Supplement to
BUCKLING OF STIFFENED, FLAT, PLYWOOD PLATES IN COMPRESSION

A SINGLE STIFFENER PERPENDICULAR TO STRESS. FACE GRAIN OF PLYWOOD AT 45° TO ITS EDGES

November 1946

**This Report is One of a Series
Issued In Cooperation with the
ARMY-NAVY-CIVIL COMMITTEE
on
AIRCRAFT DESIGN CRITERIA
Under the Supervision of the
AERONAUTICAL BOARD**

No. 1553-A

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

Supplement to

BUCKLING OF STIFFENED, FLAT, PLYWOOD PLATES IN COMPRESSION

A Single Stiffener Perpendicular to Stress. Face Grain of Plywood at 45° to Its Edges[1]

By

T. B. HEEBINK, Engineer
and
C. B. NORRIS, Engineer

Summary

This report presents the results of tests performed at Forest Products Laboratory on flat plywood plates, stiffened with single, horizontal stiffeners, and loaded vertically in edgewise compression, with the stress applied at 45° to the direction of the grain of the face plies. An approximate formula for the critical stiffness of the stiffeners is presented, which was obtained from data on 74 tests of 9 stiffened plates. The development of the formula makes use of several assumptions; it is believed, however, that the assumptions are reasonable and that the formula safely applies to plates of any practical dimensions.

Introduction

In aircraft structures involving plywood, panels are frequently employed in which the grain directions of the various plies make angles of 45° with the edges of the panels. Such panels are very strong and rigid when subjected to shear stresses and can be used economically at positions in the structure where such stresses are high. A panel used in this way, however, may also have to carry an edgewise compressive stress and if designed for the shear stress alone may have insufficient elastic stability to withstand the required compressive stress. This difficulty

---

[1] This is one of a series of progress reports prepared by the Forest Products Laboratory relating to the use of wood in aircraft. Results here reported are preliminary and may be revised as additional data become available.

may be overcome by fixing a stiffener along the central line of the panel and perpendicular to the direction of the compressive stress. Good design requires that the stiffener be just heavy enough to cause the panel to act essentially as two independent panels when it is subjected to the edgewise compressive stress. The study reported here was undertaken to determine the minimum size of a stiffener adequate for this purpose.

The plywood plates tested were approximately square, and a rather deep stiffener was glued to one face of each plate on the horizontal centerline. The plates were tested in vertical edgewise compression. The stiffeners were then reduced in depth by small increments. The plates were tested after each reduction, and compressive strains were measured at various points. As the stiffeners were reduced in size, the pattern of the buckles changed progressively from a full wave (a half wave in each half of the panel) with a node at the stiffener to a half wave with an antinode at the stiffener.

By plotting the data from these tests against suitable parameters, it is possible to determine the critical size of the stiffeners, which is defined as the stiffness that is just great enough to cause the plate to buckle into two half waves. The critical stress of the plate with such a stiffener is considerably greater than that of the unstiffened plate. The critical stress of the plate, both with a stiffener of critical size or greater and without a stiffener, can be computed by the method outlined in Forest Products Laboratory Report No. 1316-G.

Description of Specimens

All the plywood plates were cut from three-, four-, or five-ply yellow birch or yellow-poplar plywood of aircraft grade. In the three- and five-ply panels, the direction of the grain of each ply was perpendicular to that of the adjacent plies. The four-ply panels differed only in that the grain of the two core plies was parallel, making in effect a three-ply construction with a center ply of double thickness. The widths of the plates were 12 and 18 inches; the lengths ranged from 9-1/2 to 18 inches. In the tests the load was applied to the ends of the panels. The direction of the grain of the face plies of each plate was at an angle of 45° to the direction of the load.

The stiffeners were made of Sitka spruce and varied in width from 3/16 to 3/8 inch and in depth from 0 to 1 inch. Each stiffener was cut 1-1/4 inches shorter than the width of the plate to which it was glued, as shown in figure 12.[2] The plates and the stiffeners were stored in an atmosphere of 65 percent relative humidity at a temperature of 70° F. both before and after assembly and until time of test.

---

[2]The figures, tables, and equations in this report are numbered consecutively with those of Forest Products Laboratory Report No. 1553.

Procedure of Tests

The apparatus used and the test methods are identical to those described in Forest Products Laboratory Report No. 1553, with the exception of the method of determining the critical load.

A modification in the method described in Report No. 1553 of the determination of the critical load was found to be necessary. Exploratory tests in which this method was used indicated that in many instances the average strain at the center of the plate continued to increase with increasing load, even after the plate was obviously buckled; thus it was impossible to determine the critical load. The following modified method was adopted. The compressive strains were measured at points one-half inch from each edge just below the horizontal centerline and just below the center of the plate by averaging values obtained from strain gages (fig. 13) placed on opposite faces of the plate. Typical load-strain curves for these points are shown in figure 14. An apparent critical load was found by plotting the difference between the average of the strains at the edges and the strain at the center against the load. This resulted in a curve which changed direction rather suddenly (fig. 14). The load at the intersection of the extensions of the two straight-line portions of this curve was picked as a critical load.

It was discovered that this apparent critical load, obtained by the strain-difference method, is not equal to that obtained by the method described in Forest Products Laboratory Report No. 1316-D, in which the edges of the specimen were adjusted until buckling was indicated by a sharp bend in the load-lateral deflection curve. Data obtained in this manner are tabulated in table 3 and are plotted in figure 15, in which they are compared to the correction curve given in figure 103 of Forest Products Laboratory Report No. 1316-G. This comparison shows that the values of the apparent critical load are less than those of the correct critical load for small values of b/b', the ratio of the half-wave length of the buckles to the ideal half-wave length of a corresponding infinitely long panel. Since no better method of determining the critical load was available, however, use was made of the apparent critical load (fig. 14) in determining the critical size of stiffener. An approximate relationship exists between the apparent and the correct critical load, which will be discussed later.

Notation

The following symbols are the major ones used in this report:

a = the length of the loaded sides of a plywood plate, for compressive loads.

b = the length of the unloaded sides of a plywood plate, for compressive loads.

b' = the half-wave length of the buckled surface in the case of an infinitely long plate.

d = the depth of the stiffener, measured perpendicular to the face of the plywood.

h = thickness of the plywood.

t = the width of the stiffener, measured parallel to the face of the plywood.

E_{fw} = effective modulus of elasticity of plywood in bending measured parallel to the grain direction of the face plies.

E_{fx} = effective modulus of elasticity of plywood in bending measured perpendicular to the grain direction of the face plies.

E_L = modulus of elasticity of wood in the direction parallel to the grain, $20/21\ (E_{fw} + E_{fx})$.

E_s = modulus of elasticity of stiffener in the direction parallel to the grain, as determined from a static bending test.

$(EI)_s$ = a measure of the stiffness of the stiffener. Product of modulus of elasticity and moment of inertia about the neutral axis of the stiffener.

$(EI)_{scr}$ = the minimum stiffness of stiffener necessary to effectively stiffen a plywood plate.

k_c = coefficient in formula, $p_{cr} = k_c E_L \frac{h^2}{a^2}$.

$k_{c\infty}$ = value of the coefficient, k_c, for an infinitely long plate.

P_{cr} = uniform compressive load for which buckling occurs.

p_{cr} = uniform compressive stress for which buckling occurs.

p_{crp} = p_{cr} for a stiffened plywood plate when the stiffener has been removed.

p_{crm} = p_{cr} for a stiffened plywood plate, stiffened with an adequate stiffener.

σ_{cr} = an apparent observed critical stress obtained by the strain-difference method.

σ_{crp} = σ_{cr} for a stiffened plywood plate when the stiffener has been removed.

σ_{crm} = σ_{cr} for a stiffened plywood plate, stiffened with an adequate stiffener.

Explanation of Tables and Figures

Table 3 shows the construction, dimensions, elastic properties, and the observed critical stresses of the unstiffened plywood plates tested. Also shown are the ratios $k_c/(k_c)_\infty$, which were computed from the dimensions and elastic properties. Data from stiffened plates are included in this table only if the plates were stiffened with a large stiffener, so that the half plates could be analyzed separately, or if the plates had had the stiffeners completely removed. Columns 1 through 6 show plate designations, species, constructions, and dimensions. The ratios of the half wave lengths of the buckled surfaces in the case of infinitely long plates to the widths of the plates are presented in column 7. These values were taken from the lower curve of figure 17, which is plotted from the results of calculations made in connection with Forest Products Laboratory Report No. 1316-B. Values in column 8 were computed in the following manner: $\frac{b}{b'} = \frac{b}{a \times \frac{b'}{a}}$. Column 9 shows observed critical stresses, obtained by dividing the critical loads by the cross-sectional areas of the plates. Values of $(k_c)_\infty$, which are coefficients in the formula, $p_{cr} = k_c E_L \frac{h^2}{a^2}$, in the case of infinitely long plates are given in column 10. These values were obtained from the upper curve of figure 17, which is a reproduction of part of figure 35 of Forest Products Laboratory Report No. 1316-B. Values of $k_c/(k_c)_\infty$ in column 11 are obtained from: $\frac{k_c}{(k_c)_\infty} = \frac{\sigma_{cr}}{(k_c)_\infty E_L \frac{h^2}{a^2}}$, which is a variation of equation 6 of Forest Products Laboratory Report No. 1316, in which the experimentally determined apparent critical stress replaces the correct critical stress. Column 12 contains the ratios of $\frac{p_{cr}}{\sigma_{cr}}$ obtained from figure 18 for the corresponding values of b/b'. The correct ratio, $k_c/(k_c)_\infty$, containing the correct critical stress, is shown in column 13. These are obtained by multiplying the values of $k_c/(k_c)_\infty$ given in column 11 by the ratios given in column 12. Columns 14 and 15 show the effective modulus of elasticity of the plywood in bending measured parallel and perpendicular, respectively, to the direction of the grain of the face plies. Values of the modulus of elasticity of the wood in the direction parallel to the grain are presented in column 16. These values were computed from the equation: $E_L = \frac{20}{21} (E_{fw} + E_{fx})$.

Table 4 presents the data obtained from edgewise compression on stiffened panels and the computed values required for plotting in figure 16. Column 1 contains the designation of the plates. The numerical part of the designation refers to the construction of the plywood, which can be found in table 3. Column 2 gives the apparent critical stresses (σ_{cr}) obtained from the tests. A number of such stresses were obtained for each plate since each plate was tested a number of times, each time with a different depth of stiffener. Column 3 contains the ratio of the increases in apparent critical stress required for plotting as ordinates in figure 16. In this ratio, σ_{crp} is the apparent critical stress of the plate after the stiffener was removed; σ_{crm} is the average of the larger apparent critical stresses obtained when the stiffener was obviously stiffer than the critical stiffness; and σ_{cr} is the apparent critical stress given in column 2. All of these stresses are recorded in column 2. Column 4 gives the widths and column 5 the depths of the stiffeners. Column 6 gives the values for plotting as abscissas in figure 16. In this expression $(EI)_s = \frac{1}{12} E_s\ t\ d^3$; that is, the stiffness of the stiffener alone: (a), (b), and (h) are the width, length, and thickness of the plate. Column 7 gives the modulus of elasticity of the stiffener.

Table 5 contains the data from which the ratios were obtained of the correct critical stresses to the apparent ones from the strain-difference method. The first 11 columns are similar to the corresponding columns in table 3. Those plates for which the critical loads were obtained by the strain-difference method described herein and therefore are not correct but apparent are indicated by a footnote. The data from plates matched to these for which the correct critical loads were obtained from load-deflection curves are placed in the table directly above the data for these plates. The ratio in column 12 is a ratio of the $k_c/(k_c)_\infty$ obtained by load-lateral deflection to that obtained by the strain-difference method; therefore, the values given are also ratios of the correct to the apparent critical stress. Columns 13, 14, and 15 show the elastic properties of the plywood.

Figure 12 shows a plywood plate ready for test. The segmented rods are shown in place on the ends of the plate and the coil springs on its edges. The steel clamps at the ends of the stiffener inhibit failure in the glue bond at these points. The three strain gages shown are duplicated by three more gages on the other side of the plate.

Figure 13 shows the complete test apparatus as it stands in the testing machine. The strain gages just opposite each other on each side of the plate are connected in series so that the average compressive strain is obtained. The lateral deflection gage is not shown.

Figure 14 is a plot of the data obtained from a typical plate and shows how the apparent critical load was obtained.

Figure 15 shows the values of $k_c/(k_c)_\infty$, obtained from apparent critical stresses measured by the strain-difference method plotted as ordinates against b/b' ratios plotted as abscissas. The curve shown is reproduced from the upper curve of figure 103 of Forest Products Laboratory Report No. 1316-G, or the curve of figure 12 of Forest Products Laboratory Report No. 1316.

Figure 16 is a plot of the data recorded in table 1.

Figure 17 contains a plot of values of the coefficient $(k_c)_\infty$ in the formula $p_{cr} = k_c E_L \frac{h^2}{a^2}$ applied to infinitely long plates plotted against $\frac{E_{fw}}{E_{fw} + E_{fx}}$. This plot is reproduced from figure 35 of Forest Products Laboratory Report No. 1316-B. This figure also contains a plot of the ratio $(\frac{b'}{a})$ of half the wave length of an infinitely long panel to the width of the panel taken from results of calculations made in connection with Forest Products Laboratory Report No. 1316-B.

Ratios of $\frac{p_{cr}}{\sigma_{cr}}$ from column 12, table 3 are plotted in figure 18 as ordinates and b/b' ratios as abscissas. A smooth curve was drawn through the points as an average curve.

Figure 19 is similar to figure 15. In this figure, however, the ratios $k_c/(k_c)_\infty$ have been corrected by multiplying by the ratios $\frac{p_{cr}}{\sigma_{cr}}$ given in figure 18. The curve in figure 19 is identical with that shown in figure 15.

Analysis of Data

A mathematical determination of the critical stiffness of a stiffener, such as that given in Forest Products Laboratory Report No. 1553, is not available for plywood plates in which the directions of the grain of the various plies make angles of 45° with the edges of the plates; nor is an analysis of the stiffness added to a plate by a stiffener, such as that given in Forest Products Laboratory Report No. 1557, available for such plywood plates. Equation (34) of Report No. 1553, however, can be applied to the data reported herein and an estimate of the critical stiffness of a stiffener obtained.

The stiffness added to a plate by a stiffener will be considered approximately equal to the stiffness of the stiffener alone; $(EI)_s = \frac{1}{12} E_s t d^3$. Thus, it is assumed that the neutral axis of the plate and the stiffener acting together passes through the center of the cross section of the stiffener. This assumption is probably not greatly in error because the ratio of the modulus of elasticity of the stiffener to that of the plywood at 45° to the direction of the grain of the plies is very large.

Equation (34) of Report No. 1553 then applies to stiffened panels for which the stiffener has a stiffness less than the critical value, and the following equation may be written:

$$\frac{\sigma_{cr} - \sigma_{crp}}{\sigma_{crm} - \sigma_{crp}} = F \frac{2\pi^2 \frac{b}{ha^4} (EI)_s}{\sigma_{crm} - \sigma_{crp}} \qquad (39)$$

where σ_{cr}, σ_{crp}, etc. denote apparent critical stresses as determined by the strain-difference method as distinguished from p_{cr}, p_{crp}, etc., the corresponding correct critical stresses. In this equation, the factor F presumably takes care of the approximations that have been made.

Figure 16 is a plot of the experimental data in which values of the left-hand member of equation (39) are plotted as ordinates and values of the right-hand member, excluding the factor F, are plotted as abscissas. Examination of the figure indicates that a value of F = 2 is acceptable.

The critical stiffness of the stiffener is the value of $(EI)_s$ that causes σ_{cr} to equal σ_{crm} and thus reduces the left-hand member of equation (39) to unity. With F taken as 2, the critical stiffness of the stiffener is, therefore given by

$$(EI)_{scr} = \frac{ha^4}{4\pi^2 b} (\sigma_{crm} - \sigma_{crp}) \qquad (40)$$

The quantities in the parentheses in the right-hand member of equation (40) are the apparent critical stress of the half plate, on one side of the stiffener, considered alone, and the apparent critical stress of the whole plate with the stiffener removed. It remains to find a relationship between these apparent critical stresses and the correct critical stresses as computed by the methods presented in Forest Products Laboratory Report No. 1316-B, and experimentally verified in No. 1316-G. This relationship was found empirically in the following manner.

Seven unstiffened 45° plates with various length-to-width ratios were tested and the critical loads determined by the method used in Forest Products Laboratory Report No. 1316-D of inducing curvatures along the unloaded edges to compensate for the lack of flatness of the plywood, and then obtaining values of the critical loads from the load-lateral deflection curves. Seven matched unstiffened plates were also tested and the apparent critical loads determined by the strain-difference method described herein.

The ratios of critical stresses obtained by the lateral deflection method to the apparent critical stresses obtained by the strain-difference method are tabulated in table 3 and plotted against ratios of b/b' in figure 18. Included also in table 3 and in figure 18 are some applicable data from previous tests. An approximate analysis of the strain-difference method shows that the apparent critical stress obtained is influenced by the original lack of flatness of the specimen; the greater the lack of flatness the lower is the apparent critical stress. This fact explains the scatter of the plotted points. A smooth average curve was drawn through the plotted points in figure 18 from which the apparent critical stress (σ_{cr}) can be determined, the ratio of b/b' and the correct critical stress (p_{cr}) being determined by the methods given in Report 1316-B.

By reversing this method, correct critical stresses were obtained from the apparent critical stresses plotted in figure 15 (k_c is proportional to stress) and plotted in figure 19 in which they are compared with the correction curve given in figure 12 of Report 1316 and in figure 103 of Report No. 1316-G. It is apparent that these correct values approximately fit the curve.

It can be concluded, therefore, that the curve of figure 18 is a reasonably accurate means of converting apparent critical stresses obtained by the strain-difference method as described herein to accurate values of critical stresses for 45° plywood and vice versa. To determine the critical size of a stiffener by using equation (40), the correct critical stresses, p_{crm} and p_{crp}, as obtained by the equation and curves of Forest Products Laboratory Reports Nos. 1316-B and G, are converted to apparent critical stresses, σ_{crm} and σ_{crp}, by means of figure 18. These apparent critical stresses are then substituted in equation (40) to obtain the critical stiffness of the stiffener.

Equation (40) is approximate and the plates tested were all nearly square; however, it is believed that this equation will safely apply to plates of any practical dimensions.

Table 3.—Test data and computed values for unstiffened plywood plates tested in uniform edgewise compression

Plate No.	Species	No. and thickness of plies	h	b	a	$\frac{b'}{a}$	$\frac{b}{b'}$	σ_{cr}	$(k_c)_\infty$	Apparent $\frac{k_c}{(k_c)_\infty}$	$\frac{p_{cr}}{\sigma_{cr}}$	Correct $\frac{k_c}{(k_c)_\infty}$	E_{fw}	E_{fx}	E_L
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
			Inch	Inches	Inches			P.s.i.					1,000 p.s.i.	1,000 p.s.i.	1,000 p.s.i.
3a	Yellow	3 - 1/16"	0.181	14.01	12.02	0.845	1.42	598	0.870	1.16	1.10	1.28	2,365	203	2,446
	Birch			11.98			1.22	552		1.07	1.19	1.27			
				10.00			1.02	643		1.25	1.32	1.65			
				8.01			.81	735		1.43	1.52	2.17			
				5.98			.61	965		1.87	1.80	3.37			
3b	Yellow	3 - 1/16"	.175	23.02	12.00	.844	2.35	476	.865	1.07	1.00	1.07	2,190	184	2,261
	Birch			18.01			1.84	485		1.09	1.00	1.09			
				12.00			1.22	510		1.15	1.19	1.37			
				9.01			.92	571		1.29	1.41	1.82			
				5.98			.61	786		1.77	1.80	3.19			
3c	Yellow	3 - 1/16"	.178	24.02	8.00	.860	3.66	1,067	.915	1.02	1.00	1.02	2,005	193	2,093
	Birch			21.03			3.21	1,067		1.02	1.00	1.02			
				18.00			2.74	1,116		1.07	1.00	1.07			
				15.01			2.29	983		.94	1.00	.94			
				12.01			1.83	1,004		.96	1.00	.96			
				9.02			1.38	1,110		1.06	1.11	1.18			
				7.03			1.07	1,116		1.07	1.28	1.37			
				5.00			.76	1,292		1.24	1.58	1.96			
3d	Yellow	3 - 1/16"	.180	6.00	12.02	.833	.62	735	.825	1.61	1.78	2.86	2,268	171	2,321
	Birch														
3e	Yellow	3 - 1/16"	.176	10.02	12.01	.847	1.02	437	.870	.89	1.32	1.17	2,393	204	2,472
	Birch														
6a	Yellow-	3 - 1/16"	.182	14.00	12.02	.842	1.43	411	.855	1.15	1.09	1.25	1,666	137	1,717
	Poplar			12.02			1.22	434		1.21	1.19	1.44			
				10.00			1.02	411		1.15	1.32	1.52			
				8.04			.82	480		1.34	1.51	2.02			
				6.03			.61	731		2.04	1.80	3.67			
6b	Yellow-	3 - 1/16"	.177	22.77	12.02	.816	2.40	296	.775	1.11	1.00	1.11	1,471	94	1,490
	Poplar			18.03			1.90	306		1.15	1.00	1.15			
				11.98			1.26	306		1.15	1.17	1.35			
				9.00			.95	348		1.30	1.38	1.79			
				6.00			.63	522		1.96	1.77	3.47			
6c	Yellow-	3 - 1/16"	.170	24.02	8.00	.816	3.86	640	.775	1.03	1.00	1.03	1,585	102	1,607
	Poplar			18.01			2.89	640		1.03	1.00	1.03			
				12.02			1.93	647		1.04	1.00	1.04			
				9.03			1.45	750		1.21	1.08	1.31			
				6.02			.97	816		1.32	1.36	1.80			

Table 3.—Test data and computed values for unstiffened plywood plates tested in uniform edgewise compression (continued)

Plate No.	Species	No. and thickness of plies	h	b	a	$\frac{b'}{a}$	$\frac{b}{b'}$	σ_{cr}	$(k_c)_\infty$	Apparent $\frac{k_c}{(k_c)_\infty}$	$\frac{p_{cr}}{\sigma_{cr}}$	Correct $\frac{k_c}{(k_c)_\infty}$	E_{fw}	E_{fx}	E_L
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
			Inch	Inches	Inches			P.s.i.					1,000 p.s.i.	1,000 p.s.i.	1,000 p.s.i.
38a	Yellow Birch	4 - 1/20"	0.195	14.00	12.00	0.937	1.29	1,026	1.237	1.26	1.15	1.45	2,055	410	2,348
				12.02			1.10	940		1.15	1.26	1.45			
				10.02			.92	855		1.05	1.41	1.48			
				8.00			.73	1,026		1.26	1.62	2.04			
				6.05			.56	1,325		1.62	1.88	3.05			
38b	Yellow Birch	4 - 1/20"	.190	24.01	12.02	.919	2.24	779	1.150	1.17	1.00	1.17	1,960	327	2,178
				18.02			1.68	709		1.06	1.03	1.09			
				11.97			1.12	661		.99	1.25	1.24			
				8.98			.84	740		1.11	1.49	1.65			
				5.95			.56	998		1.50	1.88	2.82			
38c	Yellow Birch	4 - 1/20"	.192	24.02	8.02	.935	3.36	1,617	1.232	1.00	1.00	1.00	1,833	363	2,091
				17.88			2.50	1,805		1.11	1.00	1.11			
				12.00			1.68	1,630		1.00	1.03	1.03			
				9.00			1.26	1,539		.95	1.17	1.11			
				6.02			.84	1,630		1.00	1.49	1.49			
38d	Yellow Birch	4 - 1/20"	.192	10.02	12.02	.930	.92	818	1.195	.97	1.41	1.37	2,296	420	2,584
41a	Yellow-Poplar	4 - 1/20"	.183	14.00	12.01	.930	1.29	637	1.192	1.21	1.15	1.39	1,591	290	1,791
				11.98			1.11	637		1.21	1.26	1.52			
				9.97			.92	614		1.16	1.41	1.64			
				7.98			.74	637		1.21	1.61	1.95			
				5.99			.55	864		1.64	1.90	3.12			
41b	Yellow-Poplar	4 - 1/20"	.184	23.03	12.01	.922	2.15	493	1.154	1.02	1.00	1.02	1,500	252	1,669
				18.03			1.68	534		1.11	1.03	1.14			
				12.00			1.12	407		.84	1.25	1.05			
				9.01			.84	462		.96	1.49	1.43			
41c	Yellow-Poplar	4 - 1/20"	.182	24.01	7.99	.923	3.42	1,018	1.162	1.09	1.00	1.09	1,260	215	1,405
				18.02			2.56	983		1.05	1.00	1.05			
				12.00			1.71	900		.96	1.02	.98			
				8.99			1.28	1,004		1.08	1.16	1.25			
				5.99			.85	949		1.02	1.48	1.51			
42a	Yellow-Poplar	4 - 1/16"	.240	24.02	18.00	.906	1.50	345	1.082	.98	1.07	1.05	1,620	233	1,765
				20.97			1.31	312		.88	1.14	1.00			
				18.05			1.13	299		.85	1.24	1.05			
				15.02			.94	252		.71	1.39	.99			
				11.98			.75	280		.79	1.59	1.26			
				9.02			.56	361		1.02	1.88	1.92			
				7.02			.44	491		1.40	2.12	2.97			

Table 3.—Test data and computed values for unstiffened plywood plates tested in uniform edgewise compression (continued)

Plate No.	Species	No. and thickness of plies	h	b	a	$\frac{b'}{a}$	$\frac{b}{b'}$	σ_{cr}	$(k_c)_\infty$	Apparent $\frac{k_c}{(k_c)_\infty}$	$\frac{P_{cr}}{\sigma_{cr}}$	Correct $\frac{k_c}{(k_c)_\infty}$	E_{fw}	E_{fx}	E_L
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
			Inch	Inches	Inches			P.s.i.					1,000 p.s.i.	1,000 p.s.i.	1,000 p.s.i.
42b	Yellow-Poplar	4 - 1/16"	0.242	16.03	18.01	0.914	0.99	314	1.117	0.94	1.35	1.27	1,443	225	1,588
42c	Yellow-Poplar	4 - 1/16"	.246	12.00	18.01	.918	.74	273	1.137	.75	1.61	1.21	1,494	244	1,654
17a	Yellow-Poplar	5 - 1/20"	.228	24.02	18.02	.971	1.40	375	1.468	.97	1.10	1.07	1,245	409	1,575
				21.02			1.23	443		1.15	1.18	1.36			
				18.01			1.05	341		.88	1.30	1.14			
				15.00			.88	316		.82	1.45	1.19			
				12.02			.70	414		1.07	1.66	1.78			
				9.02			.53	496		1.28	1.94	2.48			
				7.03			.41	650		1.68	2.18	3.66			
				5.02			.29	1,112		2.88	.....	.....			
17b	Yellow-Poplar	5 - 1/20"	.226	18.02	18.02	.949	1.08	221	1.314	.68	1.28	.87	1,290	300	1,514
17c	Yellow-Poplar	5 - 1/20"	.235	15.03	18.01	.955	.89	300	1.358	.93	1.44	1.34	1,128	288	1,348
3s	Yellow Birch	3 - 1/16"	.146	12.95	12.00	.852	1.30	314	.890	.96	1.15	1.10	2,246	204	2,333
				6.48			.65	558		1.70	1.74	2.96			
6s	Yellow-Poplar	3 - 1/16"	.182	9.51	12.02	.833	.98	247	.825	.77	1.35	1.04	1,547	116	1,584
				4.76			.49	622		1.95	2.01	3.92			
38s	Yellow Birch	4 - 1/20"	.195	12.02	12.01	.936	1.10	700	1.237	.86	1.26	1.08	2,055	408	2,346
				6.01			.55	1,021		1.25	1.90	2.38			
38ss	Yellow Birch	4 - 1/20"	.190	16.50	18.00	.933	1.00	263	1.214	.74	1.34	.99	2,221	424	2,519
				8.25			.50	541		1.52	2.00	3.04			
41s	Yellow-Poplar	4 - 1/20"	.171	11.02	12.03	.929	1.02	379	1.188	.76	1.32	1.00	1,741	314	1,957
				5.51			.51	781		1.56	1.98	3.09			
41ss	Yellow-Poplar	4 - 1/20"	.183	16.50	17.98	.935	1.00	208	1.232	.97	1.34	1.30	1,410	278	1,608
				8.25			.50	330		1.54	2.00	3.08			
42s	Yellow-Poplar	4 - 1/16"	.238	16.01	18.02	.942	.96	252	1.274	.67	1.37	.92	1,394	300	1,613
				8.00			.48	461		1.23	2.03	2.50			
14s	Yellow Birch	5 - 1/20"	.245	17.54	18.00	.967	1.03	544	1.438	.78	1.31	1.02	2,008	615	2,498
				8.77			.51	906		1.31	1.98	2.59			
17s	Yellow-Poplar	5 - 1/20"	.229	17.53	18.00	.970	1.02	400	1.454	.93	1.32	1.23	1,401	444	1,757
				8.76			.51	503		1.16	1.98	2.30			

Table 4.--Test data and computed values for stiffened plywood plates tested in uniform edgewise compression

Plate No.	σ_{cr}	$\frac{\sigma_{cr}-\sigma_{crp}}{\sigma_{crm}-\sigma_{crp}}$	t	d	$\frac{2\pi^2 \frac{b}{ha^4}(EI)_s}{\sigma_{crm}-\sigma_{crp}}$	E_s	Plate No.	σ_{cr}	$\frac{\sigma_{cr}-\sigma_{crp}}{\sigma_{crm}-\sigma_{crp}}$	t	d	$\frac{2\pi^2 \frac{b}{ha^4}(EI)_s}{\sigma_{crm}-\sigma_{crp}}$	E_s
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	P.s.i.		Inch	Inch		1,000 p.s.i.		P.s.i.		Inch	Inch		1,000 p.s.i.
3s	514	0.82	0.252	0.993	13.65	1,690	41ss	331	1.01	0.246	0.983	4.89	1,660
	559	1.00		.732	5.47			325	.96		.726	1.97	
	582	1.10		.612	3.20			322	.93		.623	1.24	
	565	1.03		.495	1.69			340	1.08		.505	.66	
	582	1.10		.377	.74			304	.79		.382	.28	
	548	.96		.265	.26			255	.38		.265	.10	
	434	.49		.136	.04			219	.09		.122	.01	
	314	.00		.000	.00			208	.00		.000	.00	
6s	668	1.12	.189	.989	3.62	1,590	42s	473	1.06	.247	1.003	2.30	1,695
	576	.88		.751	1.58			473	1.06		.882	1.57	
	622	1.00		.580	.73			457	.98		.751	.97	
	448	.54		.501	.47			450	.95		.634	.58	
	375	.34		.365	.18			450	.95		.500	.28	
	306	.16		.252	.06			382	.62		.381	.12	
	274	.07		.126	.01			341	.42		.250	.04	
	247	.00		.000	.00			273	.10		.127	.01	
								252	.00		.000	.00	
38s	1,033	1.04	.248	.994	6.92	1,650	17s	510	1.07	.246	1.006	5.14	1,620
	1,042	1.06		.744	2.90			512	1.09		.760	2.22	
	991	.91		.622	1.70			488	.85		.627	1.24	
	1,029	1.02		.498	.87			502	.99		.503	.64	
	1,012	.97		.375	.37			461	.59		.385	.29	
	966	.83		.244	.10			422	.21		.248	.08	
	897	.61		.185	.04			434	.33		.131	.01	
	859	.50		.125	.02			400	.00		.000	.00	
	700	.00		.000	.00								
38ss	548	1.02	.252	.995	2.22	1,685	14s	902	.99	.374	1.000	2.01	1,595
	538	.99		.756	.98			909	1.01		.753	.86	
	518	.92		.628	.56			952	1.13		.627	.50	
	562	1.08		.503	.29			728	.51		.507	.26	
	450	.67		.380	.12			646	.28		.373	.10	
	368	.38		.248	.04			592	.13		.248	.03	
	307	.16		.129	.01			501	- .12		.100	.00	
	263	.00		.000	.00			544	.00		.000	.00	
41s	798	1.04	.186	.995	4.44	1,700							
	754	.93		.746	1.87								
	793	1.03		.632	1.14								
	875	1.23		.500	.56								
	666	.71		.378	.24								
	496	.29		.249	.07								
	438	.14		.131	.01								
	379	.00		.000	.00								

Table 5.—Test data and computed values for unstiffened plywood plates tested in uniform edgewise compression. A comparison of methods for determining the critical loads.

Plate No.	Species	No. and thickness of plies	h	b	a	$\frac{b'}{a}$	$\frac{b}{b'}$	p_{cr}	$(k_c)_\infty$	$\frac{k_c}{(k_c)_\infty}$	$\frac{p_{cr}}{\sigma_{cr}}$	E_{fw}	E_{fx}	E_L
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
			Inch	Inches	Inches			P.s.i.				1,000 p.s.i.	1,000 p.s.i.	1,000 p.s.i.
3dd	Yellow Birch	3 - 1/16"	0.179	5.99	11.98	0.848	0.60	994	0.875	2.21	....	2,180	189	2,256
3d[1]			.180	6.00	12.02	.833	.62	735	.825	1.61	1.37	2,268	171	2,321
3ee	Yellow Birch	3 - 1/16"	.175	10.00	12.00	.851	.99	629	.884	1.37	....	2,293	205	2,379
3e[1]			.176	10.02	12.01	.847	1.02	437	.870	.89	1.54	2,393	204	2,472
38dd	Yellow Birch	4 - 1/20"	.192	10.02	12.02	.941	.90	935	1.262	1.36	....	1,308	376	2,080
38d[1]			.192	10.02	12.02	.930	.92	818	1.195	.97	1.39	2,296	420	2,584
42bb	Yellow-Poplar	4 - 1/16"	.245	16.02	18.03	.904	.99	416	1.072	1.29	....	1,484	210	1,613
42b[1]			.242	16.03	18.01	.914	.99	314	1.117	.94	1.37	1,443	225	1,588
42cc	Yellow-Poplar	4 - 1/16"	.240	12.01	18.03	.912	.74	415	1.109	1.25	....	1,529	233	1,679
42c[1]			.246	12.00	18.01	.918	.74	273	1.137	.75	1.67	1,494	244	1,654
17bb	Yellow-Poplar	5 - 1/20"	.235	18.03	18.03	.941	1.07	360	1.265	1.07	....	1,342	280	1,546
17b[1]			.226	18.02	18.02	.949	1.08	221	1.314	.68	1.57	1,290	300	1,514
17cc	Yellow-Poplar	5 - 1/20"	.229	15.02	18.03	.932	.90	339	1.207	1.05	....	1,437	268	1,623
17c[1]			.235	15.03	18.01	.955	.89	300	1.358	.93	1.13	1,128	288	1,348
3b	Yellow Birch	3 - 1/16"	.175	23.02	12.00	.844	2.35	524	.865	1.18	....	2,190	184	2,261
[1]			.175	23.02	12.00	.844	2.35	476	.865	1.07	1.10	2,190	184	2,261
6c	Yellow-Poplar	3 - 1/16"	.170	12.02	8.00	.816	1.93	661	.775	1.06	....	1,585	102	1,607
[1]			.170	12.02	8.00	.816	1.93	647	.775	1.04	1.02	1,585	102	1,607
			.170	9.03	8.00	.816	1.45	735	.775	1.19	....	1,585	102	1,607
[1]			.170	9.03	8.00	.816	1.45	750	.775	1.21	.98	1,585	102	1,607
38b	Yellow Birch	4 - 1/20"	.190	24.01	12.02	.919	2.24	796	1.150	1.20	....	1,960	327	2,178
[1]			.190	24.01	12.02	.919	2.24	779	1.150	1.17	1.02	1,960	327	2,178
41b	Yellow-Poplar	4 - 1/20"	.184	23.03	12.01	.922	2.15	543	1.154	1.12	....	1,500	252	1,669
[1]			.184	23.03	12.01	.922	2.15	493	1.154	1.02	1.10	1,500	252	1,669
			.184	18.03	12.01	.922	1.68	543	1.154	1.13	....	1,500	252	1,669
[1]			.184	18.03	12.01	.922	1.68	534	1.154	1.11	1.02	1,500	252	1,669
41c	Yellow-Poplar	4 - 1/20"	.182	24.01	7.99	.923	3.42	1,032	1.162	1.10	....	1,260	215	1,405
[1]			.182	24.01	7.99	.923	3.42	1,018	1.162	1.09	1.01	1,260	215	1,405
42a	Yellow-Poplar	4 - 1/16"	.240	24.02	18.00	.906	1.50	370	1.082	1.05	....	1,620	233	1,765
[1]			.240	24.02	18.00	.906	1.50	345	1.082	.098	1.07	1,620	233	1,765
17a	Yellow-Poplar	5 - 1/20"	.228	24.02	18.02	.971	1.40	377	1.468	.98	....	1,245	409	1,575
[1]			.228	24.02	18.02	.971	1.40	375	1.468	.97	1.01	1,245	409	1,575

[1] Panels for which the critical loads were obtained by the strain-difference method, and therefore apparent values appear in columns 9 and 11.

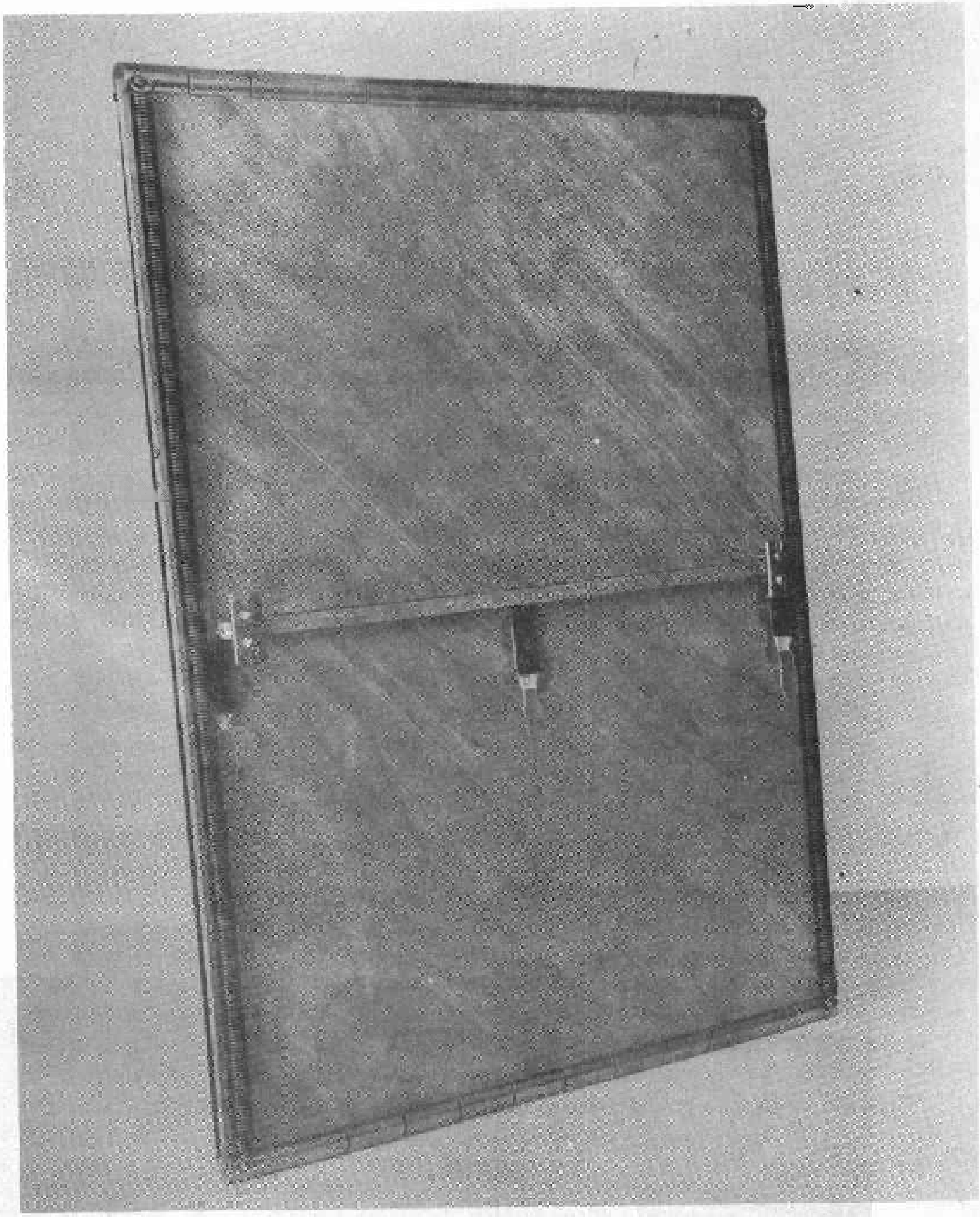

Figure 12.--Stiffened flat plywood plate mounted in segmented cylindrical steel loading rods prior to test. The method of restraining the ends of the stiffener to prevent separation at the ends, the metalectric strain gages for measuring deformation, and the attachment of coil springs at the edges to reduce frictional restraint during test are shown.

Z M 70770 F

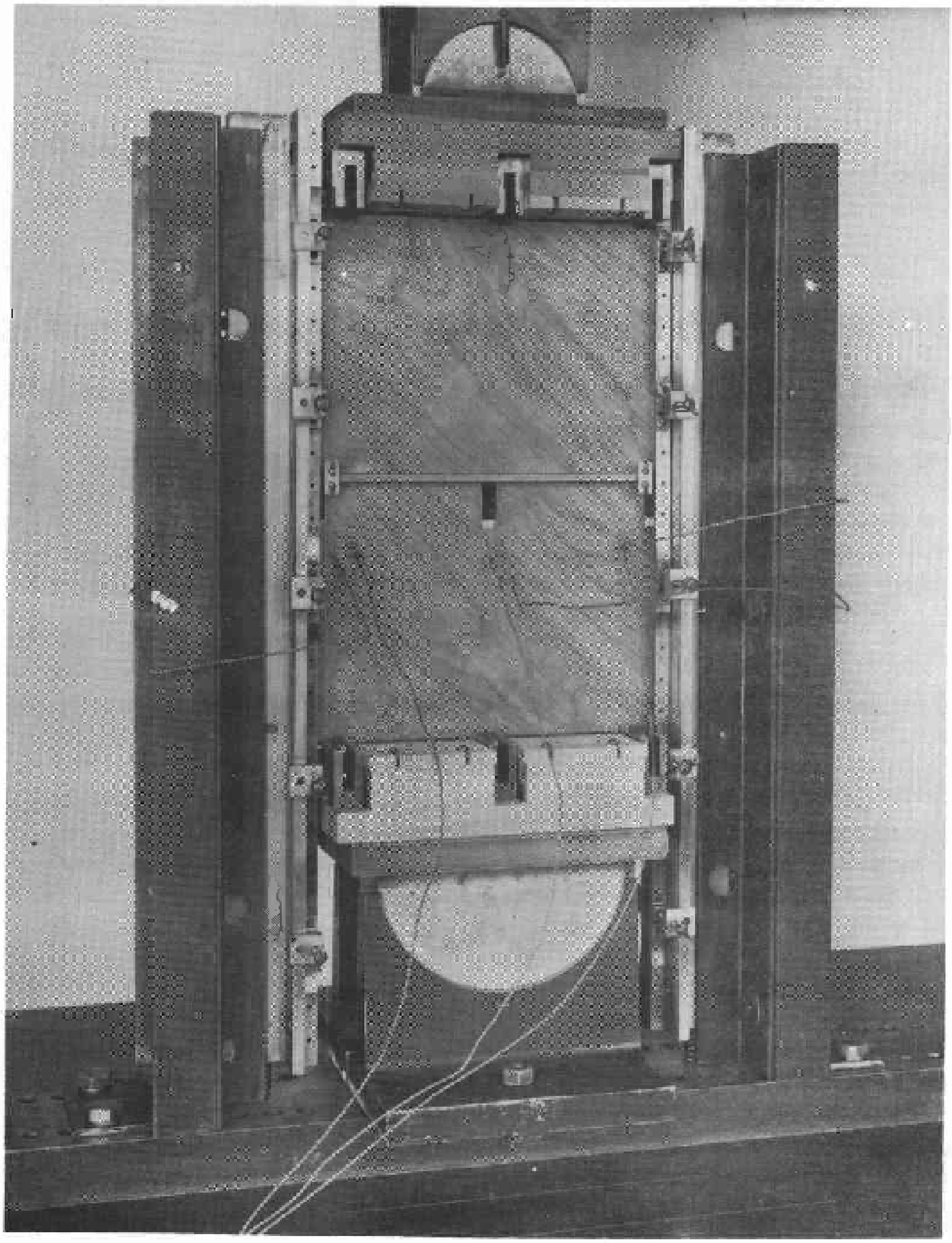

Figure 13.--Stiffened flat plywood plate ready for test. Metalectric strain gages mounted below horizontal stiffener are used in measuring deformations in the specimens.

Z M 70771 F

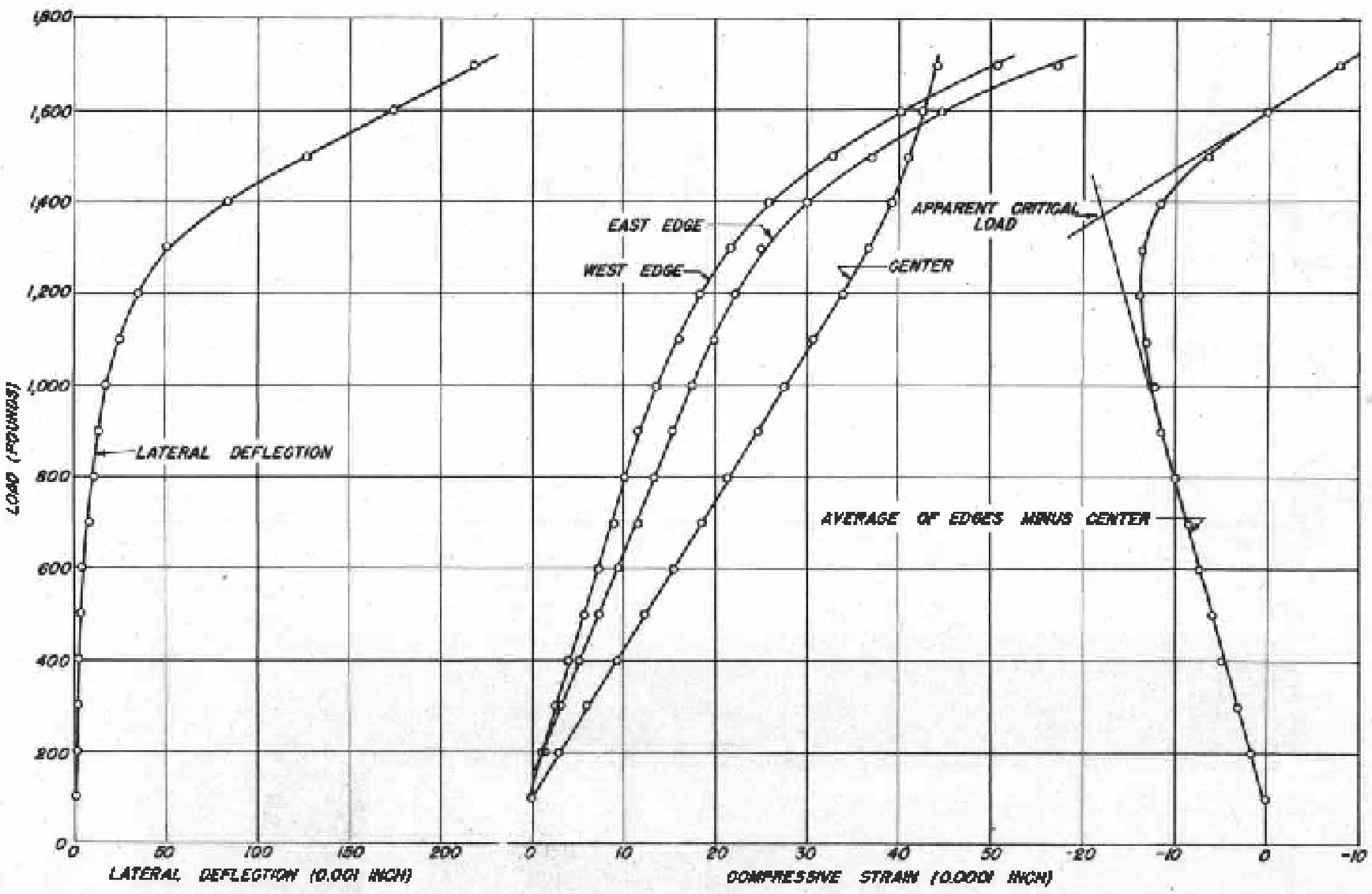

Figure 14.--Typical load-strain curves, plotted to determine critical load of a stiffened plywood plate in compression.

2 M 69853 F

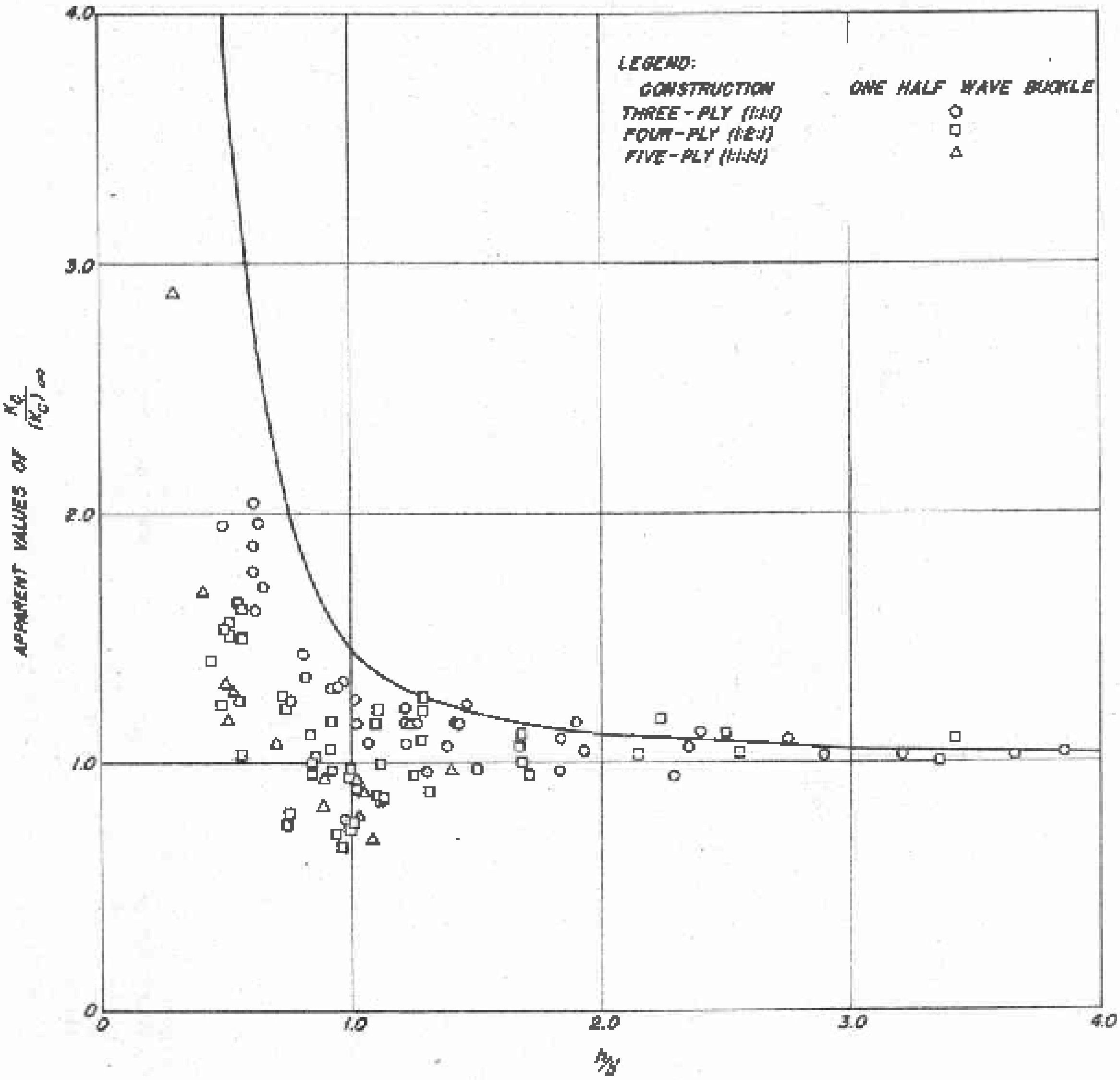

Figure 15.--Apparent values of $k_c/k_{c\infty}$ and design curve for plywood plates under uniform compression at 45° to the direction of the grain of the face plies.

Z M 59650 F

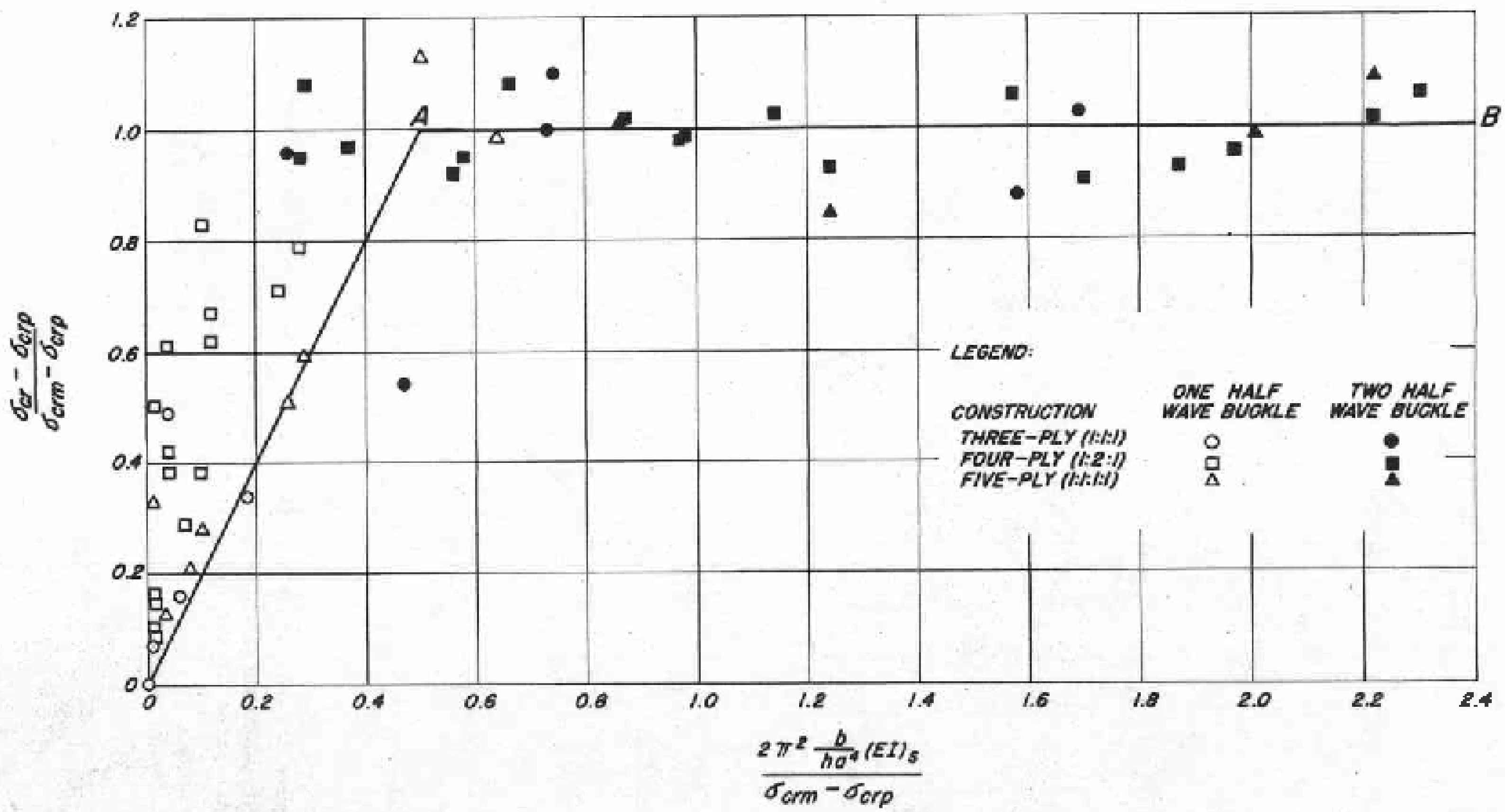

Figure 16.--Differences between observed apparent critical stresses of stiffened plates and observed apparent critical stresses of unstiffened plates plotted against $2\pi^2 \frac{b}{ha^4}(EI)_s$ both expressed as ratios to the differences between observed apparent critical stresses of stiffened plates, stiffened with large effective stiffeners, and observed apparent critical stresses of unstiffened plates.

2 · h

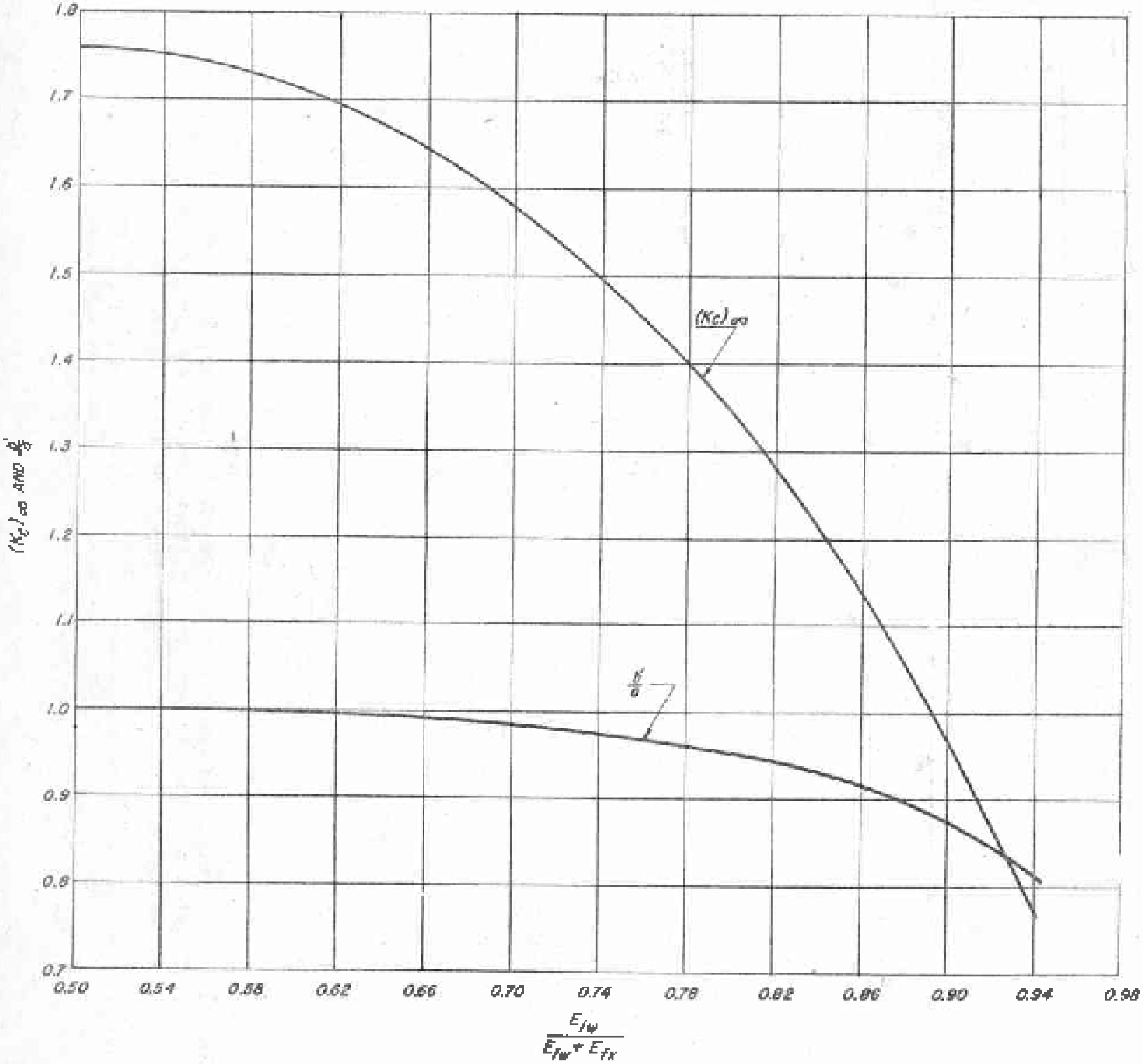

Figure 17.—The constants $k_{c\infty}$ and b'/a, both plotted as functions of the ratio, $\frac{E_{fw}}{E_{fw} + E_{fx}}$. Buckling of infinitely long plates of symmetrical construction, having the direction of the grain of the face plies 45° to the direction of the applied uniform compressive stress.

Z M 69655 F

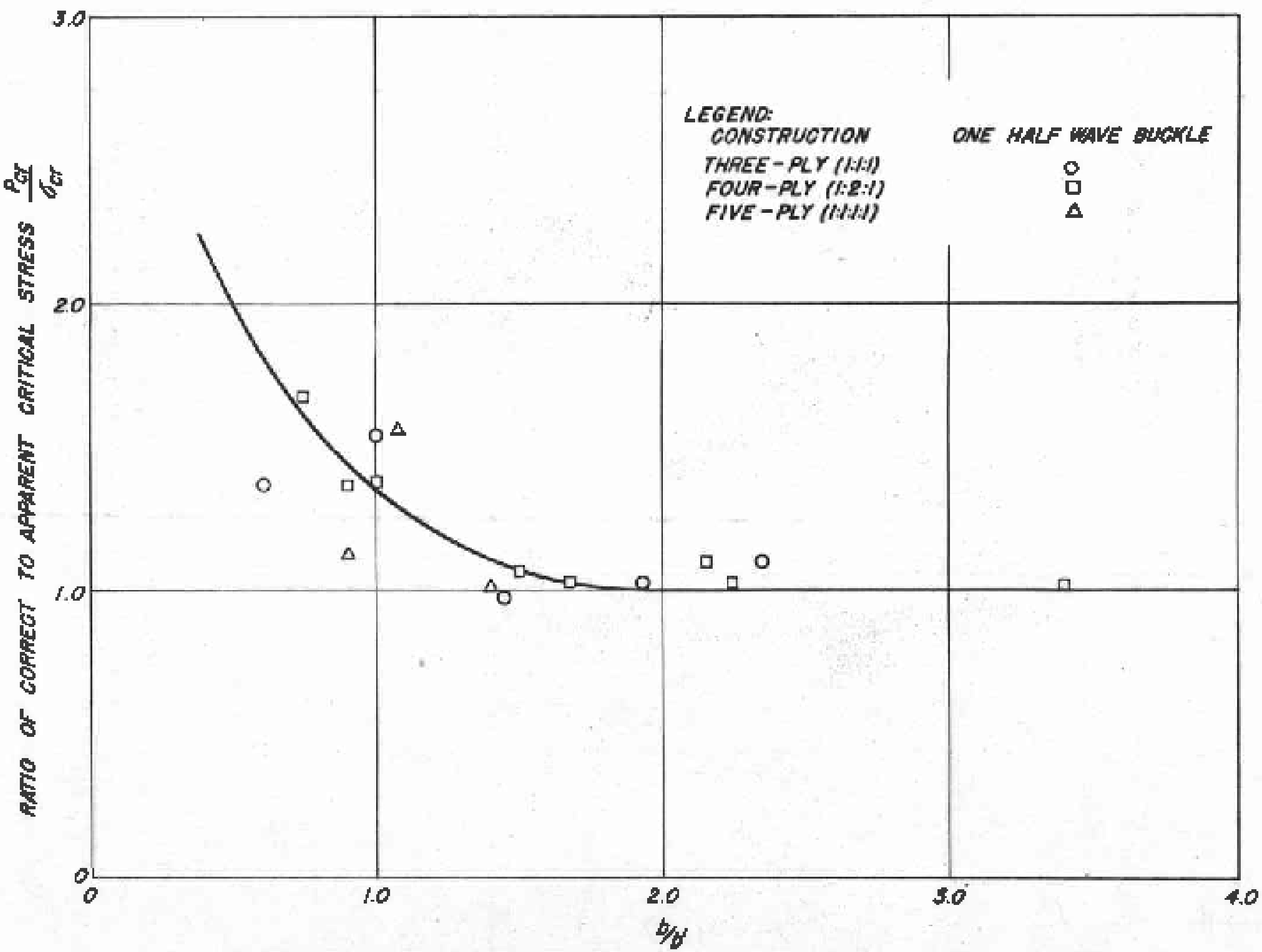

Figure 18.--Ratios of correct to apparent critical stresses, plotted as ordinates, against b/b' ratios, plotted as abscissas.

Z M 63507 F

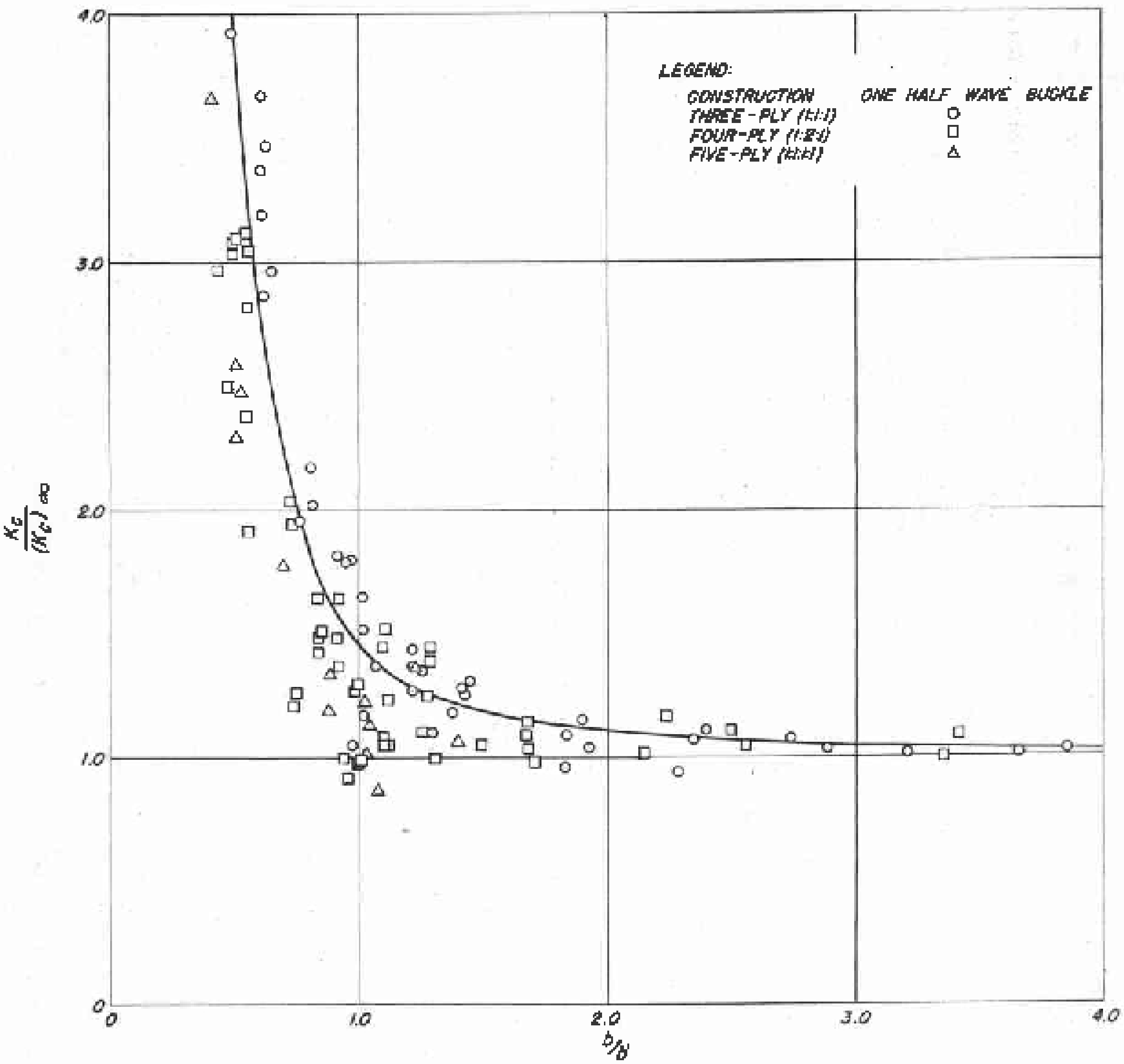

Figure 19.--Apparent values of $k_c/(k_c)_\infty$ converted to correct values by means of figure 7 and design curve for plywood plates under uniform compression at 45° to the direction of the grain of the face plies.

Z M 69658 F