression, and tension. No attempt was made to match veneers among cylinders of different sizes or constructions.

All plywood (cylinders and flat plates) was made by bonding the veneers with a film glue, set in a hot press.

No attempt was made to condition the specimens to a particular moisture content other than to keep them in the testing laboratory for about a week before testing. The specimens all had approximately 4 percent moisture content.

The plywood cylinders were manufactured by bending a flat plywood plate around a mandrel. Prior to their forming, the plywood was scarfed and moistened to facilitate bending. It was then bent around the mandrel, and the scarf joint glued with a thermosetting synthetic resin glue.

The ends of the cylinders were trimmed square and true in a turning lathe prior to testing and fitted with plywood end blocks, 1/4 inch thick, to maintain the circular shape of the ends. The end blocks fitted snugly, but were not otherwise fastened to the cylinders. They were placed about 1/16 inch from the ends of the cylinder.

Testing Methods

All cylinders were tested in a hydraulic testing machine. The top of the specimen was allowed to bear against the flat machined surface of the upper head of the testing machine, and the bottom rested on a flat machined plate mounted on a spherical bearing on the lower head. The spherical bearing was adjusted until uniform bearing was assured on the top and bottom of the cylinder, after which screw jacks were placed under the corners of the bottom plate to prevent tilting. During the test the load was applied at a slow, uniform rate until failure occurred.

Immediately after failure the end plugs were removed from the cylinder, the entire cylinder was weighed, and a small section was sawed out for moisture content determination. Tests of minor specimens are discussed in the appendix.

Results of Tests

In general, the primary failure of all cylinders was by localized buckling. The critical buckling load was often evidenced by a sudden failure in which many indentations or buckles appeared at the same moment at different points on the cylinder. If the specimen was longer than the length of a buckle, several rows of indentations appeared; in shorter cylinders only a single row of buckles appeared. A rapid drop in load occurred immediately. Many of the shorter specimens failed by buckling, which was followed immediately by breaking. This was observed in some instances in specimens having $\frac{L}{\sqrt{hr}} \left(\frac{E_2}{E_1}\right)^{1/4}$ ratios less than about 4.

Presentation of Results

The buckling constants for each cylinder tabulated in table 1 were computed by the formula

$$k = \frac{pr}{E_L h}$$

where: p = buckling stress in pounds per square inch.

E_L = modulus of elasticity parallel to the grain of the wood in the veneers of the plywood in pounds per square inch.

h = plywood thickness in inches.

r = mean radius of cylinder in inches.

The buckling stress was obtained by dividing the test buckling load by the cross-sectional area of the plywood shell.

Values of E_L were obtained from test data on minor coupons as follows: Tests of the plywood in bending, compression, and tension furnished data for calculating the E_1, E_2, E_a, and E_b of the plywood where:

E_1 = bending modulus of elasticity of the plywood with the face-grain direction parallel to the span.

E_2 = bending modulus of elasticity of the plywood with the face-grain direction perpendicular to the span.

E_a = compression or tension modulus of elasticity of the plywood with the face-grain direction parallel to the direction of the applied load.

E_b = compression or tension modulus of elasticity of the plywood with the face-grain direction perpendicular to the direction of the applied load.

The results of minor tests are tabulated in table 2. From the relations

$$E_1 + E_2 = E_a + E_b = E_L + E_T = E_L(1 + C)$$

the value for E_L can be calculated by assuming that the ratio of $\frac{E_T}{E_L}$ or (C) is equal to 0.037[3] for yellow-poplar and 0.045[3] for yellow birch.

Theoretical values for the buckling constant, k_∞, for cylinders of infinite length are obtained from entering the curve of figure 1 with the appropriate $\frac{E_1}{E_1 + E_2}$ ratio. This curve was presented in Forest Products Laboratory Report No. 1322, "The Buckling of Long, Thin, Plywood Cylinders in Axial Compression."

In figure 2 the average value of $\frac{k}{k_\infty}$ is plotted against the average value of $\frac{L}{\sqrt{hr}} \left(\frac{E_2}{E_1}\right)^{1/4}$ for each group of three specimens having face-grain directions axial or circumferential. The parameter $\frac{L}{\sqrt{hr}} \left(\frac{E_2}{E_1}\right)^{1/4}$ was obtained from the theory for long cylinders in compression.[4] This theory showed that the buckling constant k depended upon values of η (equation 48 or Report No. 1322-A), where

$$\eta = n\frac{2h}{r}$$

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[3]These ratios were from tests and were reported in Forest Products Laboratory Report No. 1304, "Methods of Computing the Strength and Stiffness of Plywood Strips in Bending."

[4]Forest Products Laboratory Report No. 1322-A.

but

$$n = \frac{2\pi r}{b}, \quad b = \text{width of the buckle.}$$

Then

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

The aspect ratio of the buckle is $Z = (\frac{E_2}{E_1})^{1/4}$. Therefore, if L is the length of the buckle, then $b = L(\frac{E_2}{E_1})^{1/4}$ and $\eta = \frac{4\pi^2 hr}{L^2}(\frac{E_1}{E_2})^{1/2}$. For convenience, the parameter was chosen to be $\frac{L}{\sqrt{hr}}(\frac{E_2}{E_1})^{1/4}$.

The smooth curve in figure 2 is an empirical curve drawn to represent the average of the plotted points. The data is also presented in figure 3 plotted against the parameter $\frac{L}{r}(\frac{E_2}{E_1})^{1/4}$.

In computing ratios of $\frac{E_1}{E_1 + E_2}$ or $(\frac{E_2}{E_1})^{1/4}$, E_1 is the bending stiffness of the plywood measured parallel to the axis of the cylinder, and E_2 is the bending stiffness in the circumferential direction.

A theoretical analysis for cylinders having face-grain directions at 45° to the axis has not been worked out. In Forest Products Laboratory Report No. 1322, the buckling constants for such cylinders were found to be the averages of those for specimens with face grain axial and face grain circumferential.

This relationship was applied to this length-effect study as follows. The theoretical buckling constant for long cylinders was obtained from figure 1, with the face-grain direction assumed to be axial ($\theta = 0°$). The ratio $(\frac{E_2}{E_1})^{1/4}$ for this axial grain was multiplied by the $\frac{L}{\sqrt{hr}}$ ratio for the 45° specimen and a value of $\frac{k}{k_\infty}$ obtained from the smooth curve of figure 2. Multiplying $\frac{k}{k_\infty}$ by k_∞ from figure 1 gave a value of $k_\theta = 0°$. Through the same procedure a value $k_\theta = 90°$ was obtained for a cylinder with its face-grain direction assumed to be circumferential ($\theta = 90°$). The value of k_{theor} for a short cylinder with face grain at 45° was then the average of $k_\theta = 0°$ and $k_\theta = 90°$. Figure 4 shows the ratio of

$\frac{k_{obs}}{k_\infty}$ plotted against ratios of $\frac{k_{theor}}{k_\infty}$. The values of k_∞ were taken to be the averages of the $k_\theta = 0°$ and $k_\theta = 90°$ for cylinders of infinite length.

Discussion of Results

Although the points representing test results as plotted in figures 2 and 3 show a great deal of scatter, this is to be expected and is attributed to the small initial imperfections that may cause early buckling and to variations in dimensions of the specimen and in mechanical properties of the material. These variations were pointed out in more detail in Forest Products Laboratory Report No. 1322-B.

The results of tests on specimens having the face grain at 45° are compared with calculated values in figure 4. The observed and calculated values agree closely for moderately short specimens ($\frac{L}{r}$ not less than about 0.5). For extremely short cylinders, the points fall below the theoretical line. This may be due to an inaccuracy of the smooth curve in figure 2, to the difficulty in picking a value on the very steep part of the curve, or to the fact that in some of the tests the plywood in the cylinders may have been stressed above the proportional-limit stress beyond which the theory no longer applies.

Conclusions

If the value of $\frac{L}{\sqrt{hr}}\left(\frac{E_2}{E_1}\right)^{1/4}$ is greater than 16, the buckling strengths of thin-walled plywood cylinders in axial compression can be computed by means of the theory developed in Forest Products Laboratory Report No. 1322-A. If the value is less than 16, the buckling strengths can be computed by using the smooth curve of figure 2.

Design Procedure

The following method can be used for designing plywood cylinders in axial compression.

Face-Grain Direction Axial or Circumferential

1. Knowing the length, diameter, thickness, and plywood construction, calculate E_1 and E_2, the ratio

$\frac{E_1}{E_1 + E_2}$, and the ratio $\frac{L}{\sqrt{hr}}\left(\frac{E_2}{E_1}\right)^{1/4}$. (Directions in which E_1 and E_2 are to be taken are indicated in sketch on fig. 2.)

2. Enter the curve of figure 1 with the ratio $\frac{E_1}{E_1 + E_2}$ and obtain the value of k_∞ for a cylinder of infinite length.

3. Enter the curve of figure 2 with the value $\frac{L}{\sqrt{hr}}\left(\frac{E_2}{E_1}\right)^{1/4}$ and obtain the value of $\frac{k}{k_\infty}$.

4. Multiply the value of k_∞ from figure 1 by the ratio $\frac{k}{k_\infty}$ from figure 2 and obtain k.

5. Using this k, compute the buckling stress of the cylinder by means of the formula $p = kE_L\frac{h}{r}$.

6. Compute the compressive stress at proportional limit[5] for the plywood and determine the ratio of computed buckling stress to proportional-limit stress. Enter the curve of figure 5 and determine the ratio of the design buckling stress to the proportional-limit stress.

Face-Grain Direction at 45°

1. Determine k for a cylinder having the face-grain direction axial and for a cylinder with circumferential face grain as outlined in steps 1 to 4 of the previous design procedure.

2. Average the $k_\theta = 0°$ and $k_\theta = 90°$ to obtain the $k_\theta = 45°$.

3. Using this $k_\theta = 45°$, compute the buckling stress of the cylinder by means of the formula $p = k_\theta = 45° E_L\frac{h}{r}$.

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[5]Forest Products Laboratory Report No. 1315.

4. Compute the compressive stress at proportional limit for the plywood and determine the ratio of computed buckling stress to proportional-limit stress. Enter the curve of figure 5 and determine the ratio of the design buckling stress to the proportional-limit stress.

APPENDIX

Tests of Minor Specimens

The bending specimens were 1 inch wide and were tested on a span length 48 or more times the thickness of the specimen for face-grain direction parallel to the span and 24 or more times for face-grain direction perpendicular to the span, which thus eliminated the necessity of correcting for shear deformation. The specimens rested on end supports rounded to about 1/16-inch radius. The load was applied at the center with a bar of about 1/8-inch radius. The stiffer specimens 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 the driving force were obtained from a testing machine on which the scale was mounted (fig. 6). Specimens not stiff enough to test on the platform-scale apparatus were tested on an apparatus that used water as a load. The load increments could be read to 10 grams, and the rate of loading was controlled by the size of nozzle (fig. 7).

Immediately after testing, a sample was cut from the specimen for moisture content determination. The specific gravity was obtained from measurements and weights taken before testing and subsequently corrected for moisture content. During the test, load-deflection curves were plotted. Properties computed from the test data were the modulus of elasticity, the fiber stress on the most remote fiber at the proportional-limit load, the modulus of rupture, the moisture content, and the specific gravity. Because the specimen was sometimes pulled down between the supports and wood failure did not occur, the modulus of rupture could not always be computed.

The tension specimens were 1 inch wide and 11 inches long with face-grain directions parallel and perpendicular to the direction of the load. The ends of the specimens were gripped in Templin grips fastened to the testing machine by bolts passed through spherical bearings. The strain over a 2-inch gage length was measured at the center of the specimen with an extensometer reading to 0.0001 of an inch (fig. 8). The rate of loading was 0.05 inch per minute. During the test, load-deformation curves were plotted. Properties computed from the test data were the modulus of elasticity, the moisture

content, and the specific gravity. Moisture content and specific gravity were determined as they were for the bending specimens.

The compressive specimens were 1 inch wide and 4 inches long with face-grain directions parallel and perpendicular to the direction of the load. Because of the thinness of the specimen, an apparatus consisting of thin spring fingers was used to give lateral support (fig. 9). The strain was measured over a 2-inch gage length with a Marten's mirror apparatus. Load-deformation curves were plotted as the test was run. Properties computed from the test data were the modulus of elasticity, the compressive stress at the proportional-limit load, the moisture content, and the specific gravity. The moisture content and specific gravity were determined as they were for the bending specimens.

Table 1.--Test data for thin plywood cylinders in axial compression

Specimen number	Species[1]	Plywood construction: θ	Number of plies	Ply thicknesses: F	XB	C	Moisture content	Specific gravity	Plywood thickness h	Outside diameter 2r+h	Length L	Buckling load P	Buckling stress p	E_L^2	k
		Degrees		Inch	Inch	Inch	Percent		Inch	Inch	Inch	Pounds	Lb. per sq. in.	1,000 lb. per sq. in.	
CL1-1	YP	0	5	0.01	0.01	0.01	3.6	0.40	0.053	10.7	15.0	4,100	2,320	2,095	0.111
2	YP	0	5	.01	.01	.01	4.0	.39	.051	10.7	15.0	4,005	2,340	2,095	.117
3	YP	0	5	.01	.01	.01	3.3	.40	.049	10.8	15.0	3,790	2,300	2,095	.120
Av.															.116
CL2-1	YP	0	5	.01	.01	.01	3.7	.43	.050	10.7	10.0	4,890	2,920	2,050	.151
2	YP	0	5	.01	.01	.01	4.0	.44	.048	10.7	10.0	4,580	2,850	2,050	.154
3	YP	0	5	.01	.01	.01	3.8	.40	.052	10.7	10.0	4,730	2,720	2,050	.135
Av.															.147
CL3-1	YP	0	5	.01	.01	.01	3.8	.38	.053	10.7	8.0	4,740	2,670	1,990	.134
2	YP	0	5	.01	.01	.01	4.0	.40	.051	10.7	8.0	4,540	2,660	1,990	.139
3	YP	0	5	.01	.01	.01	3.9	.41	.050	10.7	8.0	4,060	2,430	1,990	.130
Av.															.134
CL4-1	YP	0	5	.01	.01	.01	4.0	.40	.050	10.7	6.0	4,270	2,560	1,990	.137
2	YP	0	5	.01	.01	.01	4.1	.39	.052	10.7	6.0	4,350	2,500	1,990	.128
3	YP	0	5	.01	.01	.01	3.8	.41	.050	10.7	6.0	4,310	2,580	1,990	.138
Av.															.134
CL5-1	YP	0	5	.01	.01	.01	3.8	.42	.050	10.7	4.0	5,360	3,210	1,990	.172
2	YP	0	5	.01	.01	.01	3.5	.43	.049	10.7	4.0	5,090	3,110	1,990	.170
3	YP	0	5	.01	.01	.01	3.5	.44	.049	10.7	4.0	5,290	3,230	1,990	.176
Av.															.173
CL6-1	YP	0	5	.01	.01	.01	3.8	.38	.054	10.7	2.0	7,320	4,060	1,990	.200
2	YP	0	5	.01	.01	.01	3.4	.39	.053	10.7	2.0	7,010	3,960	1,990	.199
3	YP	0	5	.01	.01	.01	3.8	.39	.052	10.7	2.0	6,900	3,970	1,990	.203
Av.															.201
CL7-1	YP	0	5	.01	.01	.01	3.3	.41	.051	10.7	1.0	9,105	5,340	1,990	.279
2	YP	0	5	.01	.01	.01	3.3	.30	.051	10.7	1.0	9,155	5,370	1,990	.281
3	YP	0	5	.01	.01	.01	4.0	.47	.052	10.7	1.0	8,360	4,810	1,990	.246
Av.															.269
CL8-1	YP	90	5	.01	.01	.01	4.7	.40	.050	10.7	15.0	3,470	2,070	2,130	.104
2	YP	90	5	.01	.01	.01	3.7	.40	.052	10.7	15.0	3,760	2,160	2,130	.104
3	YP	90	5	.01	.01	.01	3.7	.41	.050	10.7	15.0	3,890	2,330	2,130	.117
Av.															.108
CL9-1	YP	90	5	.01	.01	.01	3.8	.41	.051	10.7	10.0	3,910	2,300	2,000	.120
2	YP	90	5	.01	.01	.01	3.8	.40	.050	10.7	10.0	4,000	2,400	2,000	.128
3	YP	90	5	.01	.01	.01	3.8	.40	.051	10.7	10.0	4,210	2,470	2,000	.129
Av.															.126
CL10-1	YP	90	5	.01	.01	.01	4.3	.40	.051	10.7	8.0	4,320	2,540	2,075	.128
2	YP	90	5	.01	.01	.01	3.7	.42	.048	10.7	8.0	4,030	2,510	2,075	.134
3	YP	90	5	.01	.01	.01	3.8	.39	.049	10.7	8.0	3,710	2,260	2,075	.118
Av.															.127
CL11-1	YP	90	5	.01	.01	.01	3.6	.38	.050	10.7	6.0	4,170	2,490	2,075	.128
2	YP	90	5	.01	.01	.01	3.6	.37	.050	10.7	6.0	4,110	2,460	2,075	.126
3	YP	90	5	.01	.01	.01	3.5	.38	.053	10.7	6.0	4,360	2,460	2,075	.119
Av.															.124
CL12-1	YP	90	5	.01	.01	.01	3.6	.41	.052	10.7	4.0	4,860	2,800	2,080	.137
2	YP	90	5	.01	.01	.01	3.6	.41	.052	10.7	4.0	4,360	2,510	2,080	.123
3	YP	90	5	.01	.01	.01	3.5	.43	.050	10.7	4.0	4,570	2,730	2,080	.140
Av.															.133

Table 1.--Test data for thin plywood cylinders in axial compression (continued)

Specimen number	Species[1]	Plywood construction: θ	Number of plies	Ply thicknesses: F	XB	C	Moisture content	Specific gravity	Plywood thickness h	Outside diameter 2r+h	Length L	Buckling load P	Buckling stress p	R_L^2	k
		Degrees		Inch	Inch	Inch	Percent		Inch	Inch	Inch	Pounds	Lb. per sq. in.	1,000 lb. per sq. in.	
CL13-1	YP	90	5	.01	.01	.01	3.8	.42	.050	10.7	2.0	5,105	3,050	2,080	.156
2	YP	90	5	.01	.01	.01	3.3	.42	.050	10.7	2.0	4,710	2,800	2,080	.143
3	YP	90	5	.01	.01	.01	3.8	.42	.049	10.8	2.0	4,415	2,680	2,080	.140
Av.															.146
CL14-1	YP	90	5	.01	.01	.01	3.8	.41	.048	10.8	1.0	6,010	3,720	2,080	.199
2	YP	90	5	.01	.01	.01	3.3	.44	.047	10.8	1.0	6,365	4,030	2,080	.220
3	YP	90	5	.01	.01	.01	4.2	.42	.049	10.8	1.0	5,700	3,460	2,080	.181
Av.															.200
CL15-1	YB	45	5	.01	.01	.01	3.5	.63	.052	18.2	30.0	6,150	2,080	3,315	.109
2	YB	45	5	.01	.01	.01	3.4	.65	.051	18.1	30.0	6,150	2,120	3,315	.113
3	YB	45	5	.01	.01	.01	3.5	.60	.053	18.0	30.0	6,100	2,040	3,315	.104
Av.															.109
CL16-1	YB	45	5	.01	.01	.01	3.4	.63	.052	18.2	10.0	6,400	2,160	3,390	.111
2	YB	45	5	.01	.01	.01	3.4	.65	.051	18.2	10.0	6,600	2,270	3,390	.119
3	YB	45	5	.01	.01	.01	3.4	.66	.050	18.3	10.0	6,600	2,310	3,390	.124
Av.															.118
CL17-1	YB	45	5	.01	.01	.01	3.4	.64	.050	18.2	8.0	6,980	2,460	3,390	.131
2	YB	45	5	.01	.01	.01	3.5	.68	.051	18.1	8.0	6,800	2,340	3,390	.123
3	YB	45	5	.01	.01	.01	3.4	.61	.052	18.1	8.0	6,820	2,310	3,390	.119
Av.															.124
CL18-1	YB	45	5	.01	.01	.01	3.5	.69	.049	18.2	6.0	6,000	2,150	3,390	.117
2	YB	45	5	.01	.01	.01	3.6	.75	.050	18.2	6.0	6,400	2,250	3,390	.120
3	YB	45	5	.01	.01	.01	3.2	.62	.048	18.1	6.0	5,600	2,050	3,390	.114
Av.															.117
CL19-1	YB	45	5	.01	.01	.01	3.6	.70	.048	18.1	4.0	8,280	3,040	3,390	.169
2	YB	45	5	.01	.01	.01	3.9	.68	.049	18.2	4.0	7,840	2,810	3,390	.153
3	YB	45	5	.01	.01	.01	3.8	.67	.049	18.1	4.0	7,640	2,740	3,390	.149
Av.															.157
CL20-1	YB	45	5	.01	.01	.01	4.1	.69	.048	18.1	2.0	9,000	3,300	3,390	.183
2	YB	45	5	.01	.01	.01	3.8	.72	.047	18.1	2.0	8,900	3,330	3,390	.189
3	YB	45	5	.01	.01	.01	4.1	.69	.047	18.1	2.0	8,180	3,060	3,390	.174
Av.															.182
CL21-1	YB	45	5	.01	.01	.01	3.2	.69	.048	18.1	1.0	15,100	5,540	3,390	.308
2	YB	45	5	.01	.01	.01	3.5	.69	.048	18.1	1.0	12,500	4,590	3,390	.255
3	YB	45	5	.01	.01	.01	3.1	.69	.048	18.1	1.0	13,600	4,990	3,390	.277
Av.															.280
CL22-1	YB	0	5	.01	.017	.017	3.4	.55	.068	18.3	30.0	9,060	2,330	2,845	.110
2	YB	0	5	.01	.017	.017	3.2	.55	.068	18.2	30.0	8,230	2,120	2,845	.099
3	YB	0	5	.01	.017	.017	3.5	.54	.069	18.3	30.0	8,220	2,080	2,845	.096
Av.															.102
CL23-1	YB	0	5	.01	.017	.017	3.4	.58	.065	18.3	10.0	8,340	2,240	2,800	.112
2	YB	0	5	.01	.017	.017									
3	YB	0	5	.01	.017	.017	3.3	.56	.067	18.3	10.0	8,800	2,300	2,800	.112
Av.															.112
CL24-1	YB	0	5	.01	.017	.017	3.5	.56	.067	18.3	8.0	9,200	2,400	2,800	.116
2	YB	0	5	.01	.017	.017	3.8	.62	.060	18.3	8.0	7,380	2,150	2,800	.117
3	YB	0	5	.01	.017	.017	3.4	.58	.065	18.3	8.0	8,400	2,260	2,800	.113
Av.															.115

Table 1.--Test data for thin plywood cylinders in axial compression (continued)

Specimen number	Species[1]	Plywood construction: θ	Number of plies	Ply thicknesses: F	XB	C	Moisture content	Specific gravity	Plywood thickness h	Outside diameter 2r+h	Length L	Buckling load P	Buckling stress p	$E_L t^2$	k
		Degrees		Inch	Inch	Inch	Percent		Inch	Inch	Inch	Pounds	Lb. per sq. in.	1,000 lb. per sq. in.	
CL25-1	YB	0	5	.01	.017	.017	3.4	.57	.066	18.2	6.0	9,280	2,460	2,800	.121
2	YB	0	5	.01	.017	.017	4.0	.61	.061	18.3	6.0	8,800	2,520	2,800	.135
3	YB	0	5	.01	.017	.017	3.2	.57	.066	18.3	6.0	8,800	2,330	2,800	.115
Av.															.124
CL26-1	YB	0	5	.01	.017	.017	3.7	.56	.066	18.2	4.0	12,400	3,290	2,800	.162
2	YB	0	5	.01	.017	.017	4.2	.60	.061	18.3	3.9	11,620	3,320	2,800	.177
3	YB	0	5	.01	.017	.017	3.6	.58	.065	18.3	3.9	12,700	3,410	2,800	.171
Av.															.170
CL27-1	YB	0	5	.01	.017	.017	4.0	.57	.064	18.2	2.0	16,700	4,560	2,800	.231
2	YB	0	5	.01	.017	.017	4.1	.62	.058	18.3	2.0	14,480	4,360	2,800	.245
3	YB	0	5	.01	.017	.017	3.9	.56	.065	18.3	2.0	16,620	4,470	2,800	.224
Av.															.233
CL28-1	YB	0	5	.01	.017	.017	3.0	.60	.062	18.2	1.0	20,700	5,850	2,800	.306
2	YB	0	5	.01	.017	.017	3.5	.61	.059	18.2	1.0	19,980	5,920	2,800	.327
3	YB	0	5	.01	.017	.017	2.8	.57	.066	18.3	1.0	20,000	5,300	2,800	.261
Av.															.298
CL29-1	YB	90	5	.01	.017	.017	3.6	.53	.070	18.3	30.0	8,800	2,200	2,785	.103
2	YB	90	5	.01	.017	.017	3.9	.53	.070	18.3	30.0	9,300	2,320	2,785	.108
3	YB	90	5	.01	.017	.017	3.9	.56	.069	18.3	30.0	9,500	2,410	2,785	.114
Av.															.108
CL30-1	YB	90	5	.01	.017	.017	3.5	.56	.067	18.2	10.0	8,740	2,280	2,810	.110
2	YB	90	5	.01	.017	.017	3.8	.63	.059	18.3	10.0	6,700	1,980	2,810	.109
3	YB	90	5	.01	.017	.017	3.0	.57	.066	18.3	10.0	8,440	2,240	2,810	.110
Av.															.110
CL31-1	YB	90	5	.01	.017	.017	3.6	.56	.067	18.2	8.0	8,900	2,330	2,810	.112
2	YB	90	5	.01	.017	.017	3.9	.61	.061	18.3	8.0	6,600	1,890	2,810	.101
3	YB	90	5	.01	.017	.017	3.6	.56	.067	18.3	8.0	8,610	2,250	2,810	.109
Av.															.107
CL32-1	YB	90	5	.01	.017	.017	3.7	.62	.067	18.2	6.0	8,720	2,280	2,810	.110
2	YB	90	5	.01	.017	.017	3.8	.61	.061	18.3	6.0	6,580	1,880	2,810	.100
3	YB	90	5	.01	.017	.017	3.4	.56	.067	18.2	6.0	8,640	2,260	2,810	.109
Av.															.106
CL33-1	YB	90	5	.01	.017	.017	4.1	.59	.067	18.2	4.0	9,220	2,410	2,810	.116
2	YB	90	5	.01	.017	.017	4.6	.61	.058	18.3	4.0	7,400	2,230	2,810	.125
3	YB	90	5	.01	.017	.017	4.4	.57	.066	18.3	4.0	8,740	2,320	2,810	.114
Av.															.118
CL34-1	YB	90	5	.01	.017	.017	4.2	.58	.067	18.2	2.0	11,120	2,910	2,810	.141
2	YB	90	5	.01	.017	.017	4.4	.56	.063	18.3	2.0	10,140	2,810	2,810	.145
3	YB	90	5	.01	.017	.017	4.4	.57	.066	18.2	2.0	11,240	2,980	2,810	.146
Av.															.144
CL35-1	YB	90	5	.01	.017	.017	3.2	.54	.066	18.2	1.0	15,100	4,010	2,810	.196
2	YB	90	5	.01	.017	.017	3.3	.60	.059	18.3	1.0	13,050	3,860	2,810	.212
3	YB	90	5	.01	.017	.017	3.4	.58	.065	18.2	1.0	14,750	3,970	2,810	.198
Av.															.202
CL36-1	YB	45	5	.01	.017	.017	3.3	.54	.069	18.3	30.0	8,980	2,280	2,710	.111
2	YB	45	5	.01	.017	.017	3.2	.54	.069	18.3	30.0	9,440	2,390	2,710	.117
3	YB	45	5	.01	.017	.017	3.1	.56	.067	18.3	29.9	8,850	2,310	2,710	.116
Av.															.115

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Table 1.--Test data for thin plywood cylinders in axial compression (continued)

Specimen number	Plywood construction: Species[1]	θ	Number of plies	Ply thicknesses: F	XB	C	Moisture content	Specific gravity	Plywood thickness h	Outside diameter 2r+h	Length L	Buckling load P	Buckling stress p	E_L^2	k
		Degrees		Inch	Inch	Inch	Percent		Inch	Inch	Inch	Pounds	Lb. per sq. in.	1,000 lb. per sq. in.	
CL37-1	YB	45	5	.01	.017	.017	3.2	.56	.067	18.3	10.0	9,220	2,410	2,640	.124
2	YB	45	5	.01	.017	.017	3.0	.57	.066	18.3	10.0	9,800	2,600	2,640	.136
3	YB	45	5	.01	.017	.017	3.0	.56	.067	18.3	10.0	9,960	2,600	2,640	.134
Av.															.131
CL38-1	YB	45	5	.01	.017	.017	3.1	.56	.067	18.3	8.0	9,540	2,490	2,640	.128
2	YB	45	5	.01	.017	.017	3.5	.55	.068	18.3	8.0	9,270	2,380	2,640	.121
3	YB	45	5	.01	.017	.017	3.4	.57	.066	18.3	8.0	9,900	2,620	2,640	.137
Av.															.129
CL39-1	YB	45	5	.01	.017	.017	3.2	.57	.066	18.3	6.0	9,800	2,600	2,640	.136
2	YB	45	5	.01	.017	.017	3.4	.56	.067	18.3	6.0	9,240	2,410	2,640	.124
3	YB	45	5	.01	.017	.017	3.4	.58	.065	18.3	6.0	10,400	2,800	2,640	.149
Av.															.136
CL40-1	YB	45	5	.01	.017	.017	3.5	.57	.066	18.3	4.0	11,000	2,910	2,640	.152
2	YB	45	5	.01	.017	.017	3.6	.57	.066	18.3	4.0	10,820	2,870	2,640	.150
3	YB	45	5	.01	.017	.017	3.5	.56	.066	18.3	4.0	11,200	2,960	2,640	.155
Av.															.152
CL41-1	YB	45	5	.01	.017	.017	3.9	.59	.063	18.2	2.0	12,600	3,500	2,640	.191
2	YB	45	5	.01	.017	.017	3.7	.58	.064	18.2	2.0	11,660	3,190	2,640	.172
3	YB	45	5	.01	.017	.017	3.6	.57	.064	18.3	2.0	11,740	3,210	2,640	.173
Av.															.179
CL42-1	YB	45	5	.01	.017	.017	2.4	.58	.065	18.2	1.0	18,680	5,030	2,640	.267
2	YB	45	5	.01	.017	.017	2.8	.62	.060	18.2	1.0	15,500	4,520	2,640	.260
3	YB	45	5	.01	.017	.017	3.0	.54	.066	18.3	1.0	17,200	4,560	2,640	.238
Av.															.255
CL43-1	YB	90	3	.01	.....	.01	9.3	.67	.028	10.6	30.0	1,510	1,600	2,705	.111
2	YB	90	3	.01	.....	.01	8.0	.67	.029	10.6	30.0	1,470	1,530	2,705	.104
3	YB	90	3	.01	.....	.01	7.6	.68	.028	10.6	30.0	1,410	1,490	2,705	.103
Av.															.106
CL44-1	YB	90	3	.01	.....	.01	7.0	.66	.029	10.6	20.0	1,555	1,600	2,520	.116
3	YB	90	3	.01	.....	.01	8.0	.65	.029	10.6	20.0	1,210	1,240	2,520	.089
Av.															.102
CL45-1	YB	90	3	.01	.....	.01	7.4	.64	.030	10.6	15.0	1,375	1,380	2,595	.094
3	YB	90	3	.01	.....	.01	6.6	.64	.030	10.6	15.0	1,540	1,530	2,595	.103
Av.															.098
CL46-1	YB	90	3	.01	.....	.01	6.5	.65	.030	10.6	10.0	1,475	1,490	2,520	.106
2	YB	90	3	.01	.....	.01	6.8	.63	.030	10.7	10.0	1,070	1,060	2,520	.074
3	YB	90	3	.01	.....	.01	7.2	.64	.030	10.7	10.0	1,215	1,215	2,520	.086
Av.															.089
CL47-1	YB	90	3	.01	.....	.01	6.7	.62	.031	10.7	8.0	1,440	1,380	2,595	.091
2	YB	90	3	.01	.....	.01	6.4	.62	.031	10.6	8.0	1,410	1,350	2,595	.088
3	YB	90	3	.01	.....	.01	6.5	.65	.030	10.7	8.0	1,415	1,420	2,595	.098
Av.															.092
CL48-1	YB	90	3	.01	.....	.01	6.6	.65	.030	10.7	6.0	1,325	1,330	2,595	.092
2	YB	90	3	.01	.....	.01	6.5	.65	.030	10.6	6.0	1,365	1,365	2,595	.093
3	YB	90	3	.01	.....	.01	6.3	.64	.030	10.7	6.0	1,240	1,255	2,595	.087
Av.															.091

Table 1.—Test data for thin plywood cylinders in axial compression (continued)

Specimen number	Species[1]	Plywood construction: θ	Number of plies	Ply thicknesses: F	XB	C	Moisture content	Specific gravity	Plywood thickness h	Outside diameter 2r+h	Length L	Buckling load P	Buckling stress p	E_L[2]	k
		Degrees		Inch	Inch	Inch	Percent		Inch	Inch	Inch	Pounds	Lb. per sq. in.	1,000 lb. per sq. in.	
CL49-1	YB	90	3	.01	.....	.01	5.9	.62	.030	10.7	4.0	1,365	1,340	2,595	.090
2	YB	90	3	.01	.....	.01	5.5	.63	.031	10.7	4.0	1,500	1,455	2,595	.097
3	YB	90	3	.01	.....	.01	6.2	.64	.030	10.7	4.0	1,375	1,360	2,595	.092
Av.															.093
CL50-1	YB	90	3	.01	.....	.01	5.5	.66	.030	10.6	2.0	1,630	1,635	2,705	.107
2	YB	90	3	.01	.....	.01	5.2	.64	.030	10.6	2.0	1,920	1,935	2,705	.128
3	YB	90	3	.01	.....	.01	5.1	.65	.030	10.6	2.0	1,860	1,860	2,705	.122
Av.															.119
CL51-1	YB	90	3	.01	.....	.01	5.0	.65	.030	10.6	1.0	2,320	2,330	2,705	.154
2	YB	90	3	.01	.....	.01	5.0	.64	.030	10.6	1.0	2,470	2,470	2,705	.162
3	YB	90	3	.01	.....	.01	5.0	.66	.029	10.6	1.0	1,750	1,800	2,705	.121
Av.															.146
CL52-1	YB	0	3	.01	.....	.01	7.0	.65	.030	10.7	30.0	1,165	1,180	2,645	.080
2	YB	0	3	.01	.....	.01	7.2	.65	.030	10.7	30.0	1,030	1,035	2,645	.070
3	YB	0	3	.01	.....	.01	7.5	.65	.029	10.7	30.0	1,085	1,105	2,645	.076
Av.															.075
CL53-1	YB	0	3	.01	.....	.01	7.0	.63	.030	10.7	20.0	950	955	2,530	.068
2	YB	0	3	.01	.....	.01	6.6	.63	.030	10.7	20.0	975	965	2,530	.067
3	YB	0	3	.01	.....	.01	7.0	.63	.029	10.7	20.0	1,050	1,080	2,530	.078
Av.															.071
CL54-1	YB	0	3	.01	.....	.01	7.0	.63	.030	10.7	15.0	1,250	1,235	2,580	.084
2	YB	0	3	.01	.....	.01	6.8	.63	.030	10.7	15.0	1,080	1,085	2,580	.075
3	YB	0	3	.01	.....	.01	7.0	.63	.030	10.7	15.0	1,000	1,000	2,580	.069
Av.															.076
CL55-1	YB	0	3	.01	.....	.01	7.0	.64	.030	10.7	10.0	1,385	1,385	2,530	.098
2	YB	0	3	.01	.....	.01	7.0	.65	.030	10.7	10.0	1,585	1,580	2,530	.111
3	YB	0	3	.01	.....	.01	6.8	.64	.029	10.7	10.0	1,025	1,050	2,530	.076
Av.															.095
CL56-1	YB	0	3	.01	.....	.01	6.8	.59	.032	10.7	8.0	1,125	1,040	2,580	.066
2	YB	0	3	.01	.....	.01	6.9	.64	.030	10.7	8.0	1,175	1,175	2,580	.081
3	YB	0	3	.01	.....	.01	7.1	.62	.031	10.7	8.0	1,235	1,205	2,580	.081
Av.															.076
CL57-1	YB	0	3	.01	.....	.01	7.0	.60	.032	10.7	6.0	1,475	1,385	2,580	.090
2	YB	0	3	.01	.....	.01	6.7	.62	.031	10.7	6.0	1,535	1,480	2,580	.099
3	YB	0	3	.01	.....	.01	7.1	.64	.030	10.7	6.0	1,465	1,450	2,580	.100
Av.															.096
CL58-1	YB	0	3	.01	.....	.01	5.1	.63	.030	10.7	4.0	2,010	2,010	2,580	.139
2	YB	0	3	.01	.....	.01	5.2	.65	.029	10.7	4.0	2,040	2,090	2,580	.148
3	YB	0	3	.01	.....	.01	5.1	.64	.030	10.7	4.0	2,150	2,150	2,580	.148
Av.															.145
CL59-1	YB	0	3	.01	.....	.01	5.2	.65	.030	10.7	2.0	4,110	4,130	2,645	.278
2	YB	0	3	.01	.....	.01	6.5	.62	.030	10.7	2.0	3,980	3,950	2,645	.264
3	YB	0	3	.01	.....	.01	5.0	.64	.030	10.7	2.0	3,750	3,770	2,645	.256
Av.															.266
CL60-1	YB	0	3	.01	.....	.01	5.2	.64	.029	10.7	1.0	4,590	4,680	2,645	.320
2	YB	0	3	.01	.....	.01	5.0	.64	.030	10.7	1.0	5,480	5,535	2,645	.376
3	YB	0	3	.01	.....	.01	5.1	.62	.030	10.7	1.0	5,490	5,450	2,645	.364
Av.															.353

[1] YP - Yellow-poplar.
YB - Yellow birch.

[2] E_L from minor data.

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Table 2.--Results of tests on minor coupons

Matching cylinder group number	Static bending: Face grain parallel to span: E_1 (1,000 lb. per sq. in.)	Static bending: Face grain parallel to span: Moisture content (Percent)	Static bending: Face grain parallel to span: Specific gravity	Static bending: Face grain perpendicular to span: E_2 (1,000 lb. per sq. in.)	Static bending: Face grain perpendicular to span: Moisture content (Percent)	Static bending: Face grain perpendicular to span: Specific gravity	Compression: Face grain parallel to load: E_a (1,000 lb. per sq. in.)	Compression: Face grain parallel to load: Proportional limit stress (Lb. per sq. in.)	Compression: Face grain parallel to load: Moisture content (Percent)	Compression: Face grain parallel to load: Specific gravity	Compression: Face grain perpendicular to load: E_b (1,000 lb. per sq. in.)	Compression: Face grain perpendicular to load: Proportional limit stress (Lb. per sq. in.)	Compression: Face grain perpendicular to load: Moisture content (Percent)	Compression: Face grain perpendicular to load: Specific gravity	Tension: Face grain parallel to load: E_a (1,000 lb. per sq. in.)	Tension: Face grain parallel to load: Moisture content (Percent)	Tension: Face grain parallel to load: Specific gravity	Tension: Face grain perpendicular to load: E_b (1,000 lb. per sq. in.)	Tension: Face grain perpendicular to load: Moisture content (Percent)	Tension: Face grain perpendicular to load: Specific gravity
	1,145	4.2	0.55	502	3.1	0.56	1,217	3,030	3.2	0.56	956	2,520	3.1	0.56	1,407	3.6	0.58	1,018	3.7	0.55
	1,274	4.2	.55	524	2.9	.58	1,065	3,020	3.6	.57	1,002	2,610	3.1	.55	1,375	3.5	.60	914	3.7	.54
CL1	1,568	4.4	.57	528	3.0	.57	1,190	3,150	3.4	.58	904	1,740	3.2	.57	1,612	3.4	.62	968	3.6	.58
	1,350	4.0	.58	540	3.0	.57	1,160	3,610	3.6	.56	936	2,410	3.2	.54	1,107	3.4	.55	1,114	3.5	.57
	1,544	4.4	.58	508	3.1	.56	1,211	3,530	3.5	.56	946	3,260	3.3	.56	1,172	3.6	.57	1,142	3.6	.61
	1,624	4.2	.61	580	4.0	.58	1,234	3,790	3.2	.56	1,046	2,600	3.5	.55	1,340	3.0	.58	1,329	3.6	.65
Av.	1,418			530			1,180	3,360			965	2,520			1,336			1,081		
	1,192	4.2	.55	540	4.1	.57	1,199	4,160	3.5	.57	1,014	2,810	3.7	.59	1,256	3.2	.57	1,052	3.8	.61
	1,050	5.0	.54	518	3.9	.55	949	4,280	3.6	.56	910	2,250	3.8	.59	1,289	3.2	.59	1,126	3.9	.62
CL2	1,006	4.1	.55	508	3.5	.56	1,129	3,470	3.6	.56	944	1,960	3.1	.58	1,368	3.0	.59	1,209	3.5	.63
	1,364	3.9	.60	518	3.8	.58	1,230	3,730	3.6	.58	951	2,820	3.9	.56	1,394	2.9	.64	1,182	3.5	.60
	1,440	3.8	.62	524	3.7	.58	1,340	4,710	3.6	.61	1,009	3,010	3.6	.57	1,430	3.0	.62	1,062	3.6	.58
	1,437	4.0	.63	617	3.6	.60	1,169	3,270	3.5	.60	993	2,780	3.5	.56	1,268	3.2	.54	1,111	3.5	.57
Av.	1,248			538			1,169	3,940			970	2,600			1,334			1,124		
	1,110	4.1	.55	566	3.6	.61	1,001	2,120	3.7	.56	1,024	3,400	5.0	.54	1,166	3.3	.54	1,002	3.0	.56
	889	3.7	.55	526	3.9	.61	991	3,150	3.8	.56	1,087	3,020	3.5	.55	1,380	3.3	.57	1,003	3.0	.56
CL3	1,182	4.0	.54	580	3.8	.62	1,104	3,330	3.6	.54	952	2,610	3.4	.52	1,346	3.2	.60	980	3.5	.55
CL4	1,828	3.9	.59	558	3.8	.59	1,036	3,140	3.5	.54	929	2,930	3.6	.53	1,032	3.1	.52	1,022	3.5	.57
	1,478	3.7	.58	544	3.8	.59	1,119	3,090	3.5	.56	944	2,700	6.1	.52	1,218	2.9	.54	1,196	3.6	.59
	1,302	3.8	.56	602	3.5	.61	1,149	3,340	3.7	.57	1,070	3,100	3.7	.55	1,082	3.1	.54	1,140	3.8	.59
Av.	1,298			564			1,067	3,030			1,001	2,960			1,204			1,057		
	1,214	3.6	.60	580	3.6	.61	918	2,820	4.2	.54	711	2,980	3.7	.54	1,340	4.4	.59	1,036	3.7	.57
	1,092	3.6	.57	589	4.0	.60	964	2,780	4.1	.54	1,023	2,920	7.1	.52	1,388	4.3	.58	976	3.6	.55
CL5	880	3.7	.57	625	3.7	.63	1,076	3,200	3.9	.57	1,052	3,530	3.9	.54	1,354	4.2	.58	1,054	3.8	.55
CL6	1,162	3.5	.56	577	3.9	.57	1,122	3,200	3.9	.57	1,056	3,590	3.8	.55	1,006	3.7	.53	1,374	3.6	.63
CL7	1,302	3.4	.58	582	3.7	.59	1,072	3,270	3.6	.54	1,125	3,280	3.7	.58	1,138	3.8	.54	1,146	3.7	.61
	1,343	3.6	.57	626	3.9	.60	1,252	3,790	3.7	.58	1,130	3,760	3.9	.59	1,210	3.9	.54	1,098	3.7	.60
Av.	1,166			596			1,067	3,180			1,016	3,340			1,239			1,114		
	1,632	3.5	.68	642	3.7	.60	1,136	3,320	6.5	.56	996	2,980	3.8	.54	1,321	3.8	.61	1,140	3.1	.60
	1,433	3.6	.64	624	3.7	.59	1,199	3,660	3.9	.63	995	3,100	3.7	.54	1,231	3.8	.58	1,031	3.3	.57
CL8	1,298	3.7	.59	607	3.8	.59	1,130	3,210	4.0	.59	983	3,340	3.8	.55	1,229	3.3	.60	1,106	3.1	.60
	1,147	.....	.....	594	3.8	.61	1,162	2,940	2.9	.60	1,199	4,020	3.8	.61	1,346	3.4	.60	1,160	3.4	.62
	1,190	3.5	.61	608	3.8	.62	1,182	3,540	4.0	.59	1,197	3,630	4.0	.62	1,351	3.9	.59	1,062	3.3	.61
	1,208	3.8	.63	634	3.7	.63	1,198	3,610	4.2	.59	1,206	3,500	3.8	.63	1,266	3.6	.58	1,192	3.4	.61
Av.	1,318			618			1,168	3,380			1,096	3,430			1,307			1,115		
	1,454	3.4	.57	485	5.0	.58	1,057	3,410	3.9	.53	1,034	3,030	3.6	.57	1,556	3.6	.60	.....	.....	.....
	1,359	3.5	.57	454	3.9	.56	1,134	3,460	3.8	.55	945	3,400	3.7	.57	1,413	3.4	.61	1,026	2.8	.57
CL9	1,179	3.4	.57	481	4.1	.58	1,101	3,160	4.0	.57	888	2,800	3.8	.56	1,532	4.8	.61	1,031	3.0	.58
	1,321	3.6	.59	489	4.2	.57	1,298	3,020	3.9	.58	934	3,150	3.7	.56	1,208	3.9	.56	826	3.3	.55
	1,394	3.5	.59	490	3.6	.59	1,166	3,220	3.8	.57	896	2,640	6.4	.55	1,332	3.8	.56	934	3.0	.57
	1,222	3.3	.59	478	3.9	.58	1,106	3,220	3.7	.57	868	2,900	4.0	.56	1,282	4.1	.58	992	2.9	.57
Av.	1,322			480			1,144	3,250			928	2,950			1,387			962		
	1,186	3.1	.56	618	3.8	.62	1,190	2,790	3.6	.56	1,009	3,150	3.8	.58	1,214	3.9	.58	968	3.1	.57
	1,250	3.4	.56	599	3.6	.61	1,058	3,100	3.7	.55	1,096	2,890	3.5	.57	1,206	3.7	.64	1,006	3.4	.58
CL10	1,192	3.3	.57	596	3.9	.61	1,002	2,820	3.6	.53	1,092	3,220	3.6	.57	1,309	4.3	.61	1,064	3.3	.58
CL11	1,444	3.2	.59	580	3.9	.58	1,024	3,110	3.8	.51	1,057	3,530	3.5	.57	1,388	3.7	.58	1,056	3.0	.58
	1,378	3.4	.61	616	3.8	.59	1,266	3,240	3.8	.59	1,020	3,090	3.6	.55	1,330	3.7	.56	1,124	2.9	.59
	1,378	3.3	.59	568	3.9	.57	1,297	3,020	3.9	.58	1,111	3,710	3.8	.55	1,352	3.9	.56	1,000	3.0	.56
Av.	1,305			596			1,140	3,030			1,064	3,260			1,316			1,036		
	1,611	3.4	.60	468	3.6	.53	1,345	3,610	3.7	.60	984	3,290	3.6	.54	1,140	3.8	.54	1,056	3.2	.56
	1,660	3.2	.58	489	3.6	.54	1,314	4,060	3.5	.58	992	3,160	3.6	.55	1,200	3.4	.53	1,094	3.2	.57
CL12	1,332	3.3	.55	504	3.7	.54	1,096	3,280	3.7	.56	948	2,930	3.9	.53	1,096	3.7	.54	1,096	2.6	.55
CL13	1,220	3.3	.56	520	3.8	.58	1,204	3,020	3.6	.56	926	3,030	3.8	.56	1,486	3.7	.58	1,077	3.1	.58
CL14	1,346	3.5	.56	476	3.8	.58	1,117	3,160	3.9	.53	952	2,780	3.6	.55	1,390	3.6	.58	1,114	3.1	.61
	1,358	3.6	.56	514	3.9	.58	1,176	3,470	3.8	.53	1,002	2,520	3.6	.57	1,416	3.7	.57	1,127	3.2	.63
Av.	1,421			495			1,209	3,440			964	2,950			1,288			1,094		
	2,730	3.5	.73	668	3.4	.61	2,111	5,860	3.4	.68	1,246	4,920	3.1	.63	2,070	3.6	.67	1,695	3.9	.71
	2,642	3.4	.72	640	3.1	.62	1,962	5,320	3.4	.67	1,266	5,740	3.1	.65	1,984	3.6	.66	1,562	3.9	.65
CL15	2,397	3.4	.63	748	3.1	.65	2,091	4,930	3.4	.66	1,510	5,540	3.2	.65	1,916	3.4	.64	1,598	3.5	.66
	2,444	3.3	.63	620	3.4	.63	1,987	5,740	3.4	.66	1,592	5,240	3.2	.68	2,094	3.7	.67	1,661	3.7	.71
	2,338	3.6	.63	534	3.1	.66	2,102	7,180	3.4	.67	1,482	5,340	3.1	.68	2,023	3.6	.67	1,697	3.8	.71
	2,620	3.5	.66	716	3.2	.67	2,174	5,530	3.6	.68	1,578	5,760	8.0	.66	1,881	3.5	.67	1,550	3.5	.68
Av.	2,528			704			2,071	5,760			1,462	5,440			1,995			1,627		
CL16	2,692	3.6	.63	717	3.4	.66	1,930	5,420	3.6	.64	1,476	5,440	3.1	.68	1,936	3.5	.69	1,668	3.6	.70
CL17	2,508	3.4	.64	665	3.1	.65	1,900	6,820	3.4	.64	1,497	5,020	3.2	.68	2,030	4.0	.68	1,638	3.4	.69
CL18	2,821	3.4	.69	698	3.2	.65	2,151	5,530	3.7	.67	1,506	5,120	3.2	.70	2,083	3.4	.70	1,678	3.4	.71
CL19	2,662	3.4	.68	636	3.2	.63	2,159	5,430	3.7	.68	1,510	4,720	3.1	.67	2,110	3.6	.69	1,644	3.5	.69
CL20	2,920	3.5	.70	674	3.4	.65	2,071	5,660	3.8	.70	1,473	4,490	.....	.....	2,130	3.6	.68	1,576	3.4	.68
CL21	2,550	3.4	.67	715	3.5	.65	2,173	5,680	3.8	.70	1,333	4,810	3.2	.65	2,197	3.6	.70	1,630	3.5	.71
Av.	2,692			684			2,064	5,760			1,466	4,930			2,081			1,639		

Table 2.--Results of tests on minor coupons (continued)

Matching cylinder group number	Static bending						Compression						Tension					
	Face grain parallel to span			Face grain perpendicular to span			Face grain parallel to load				Face grain perpendicular to load				Face grain parallel to load			Face grain perpendicular to load		
	E_1	Moisture content	Specific gravity	E_2	Moisture content	Specific gravity	E_a	Proportional limit stress	Moisture content	Specific gravity	E_b	Proportional limit stress	Moisture content	Specific gravity	E_a	Moisture content	Specific gravity	E_b	Moisture content	Specific gravity
	1,000 lb. per sq. in.	Per cent		1,000 lb. per sq. in.	Per cent		1,000 lb. per sq. in.	Lb. per sq. in.	Per cent		1,000 lb. per sq. in.	Lb. per sq. in.	Per cent		1,000 lb. per sq. in.	Per cent		1,000 lb. per sq. in.	Per cent	
	2,392	3.4	.60	612	3.4	.58	1,680	4,690	3.4	.59	1,269	4,220	3.1	.64	1,729	3.2	.60	1,318	3.1	.68
	2,548	3.5	.61	578	3.6	.58	1,694	4,880	3.4	.60	1,125	3,840	2.8	.60	1,714	3.4	.61	1,452	3.4	.70
CL22	2,548	3.5	.60	644	3.6	.59	1,646	5,700	3.6	.59	1,072	4,020	3.0	.60	1,682	3.4	.62	1,414	3.4	.68
	2,453	3.3	.58	618	3.4	.58	1,611	5,420	3.4	.57	1,121	3,050	2.7	.60	1,690	3.5	.62	1,252	3.4	.64
	2,390	3.5	.59	514	3.5	.60	1,696	4,780	3.6	.61	1,041	4,070	2.8	.59	1,769	3.4	.62	1,273	3.5	.62
	2,524	3.5	.59	580	3.6	.60	1,828	4,500	3.5	.63	1,084	4,170	2.8	.59	1,606	3.4	.59	1,265	3.5	.68
Av.	2,476			607			1,676	4,960			1,119	3,900			1,698			1,346		
CL23	2,237	3.7	.59	590	3.6	.60	1,638	4,790	3.4	.58	934	4,150	3.0	.61	1,655	3.5	.61	1,354	3.7	.....
CL24	2,432	3.8	.60	673	3.3	.64	1,690	5,510	3.4	.60	1,122	4,180	2.8	.60	1,742	3.6	.61	1,295	3.7	.67
CL25	2,340	3.7	.58	588	3.3	.60	1,610	5,180	3.4	.59	1,050	3,620	5.6	.57	1,766	3.5	.61	1,281	3.6	.67
CL26	2,370	3.7	.58	578	3.4	.59	1,561	4,710	3.6	.56	1,227	4,200	3.1	.61	1,771	3.2	.59	1,304	3.5	.63
CL27	2,382	3.9	.58	650	3.5	.62	1,720	4,420	3.3	.60	1,195	4,360	3.2	.60	1,712	3.3	.60	1,342	3.6	.62
CL28	2,219	3.6	.58	582	3.2	.59	1,678	6,240	3.6	.62	1,196	4,040	3.2	.60	1,814	3.2	.57	1,342	3.3	.63
Av.	2,330			610			1,653	5,140			1,121	4,090			1,743			1,320		
	2,301	4.0	.60	620	3.4	.58	1,608	5,180	3.6	.61	1,040	3,180	2.7	.60	1,562	3.5	.56	1,214	3.4	.62
	2,321	3.9	.59	612	3.5	.58	1,540	5,020	3.5	.58	1,052	3,840	3.0	.59	1,510	3.8	.56	1,297	3.4	.61
CL29	2,448	4.0	.62	616	3.7	.58	1,561	4,760	3.7	.60	1,130	3,520	2.9	.59	1,424	3.7	.56	1,188	3.3	.60
	2,449	3.9	.62	680	3.4	.60	1,768	4,680	3.5	.59	1,190	3,870	3.0	.62	1,667	3.8	.61	1,340	3.3	.64
	2,460	3.8	.62	680	3.3	.60	1,722	5,020	3.6	.59	1,309	3,520	3.3	.62	1,527	3.7	.59	1,460	3.1	.65
	2,342	3.7	.62	618	3.4	.59	1,705	4,690	3.4	.58	1,200	4,140	2.9	.62	1,708	3.8	.58	1,482	3.2	.65
Av.	2,387			638			1,651	4,890			1,154	3,680			1,566			1,330		
CL30	2,258	3.8	.60	630	3.5	.56	1,702	4,930	3.2	.60	1,092	3,740	2.9	.59	1,653	4.0	.58	1,198	3.4	.64
CL31	2,202	3.8	.60	619	3.5	.57	1,462	4,770	3.2	.56	1,136	4,150	2.7	.60	1,818	3.6	.60	1,349	3.3	.66
CL32	2,269	3.8	.57	704	3.5	.60	1,533	4,850	3.0	.56	1,075	4,270	2.9	.58	1,797	3.6	.60	1,320	3.0	.63
CL33	2,102	3.7	.55	676	3.5	.58	1,560	4,600	3.3	.57	1,102	4,100	2.9	.57	1,917	3.7	.62	1,323	3.3	.64
CL34	2,468	4.1	.58	764	3.5	.59	1,726	4,590	3.4	.59	1,128	4,140	3.2	.61	1,752	3.6	.60	1,317	3.4	.65
CL35	2,390	4.0	.56	876	3.4	.61	1,752	5,180	3.8	.60	1,170	3,450	3.1	.61	1,698	3.8	.59	1,302	3.3	.64
Av.	2,282			710			1,622	4,830			1,117	3,980			1,772			1,302		
	2,151	4.0	.59	766	3.2	.56	1,472	4,780	3.2	.59	1,361	4,760	3.0	.66	1,484	3.5	.57	1,482	3.4	.62
	2,233	3.9	.60	679	3.5	.54	1,576	4,370	3.3	.60	1,271	4,140	2.7	.60	1,420	3.5	.56	1,495	3.2	.66
CL36	2,158	3.6	.57	678	3.4	.55	1,482	4,700	3.7	.58	1,168	4,240	2.8	.57	1,534	3.7	.57	1,550	3.3	.65
	2,051	3.9	.56	659	3.4	.53	1,378	4,650	3.3	.55	1,186	3,970	2.6	.58	1,546	3.6	.59	1,342	3.4	.58
	2,054	2.9	.57	797	3.5	.57	1,456	4,060	3.4	.60	1,212	4,070	3.0	.59	1,600	3.5	.61	1,256	3.4	.58
	2,079	2.8	.56	766	3.4	.56	1,505	4,000	3.4	.59	1,201	4,280	2.9	.59	1,582	3.7	.56	1,337	3.2	.59
Av.	2,121			734			1,478	4,430			1,233	4,240			1,528			1,410		
CL37	2,332	3.0	.62	743	3.3	.56	1,557	5,020	3.7	.59	1,169	4,220	2.9	.56	1,408	3.8	.57	1,324	3.4	.59
CL38	2,022	3.1	.58	704	3.1	.57	1,467	4,860	7.0	.57	1,173	3,860	2.9	.56	1,420	3.6	.55	1,288	3.4	.57
CL39	2,297	3.9	.61	672	3.1	.56	1,491	4,770	3.5	.59	1,165	4,160	3.0	.56	1,372	3.8	.53	1,302	3.4	.56
CL40	2,160	2.8	.60	652	3.4	.57	1,464	4,780	2.9	.57	1,080	3,620	3.0	.59	1,516	3.7	.59	1,228	3.3	.60
CL41	2,147	2.9	.59	646	3.1	.59	1,344	5,240	2.8	.55	1,170	3,940	3.2	.59	1,576	3.7	.60	1,334	3.4	.62
CL42	2,180	2.9	.59	702	3.3	.59	1,409	5,080	3.0	.56	1,196	3,340	3.4	.58	1,580	3.9	.58	1,336	.....	.....
Av.	2,190			686			1,455	4,960			1,159	3,870			1,479			1,302		
	2,582	6.0	.64	232	5.8	.62	1,860	5,540	5.6	.68	940	2,520	5.8	.61	1,946	8.0	.65	1,026	6.3	.64
CL43	2,472	6.0	.64	214	5.3	.59	1,696	6,480	5.6	.66	986	2,820	6.1	.61	1,703	7.5	.62	965	7.4	.63
CL50	2,730	6.0	.62	209	5.4	.60	1,722	5,160	5.4	.65	910	2,820	6.7	.61	1,614	7.8	.57	956	7.1	.62
CL51	2,736	5.8	.62	171	5.9	.60	1,661	5,010	5.8	.63	1,614	3,950	6.5	.62	1,822	7.2	.62	.....	.....	.....
	2,741	6.2	.59	228	5.6	.62	1,873	4,710	6.0	.60	1,004	2,100	6.2	.57	1,800	7.4	.62	1,108	7.2	.62
	2,738	5.9	.60	216	6.0	.61	1,972	5,060	6.4	.61	986	2,880	5.8	.62	1,854	7.2	.67	1,163	6.8	.64
Av.	2,666			212			1,797	5,330			973	2,850			1,790			1,043		
	2,220	5.9	.63	243	5.3	.59	1,770	4,200	6.1	.62	990	2,430	7.2	.61	1,655	6.8	.65	920	7.3	.59
	1,914	5.9	.65	230	5.6	.59	1,824	5,530	6.0	.70	976	2,820	6.2	.60	1,684	6.1	.63	1,032	7.4	.63
CL44	2,031	5.6	.56	220	5.2	.60	1,675	5,360	5.8	.62	914	2,910	6.5	.58	1,638	6.3	.59	980	7.1	.62
CL46	2,490	5.8	.58	202	5.1	.57	1,544	5,640	5.5	.59	1,036	3,040	7.7	.59	1,748	6.2	.63	1,005	7.2	.59
	2,362	6.0	.58	227	5.3	.61	1,686	.....	6.1	.57	982	3,290	6.6	.62	1,884	6.3	.65	992	7.0	.62
	2,424	5.8	.59	213	5.5	.61	1,866	3,640	5.6	.60	1,004	.....	6.6	.64	1,780	6.0	.66	1,050	6.8	.62
Av.	2,240			222			1,728	4,870			984	2,900			1,732			996		
	2,358	5.2	.59	232	5.7	.62	1,704	5,950	5.2	.61	871	2,650	6.5	.56	1,816	6.3	.69	1,085	6.7	.62
CL45	2,657	5.6	.65	188	5.9	.58	1,719	5,330	5.6	.62	883	3,350	6.6	.58	1,796	6.3	.63	988	7.2	.60
CL47	2,251	5.8	.58	202	5.6	.60	1,698	4,570	5.6	.63	913	2,290	6.3	.59	1,771	6.2	.62	934	7.2	.60
CL48	2,332	5.8	.59	218	5.6	.59	1,770	6,260	5.4	.64	1,122	2,430	6.6	.61	1,760	6.2	.58	1,150	6.8	.63
CL49	2,392	5.8	.58	189	5.8	.58	1,719	5,000	5.8	.59	1,110	2,190	6.6	.63	1,623	5.7	.57	1,164	7.4	.62
	2,572	6.0	.59	190	5.8	.59	1,682	4,210	6.1	.60	1,029	2,960	6.5	.60	1,689	5.4	.63	1,088	7.2	.62
Av.	2,427			203			1,715	5,220			988	2,640			1,742			1,068		
	2,727	6.0	.59	240	6.2	.64	1,823	4,860	5.5	.61	937	3,150	6.6	.61	1,868	6.2	.64	1,034	6.8	.62
CL52	2,598	6.1	.61	214	5.8	.63	1,648	4,880	5.8	.62	898	3,050	6.5	.59	1,724	5.9	.63	956	7.1	.60
CL59	2,498	6.7	.60	214	5.6	.62	1,779	4,720	5.6	.65	1,027	2,440	6.5	.64	1,842	5.6	.63	996	7.7	.60
CL60	2,484	5.9	.59	176	5.8	.58	1,802	4,680	5.4	.65	1,019	2,510	6.3	.63	1,848	5.6	.59	924	7.7	.55
	2,420	5.6	.60	236	5.0	.61	1,894	3,930	6.2	.62	1,000	2,740	6.8	.60	1,686	8.6	.62	950	7.7	.52
	2,533	6.0	.60	186	5.5	.59	1,814	4,640	6.1	.65	1,293	3,140	6.5	.62	1,788	7.7	.62	908	7.7	.56
Av.	2,543			211			1,793	4,380			1,029	2,840			1,769			961		

Table 2.--Results of tests on minor coupons (continued)

Matching cylinder group number	Static bending						Compression						Tension					
	Face grain parallel to span			Face grain perpendicular to span			Face grain parallel to load				Face grain perpendicular to load				Face grain parallel to load			Face grain perpendicular to load		
	E_1	Moisture content	Specific gravity	E_2	Moisture content	Specific gravity	E_a	Proportional limit stress	Moisture content	Specific gravity	E_b	Proportional limit stress	Moisture content	Specific gravity	E_a	Moisture content	Specific gravity	E_b	Moisture content	Specific gravity
	1,000 lb. per sq. in.	Percent		1,000 lb. per sq. in.	Percent		1,000 lb. per sq. in.	Lb. per sq. in.	Percent		1,000 lb. per sq. in.	Lb. per sq. in.	Percent		1,000 lb. per sq. in.	Percent		1,000 lb. per sq. in.	Percent	
	2,410	5.7	.63	209	5.3	.60	1,528	5,720	5.7	.64	946	.....	7.0	.60	1,852	8.1	.66	958	6.2	.53
	2,432	6.3	.66	187	5.4	.59	1,692	4,530	5.6	.68	1,010	2,600	6.7	.58	1,811	7.8	.59	1,036	5.8	.57
CL53	2,770	6.4	.58	220	4.7	.61	1,651	5,180	6.0	.58	1,008	2,430	7.0	.57	1,855	7.5	.62	954	5.8	.57
CL55	2,350	6.4	.58	187	6.1	.60	1,688	5,500	6.1	.61	980	.....	6.5	.64	1,706	8.3	.62	980	5.5	.57
	2,220	6.5	.56	198	5.8	.60	1,543	4,550	6.4	.56	985	.....	6.6	.60	1,608	8.2	.66	973	6.0	.59
	2,220	6.4	.59	187	5.5	.61	1,549	4,880	6.4	.60	1,038	2,030	6.7	.62	1,776	7.8	.67	890	5.5	.57
Av.	2,400			198			1,608	5,060			991	2,350			1,768			965		
	2,371	6.1	.55	171	5.8	.62	1,718	.....	5.9	.58	1,034	.....	6.5	.59	1,683	7.7	.64	964	5.3	.56
CL54	2,480	5.8	.61	187	5.6	.62	1,770	4,700	5.8	.60	1,070	.....	6.2	.61	1,857	7.5	.65	964	6.2	.56
CL56	2,503	5.8	.60	207	5.9	.62	1,690	5,340	5.4	.64	1,026	.....	6.5	.59	1,796	7.6	.60	930	6.0	.56
CL57	2,487	5.7	.59	188	6.0	.60	1,526	5,010	5.7	.63	1,100	.....	6.5	.65	1,824	7.8	.58	930	6.5	.56
CL58	2,642	5.9	.61	168	6.1	.59	1,634	3,770	6.4	.59	1,071	.....	6.6	.62	1,742	7.7	.63	970	6.4	.56
	2,400	5.8	.60	188	6.1	.62	1,622	4,860	6.2	.58	1,057	.....	6.3	.60	1,814	7.5	.66	944	6.2	.57
Av.	2,480			185			1,658	4,740			1,060				1,753			947		

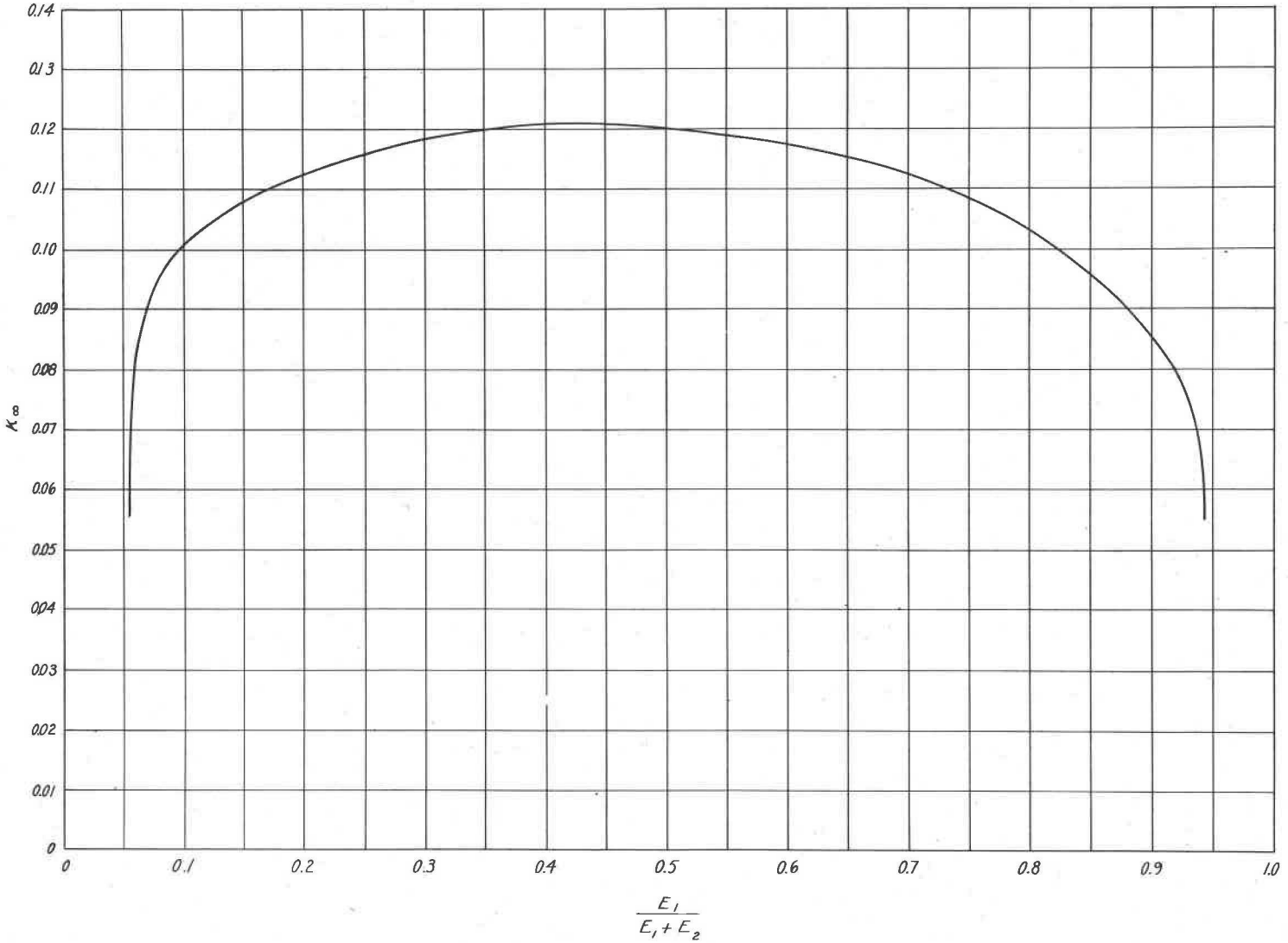
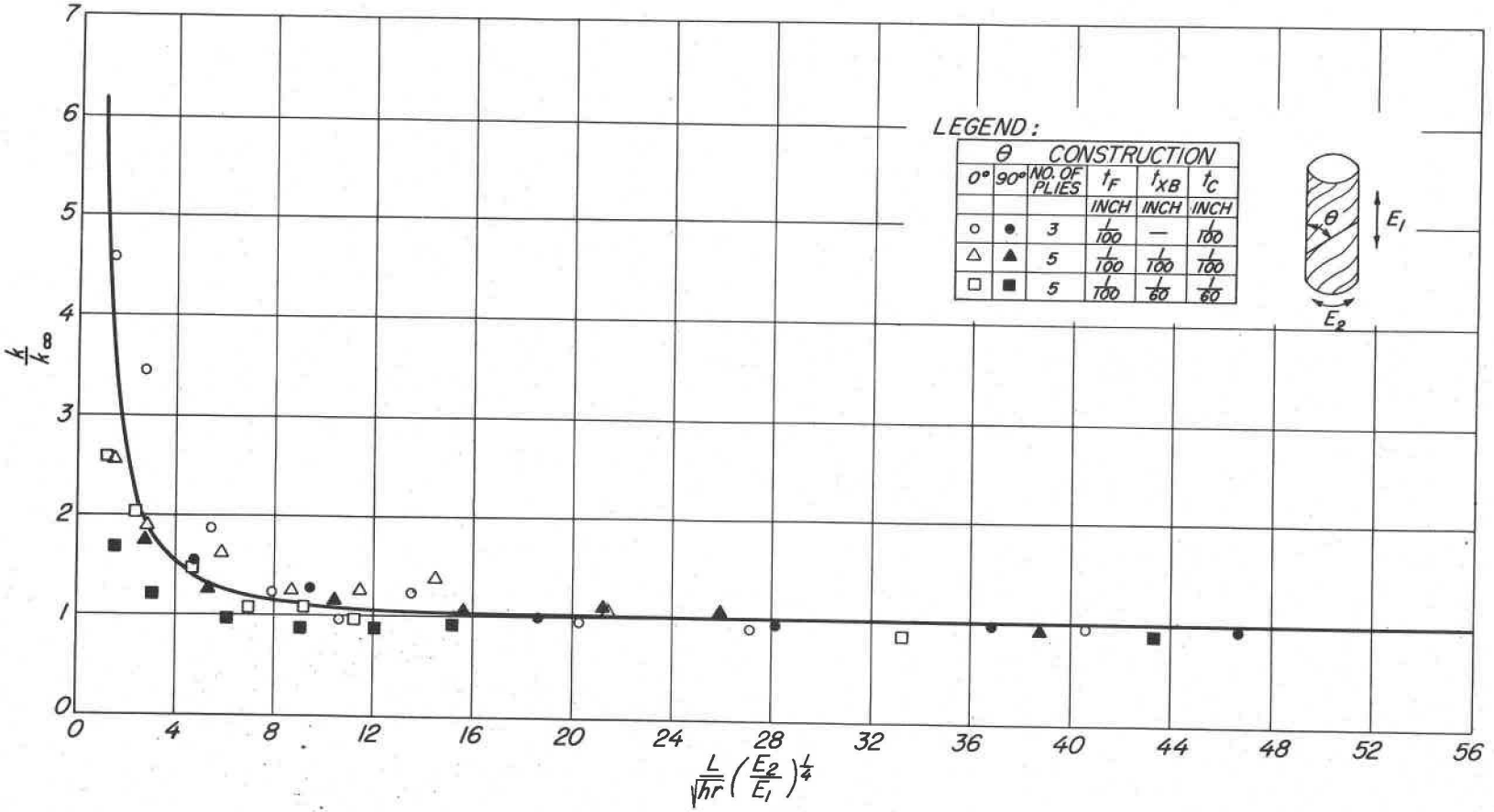


Figure 1.--Theoretical curve for long, thin, plywood cylinders in axial compression. The ordinates represent k in the formula $p = kE_L\, h/r$, where p is the buckling stress. The abscissas represent the ratio $E_1/(E_1 + E_2)$ where E_1 and E_2 are proportional to the stiffness of the plywood in the axial and circumferential directions, respectively.

Z M 76521 F



ZM 76522 F

Figure 2.--The effect of length, $\frac{L}{\sqrt{hr}}\left(\frac{E_2}{E_1}\right)^{1/4}$, of specimen on the buckling constant for thin plywood cylinders in axial compression. Each point represents three test specimens.

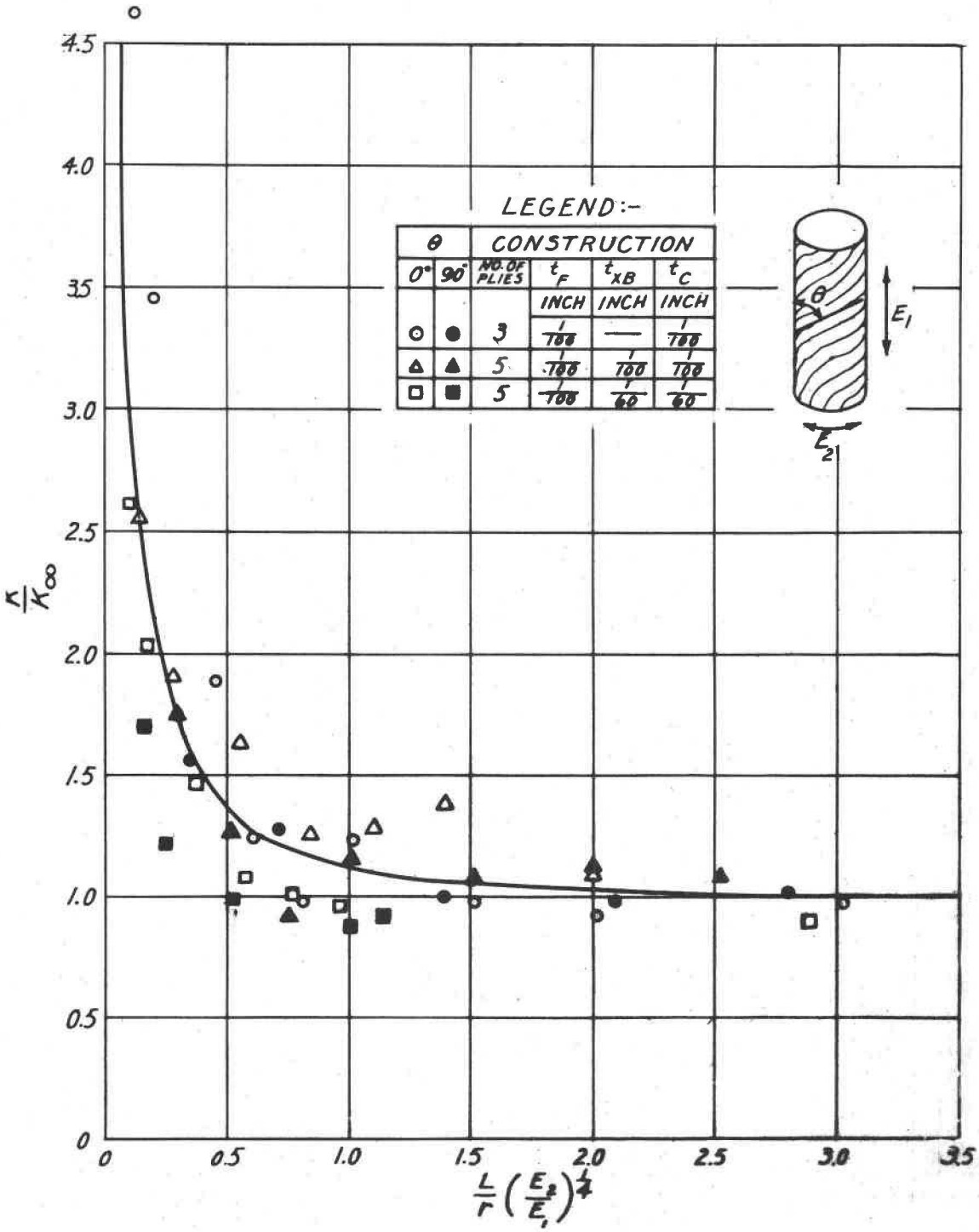


Figure 3.--The effect of length, $\frac{L}{r}\left(\frac{E_2}{E_1}\right)^{1/4}$, of specimen on the buckling constant for thin plywood cylinders in axial compression. Each point represents three test specimens.

Z M 55826 F

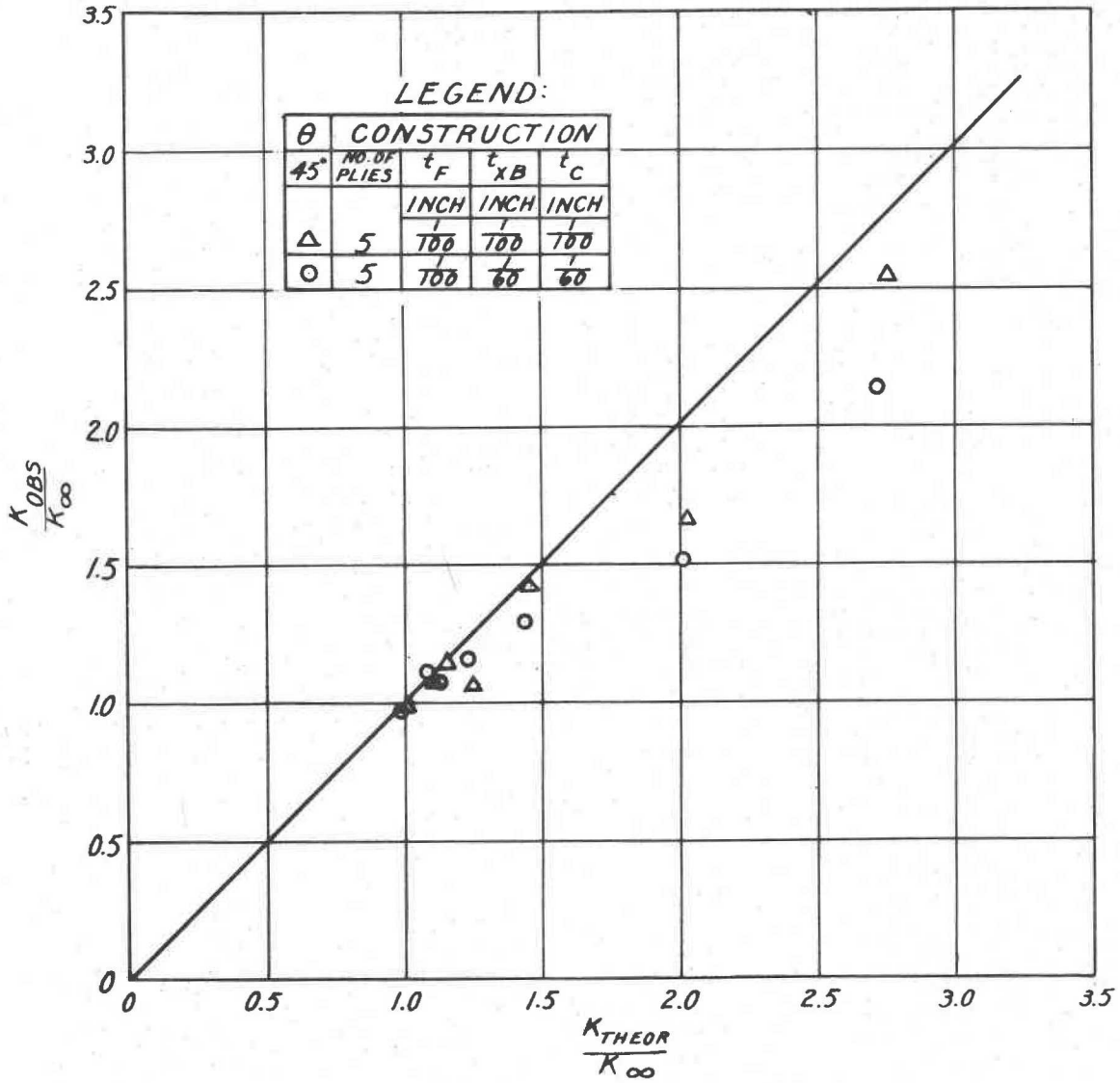


Figure 4.--A comparison of observed buckling constants with theoretical constants computed from the curve of figure 3 for thin plywood cylinders in axial compression. The face grain of these specimens was at 45° to the axis of the cylinder.

Z M 55827 F

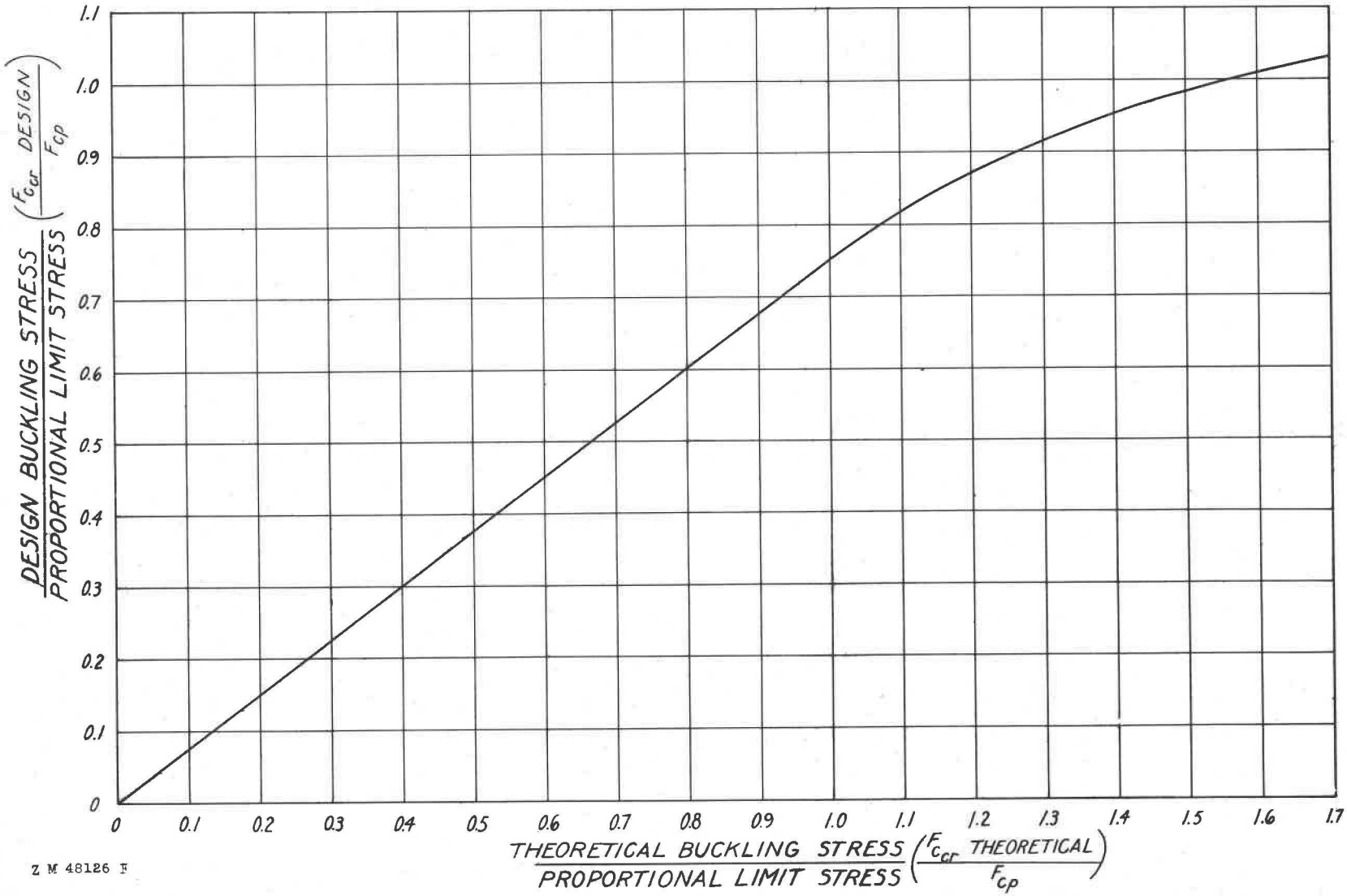


Figure 5.--Design curve for long thin-walled plywood cylinders. This curve can also be used for designing thin, curved, plywood plates.

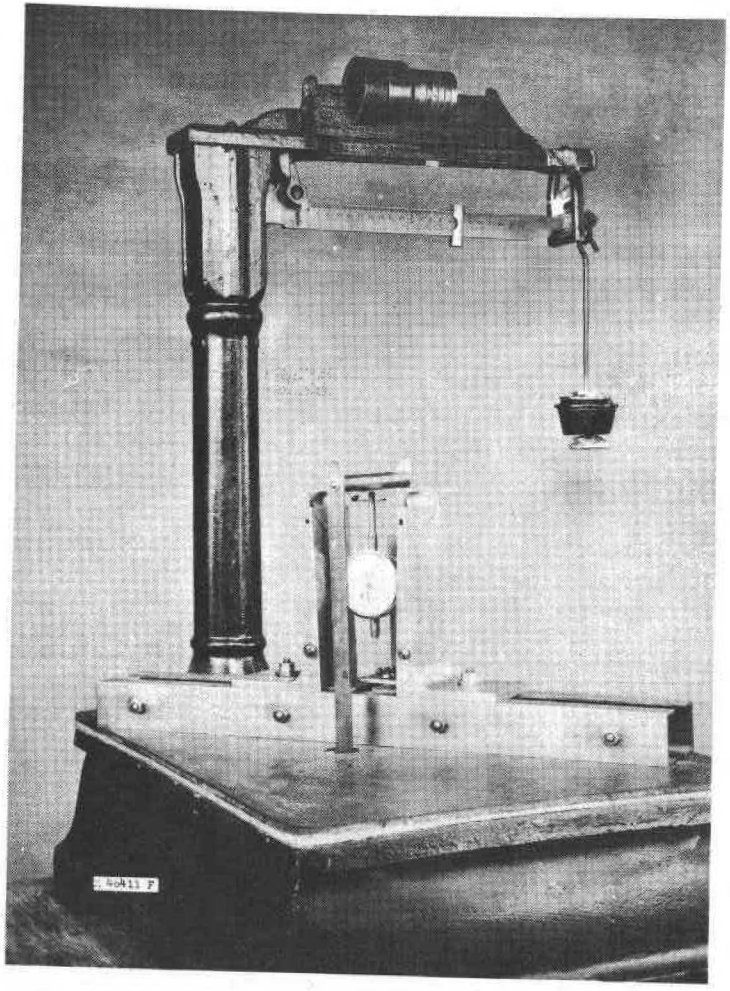


Figure 6.--Bending test of a plywood specimen on a platform-scale apparatus.

Z|M 48829 F

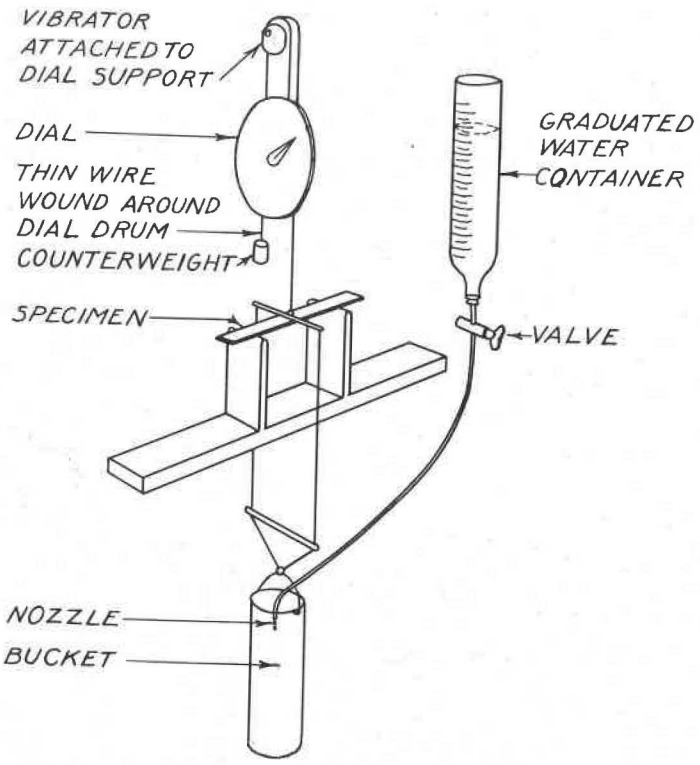


Figure 7.--Apparatus for bending tests of plywood specimens not stiff enough to be tested on the platform-scale apparatus of figure 6.

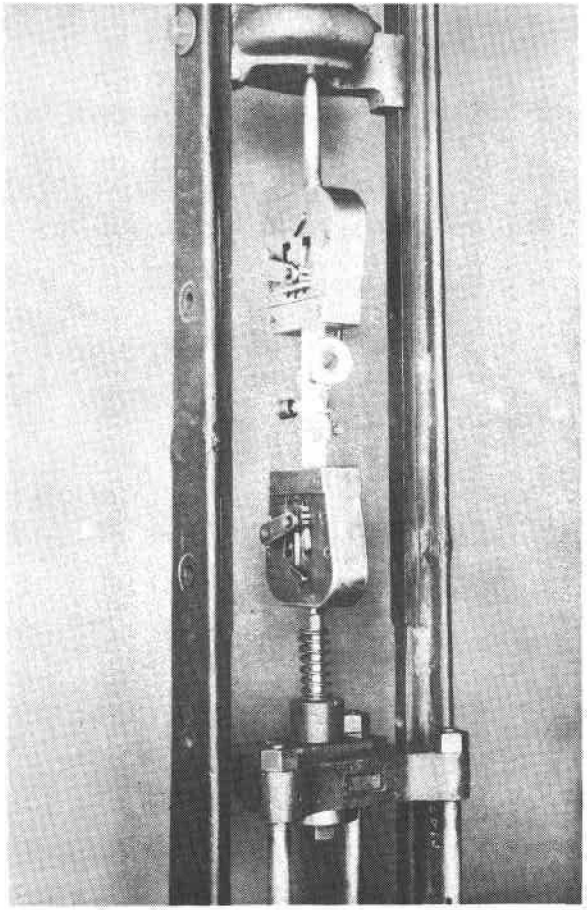


Figure 8.--Tension test of plywood.

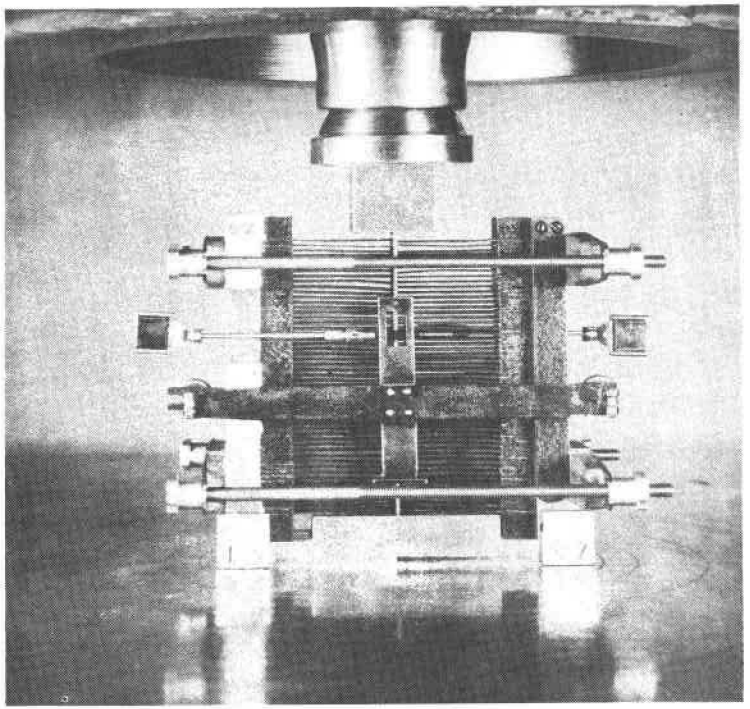


Figure 9.--Compression test of thin plywood.