Supplement to

BUCKLING OF FLAT PLYWOOD PLATES IN COMPRESSION, SHEAR, OR COMBINED COMPRESSION AND SHEAR

Buckling Tests of Flat Plywood Plates in Compression With Face Grain at 15°, 30°, 45°, 60°, and 75°, to Load

Information Reviewed and Reaffirmed

August 1955

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. 1316-G

UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE
FOREST PRODUCTS LABORATORY
Madison 5, Wisconsin
In Cooperation with the University of Wisconsin

BUCKLING TESTS OF FLAT PLYWOOD PLATES IN COMPRESSION WITH FACE GRAIN AT 15°, 30°, 45°, 60°, AND 75° TO LOAD[1,2]

By

C. B. NORRIS, Engineer
and
A. W. VOSS, Engineer

Forest Products Laboratory,[3] Forest Service
U. S. Department of Agriculture

This report presents test data in substantiation of formula (16), $P_{cr} = k_c E_L \frac{h^2}{a^2}$, for the buckling stress of plywood plates in compression as presented in Forest Products Laboratory Report No. 1316, "Buckling of Flat Plywood Plates in Compression, Shear, or Combined Compression and Shear." These data were obtained in the same manner as the data presented in Report No. 1316-D, "Buckling of Flat Plywood Plates in Compression with Face Grain at 0° and 90° to Load."

For a discussion of the problem, the materials used, the system of matching and marking specimens, and the method of test, see Report No. 1316-D.

Very few modifications of the procedure used in the compression tests of plywood at 0° and 90° to the direction of the face grain were necessary when the direction of the face grain was placed at other angles to

---

[1] This report 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.

[2] Original report dated November 1943.

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

the load. Modifications were necessary, however, in the layout of specimens and plate sizes, and in the determination of the critical buckling load of thick specimens.

A modification of specimen layout was necessary to obtain specimens and matched coupons for pack compression tests having the face grain at the same angles to their edges. The layouts were as shown in figure 91.[4]

The plate sizes were again computed from the elastic properties of the plywood to obtain the length-width ratio for the formation of a buckle in a single half wave. Dimensions of the plates from each panel were as shown in table 15.

The second modification of the procedure used in the compression buckling tests at 0° and 90°, for this series of tests at other angles, was an improvement in the technique of observing the critical buckling load of thick specimens when the critical buckling load was greater than 0.75 of the proportional-limit load. It was observed in the effective width tests (Report No. 1316-E) that the rate of increase of the average strain at the center of the plate decreases and that the rate of increase of the average strain at the transverse centerline near the edges increases at and above the critical buckling load. Therefore, in addition to the buckling deflection, strains were measured at three points on both faces of the thick plates, at the center and at 3/8 inch from the edges on the transverse centerline. When the lateral, or buckling, deflection curve gave no indication of a critical buckling load, the critical buckling load was taken from the strain curves as the load at which the distribution of strain at the center and the average strain at the edges started to change rapidly. A typical example of the method is presented in figure 92, in which the buckling deflection curve and the strain curves are plotted.[5] It may be noted that there is a sudden break in the "center" load-strain curve at a load of 2,800 pounds which is taken as the critical buckling load in this instance.

Except for these two modifications, the same system of marking and matching of material, and the same buckling-test apparatus and procedure were used in this series of buckling tests in compression at 15°, 30°, 45°, 60°, and 75° to the face grain direction as were used in the compression buckling tests at 0° and 90° to the face grain direction.

---

[4]The figures and tables in this supplement are numbered consecutively with those of Report No. 1316 and its supplements, 1316-B, -C, -D, -E, and -F.

[5]The Southwell method of determining the critical load is not applicable to flat plates in compression. (Report No. 1316, page 15, and Report No. 1316-D, page 4.)

Presentation of Data

Data obtained in this series of tests are presented in table 15, together with various computed values and in figures 93 through 102, and 104 through 107. All test data from each panel are tabulated following the panel number given in column 1 of table 15. The test data for the plates are given in columns 2, 3, 4, 6, 11, 12, 13, and 15. When only one plate was obtained from a panel 24 by 24 inches, as for compression at 45° to the face grain, columns 11 through 19 and column 20 are omitted. Data obtained from the tests of coupons are presented in columns 20 through 23.

In figures 93 through 97, and 104 through 107, are plotted the ratios of the observed critical buckling load to the proportional-limit load against the ratios of the computed buckling loads to the proportional-limit load. Two critical buckling loads were computed for each specimen by the method presented in Report No. 1316, first, (figs. 93-97) using $\frac{k_c}{k_{c\infty}}$ assumed equal to $\frac{k_s}{k_{s\infty}}$ as given in figure 12 of Report No. 1316, and second, (figs. 104-107) using the values of $\frac{k_c}{k_{c\infty}}$ obtained from these tests as discussed later. Figures 93 and 104 show the results of tests in which the load was applied at 15° to the face grain direction; figures 94 and 105 at 30°; figure 95 at 45°; figures 96 and 106 at 60°; and figures 97 and 107 at 75°. These figures present graphically an indication of the accuracy of the method used for computing the critical buckling load. Only the data included in the range for which the critical buckling load is from 0.1 to 0.9 of the proportional-limit load are significant in determining the accuracy of the formula (Report No. 1316-D, pages 5 and 6).

For tests within this range, the average ratios of the observed critical buckling load to the critical load computed using $\frac{k_c}{k_{c\infty}}$ assumed equal to $\frac{k_s}{k_{s\infty}}$ are:

Angle of compressive stress to direction of face grain	Observed critical buckling load expressed in percent of computed load
15°	68
30°	82
45°	99
60°	92
75°	88

The curves in figures 93 through 97 and these percentages show that the assumption that $\frac{k_c}{k_{c\infty}}$ equals $\frac{k_s}{k_{s\infty}}$ is correct only for the plates in which the face grain is at an angle of 45° to the direction of the load, and gives high values of the buckling load for other angles.

The method of computing the critical buckling load is given in Report No. 1316 with the formula for the critical buckling stress

$$p_{cr} = k_c E_L \frac{h^2}{a^2}$$

In this formula, h is the thickness and a is the width of the plate. These quantities were measured and checked at the time of test and are not questioned. The value of the modulus of elasticity of the individual plies in a direction parallel to the grain (E_L) was determined by static bending tests of coupons and the formula

$$E_L = \frac{20}{21} (E_1 + E_2)$$

in which E_1 and E_2 are the bending moduli of elasticity of the plywood parallel and perpendicular to the face grain, respectively. This formula assumes that the ratio of the transverse to the longitudinal modulus of elasticity of the individual plies is 0.05 and has given satisfactory results previously. The value of E_L is, therefore, believed reliable.

The only other term in the formula is k_c. This term is made up of two factors, $k_{c\infty}$ which is mathematically determined by the energy method and applies to panels infinitely long, and a correction factor for length. It is assumed that the correction factor for length is in error. The value of k_c was determined for each specimen from the value of $k_{c\infty}$ for each specimen by the use of figure 12 of Report No. 1316. In that figure the ratios of these factors for panels subjected to shear stress applied parallel and perpendicular to the direction of the face grain ($\frac{k_s}{k_{s\infty}}$) are plotted as ordinates and the ratio of the length of the panel to the length of a single ideal half wave ($\frac{b}{b'}$) as abscissas. The ordinates were assumed to be the same for $\frac{k_c}{k_{c\infty}}$.

This assumption was studied by computing an observed k_c from the observed critical buckling load, the E_L, and the plate dimensions. These observed values of k_c were divided by the values of $k_{c\infty}$ obtained from Report No. 1316. These ratios were plotted as ordinates and the ratios of $\frac{b}{b'}$ were plotted as abscissas in figures 98 through 102. Also shown in these figures by dashed lines is the curve for $\frac{k_s}{k_{s\infty}}$ from figure 12. It is apparent from a study of these figures (98 through 102) that the ratio of $\frac{k_c \text{ observed}}{k_{c\infty}}$ does not agree with $\frac{k_s}{k_{s\infty}}$ when the load is applied at angles of 15°, 30°, 60°, or 75° to the face grain direction.

It was assumed that the values of $k_{c\infty}$ are correct; and that the ratios $\frac{k_c}{k_{c\infty}}$ are not equal to $\frac{k_s}{k_{s\infty}}$. Therefore a new group of curves similar to figure 12 of Report No. 1316 were drawn for each angle between load and face grain. In drawing these curves, it was assumed that the form of the curve given in figure 12 of Report No. 1316 is correct. The new curves were, therefore, obtained from the old one by adjusting its ordinates so that the new curves passed through the average values of the test results and so that the value of the asymptote $(\frac{k_s}{k_{s\infty}} = 1)$ was not changed.

This adjustment was made by determining a factor F from each test using the formula

$$F = \frac{\left(\frac{k_c \text{ observed}}{k_{c\infty}}\right) - 1}{\left(\frac{k_s}{k_{s\infty}}\right) - 1}$$

and then finding the average factor for the tests at each grain angle. Using these average factors, the new curves were drawn for each angle with $\frac{k_c}{k_{c\infty}} = 1 + F\left[\left(\frac{k_s}{k_{s\infty}}\right) - 1\right]$ for all values of $\frac{b}{b'}$.

Curves corrected in this way to agree with the observed data are presented in figure 103 as a family of curves for $\frac{k_c}{k_{c\infty}}$ at various angles to the face grain direction. The average correction factors, F, used are:

Angle of load to face grain direction	Correction factor F
15°	0.47
30°	.58
45°	1.00
60°	.86
75°	.66

The critical buckling loads were computed using this method for the determination of $\frac{k_c}{k_{c\infty}}$ and are plotted in figures 104 through 107.

Conclusions

The critical buckling stress of flat plywood plates in compression with the face grain at 15°, 30°, 45°, 60°, and 75° may be computed by formula (16) of Report No. 1316,

$$p_{cr} = k_c E_L \frac{h^2}{a^2}$$

if the curves of figure 103 of this report are used for determining k_c instead of the curve of figure 12. The values obtained by this method agree with the average experimental results obtained.

The curves of figure 103 have not been experimentally determined throughout their entire lengths, but each curve agrees with the average experimental results. The curves were drawn according to the form of the curve given in figure 12 of Report No. 1316, and represent the best available information.

From consideration of the data in figures 98 to 102, it is evident that values of $\frac{k_c}{k_{c\infty}}$ given in figure 103 are in best accord with the experimental data for θ = 45°. The deviation of the data from the curves of figure 103 is greater for θ = 30° and θ = 60°, and still greater for θ = 15° or 75°. For the grain inclinations of 15° or 75°, the ratio $\frac{k_c}{k_{c\infty}}$ ranges approximately 20 percent on either side of the mean. Therefore, the lack of data for a wide range in values of $\frac{b}{b'}$ and the deviation in the observed data at the tested values of $\frac{b}{b'}$ should be given due consideration in using the curves of figure 103.

Table 15.--Test data and computed values for buckling test plates and coupons.

Panel no.	Compression buckling test plates — Loaded at 75° to direction of face grain: Length	Width	Thickness	Computed critical buckling load	Observed critical buckling load	Computed load at proportional limit	$\frac{b}{b'}$	$\frac{k_s}{k_{s_\infty}}$	$\frac{k_c \text{ observed}}{k_{c_\infty}}$	Loaded at 15° to direction of face grain: Length	Width	Thickness	Computed critical buckling load	Observed critical buckling load	Computed load at proportional limit	$\frac{b}{b'}$	$\frac{k_s}{k_{s_\infty}}$	$\frac{k_c \text{ observed}}{k_{c_\infty}}$	Properties of plate material — Average proportional limit stress in compression: At 75° to face grain (Coupons M & N)	At 15° to face grain (Coupons O & P)	Average modulus of elasticity in bending: With face grain parallel to span (Coupons D & E)	With face grain perpendicular to span (Coupons F & G)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)
	In.	In.	In.	Lb.	Lb.	Lb.				In.	In.	In.	Lb.	Lb.	Lb.				Lb. per sq. in.	Lb. per sq. in.	1,000 lb. per sq. in.	1,000 lb. per sq. in.
1q										14.46	9.50	0.067	69	98	1,941	1.018	1.442	2.385	2,020	3,050	1,214.0	171.0
2q	5.99	9.48	0.145	722	675	3,192	1.128	1.350	1.263	14.50	9.49	.142	898	725	5,121	0.934	1.539	1.243	2,320	3,800	2,263.0	178.2
3q	5.99	9.48	.166	1,135	900	2,784	1.065	1.378	1.093	14.53	9.51	.167	1,471	1,600	6,639	.934	1.509	1.641	2,360	4,180	2,212.0	199.3
3n	6.00	9.50	.186	1,392	1,200	[illegible]	1.136	1.345	1.159	14.50	9.52	.187	1,888	1,600	3,596	.928	1.547	1.313	1,294	2,020	2,096.5	181.2
4q										14.47	9.43	.066	54		1,214	.925	1.550		1,630	1,840	1,363.0	131.5
4n	4.00	9.50	.057	26	60	823	1.034	1.427	3.302	14.52	9.52	.058	33	70	1,176	.939	1.472	3.126	1,150	2,130	1,104.0	127.2
5q	5.99	9.48	.144	481	440	1,925	1.095	1.376	1.260	14.49	9.49	.145	627	900	3,137	.934	1.509	1.203	1,410	2,280	1,437.0	129.4
5n	6.01	9.50	.150	569	500	1,807	1.115	1.358	1.194	14.52	9.50	.149	729	550	2,605	.912	1.527	1.152	1,268	1,840	1,369.5	131.2
6q	5.99	9.48	.183	1,043	800	2,724	1.186	1.310	1.004	14.53	9.51	.181	1,400	900	3,787	.934	1.581	1.017	1,570	2,200	1,808.0	111.2
6n	6.01	9.50	.186	1,052	950	1,986	1.138	1.342	1.214	14.53	9.50	.186	1,402	1,100	3,534	.931	1.543	1.211	1,124	2,000	1,587.0	120.4
7q										14.15	9.48	.064	69		1,638	.917	1.564		1,940	2,700	1,681.0	127.4
7m	6.02	9.50	.064	43	100	907	1.099	1.378	3.179	14.52	9.52	.065	58	74	1,267	.933	1.512	1.928	1,492	2,080	1,477.5	133.6
8q	5.99	9.48	.148	622	600	3,311	1.065	1.363	1.336	14.48	9.50	.146	756	650	4,314	.938	1.504	1.295	2,360	3,110	1,880.0	157.4
9q	5.99	9.48	.186	1,324		3,068	1.196	1.306		14.53	9.51	.188	1,910	1,300	5,924	.898	1.602	1.084	1,740	3,320	2,225.0	129.4
9n	6.00	9.50	.187	1,262	1,100	2,630	1.254	1.288	1.123	14.50	9.50	.188	1,850	1,400	4,281	.884	1.618	1.224	1,593	2,380	2,194.0	112.2
10q										14.47	9.47	.063	62		1,849	.950	1.611		1,940	3,100	1,924.0	189.8
10m	6.00	9.50	.062	41	80	876	1.085	1.384	2.675	12.50	9.52	.063	64	75	1,523	.825	1.742	2.051	1,488	2,540	1,522.0	141.1
11q	5.99	9.48	.143	649	650	3,172	1.099	1.377	1.380	14.49	9.50	.145	865	650	4,298	.951	1.521	1.137	2,340	3,120	1,989.0	177.6
11n	6.02	9.52	.148	693	600	2,159	1.151	1.334	1.154	14.51	9.52	.148	927	850	2,733	.920	1.549	1.414	1,532	1,940	2,135.0	153.4
12q	5.99	9.48	.182	1,252	1,000	2,761	1.150	1.334	1.067	14.49	9.50	.183	1,711	1,150	4,190	.924	1.531	1.043	1,600	2,410	2,055.0	150.4
12n	6.02	9.50	.188	1,380	1,100	2,161	1.187	1.311	1.046	14.50	9.52	.189	1,954		4,210	.903	1.588		1,221	2,340	2,195.0	137.6
13q	7.25	9.48	.098	360	350	2,769	.974	1.489	1.446	12.28	9.51	.113	597		3,632	1.001	1.459		2,980	3,380	1,821.0	594.0
14q	7.25	9.48	.248	6,180	2,950	4,138	.993	1.466	.699	12.27	9.49	.236	5,985		6,226	.986	1.475		1,760	2,780	2,032.0	611.0
14n	7.27	9.50	.242	4,770	2,800	4,350	1.030	1.436	.839	12.28	9.50	.245	5,844	3,800	5,656	.959	1.504	.976	1,892	2,430	1,854.5	482.0
15q	7.25	9.48	.295	9,566	5,400	7,383	1.051	1.413	.796	12.27	9.51	.300	12,214	5,600	9,130	.943	1.522	.697	2,640	3,200	2,158.0	516.0
16q	7.26	9.50	.108	304	320	1,539	.997	1.464	1.539	12.27	9.49	.108	345	310	2,276	.983	1.479	1.336	1,500	2,220	1,226.0	362.0
17q	7.25	9.48	.245	4,198	2,500	4,274	1.004	1.453	.865	12.28	9.50	.242	4,601	2,800	4,718	.978	1.482	.902	1,840	2,060	1,472.0	425.0
17n	7.26	9.50	.246	4,081	2,600	3,314	1.003	1.456	.927	12.28	9.50	.247	4,761	2,800	4,646	.978	1.483	.883	1,418	1,980	1,413.5	408.5
18q	7.27	9.49	.307	7,266		4,953	1.049	1.416		12.27	9.52	.305	8,644		5,343	.943	1.522		1,700	1,840	1,446.0	349.0
19q	7.27	9.49	.108	326	375	1,681	1.072	1.391	1.609	12.28	9.52	.109	420	300	2,989	.928	1.547	1.105	1,640	2,880	1,572.0	344.0
19n	7.10	9.50	.111	335	375	1,378	1.027	1.431	1.606	12.27	9.50	.111	425	400	3,543	.942	1.527	1.437	1,307	3,300	1,400.0	332.0
20q	7.24	9.48	.242	4,975	2,800	4,474	.927	1.448	.872	12.27	9.48	.246	5,227		6,320	1.043	1.418		1,950	2,710	1,460.0	581.0
20n	7.24	9.49	.250	4,926	3,200	4,033	.963	1.495	.973	12.21	9.51	.249	5,298	3,200	4,352	1.006	1.453	.893	1,700	1,838	1,455.0	501.0
21q	7.26	9.48	.313	9,671	5,900	5,994	1.034	1.427	.871	12.27	9.52	.307	10,819	5,400	7,368	.953	1.509	.753	2,020	2,520	1,754.0	446.0
22q	7.26	9.49	.103	392	325	1,525	1.020	1.449	1.193	12.28	9.49	.105	464	350	2,591	.967	1.497	1.082	1,560	2,600	1,925.0	520.0
22n	7.25	9.50	.104	340	325	1,284	1.034	1.427	1.363	12.25	9.50	.105	418	425	2,354	.953	1.512	1.539	1,300	2,360	1,689.0	426.5
23q	7.25	9.48	.243	5,121	3,300	4,815	1.004	1.453	.937	12.28	9.49	.244	5,273		5,769	.978	1.482		2,090	2,560	1,843.0	530.0
23n	7.25	9.50	.248	5,165	3,400	3,885	1.037	1.434	.937	12.28	9.50	.248	6,185	4,000	4,571	.952	1.513	.979	1,649	1,940	1,906.0	476.0
24q	7.25	9.49	.307	9,007	4,200	4,836	1.077	1.390	.849	12.27	9.51	.305	11,292		6,083	.923	1.552		1,660	2,080	1,924.0	410.0

ZM 49087 F

Table 18.--Test data and computed values for buckling test plates and coupons (Continued).

Compression buckling test plates — Loaded at 60° to direction of face grain

Panel no.	Length	Width	Thickness	Computed critical buckling load	Observed critical buckling load	Computed load at proportional limit	$\frac{b}{b'}$	$\frac{k_s}{k_{s_\infty}}$	$\frac{k_s \text{ observed}}{k_{c_\infty}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	In.	In.	In.	Lb.	Lb.	Lb.			
1p	8.28	9.48	0.065	56	58	1,534	0.901	1.559	1.660
2p	8.28	9.48	.144	643	475	2,821	.994	1.464	1.173
3p	8.28	9.48	.172	1,436	1,350	2,955	.981	1.480	1.389
3m	8.28	9.48	.188	1,089	1,500	2,040	1.011	1.449	1.366
3ml	10.36	9.50	.184	1,213	1,200	2,079	1.460	1.143	1.131
4p	....	....	....	....	....	....	....	....	....
4m	8.26	9.50	.060	38	54	642	.948	1.512	2.287
4ml	6.36	9.50	.064	38	38	303	1.463	1.270	1.221
5p	8.28	9.48	.145	577	350	1,828	.984	1.475	1.406
5m	8.28	9.50	.149	615	380	972	1.013	1.416	1.883
5ml	10.36	9.50	.160	498	500	1,484	1.482	1.182	1.102
6p	8.28	9.46	.181	1,281	1,150	2,874	1.018	1.448	1.794
6m	8.26	9.50	.188	1,159	1,200	1,359	1.026	1.414	1.484
6ml	9.36	9.50	.154	933	900	1,804	1.533	1.170	1.132
7p	8.28	9.48	.064	47	65	960	1.013	1.445	1.987
7m	8.26	9.50	.064	44	60	662	1.015	1.408	2.402
7ml	8.36	9.50	.063	39	45	798	1.553	1.210	1.416
8p	....	....	....	....	....	....	....	....	....
9p	6.78	9.48	.165	1,550	1,150	3,065	1.038	1.408	1.039
9m	8.28	9.48	.166	1,394	1,500	1,707	1.070	1.391	1.501
9ml	8.40	9.50	.165	1,143	1,150	1,750	1.435	1.202	1.210
10p	....	....	....	....	....	....	....	....	....
10m	8.25	9.50	.052	49	100	939	.978	1.463	2.029
10ml	10.36	9.50	.063	40	90	863	1.624	1.151	1.732
11p	8.25	9.46	.146	833	750	2,887	.994	1.468	1.289
11m	8.28	9.50	.143	680	780	1,668	1.047	1.415	1.588
11ml	7.40	9.50	.145	645	600	1,606	1.237	1.283	1.198
12p	8.25	9.49	.154	1,509	1,550	2,305	1.026	1.435	1.474
12m	8.26	9.48	.150	1,349	1,400	1,896	1.036	1.408	1.409
13p	7.78	9.40	.101	618	....	2,104	.926	1.542	....
14p	8.00	9.46	.239	6,297	....	4,422	.968	1.471	....
14m	8.00	9.50	.242	5,615	5,400	3,605	1.005	1.484	.834
15p	8.01	9.48	.302	11,842	5,[illegible]00	6,568	1.008	1.452	.418
16p	7.99	9.49	.103	288	310	1,457	[illegible]	1.4[illegible]	1.502
17p	7.99	9.48	.244	4,775	....	3,146	.991	[illegible]	....
17m	8.00	9.50	.246	4,572	2,000	1,808	[illegible]	[illegible]	[illegible]
18p	8.01	9.50	.308	8,471	....	3,341	.972	[illegible]	....
19p	7.99	9.48	.108	412	400	1,619	1.020	1.440	1.397
19m	8.00	9.50	.108	328	330	867	1.019	1.445	1.503
20p	8.01	9.48	.241	6,678	....	3,336	.944	1.519	....
20m	8.00	9.50	.244	5,593	2,600	1,702	.943	1.526	.767
21p	8.02	9.49	.303	10,766	4,900	4,141	1.014	1.446	.657
22p	8.00	9.48	.105	449	380	1,475	.978	1.482	1.154
22m	8.00	9.50	.103	359	375	1,105	.989	1.472	1.537
23p	8.01	9.47	.230	5,336	....	4,081	.995	1.466	....
23m	8.01	9.50	.254	6,421	3,600	1,661	1.010	1.[illegible]	.513
24p	8.01	9.48	.306	9,482	3,400	3,383	1.026	1.434	.328

Compression buckling test plates — Loaded at 30° to direction of face grain

Panel no.	Length	Width	Thickness	Computed critical buckling load	Observed critical buckling load	Computed load at proportional limit	$\frac{b}{b'}$	$\frac{k_s}{k_{s_\infty}}$	$\frac{k_s \text{ observed}}{k_{s_\infty}}$
(1)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)
	In.	In.	In.	Lb.	Lb.	Lb.			
1p	10.74	9.49	0.066	66	....	1,543	0.984	1.476	....
2p	10.75	9.53	.143	1,003	....	3,134	.978	1.465	....
3p	10.75	9.51	.174	1,797	1,700	4,137	.950	1.480	1.400
3m	10.77	9.51	.182	1,756	1,850	2,901	.961	1.474	1.054
3ml	....	....	....	....	....	....	....	....	....
4p	10.72	9.49	.063	50	....	1,016	.978	1.482	....
4m	10.77	9.50	.060	43	185	749	.984	1.477	4.330
4ml	....	....	....	....	....	....	....	....	....
5p	10.73	9.49	.145	698	590	1,437	.980	1.480	1.241
5m	10.75	9.50	.149	750	800	1,738	.980	1.480	1.180
5ml	....	....	....	....	....	....	....	....	....
6p	10.75	9.42	.180	1,341	1,500	2,433	.977	1.483	1.643
6m	10.76	9.50	.184	1,387	1,300	1,696	.980	1.480	1.377
6ml	....	....	....	....	....	....	....	....	....
7p	10.75	9.49	.063	55	140	1,206	.979	1.481	[illegible]
7m	10.76	9.50	.064	56	65	901	.981	1.478	1.435
7ml	....	....	....	....	....	....	....	....	....
8p	10.75	9.52	.147	715	700	2,641	.979	1.483	1.462
9p	10.75	9.52	.164	1,791	1,500	3,165	.976	1.485	1.243
9m	10.76	9.50	.167	1,685	1,330	2,419	.980	1.480	1.344
9ml	....	....	....	....	....	....	....	....	....
10p	10.74	9.49	.062	69	120	1,083	.981	1.480	2.282
10m	8.76	9.50	.063	77	90	862	.799	1.828	2.144
10ml	....	....	....	....	....	....	....	....	....
11p	10.74	9.49	.146	873	....	2,523	.980	1.480	....
11m	10.76	9.50	.100	863	800	2,196	.981	1.479	1.228
11ml	....	....	....	....	....	....	....	....	....
12p	10.75	9.52	.164	1,349	1,300	3,110	.977	1.483	1.048
12m	10.75	9.50	.164	1,721	1,400	1,481	.979	1.482	1.206
13p	10.50	9.52	.098	339	400	2,337	.985	1.477	1.097
14p	10.49	9.48	.239	7,254	....	4,456	.981	1.480	....
14m	10.50	9.50	.243	7,388	3,600	3,410	.978	1.484	.727
15p	10.50	[illegible]	.300	14,387	6,900	5,283	.974	1.489	.842
16p	10.49	9.50	.105	384	....	1,494	.972	1.492	....
17p	[illegible].50	9.50	.242	[illegible]484	3,300	3,517	.978	1.482	.879
17m	10.51	[illegible]	.247	5,578	2,400	2,[illegible]91	[illegible]	[illegible].478	.435
18p	10.49	9.50	.308	10,374	4,000	4,337	.982	1.479	.070
19p	[illegible].50	9.50	.110	[illegible]	400	1,709	.973	1.490	1.047
19m	10.50	9.50	.111	400	450	1,424	.973	[illegible].489	1.398
20p	10.50	9.49	.242	8,406	....	5,720	.994	1.466	....
20m	10.50	[illegible].50	.245	8,729	3,5[illegible]0	3,178	.992	1.466	.817
21p	10.50	9.50	.312	14,368	....	4,920	.976	1.487	....
22p	10.50	9.50	.102	487	380	1,483	.981	1.480	1.094
22m	10.52	9.51	.103	404	400	1,406	.98[illegible]	1.480	1.298
23p	10.50	9.[illegible]	.242	8,67[illegible]	....	3,900	.982	1.480	....
23m	10.50	9.50	.250	7,384	4,000	2,919	.975	1.487	.506
24p	10.50	9.50	.306	11,994	....	4,331	.972	1.492	....

Properties of plate material

Panel no.	Average proportional limit stress in compression: At 60° to face grain (Coupons M & N)	Average proportional limit stress in compression: At 30° to face grain (Coupons O & P)	Average modulus of elasticity in bending: With face grain parallel to span (Coupons D & E)	Average modulus of elasticity in bending: With face grain perpendicular to span (Coupons F & G)
(1)	(20)	(21)	(22)	(23)
	Lb. per sq. in.	Lb. per sq. in.	1,000 lb. per sq. in.	1,000 lb. per sq. in.
1p	2,490	2,460	1,196.0	146.0
2p	1,920	2,300	2,200.0	195.0
3p	1,800	2,300	2,172.0	198.4
3m	1,608	1,476	2,027.0	194.6
3ml	1,516	....	2,023.0	194.8
4p	1,300	1,700	1,314.0	114.0
4m	1,126	1,214	1,150.0	126.9
4ml	830	....	1,150.0	126.9
5p	1,330	1,190	1,474.0	132.3
5m	687	1,228	1,987.5	118.6
5ml	1,188	....	1,987.5	118.9
6p	1,505	1,430	1,644.0	139.0
6m	774	914	1,613.0	114.4
6ml	1,033	....	1,613.0	114.4
7p	1,580	2,020	1,530.0	117.3
7m	1,089	1,482	1,588.8	117.2
7ml	1,334	....	1,588.5	117.2
8p	1,560	2,036	1,537.0	160.4
9p	1,720	1,520	2,242.0	133.7
9m	986	1,474	2,082.0	113.2
9ml	1,000	....	2,082.0	113.2
10p	1,840	1,640	1,719.0	178.3
10m	1,595	1,440	1,577.8	148.2
10ml	1,446	....	1,577.8	148.8
11p	1,630	1,680	2,049.0	174.7
11m	1,228	1,541	2,172.0	138.0
11ml	1,311	....	2,172.0	138.0
12p	1,320	1,780	2,134.0	181.8
12m	1,075	844	2,046.0	184.0
13p	2,260	2,460	1,967.0	488.0
14p	2,040	1,980	1,984.0	981
14m	1,568	1,844	1,921.0	[illegible]
15p	1,880	2,200	1,984.0	542.0
16p	1,480	[illegible]	1,30[illegible].0	330.0
17p	1,360	1,630	1,446.0	416.9
17m	766	1,216	1,284.0	428.1
18p	1,160	1,490	1,872.0	411.0
19p	1,580	1,920	1,604.0	394.0
19m	869	1,542	1,365.0	339.5
20p	1,460	1,490	1,497.9	570.4
20m	756	1,366	1,394.0	532.4
21p	1,440	1,640	1,628.0	478.4
22p	1,480	1,530	1,616.0	506.4
22m	1,129	1,404	1,426.0	419.5
23p	1,790	1,700	1,705.9	498.4
23m	1,600	1,220	1,704.0	470.1
24p	1,170	1,490	1,623.0	402.0

Table 15.--Test data and computed values for buckling test plates and coupons (Continued).

Panel no.	Compression buckling test plates: Loaded at 45° to direction of face grain: Length	Width	Thickness	Computed critical buckling load	Observed critical buckling load	Computed load at proportional limit	$\frac{b}{b'}$	$\frac{k_s}{k_{s_m}}$	$\frac{k_s \text{ observed}}{k_{s_m}}$	Properties of plate material: Average proportional limit stress in compression: At 45° to face grain (Coupons O & P)	Average modulus of elasticity in bending: With face grain parallel to span (Coupons D & E)	With face grain perpendicular to span (Coupons F & G)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(21)	(22)	(23)
	In.	In.	In.	Lb.	Lb.	Lb.				Lb. per sq. in.	1,000 lb. per sq. in.	1,000 lb. per sq. in.
1d	12.00	9.47	0.065	48		824	1.523	1.178		1,338	1,656.0	124.2
1e	12.00	9.49	.066			874				1,395		130.6
1f	12.00	9.49	.066	51		846	1.481	1.169		1,350	1,524.0	138.9
1r	14.04	9.54	.063	39	75	766	1.679	1.144	2.200	1,275	1,276.5	140.3
1rs	8.02	9.54	.065	56	140	978	.959	1.504	3.739	1,577	1,276.5	140.3
2d	14.01	9.49	.146	672	750	1,900	1.771	1.128	1.259	1,371	2,136.0	162.2
2e	12.01	9.49	.144	655	675	2,151	1.522	1.179	1.216	1,574	2,104.0	155.4
2f	12.00	9.49	.147	670		1,705	1.554	1.170		1,222	2,200.0	136.8
3d	12.00	9.49	.183	1,544	1,450	2,558	1.502	1.182	1.111	1,473	2,295.0	187.9
3e	12.00	9.49	.183	1,565	1,550	2,747	1.521	1.179	1.168	1,582	2,448.0	182.7
3f	12.00	9.50	.182	1,493	1,440	2,656	1.485	1.188	1.146	1,536	2,160.0	193.2
3r	14.05	9.52	.171	1,097	1,240	1,784	1.720	1.137	1.284	1,096	1,940.0	185.8
3rs	8.02	9.54	.175	1,531	1,400	1,846	.979	1.482	1.356	1,106	1,940.0	185.8
4r	11.04	9.53	.066	42	85	748	1.399	1.214	2.467	1,190	1,381.0	99.9
4rs	8.03	9.54	.064	45	125	821	1.016	1.444	3.981	1,344	1,381.0	99.9
5d	12.00	9.49	.152	726		1,807	1.483	1.188		1,253	1,786.0	162.0
5e	12.00	9.49	.143	556		1,881	1.515	1.180		1,386	1,787.0	138.0
5f	12.00	9.49	.142	543		1,443	1.521	1.179		1,071	1,818.0	135.0
6r	14.02	9.53	.183	1,039	950	1,385	1.793	1.124	1.028	794	1,790.5	119.6
6rs	8.00	9.51	.181	1,286	1,070	924	1.024	1.436	1.194	537	1,790.5	119.6
8d	12.00	9.49	.143	642		2,125	1.535	1.176		1,566	2,173.0	151.5
8e	12.00	9.50	.144	666		2,172	1.513	1.180		1,588	2,098.0	161.6
8f	12.00	9.49	.144	693		1,900	1.487	1.187		1,390	2,032.0	179.4
10r	14.04	9.53	.063	47	125	1,112	1.816	1.122	2.991	1,852	2,081.0	125.0
10rs	8.02	9.55	.062	57	125	778	1.035	1.426	3.145	1,314	2,081.0	125.0
11d	12.01	9.49	.144	674		2,057	1.528	1.177		1,505	2,184.0	159.2
11e	12.02	9.49	.145	709		2,163	1.522	1.179		1,572	2,215.0	168.0
11f	12.00	9.49	.144	640		2,255	1.565	1.168		1,650	2,294.0	136.7
11r	10.79	9.54	.146	696	740	1,641	1.378	1.221	1.300	1,178	2,173.5	146.8
11rs	8.01	9.53	.147	838	800	1,205	1.024	1.436	1.375	860	2,173.5	146.8
12r	8.95	9.53	.185	1,413	1,300	1,670	1.108	1.362	1.284	947	1,722.5	150.6
12rs	8.01	9.53	.183	1,475	1,600	2,166	.991	1.470	1.594	1,242	1,722.5	150.6
13d	12.82	9.49	.110	501	425	2,087	1.398	1.213	1.030	1,999	1,672.0	496.0
13e	12.82	9.49	.109	522	525	2,286	1.392	1.215	1.223	2,210	1,712.0	551.0
13f	11.62	9.49	.109	527		1,992	1.263	1.267		1,926	1,683.0	526.0
14d	12.82	9.49	.251	6,140	4,630	4,068	1.397	1.213	.915	1,708	1,703.0	518.0
14e	11.25	9.50	.247	6,274	4,600	4,834	1.234	1.282	.940	2,060	1,836.0	501.0
14f	11.25	9.49	.252	6,066	4,800	4,844	1.234	1.282	.951	1,900	1,658.0	458.0
15d	12.82	9.50	.302	9,939		4,699	1.389	1.216		1,638	1,500.0	503.0
15e	11.25	9.49	.304	11,087	5,000	4,688	1.218	1.291	.582	1,625	1,522.0	525.0
15f	11.25	9.49	.305	11,213		5,384	1.214	1.293		1,860	1,460.0	544.0
15r	12.85	9.52	.302	11,313	6,000	3,602	1.400	1.213	.643	1,253	1,866.0	535.0

Z M 49089 F

Table 15.--Test data [illegible] values for buckling test pieces and coupons (Continued).

Panel no.	Compression buckling test plates: Loaded at 45° to direction of face grain									Properties of plate material: Average proportional limit stress in compression	Properties of plate material: Average modulus of elasticity in bending	
	Length	Width	Thickness	Computed critical buckling load	Observed critical buckling load	Computed load at proportional limit	$\frac{b}{b'}$	$\frac{k_s}{k_{s_\infty}}$	$\frac{k_c \text{ observed}}{k_{c_\infty}}$	At 45° to face grain (Coupons O & P)	With face grain parallel to span (Coupons D & E)	With face grain perpendicular to span (Coupons F & G)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(21)	(22)	(23)
	In.	In.	In.	Lb.	Lb.	Lb.				Lb. per sq. in.	1,000 lb. per sq. in.	1,000 lb. per sq. in.
16r	12.84	9.50	0.105	286	315	638	1.424	1.205	1.327	640	1,255.0	297.2
17d	11.33	9.49	.240	3,975	2,900	2,856	1.230	1.286	.938	1,255	1,152.0	372.0
17e	11.25	9.48	.240	4,171	...	2,748	1.221	1.290	...	1,208	1,180.0	395.0
17f	11.25	9.49	.240	3,775	...	3,109	1.216	1.292	...	1,365	1,041.0	366.0
17r	12.82	9.50	.245	4,807	2,750	1,606	1.400	1.213	.694	690	1,477.0	425.5
18r	12.67	9.51	.302	7,606	4,200	2,016	1.405	1.211	.669	702	1,423.5	325.0
20d	11.25	9.49	.236	5,498	3,700	3,384	1.230	1.286	.866	1,511	1,768.0	517.0
20e	11.25	9.49	.238	5,512	3,800	3,598	1.232	1.284	.885	1,593	1,776.0	495.0
20f	12.83	9.21	.236	4,625	...	...	...	...	...	1,466	1,763.0	520.0
23d	11.25	9.49	.242	5,407	3,600	3,413	1.247	1.277	.850	1,486	1,828.0	431.0
23e	11.25	9.49	.241	5,719	3,700	3,239	1.249	1.276	.826	1,416	1,966.0	460.0
23f	11.25	9.49	.242	5,542	3,600	3,224	1.243	1.279	.831	1,404	1,816.0	452.0
23r	12.84	9.52	.243	5,273	4,000	2,397	1.400	1.213	.920	1,036	1,674.0	478.0
24r	12.82	9.51	.306	8,756	4,100	2,322	1.436	1.201	.560	798	1,687.5	347.0
25d	12.00	9.50	.110	509	...	2,257	1.302	1.250	...	2,160	1,564.0	514.0
25e	12.00	9.50	.112	560	540	2,268	1.302	1.250	1.204	2,132	1,632.0	536.0
25f	12.01	9.52	.110	504	550	1,994	1.290	1.257	1.372	1,904	1,424.0	544.0
26d	12.00	9.51	.244	6,147	...	3,959	1.307	1.247	...	1,706	1,856.0	538.0
26e	12.02	9.50	.244	6,562	...	3,876	1.309	1.246	...	1,672	1,956.0	581.0
26f	12.03	9.51	.244	6,195	...	3,680	1.312	1.244	...	1,586	1,886.0	542.0
27d	12.00	9.51	.305	10,473	5,900	4,902	1.288	1.258	.708	1,690	1,356.0	538.0
27e	12.01	9.51	.308	11,256	...	5,474	1.289	1.257	...	1,881	1,398.0	549.0
27f	12.01	9.52	.305	9,963	...	4,727	1.296	1.252	...	1,628	1,394.0	484.0
29d	12.02	9.51	.247	5,739	...	2,647	1.295	1.252	...	1,127	1,473.0	536.0
29e	12.01	9.51	.236	4,880	...	3,029	1.303	1.249	...	1,348	1,579.0	484.0
29f	12.02	9.50	.235	4,642	3,150	2,641	1.315	1.243	.862	1,183	1,563.0	440.0
32d	12.00	9.50	.241	5,917	...	3,418	1.297	1.251	...	1,493	1,686.0	580.0
32e	12.03	9.51	.241	6,107	4,000	3,202	1.294	1.253	.821	1,397	1,641.0	628.0
32f	12.01	9.28	.238	5,757	...	2,840	1.336	1.237	...	1,290	1,726.0	562.0
35d	12.02	9.61	.242	5,234	3,500	2,725	1.331	1.239	.899	1,164	1,815.0	435.0
35e	12.01	9.50	.239	4,904	3,400	2,931	1.340	1.236	.857	1,291	1,874.0	404.0
35f	12.00	9.52	.241	5,180	3,700	3,228	1.325	1.240	.886	1,407	1,791.0	440.0

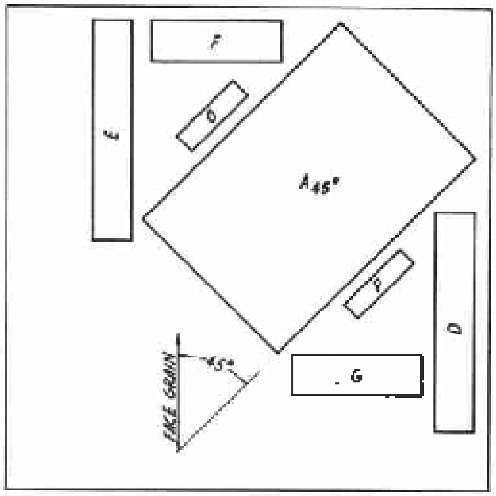
$\frac{b}{b'}$ is the ratio of the length of the plate (b) to the half wave length (b') of an infinitely long plate of the same construction and width.

$\frac{k_s}{k_{s_\infty}}$ is the ratio of the value of the factor (k_s) of formula (21) for a plate of length (b) to the value of this factor for an infinitely long plate (k_{s_∞}) of the same construction and width.

$\frac{k_c \text{ observed}}{k_{c_\infty}}$ is the ratio of the test value of the factor (k_c) of formula (6) for a plate of length (b) to the value of this factor for an infinitely long plate (k_{c_∞}) of the same construction and width.

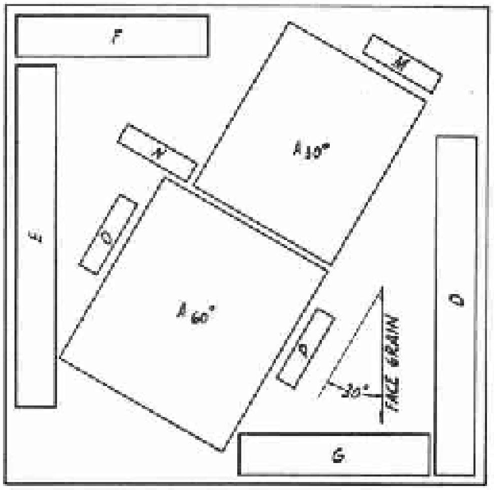
Sheet 4 of 4

Z M 49090 F

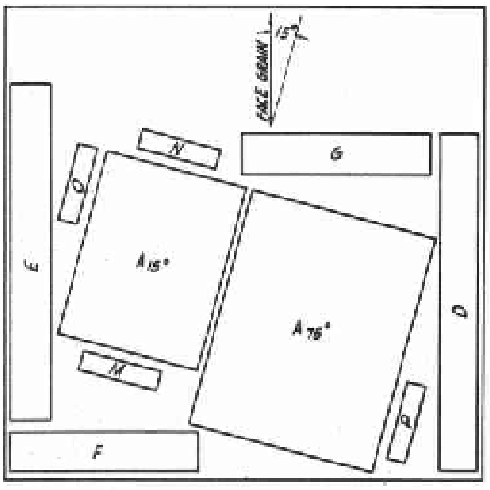


LEGEND:

$A_{45°}$	PLATE FOR BUCKLING TEST, FACE GRAIN AT 45° TO THE LOADED EDGES AND TO THE DIRECTION OF THE LOAD.
D AND E	COUPONS FOR STATIC BENDING TEST, FACE GRAIN PARALLEL TO SPAN.
F AND G	COUPONS FOR STATIC BENDING TEST, FACE GRAIN PERPENDICULAR TO SPAN.
O AND P	COUPONS FOR PACK COMPRESSION TEST, FACE GRAIN AT 45° TO LOAD.



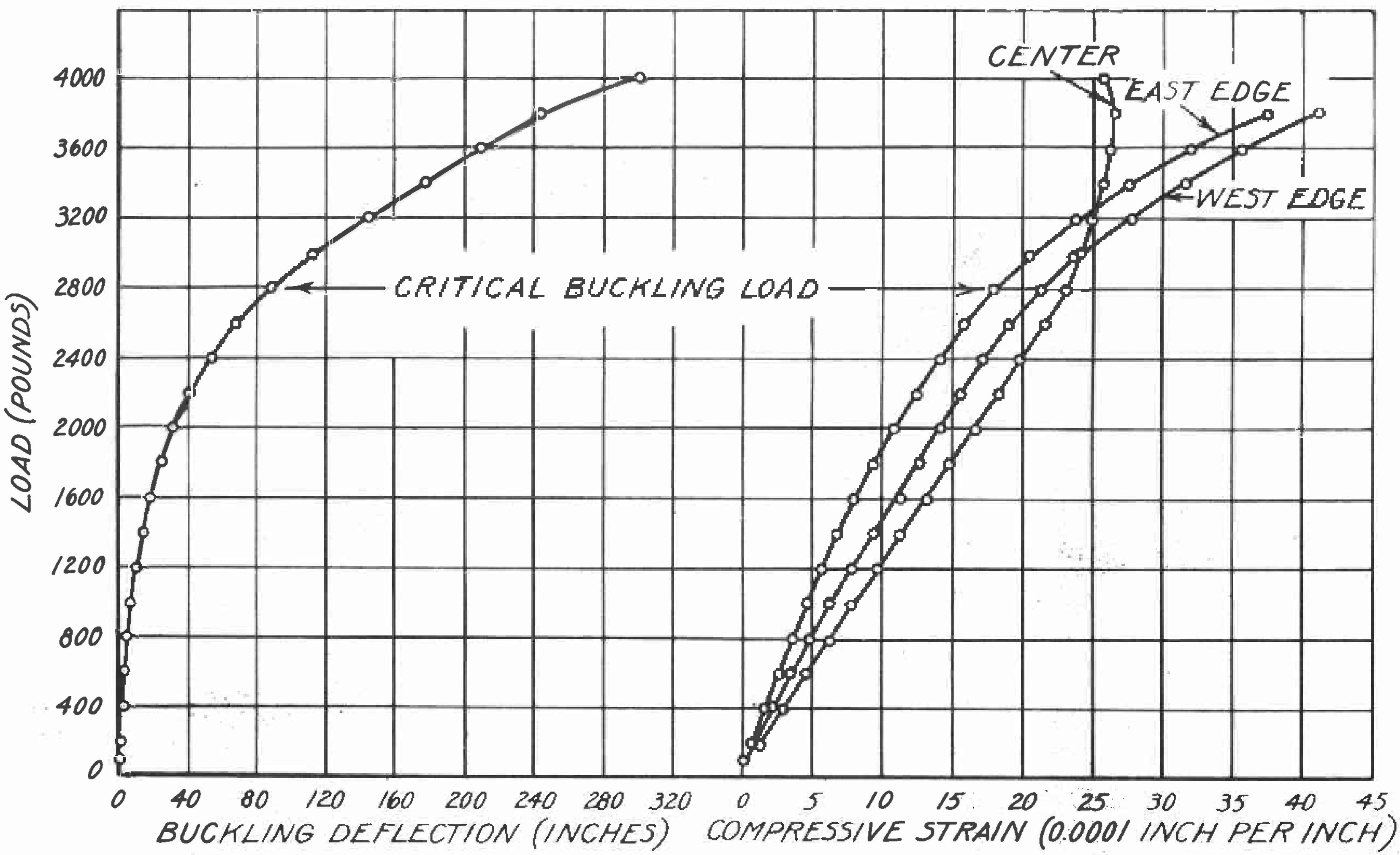
$A_{30°}$	PLATE FOR BUCKLING TEST, FACE GRAIN AT 30° TO THE LOADED EDGES, OR 60° TO THE DIRECTION OF LOAD.
$A_{60°}$	PLATE FOR BUCKLING TEST, FACE GRAIN AT 60° TO THE LOADED EDGES, OR 30° TO THE DIRECTION OF THE LOAD.
D AND E	COUPONS FOR STATIC BENDING TEST, FACE GRAIN PARALLEL TO SPAN.
F AND G	COUPONS FOR STATIC BENDING TEST, FACE GRAIN PERPENDICULAR TO SPAN.
M AND N	COUPONS FOR PACK COMPRESSION TEST, FACE GRAIN AT 60° TO LOAD.
O AND P	COUPONS FOR PACK COMPRESSION TEST, FACE GRAIN AT 30° TO LOAD.



$A_{15°}$	PLATE FOR BUCKLING TEST, FACE GRAIN AT 15° TO THE LOADED EDGES, OR 75° TO THE DIRECTION OF LOAD.
$A_{75°}$	PLATE FOR BUCKLING TEST, FACE GRAIN AT 75° TO THE LOADED EDGES, OR 15° TO THE DIRECTION OF LOAD.
D AND E	COUPONS FOR STATIC BENDING TEST, FACE GRAIN PARALLEL TO SPAN.
F AND G	COUPONS FOR STATIC BENDING TEST, FACE GRAIN PERPENDICULAR TO SPAN.
M AND N	COUPONS FOR PACK COMPRESSION TEST, FACE GRAIN AT 75° TO LOAD.
O AND P	COUPONS FOR PACK COMPRESSION TEST, FACE GRAIN AT 15° TO LOAD.

Figure 91.--Layout of plate specimens and coupons on panels.

Z M 48925 F



Z M 48926 F

Figure 92.--Example of the determination of the critical buckling load from strain data.

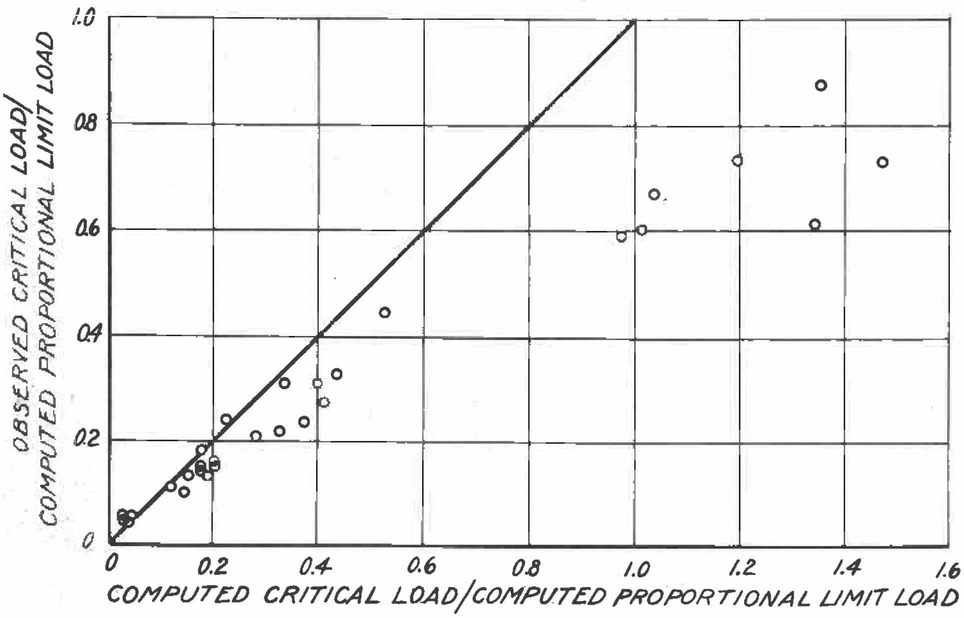


Figure 93.--Observed critical load plotted against the computed critical load, both expressed as ratios to computed proportional limit load. $k_c/k_{c\infty}$ assumed equal to $k_s/k_{s\infty}$ in computing critical load. Compression at 15° to face grain.

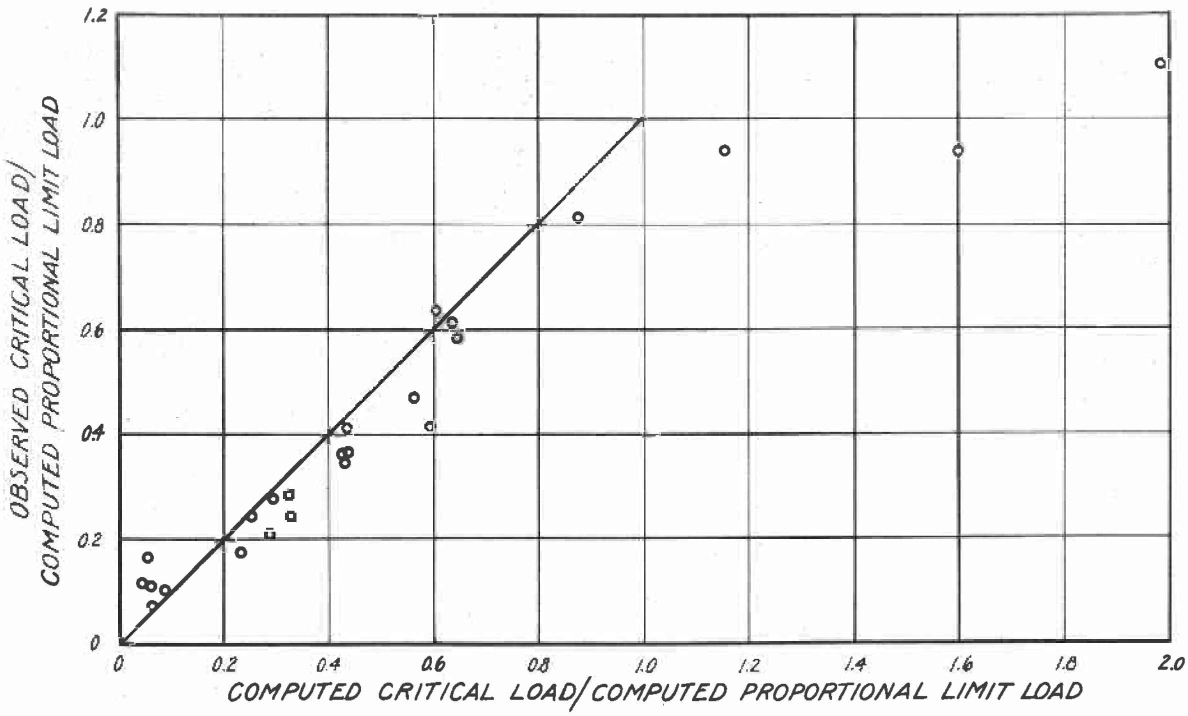


Figure 94.--Observed critical load plotted against the computed critical load, both expressed as ratios to computed proportional limit load. $k_c/k_{c\infty}$ assumed equal to $k_s/k_{s\infty}$ in computing critical load. Compression at 30° to face grain.

Z M 48927 F

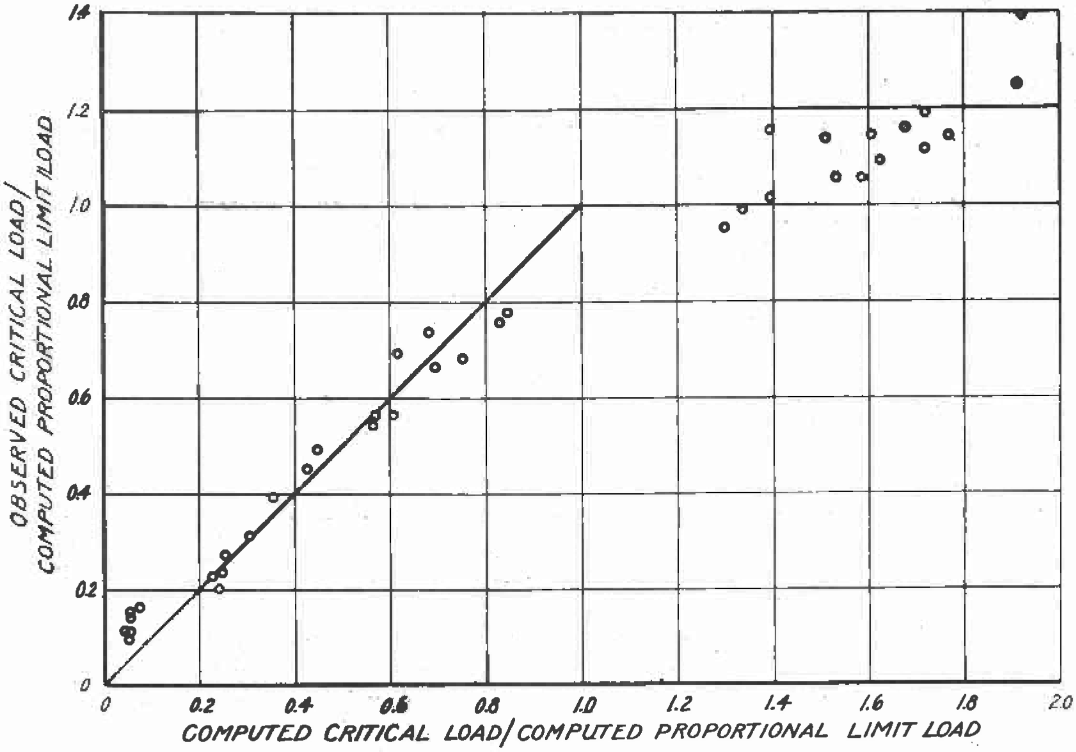


Figure 95.--Observed critical load plotted against the computed critical load, both expressed as ratios to computed proportional limit load. $k_c/k_{c\infty}$ assumed equal to $k_s/k_{s\infty}$ in computing critical load. Compression at 45° to face grain.

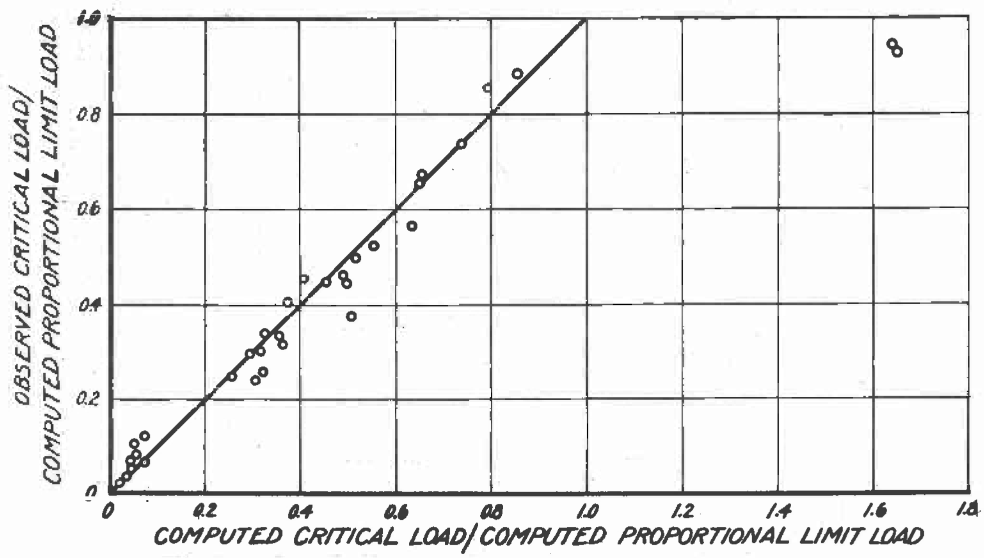


Figure 96.--Observed critical load plotted against the computed critical load, both expressed as ratios to computed proportional limit load. $k_c/k_{c\infty}$ assumed equal to $k_s/k_{s\infty}$ in computing critical load. Compression at 60° to face grain.

Z M 48928 F

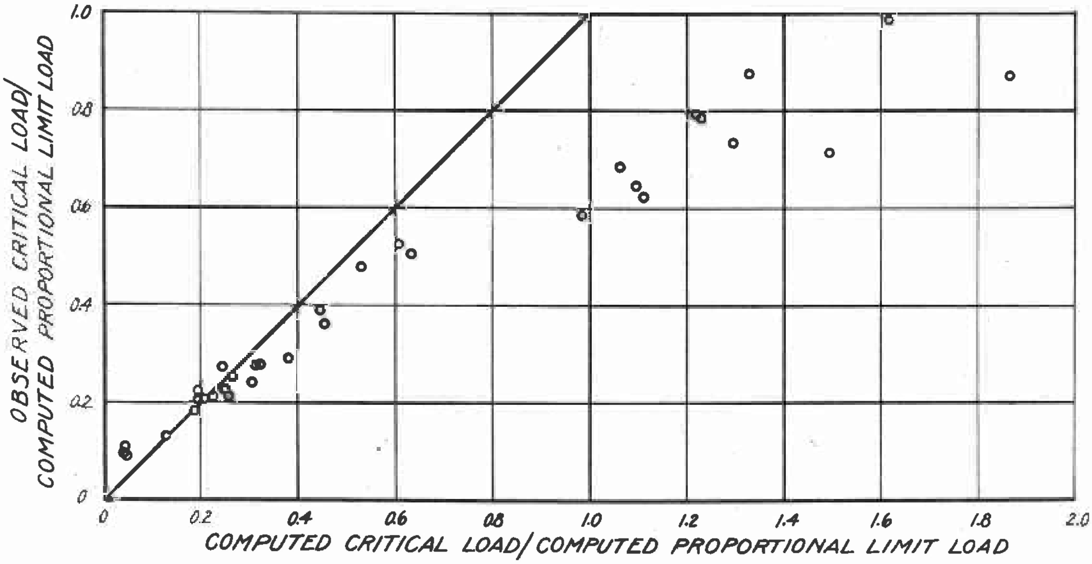
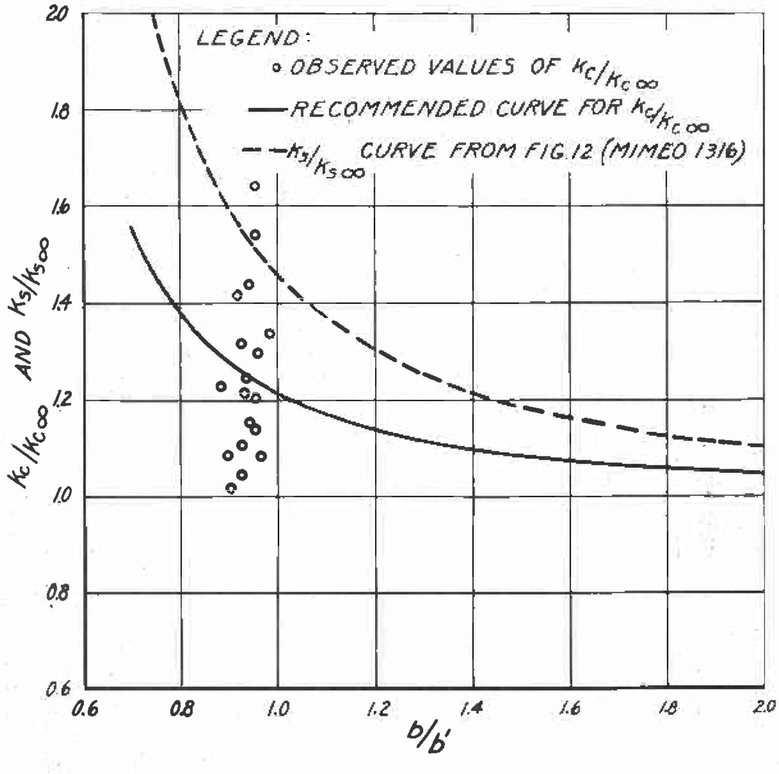


Figure 97.--Observed critical load plotted against the computed critical load, both expressed as ratios to computed proportional limit load. $k_c/k_{c\infty}$ assumed equal to $k_s/k_{s\infty}$ in computing critical load. Compression at 75° to face grain.



Z M 48929 F Figure 98.--Observed values of $k_c/k_{c\infty}$, recommended curve for $k_c/k_{c\infty}$, and curve for $k_s/k_{s\infty}$ for compression at 15° to face grain.

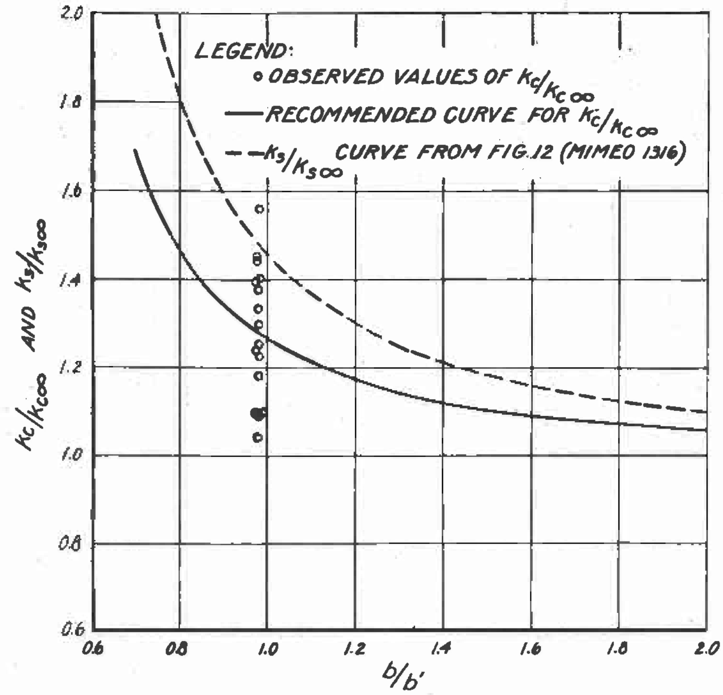


Figure 99.--Observed values of $k_c/k_{c\infty}$, recommended curve for $k_c/k_{c\infty}$, and curve for $k_s/k_{s\infty}$ for compression at 30° to face grain.

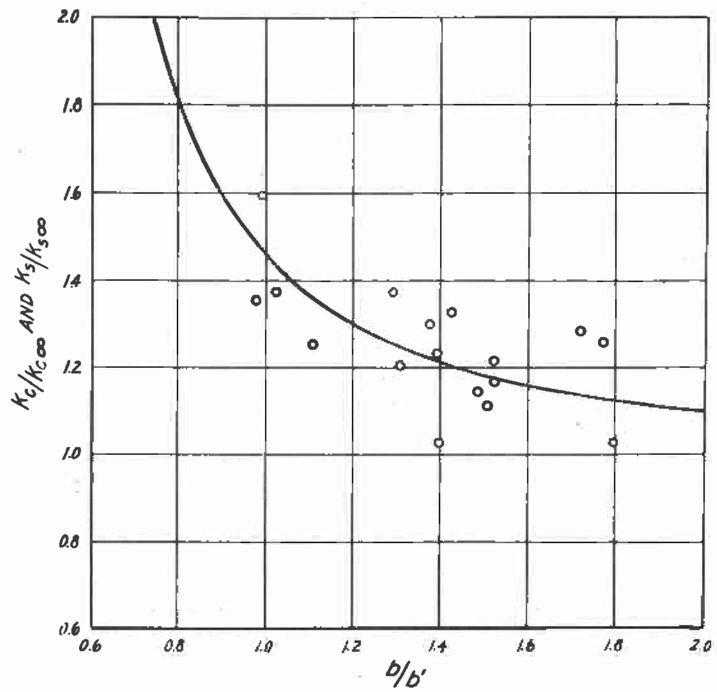


Figure 100.--Observed values of $k_c/k_{c\infty}$, recommended curve for $k_c/k_{c\infty}$, and curve for $k_s/k_{s\infty}$ for compression at 45° to face grain.

Z M 48930 F

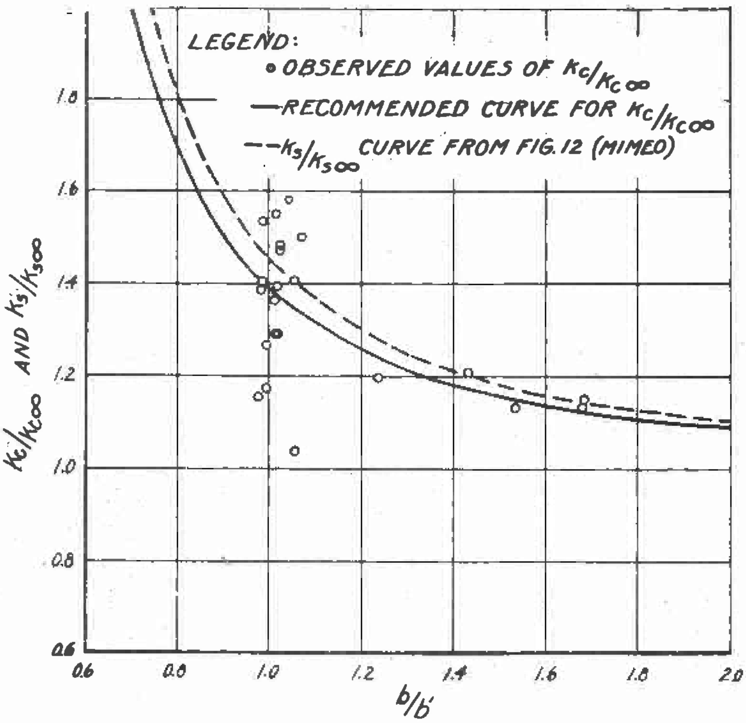


Figure 101.--Observed values of $k_c/k_{c\infty}$, recommended curve for $k_c/k_{c\infty}$, and curve for $k_s/k_{s\infty}$ for compression at 60° to face grain.

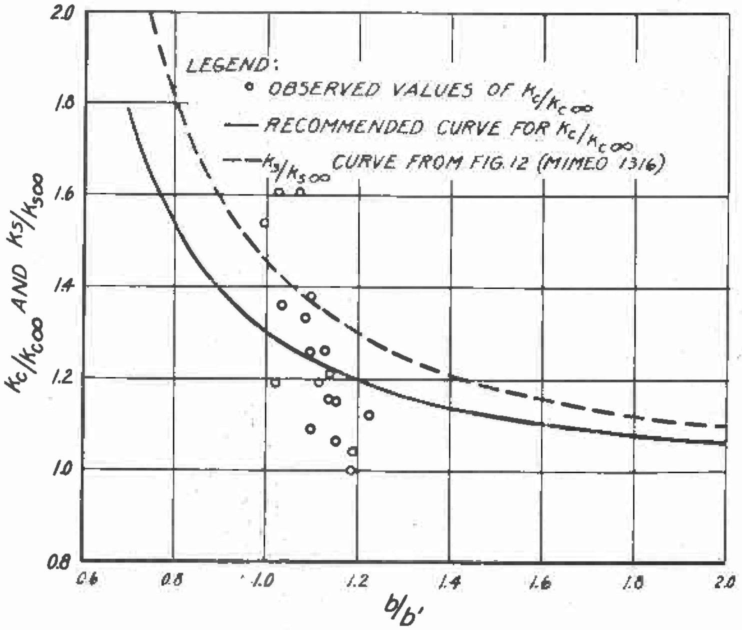


Figure 102.--Observed values of $k_c/k_{c\infty}$, recommended curve for $k_c/k_{c\infty}$, and curve for $k_s/k_{s\infty}$ for compression at 75° to face grain.

Z M 48931 F

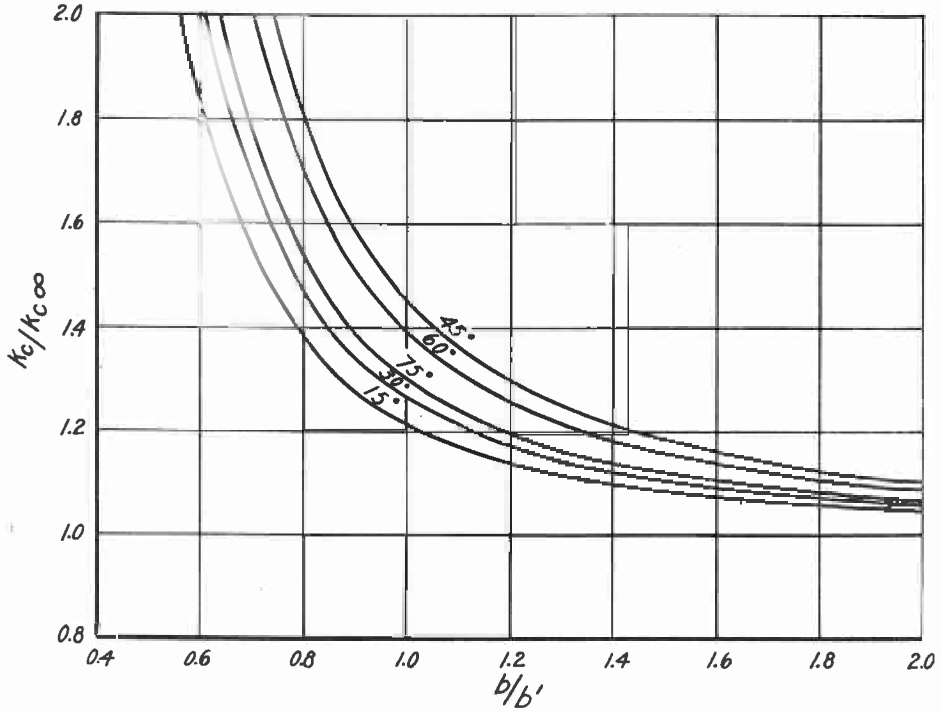


Figure 103.--Values of $k_c/k_{c\infty}$ corrected to agree with observed data for compression at various angles to face grain.

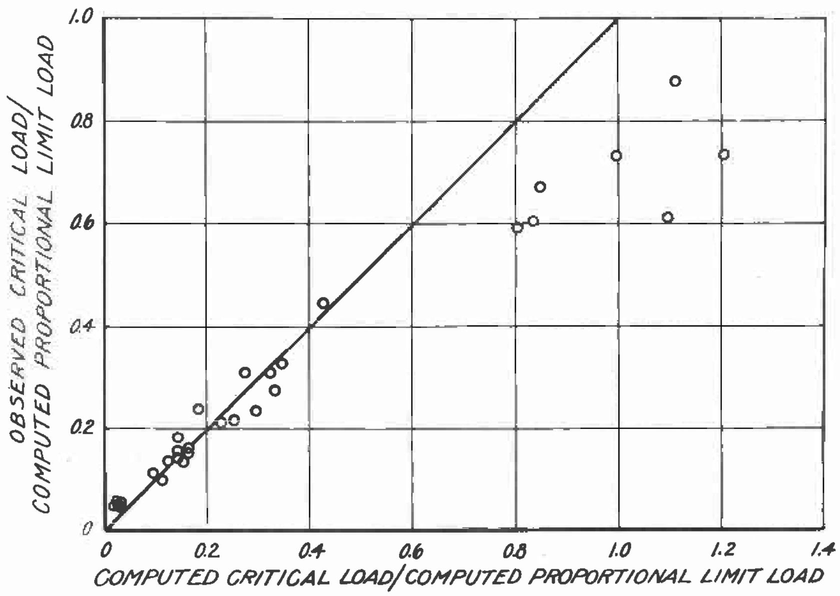


Figure 104.--$k_c/k_{c\infty}$ determined by correcting $k_s/k_{s\infty}$ in computing critical load for compression at 15° to face grain.

Z M 48932 F

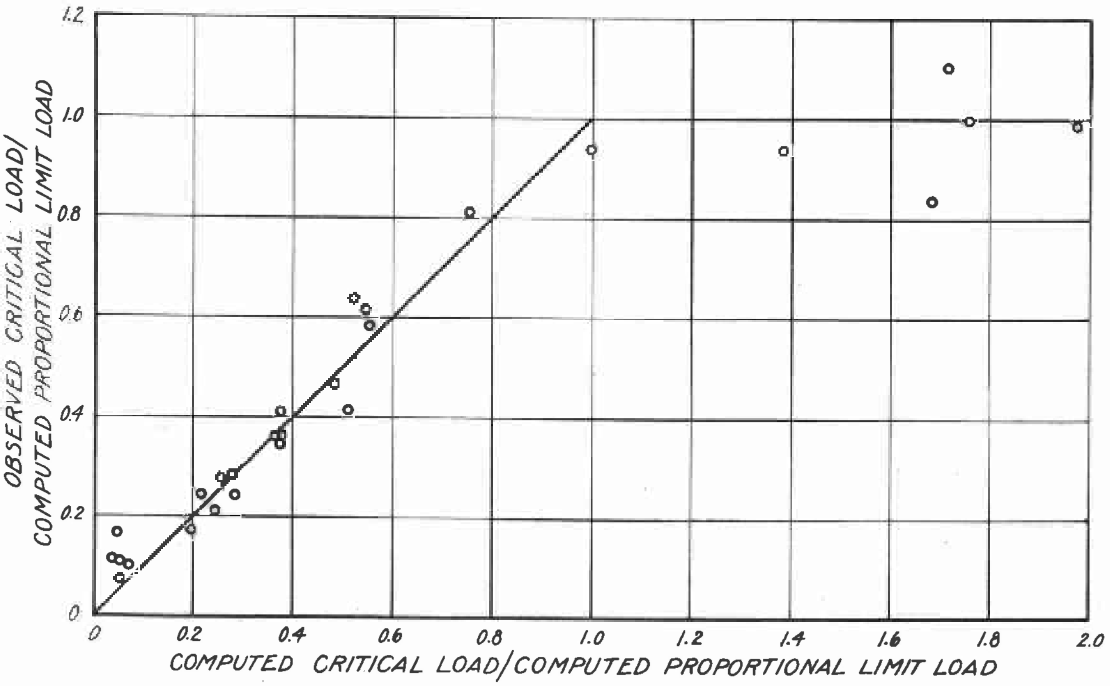


Figure 105.--$k_c/k_{c\infty}$ determined by correcting $k_s/k_{s\infty}$ in computing critical load for compression at 30° to face grain.

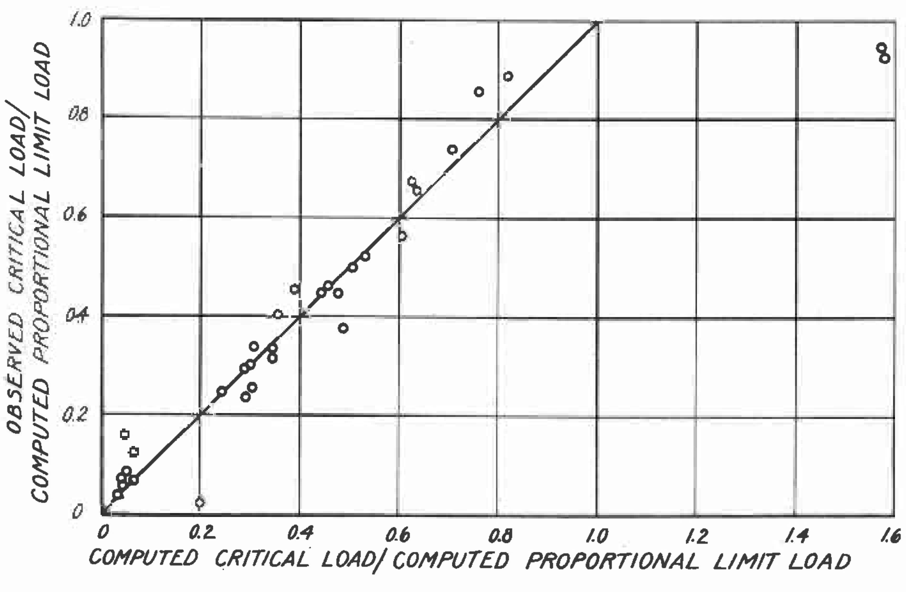


Figure 106.--$k_c/k_{c\infty}$ determined by correcting $k_s/k_{s\infty}$ in computing critical load for compression at 60° to face grain.

Z M 48933 F

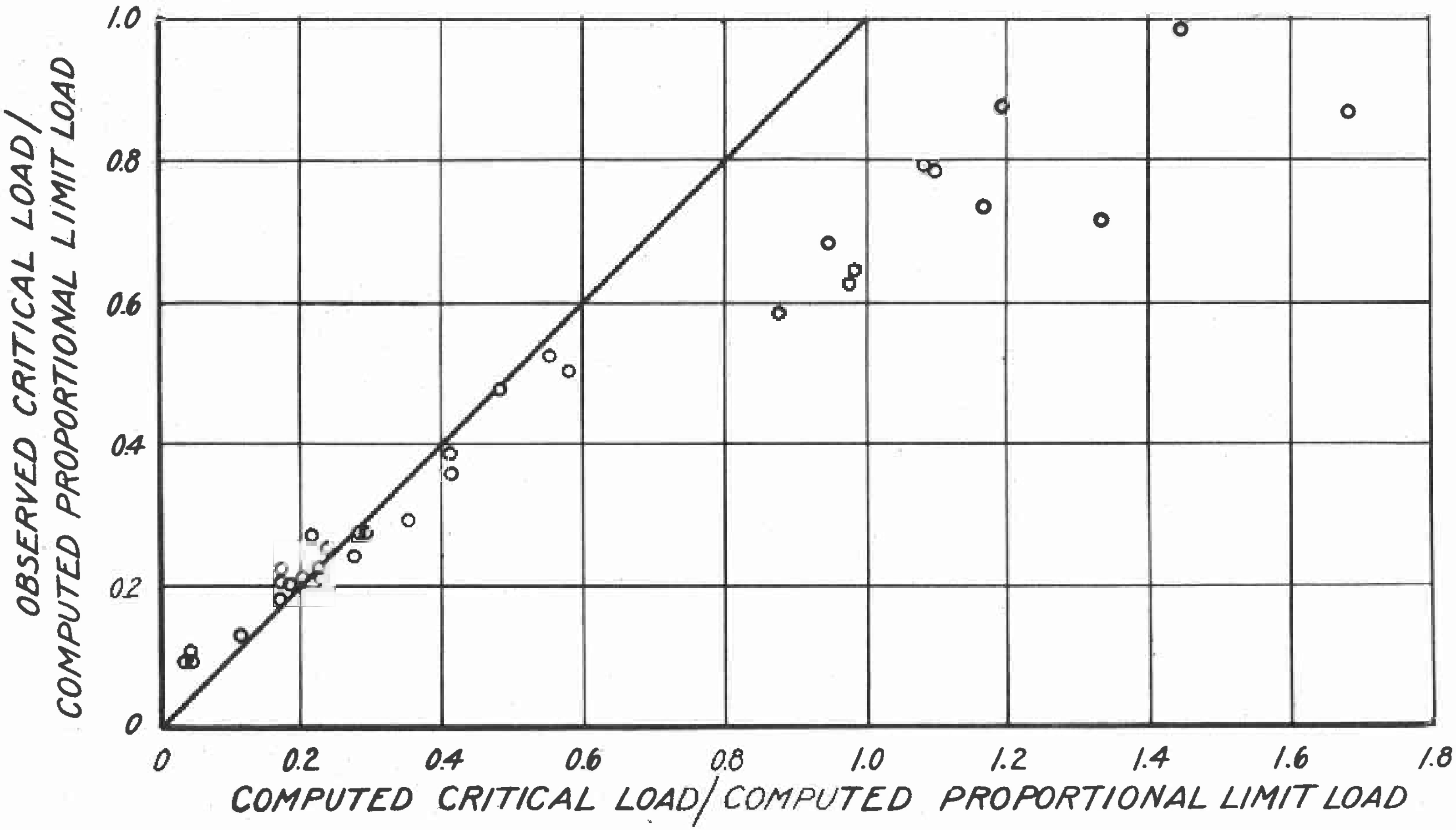


Figure 107.--$k_c/k_{c\infty}$ determined by correcting $k_s/k_{s\infty}$ in computing critical load for compression at 75° to face grain.

Z M 48934 F