BUCKLING LOADS OF FLAT SANDWICH PANELS IN COMPRESSION

Buckling of Flat Sandwich Panels with All Edges Clamped

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UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE

In Cooperation with the University of Wisconsin

BUCKLING LOADS OF FLAT SANDWICH PANELS IN COMPRESSION[1]

Buckling of Flat Sandwich Panels With All Edges Clamped[2]

(Cores of End-grain Balsa or Cellular Cellulose Acetate and Facings of Aluminum or Glass Cloth Laminate)

By

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Summary and Conclusions

This report presents the results of edgewise compression tests to determine the critical loads of flat sandwich panels having all four edges clamped. This investigation was conducted to confirm equations (19) and (20) of the theoretical analysis presented in Forest Products Laboratory Report No. 1525,[4] and modifications introduced subsequently to take into account the effect of transverse shear and of stresses greater than the proportional limit.

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[1]This report is one of a series of progress reports prepared by the Forest Products Laboratory relating to aircraft. Results here reported are preliminary and may be revised as additional data become available. Original report dated September 1947.

[2]This report is the fifth of a series of reports dealing with the buckling of flat sandwich panels in compression--tested with various types of edge conditions.

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

[4]March, H. W., and Smith, C. B. Buckling Loads of Flat Sandwich Panels in Compression--Various Types of Edge Conditions, Forest Products Lab. Rpt. 1525. March 1945.

The critical buckling loads, as determined by the tests, were about 82 percent of the computed values. It is believed that the experimental values were lower than the computed values because (1) the testing apparatus at the unloaded edges of the test panels did not rigidly clamp the panels and (2) the formula, which was derived by the energy method, may have yielded buckling loads that were as much as 8 percent too great.

Introduction

This report is one of a series prepared to confirm the mathematical analysis previously developed[4] at the Forest Products Laboratory for determining the critical loads of flat sandwich panels supported by various types of edge conditions and modifications to that analysis introduced to take into account the effect of transverse shear and of stresses greater than the proportional limit. It presents the experimental data of edgewise compression tests on the buckling of flat sandwich panels having clamped edges. Information relative to materials, testing procedures, and results is arranged according to the outline used to present similar information in Report No. 1525-A.[5] Duplications of descriptions have been avoided by omitting them and referring to previous reports.[2] Where variations from the previous reports were necessary, they are noted and fully described. The preparation and manufacture of specimens, the description of the test panels and coupons, and the procedure for determining the critical loads are identical to those described in Report No. 1525-B.[6] The scope of the work covered by this report differs from that of the work covered by Report No. 1525-B only as the edge conditions differ.

Methods of Tests

Figure 39[7] shows the apparatus used to test panels clamped at all four edges. The panels are supported along the loaded edges by clamps (fig. 33 in Report

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[5]Boller, K. H. Buckling Loads of Flat Sandwich Panels in Compression--The buckling of flat sandwich panels with edges simply supported, Forest Products Lab. Rpt. 1525-A.

[6]Boller, K. H. Buckling Loads of Flat Sandwich Panels in Compression--The buckling of flat sandwich panels with loaded edges simply supported and the remaining edges clamped, Forest Products Lab. Rpt. 1525-B.

[7]The figures and tables in this report are numbered consecutively with those of Report No. 1525 and its supplements 1525-A, 1525-B, and 1525-C.

No. 1525-C[8]) and are supported along the vertical edges by guide plates that provide a clamped edge condition (fig. 25 in Report No. 1525-B[6]). The clamps along the loaded edges support the total width of the panel; the other clamps, however, were made shorter than the length of the panel to provide room for compressive deformation. The distance between the ends of these clamps and the others was about twice the thickness of the panel.

The shear, flexure, and compression tests, made on coupons for the determination of the mechanical properties, were conducted according to methods described in Report No. 1525-B.

Presentation of Data

Experimental data and the results of computations are presented in tables 18 through 21 and figures 40 through 43. The tables are identical in form and have the same column headings as those of Report No. 1525-B. The descriptions of the columns are the same as presented in that report, except that some of the values were obtained from formulas or by methods that were different from those previously used. The variations from the methods used in Report No. 1525-B were as follows:

Column 19.--The values in column 19 were computed as follows:

(1) For panels having glass cloth facings

$$P_{cr\ comp} = \frac{4}{3}\frac{\pi^2}{a^2}\left[3D_1\frac{b^2}{a^2} + 3D_2\frac{a^2}{b^2} + 2\left(\frac{E\sigma}{\lambda}\right)_{1,2} I + 4\mu_{1,2} I\right] \quad (1)$$

(2) For panels having aluminum facings

$$P_{cr\ comp} = \frac{4}{3}\frac{\pi^2}{a^2}\frac{D_1 + D_2}{2}\left[\frac{3b^2}{a^2} + \frac{3a^2}{b^2} + 2\right] \quad (2)$$

The notation employed is that of Report No. 1525 and supplements A, B, and C.

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[8]Boller, K. H. Buckling Loads of Flat Sandwich Panels in Compression--The buckling of flat sandwich panels with loaded edges clamped and the remaining edges simply supported, Forest Products Lab. Rpt. 1525-C.

It should be noted that formulas (1) and (2) are applicable only to panels that are dimensionally proportioned so that they will buckle in a single half wave in the direction of loading. All of the panels in these tests buckled in a single half wave, and in addition several large square panels buckled into two half waves subsequent to buckling into one half wave. These square panels were border-line cases in which an increase of 10 percent in height would have caused the formation of either one or two half waves at the same load (fig. 5 of Report No. 1525). Panels that buckled in this manner are indicated in the tables by footnotes. After the second half wave developed, these panels continued to support increasing loads until failure occurred.

Column 20.--In the shear reduction factor, $\frac{1}{1 + \eta_4}$, η_4 was computed as follows:[9]

$$\eta_4 = \frac{6\, f\, c\, P_{cr\ comp}}{(h^3 - c^3)\left[(\mu_{yz})_c + (\mu_{xz})_c \frac{b^2}{a^2}\right]} \qquad (3)$$

The values of the shearing moduli that were substituted in the formula were 19,000 pounds per square inch for balsa and 3,500 pounds per square inch for cellular cellulose acetate.

Columns 21 and 22.--The values of M or N were obtained according to the definitions established in previous reports except that $P_{cr\ comp}$ and the constant, η_4, in the respective formulas, were computed in accordance with equations (1) or (2) and (3), respectively.

$$M = \frac{P_{cr\ comp}}{2f\, E_f} \qquad (4)$$

$$N = \frac{\eta_4}{E_f} \qquad (5)$$

Column 23.--This column presents the values for the critical load obtained by the methods described in Report No. 1525-B but using values of η_4, M, and N as determined by formulas (3), (4), and (5) of the present report.

[9] This approximate formula was developed by H. W. March at the Forest Products Laboratory.

Figures 40 through 43.--Ratios of observed and computed values (cols. 24, 25, and 26 of the tables) are presented graphically in figures 40 through 43. Figures 40 and 41 present the data obtained from panels having aluminum facings, and figures 42 and 43 present data obtained from panels having glass cloth facings. Figures 40 and 42 show the relationship of observed values to the values computed by use of formulas (2) and (3) ($P_{cr\ comp}$), and figures 41 and 43 show this relationship when the proper modifications of those formulas are employed. The ordinates and abscissas are the same as those used in Report No. 1525-A.

Analysis of Results

The critical loads, $P_{cr\ comp}$, of the sandwich panels tested are given by equations (19) and (20) of Report No. 1525 under the assumption that the stresses in the facings are less than the proportional limit and that the effect of transverse shear can be neglected. In the present report these equations are modified to apply when these assumptions are not warranted. The application of these modifications resulted in computed values of critical loads that are from 0 to 22 percent greater than the observed values.

From equations (19) and (20) of Report No. 1525 the value of the critical buckling load for stresses in the facings below the proportional limit, when no allowance is made for shear deformations, is given by equation (1) for panels having glass cloth facings and by equation (2) for aluminum facings. These equations apply to panels whose dimensions are such that they will buckle in a single half wave in the direction of the loading.

Values of the elastic properties obtained from tests of coupons of each plate were substituted in equation (1) or (2). The critical loads thus calculated are presented in columns 19 of the tables. Comparisons of these values with those obtained by tests are shown in figures 40 and 42. The plotted points fall to the right of the 45-degree line indicating that the computed values are greater than the observed values and that the modifications of formulas (1) and (2), subsequently described, are necessary.

Modification for shear.--The factor employed to modify formulas (1) and (2) that takes into account the effect of transverse shearing deformations in the core is $\frac{1}{1 + \eta_4}$, in which values of η_4 are obtained from equations (3) and $P_{cr\ comp}$ is obtained from equation (1) or (2).

The values of this factor for the panels tested are given in columns 20 of the tables for those panels that buckled below the proportional limit. The effect of this reduction factor on the theoretical values is shown by comparing the plotted points on figures 42 with those on figure 43. The buckling stresses of these panels were all below the proportional limit. All of the computed values in figure 43 are closer to the 45-degree line than those in figure 42. The application of the factor reduces the computed values by amounts ranging from 1 to 25 percent. Most of the observed values are lower than the computed values even after this factor is applied.

A somewhat similar effect is shown in figures 40 and 41, which are for panels having aluminum facings. The shear reduction factor was applied to values below the proportional limit (coordinates of about 0. 4 on figure 40) and the result of this application is shown on figure 41. These modified values are more nearly equal to the observed values.

Modification for shear and for stresses above the proportional limit. --The three preceding reports in this series have shown the procedure for the simultaneous application of these two modifications to the formulas given in Report No. 1525. The values of M and N are given by equations (4) and (5).

The values obtained are presented in columns 23 of the tables. A comparison of figure 40 with figure 41 shows the effect of these two modifications on the values obtained by use of equation (2). The computed values shown on figure 40 are reduced but are still greater than the observed values.

The observed values are between 80 and 98 percent of the values computed by use of the equations of Report No. 1525 with the modifications described in the present report. It is believed that the observed values are lower than the computed values because (1) the clamped edges of the test panels were not secured as firmly by the testing apparatus as had been assumed in the derivation of the formulas and (2) the formulas were derived by the energy method and may sometimes lead to buckling loads that are as much as 8 percent too great.

Table 18.--Comparison between experimental and theoretical values of compressive strength of flat sandwich panels of 0.012-inch 24ST aluminum sheet and 1/4-inch balsa (all edges clamped)

Panel No.	Dimensions: Thickness: Face f	Thickness: Core c	Thickness: Total h	Width: Free a	Width: Total a'	Height: Free b	Height: Total b'	Density: Wt.	Observed data: Panel data: Critical load $P_{cr\ obs}$	Panel data: Maximum load P_m	Panel data: Lateral deflection at maximum load	Panel data: Type of failure	Coupon data: Stiffness factors: Bending D_e	Stiffness factors: Bending D_1	Stiffness factors: $(\frac{E_c}{12}\cdot\frac{I}{12})$	Stiffness factors: Shear $\frac{I}{12}$	Coupon data: Compression strength P_{2m}	Computed data: Critical load[1] $P_{cr\ comp}$	Shear reduction ratio $\frac{1}{1+n_4}$	Constants: K	Constants: K x 10[3]	Critical load reduced[2] $P_{cr\ re}$	Comparative ratios: $\frac{P_{cr\ obs}}{P_{2m}}$	$\frac{P_{cr\ comp}}{P_{2m}}$	$\frac{P_{cr\ re}}{P_{2m}}$	$\frac{P_m}{P_{2m}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
	Inch	Inch	Inch	Inches	Inches	Inches	Inches	Lb. per sq. ft.	Lb. per in. width	Lb. per in. width	Inches						Lb. per in. width	Lb. per in. width				Lb. per in. width				
1-1	0.013	0.252	0.278	37.27	42.98	37.28	42.98	0.658	278	450	[3]0.000	Buckle	4,339	4,291	....	....	1,457	327	0.970	....	....	317	0.193	0.228	0.221	0.334
2	.013	.256	.282	37.28	42.98	37.28	42.97	.645	276	474	1.120	..do..	4,480	4,223	....	....	1,040	328	.970	....	....	318	.255	.315	.306	.456
3	.013	.247	.273	37.38	43.04	37.36	43.06	.618	290	488	[3].000	..do..	4,097	4,205	....	....	1,202	313	.971	....	....	304	.241	.260	.253	.406
4	.014	.241	.269	37.33	43.06	37.37	43.07	.558	257	473	1.090	..do..	4,000	4,181	....	....	1,151	309	.971	....	....	300	.232	.268	.261	.411
2-1	.013	.248	.274	37.31	43.06	32.34	38.04	.606	314	524	1.300	..do..	4,215	4,099	....	....	1,422	324	.966	....	....	313	.221	.226	.220	.366
2	.012	.248	.272	37.40	43.07	32.35	38.05	.607	297	533	1.240	..do..	4,023	4,220	....	....	1,162	320	.956	....	....	309	.256	.276	.266	.459
3	.013	.245	.271	37.26	42.96	32.29	37.99	.566	265	478	1.280	..do..	4,034	3,920	....	....	1,322	311	.967	....	....	301	.200	.235	.228	.362
4	.012	.255	.279	37.26	42.98	32.29	37.99	.643	291	479	.881	..do..	4,409	4,077	....	....	1,489	332	.966	....	....	321	.195	.223	.216	.322
3-1	.012	.253	.277	36.31	41.97	29.30	35.00	.658	382	543	1.282	..do..	4,280	4,366	....	....	1,359	369	.959	....	....	354	.266	.272	.260	.400
2	.011	.254	.276	36.29	41.87	29.33	35.05	.649	291	488	.900	..do..	4,309	4,594	....	....	1,348	380	.958	....	....	364	.216	.282	.270	.362
3	.012	.257	.281	36.27	41.86	29.30	35.00	.672	310	548	1.080	..do..	4,556	4,379	....	....	1,622	381	.959	....	....	365	.191	.235	.226	.338
4	.011	.257	.279	36.20	41.95	29.30	35.00	.679	329	559	1.000	..do..	4,576	4,377	....	....	1,412	383	.958	....	....	367	.233	.271	.260	.396
4-1	.012	.251	.276	28.26	35.02	23.32	29.02	.648	477	597	1.040	..do..	4,402	4,082	....	....	1,371	560	.939	....	....	526	.348	.408	.384	.435
2	.011	.255	.277	29.34	35.02	23.32	29.02	.636	471	589	.955	..do..	4,165	4,104	....	....	1,248	545	.940	....	....	515	.377	.439	.413	.472
3	.011	.256	.278	29.30	35.01	23.33	29.03	.617	451	592	.820	..do..	4,164	4,109	....	....	1,421	547	.941	....	....	515	.317	.385	.362	.417
4	.012	.251	.275	29.30	35.02	23.30	29.00	.630	474	590	1.060	..do..	4,184	4,177	....	....	1,362	554	.939	....	....	520	.348	.407	.382	.433
5-1	.014	.252	.280	25.34	31.03	20.30	26.00	.683	538	623	.765	..do..	4,577	4,138	....	....	1,319	768	....	.00277	.8847	704	.408	.582	.534	.472
2	.011	.262	.284	25.36	31.00	20.30	26.00	.691	581	708	1.000	..do..	4,800	4,242	....	....	1,619	779	....	.00356	.8876	659	.363	.513	.434	.466
3	.011	.259	.281	25.33	31.00	20.28	25.98	.686	565	650	.825	..do..	4,176	4,309	....	....	1,141	749	....	.00344	.8617	649	.495	.656	.569	.570
4	.012	.268	.282	25.27	31.00	20.30	26.00	.674	548	623	.820	..do..	4,369	4,163	....	....	1,531	755	....	.00318	.9534	670	.358	.493	.438	.407
6-1	.012	.248	.272	23.27	28.96	18.38	24.08	.619	690	724	.730	..do..	4,233	4,593	....	....	1,450	931	....	.00392	1.1180	745	.476	.642	.516	.499
2	.012	.253	.277	23.32	29.02	18.33	24.03	.626	613	665	.765	..do..	3,997	4,215	....	....	1,362	865	....	.00364	1.0232	723	.450	.635	.531	.488
3	.012	.254	.278	23.34	29.01	18.32	24.02	.606	614	673	.620	..do..	4,141	4,161	....	....	1,282	874	....	.00368	1.0319	727	.479	.682	.567	.525
4	.012	.254	.278	23.28	29.02	18.31	24.01	.604	620	680	.780	..do..	4,199	4,160	....	....	1,456	880	....	.00370	1.0382	727	.426	.604	.499	.467
7-1	.012	.259	.283	21.29	27.00	17.30	23.00	.657	596	731	.520	..do..	4,562	4,177	....	....	1,361	1,060	....	.00455	1.2199	800	.511	.794	.588	.537
2	.011	.258	.280	21.30	27.02	17.32	23.02	.625	566	709	.685	..do..	4,242	4,254	....	....	1,564	1,050	....	.00482	1.1973	763	.429	.675	.485	.456
3	.012	.257	.281	21.32	27.00	17.29	22.99	.624	696	716	.740	..do..	4,633	4,217	....	....	1,336	1,093	....	.00460	1.2443	805	.520	.817	.602	.535
4	.012	.255	.279	21.27	27.02	17.31	23.01	.631	685	720	1.095	..do..	4,332	4,269	....	....	1,416	1,065	....	.00448	1.2168	795	.484	.769	.561	.508

[1]Computed according to formulas in Forest Products Laboratory Report 1525.

[2]Computed by application of modifications to formulas in Forest Products Laboratory Report 1525.

[3]Two half waves at maximum load.

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Table 19.--Comparison between experimental and theoretical values of compressive strength of flat sandwich panels of 0.012-inch 24 ST aluminum sheet and 1/4-inch cellular cellulose acetate (all edges clamped)

Panel No.	Dimensions: Thickness: Face f	Thickness: Core c	Thickness: Total h	Width: Free a	Width: Total a'	Height: Free b	Height: Total b'	Density: Wt.	Observed data: Panel data: Critical load $P_{cr\ obs.}$	Maximum load P_m	Lateral deflection at maximum load W_o	Type of failure
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
	Inch	Inch	Inch	Inches	Inches	Inches	Inches	Lb. per sq. ft.	Lb. per in. width	Lb. per in. width	Inches	
1-1	0.012	0.244	0.268	37.27	42.97	37.29	42.99	0.537	242	366	[3]0.000	Buckle
2	.012	.243	.267	37.24	42.98	37.29	42.99	.543	223	374	.900	..do..
3	.013	.239	.265	37.27	42.98	37.29	42.99	.528	233	317	[3].000	..do..
4	.014	.240	.268	37.24	42.96	37.27	42.97	.541	223	325	.690	..do..
2-1	.012	.241	.265	37.29	43.00	32.30	38.00	.570	242	423	.850	..do..
2	.012	.240	.264	37.25	42.98	32.30	38.00	.536	233	283	.445	Glue
3	.012	.244	.268	37.28	42.99	32.32	38.02	.535	242	275	.290	..do..
4	.012	.241	.265	37.30	42.99	32.31	38.01	.536	233	367	.790	Buckle
3-1	.011	.240	.262	36.33	42.01	29.25	34.95	.559	229	305	.475	..do..
2	.012	.238	.262	36.32	42.00	29.30	35.00	.562	214	357	.740	..do..
3	.013	.243	.269	36.31	42.00	29.30	35.00	.562	267	401	.680	..do..
4	.013	.245	.271	36.32	42.00	29.30	35.00	.567	248	408	.700	..do..
4-1	.013	.245	.271	29.32	35.00	23.25	28.95	.559	343	494	.590	..do..
2	.012	.247	.271	29.31	35.00	23.25	28.95	.565	354	462	.510	..do..
3	.012	.247	.271	29.35	35.00	23.26	28.96	.562	343	455	.470	..do..
4	.012	.247	.271	29.37	35.00	23.24	28.94	.560	343	479	.510	..do..
5-1	.013	.237	.263	25.32	31.03	20.30	26.00	.488	374	387	.090	Glue
2	.012	.239	.263	25.32	31.02	20.30	26.00	.492	311	329	.010	..do..
3	.012	.240	.264	25.32	31.02	20.30	26.00	.503	387	451	.235	Buckle
4	.011	.242	.264	25.33	31.01	20.30	26.00	.488	387	464	.315	..do..
6-1	.012	.231	.255	23.35	28.95	18.30	24.00	.546	442	466	.290	..do..
2	.014	.242	.270	23.27	28.99	18.30	24.00	.536	469	551	.515	..do..
3	.012	.242	.266	23.26	28.98	18.30	24.00	.523	469	555	.360	..do..
4	.012	.239	.263	23.29	28.97	18.30	24.00	.514	414	471	.215	..do..
7-1	.012	.241	.265	21.23	26.98	17.30	23.00	.509	354	369	.015	Glue
2	.012	.239	.263	21.26	26.98	17.30	23.00	.501	457	472	.080	Compression
3	.013	.240	.266	21.32	26.99	17.30	23.00	.514	359	381	.000	Glue
4	.013	.239	.265	21.36	26.98	17.30	23.00	.525	426	435	.015	Compression
8-1	.013	.246	.272	36.32	42.00	29.30	35.00	.492	248	384	.650	Buckle
2	.013	.245	.271	36.34	42.00	29.30	35.00	.495	238	388	....	..do..

Panel No.	Observed data: Coupon data: Stiffness factors: Bending D_2	Bending D_1	$\frac{(E\sigma)}{\lambda}_{12}$	Shear μ_{12}	Compression strength P_{2m}	Computed data: Critical load[1] $P_{cr\ comp.}$	Shear reduction ratio $\frac{1}{1+\alpha_4}$	Constants: K	K x 10[3]	Critical load reduced[2] $P_{cr\ re}$	Comparative ratios: $\frac{P_{cr\ obs.}}{P_{2m}}$	$\frac{P_{cr\ comp.}}{P_{2m}}$	$\frac{P_{cr\ re}}{P_{2m}}$	$\frac{P_m}{P_{2m}}$
(1)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
					Lb. per in. width	Lb. per in. width				Lb. per in. width				
1-1	4,229	4,144	....	....	573	317	0.856	....	....	271	0.422	0.553	0.473	0.639
2	4,420	4,380	....	....	504	334	.849	....	....	284	.277	.415	.353	[illegible]
3	3,891	4,439	....	....	442	316	.855	....	....	270	.527	.715	.611	.717
4	4,406	4,161	....	....	490	325	.853	....	....	277	.455	.663	.565	.663
2-1	4,120	4,234	....	....	623	326	[illegible]	....	....	272	.388	.523	.437	.679
2	4,242	4,480	....	....	412	341	[illegible]	....	....	282	.566	.828	.684	.687
3	4,058	4,021	....	....	522	315	.840	....	....	265	.464	.603	.508	.527
4	4,115	4,376	....	....	538	331	.831	....	....	275	.433	.615	.511	.719
3-1	3,912	3,836	....	....	404	331	.821	....	....	272	.567	.819	.673	.755
2	3,902	3,991	....	....	399	337	.816	....	....	276	.536	.845	.692	.895
3	4,509	4,529	....	....	478	386	.802	....	....	310	.566	.818	.657	.850
4	4,603	4,764	....	....	507	400	.797	....	....	319	.489	.789	.629	.805
4-1	4,505	4,507	....	....	458	597	.722	....	....	431	.749	1.303	.941	1.079
2	4,594	4,610	....	....	522	610	.718	....	....	438	.678	1.169	.839	.885
3	4,540	4,658	....	....	553	609	.718	....	....	437	.620	1.101	.790	.823
4	4,543	4,788	....	....	509	617	.715	....	....	441	.674	1.212	.866	.941
5-1	3,532	4,055	....	....	316	669	....	0.00260	4.454	461	[4]1.184	[4]2.117	[4]1.459	1.225
2	3,754	4,082	....	....	316	691	....	.00291	4.604	466	.984	[4]2.187	1.475	1.041
3	4,020	4,178	....	....	446	723	....	.00304	4.791	484	.868	[4]1.621	1.085	1.011
4	3,833	4,145	....	....	435	703	....	.00323	4.671	482	.890	[4]1.616	1.108	1.067
6-1	4,186	4,158	....	....	710	873	....	.00370	6.142	543	.623	1.238	.765	.656
2	4,440	4,484	....	....	460	[illegible]	....	.00341	6.216	582	[4]1.020	[4]2.052	[4]1.265	1.198
3	4,312	4,509	....	....	434	934	....	.00393	6.241	571	[4]1.081	[4]2.152	[4]1.316	1.279
4	3,933	4,321	....	....	575	872	....	.00367	5.898	545	.720	[4]1.517	.948	.819
7-1	3,881	4,595	....	....	468	1,053	....	.00443	6.866	622	.756	[4]2.250	[4]1.329	.788
2	3,867	4,530	....	....	360	1,041	....	.00438	6.850	619	[4]1.269	[4]2.892	[4]1.719	1.311
3	4,169	4,562	....	....	428	1,078	....	.00419	7.031	633	.839	[4]2.519	[4]1.479	.890
4	3,703	4,705	....	....	405	1,036	....	.00402	6.782	616	[4]1.052	[4]2.558	[4]1.521	1.074
8-1	4,341	4,503	....	....	509	378	.807	....	....	305	.487	.743	.599	.754
2	4,413	4,428	....	....	550	377	.806	....	....	304	.433	.685	.553	.705

[1]Computed according to formulas in Forest Products Laboratory Report 1525.
[2]Computed by application of modifications to formulas in Forest Products Laboratory Report 1525.
[3]Two half waves at maximum load.
[4]Values are not plotted.

Table 20.--Comparison between experimental and theoretical values of compressive strength of flat sandwich panels of six-ply glass cloth laminate and 1/4-inch balsa (all edges clamped)

Panel No.	Dimensions: Thickness: Face	Dimensions: Thickness: Core	Dimensions: Thickness: Total	Dimensions: Width: Free	Dimensions: Width: Total	Dimensions: Height: Free	Dimensions: Height: Total	Density	Observed data: Panel data: Critical load	Observed data: Panel data: Maximum load	Observed data: Panel data: Lateral deflection at maximum load	Observed data: Panel data: Type of failure	Observed data: Coupon data: Stiffness factors: Bending	Observed data: Coupon data: Stiffness factors: Bending	Observed data: Coupon data: Stiffness factors	Observed data: Coupon data: Stiffness factors: Shear	Observed data: Coupon data: Compression strength	Computed data: Critical loads[1]	Computed data: Shear reduction ratio	Computed data: Constants	Computed data: Constants	Computed data: Critical load reduced[2]	Computed data: Comparative ratios	Computed data: Comparative ratios	Computed data: Comparative ratios	Computed data: Comparative ratios
	f	c	h	a	a'	b	b'	Wt.	$P_{cr\ obs}$	P_m	Δ_m		D_b	D_1	$(\frac{E_c}{\lambda})_{12}$	μ_{12}^{-1}	F_{2m}	$P_{cr\ comp}$	$\frac{1}{1+V_a}$	M	$N \times 10^8$	$P_{cr\ rs}$	$\frac{P_{cr\ obs}}{F_{2m}}$	$\frac{P_{cr\ comp}}{F_{2m}}$	$\frac{P_{cr\ rs}}{F_{2m}}$	$\frac{P_m}{F_{2m}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
	Inch	Inch	Inch	Inches	Inches	Inches	Inches	Lb. per sq. ft.	Lb. per in. width	Lb. per in. width	Inches						Lb. per in. width	Lb. per in. width				Lb. per in. width				
1-1	0.019	0.245	0.283	37.30	42.98	37.28	42.98	0.448	99	272	[3]0.000	Buckle	1,722	1,629	292	400	702	116	0.989			113	0.141	0.165	0.164	0.387
2	.018	.246	.282	37.30	43.00	37.28	42.98	.468	97	267	[3].000	..do..	1,668	1,652	276	392	684	114	.990			113	.142	.167	.166	.390
3	.018	.247	.283	37.27	42.96	37.27	42.97	.497	89	235	[3].000	..do..	1,698	1,637	278	393	776	115	.989			114	.128	.146	.147	.303
4	.018	.247	.283	37.30	42.98	37.28	42.96	.477	80	225	[3].000	..do..	1,678	1,675	278	384	688	115	.989			114	.116	.167	.166	.387
2-1	.019	.246	.283	36.30	42.00	29.28	34.96	.492	126	274	[3].000	..do..	1,632	1,677	292	296	772	126	.986			124	.182	.163	.161	.356
2	.017	.249	.283	36.27	42.00	29.26	34.96	.537	129	251	1.050	..do..	1,660	1,761	265	280	717	127	.986			126	.180	.177	.174	.350
3	.019	.248	.286	36.24	42.00	29.27	34.97	.493	131	228	.940	..do..	1,714	1,782	298	289	800	131	.986			129	.164	.164	.161	.286
4	.017	.248	.283	36.30	42.00	29.27	34.97	.452	108	229	1.080	..do..	1,649	1,661	265	286	835	125	.986			123	.129	.150	.147	.274
3-1	.018	.248	.282	30.27	35.98	24.30	30.00	.503	167	317	1.030	..do..	1,717	1,632	276	281	973	184	.980			180	.172	.189	.186	.328
2	.017	.248	.282	30.32	35.98	24.17	29.87	.454	161	279	.900	..do..	1,688	1,583	263	287	644	181	.980			177	.234	.281	.275	.433
3	.017	.247	.281	30.29	36.00	24.29	29.99	.495	163	281	.895	..do..	1,667	1,714	261	293	937	183	.980			179	.165	.195	.191	.300
4	.018	.248	.284	30.28	35.98	24.30	30.00	.489	165	288	.985	..do..	1,639	1,669	281	286	727	180	.980			176	.224	.248	.242	.396
4-1	.019	.247	.280	24.28	30.00	20.30	26.00	.454	212	287	.610	..do..	1,571	1,600	296	315	674	267	.972			260	.315	.396	.386	.426
2	.019	.244	.282	24.30	30.00	20.30	26.00	.530	223	358	.717	..do..	1,629	1,681	290	271	906	272	.971			264	.246	.300	.291	.395
3	.019	.244	.282	24.32	30.00	20.31	26.01	.476	217	326	.708	..do..	1,586	1,643	290	281	824	266	.972			259	.263	.328	.314	.396
4	.018	.245	.283	24.30	30.00	20.29	25.99	.450	192	195	.040	Glue	1,543	1,611	292	313	569	264	.972			257	.337	.464	.452	.343
5-1	.020	.242	.282	21.26	27.00	17.30	23.00	.474	278	364	.465	Buckle	1,629	1,609	303	309	822	362	.961			345	.338	.440	.423	.443
2	.019	.245	.283	21.27	26.99	17.30	23.00	.441	274	345	.495	..do..	1,526	1,652	292	314	692	344	.963			331	.396	.497	.478	.499
3	.017	.247	.261	21.27	26.99	17.30	23.00	.437	269	337	.450	..do..	1,564	1,651	261	320	583	348	.962			335	.461	.597	.575	.578
4	.018	.246	.262	21.16	26.99	17.30	23.00	.515	287	367	.395	..do..	1,613	1,683	276	336	709	368	.961			354	.405	.519	.499	.518
6-1	.019	.244	.282	19.30	25.00	15.30	21.00	.464	340	377	.300	..do..	1,591	1,584	290	284	684	434	.953			414	.497	.638	.605	.551
2	.019	.244	.282	19.36	25.00	15.31	21.01	.421	330	366	.290	..do..	1,576	1,497	290	308	683	428	.953			408	.483	.627	.597	.536
3	.018	.246	.262	19.30	25.00	15.31	21.01	.461	340	404	.280	..do..	1,662	1,566	276	288	830	445	.952			425	.410	.536	.511	.487
4	.018	.244	.280	19.30	25.00	15.31	21.01	.519	310	369	.290	..do..	1,489	1,450	272	305	691	410	.955			392	.449	.593	.567	.534
7-1	.018	.246	.282	18.30	24.01	14.30	20.00	.456	375	440	.210	..do..	1,694	1,530	276	293	806	505	.945			477	.465	.627	.592	.546
2	.016	.250	.282	18.28	24.00	14.30	20.00	.470	375	422	.180	..do..	1,544	1,524	249	284	670	473	.948			448	.560	.708	.669	.630
3	.015	.247	.283	18.29	24.00	14.30	20.00	.481	398	450	.300	..do..	1,667	1,546	278	310	657	504	.945			476	.603	.787	.725	.685
4	.016	.244	.280	18.32	24.00	14.30	20.00	.485	385	442	.260	..do..	1,650	1,664	272	297	725	499	.945			472	.531	.588	.651	.610

[1]Computed according to formulas in Forest Products Laboratory Report 1525.
[2]Computed by application of modifications to formulas in Forest Products Laboratory Report 1526.
[3]Two half waves at maximum load.

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Table 21.--Comparison between experimental and theoretical values of compressive strength of sandwich panels of [illegible] glass cloth laminate and 1/4-inch cellular cellulose acetate (all edges clamped)

Panel No.	Dimensions: Thickness: Face f	Thickness: Core c	Thickness: Total h	Width: Free a	Width: Total a'	Height: Free b	Height: Total b'	Density: Wt.	Observed data: Panel data: Critical load $P_{cr\ obs.}$	Maximum load P_m	Lateral deflection at maximum load δ_m	Type of failure
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
	Inch	Inch	Inch	Inches	Inches	Inches	Inches	Lb. per cu. ft.	Lb. per in. width	Lb. per in. width	Inches	
1-1	0.023	0.227	0.273	37.33	43.03	37.33	43.03	0.482	93	177	0.905	Buckle
2	.022	.230	.274	37.37	43.03	37.32	43.02	.459	107	196	[3] .000	..do..
3	.017	.241	.275	37.27	43.03	37.31	43.01	.496	98	121	.380	Glue
4	.021	.233	.275	37.45	43.00	37.31	43.01	.491	121	133	.320	..do..
2-1	.023	.228	.274	30.40	36.02	24.31	30.01	.482	144	275	1.050	Buckle
2	.027	.223	.277	30.23	36.02	24.31	30.01	.513	144	291	1.160	..do..
3	.022	.229	.273	30.38	36.02	24.32	30.02	.486	146	292	1.150	..do..
4	.023	.231	.277	30.40	36.03	24.00	30.00	.455	160	274	1.025	..do..
3-1	.023	.227	.273	21.32	27.01	17.31	23.01	.457	231	308	.480	..do..
2	.021	.235	.277	21.23	27.02	17.33	23.03	.492	222	314	.540	..do..
3	.024	.228	.276	21.24	27.02	17.33	23.03	.490	250	313	.540	..do..
4	.026	.223	.275	21.32	27.01	17.33	23.03	.462	241	330	.730	..do..
4-1	.021	.230	.272	18.32	24.06	14.33	20.03	.494	322	376	.420	..do..
2	.018	.240	.276	18.24	24.07	14.35	20.05	.416	260	295	.260	..do..
3	.021	.230	.272	18.40	24.06	14.33	20.03	.435	270	316	.320	..do..
4	.021	.231	.273	18.27	24.06	14.33	20.03	.494	260	393	.490	..do..

Panel No.	Observed data: Coupon data: Stiffness factors: Bending D_2	Bending D_1	$\left(\frac{EI}{\lambda}\right)_{12}$[1]	Shear $\mu_{12}I$	Compression strength P_{2m}	Computed data: Critical load[1] $P_{cr\ comp.}$	Shear reduction ratio $\frac{1}{1+r_4}$	Constants: M	M x 10[6]	Critical load reduced[2] $P_{cr\ rs}$	Comparative ratios: $\frac{P_{cr\ obs}}{P_{2m}}$	$\frac{P_{cr\ comp.}}{P_{2m}}$	$\frac{P_{cr\ rs}}{P_{2m}}$	$\frac{P_m}{P_{2m}}$
(1)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
					Lb. per in. width	Lb. per in. width				Lb. per in. width				
1-1	1,424	1,551	317	237	508	99	0.951	....	....	94	0.183	0.195	0.185	0.348
2	1,484	1,531	308	239	470	100	.951	....	....	95	.228	.213	.202	.417
3	1,515	1,527	289	249	557	101	.950	....	....	96	.176	.181	.172	.217
4	1,433	1,527	299	267	546	99	.951	....	....	94	.222	.181	.172	.244
2-1	1,530	1,476	320	282	574	170	.903	....	....	154	.251	.296	.268	.479
2	1,670	1,440	373	283	537	187	.897	....	....	168	.268	.348	.313	.542
3	1,627	1,535	306	282	514	176	.900	....	....	158	.284	.342	.307	.568
4	1,451	1,546	327	282	492	166	.906	....	....	150	.325	.337	.305	.557
3-1	1,514	1,630	317	250	415	340	.825	....	....	280	.557	.819	.675	.728
2	1,821	1,618	303	233	556	379	.811	....	....	307	.399	.682	.552	.565
3	1,461	1,763	336	238	512	342	.826	....	....	282	.488	.668	.551	.611
4	1,646	1,517	356	243	504	352	.822	....	....	289	.478	.695	.573	.655
4-1	1,760	1,474	292	358	481	523	.748	....	....	391	.649	1.087	.813	.786
2	1,336	1,592	264	375	326	453	.777	....	....	352	.798	1.390	1.080	.905
3	1,544	1,615	292	377	351	492	.758	....	....	373	.769	1.402	1.063	.900
4	1,643	1,780	294	365	544	526	.748	....	....	393	.478	.967	.722	.722

[1] Computed according to formulas in Forest Products Laboratory Report 1525.

[2] Computed by application of modifications to formulas in Forest Products Laboratory Report 1525.

[3] Two half waves at maximum load

Z M 74255 F

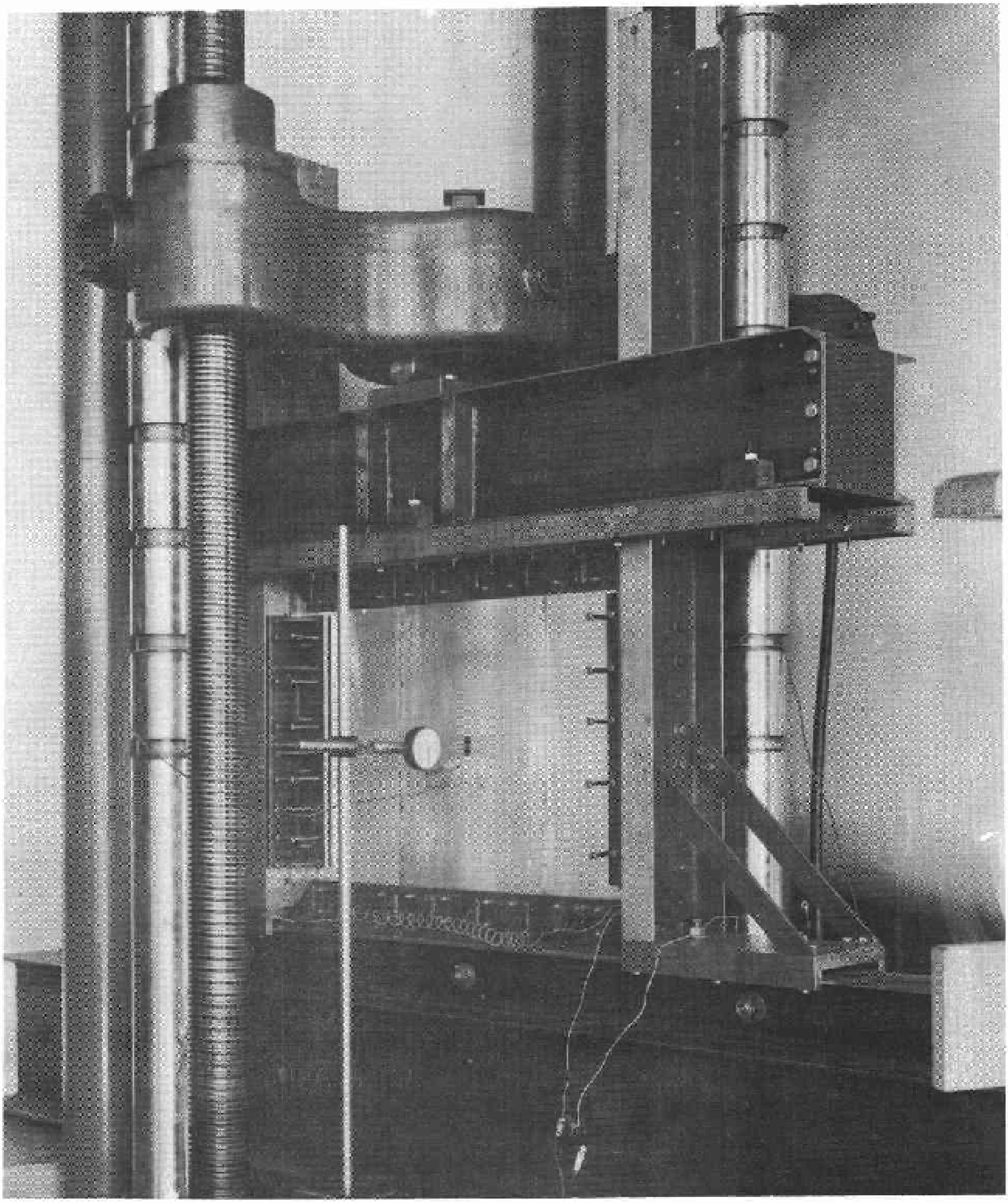

Figure 39.--Apparatus for testing sandwich panels with all edges clamped.

Z M 74931 F

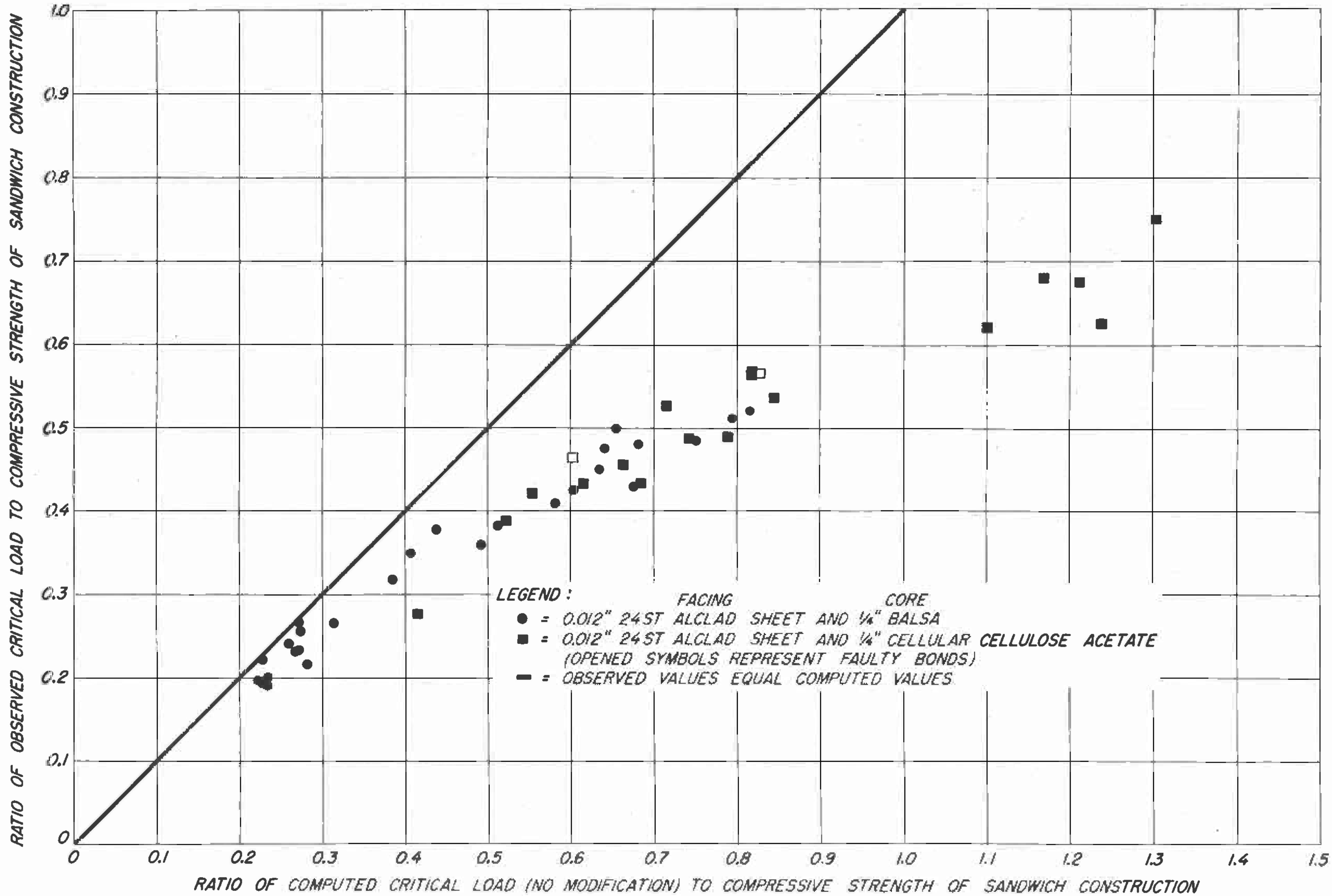

Figure 40.—Observed critical load plotted against the computed critical load (no modifications); both expressed as ratios of the compressive strength of the sandwich construction. Critical buckling of panels faced with aluminum and clamped on all four edges.

Z M 74256 F

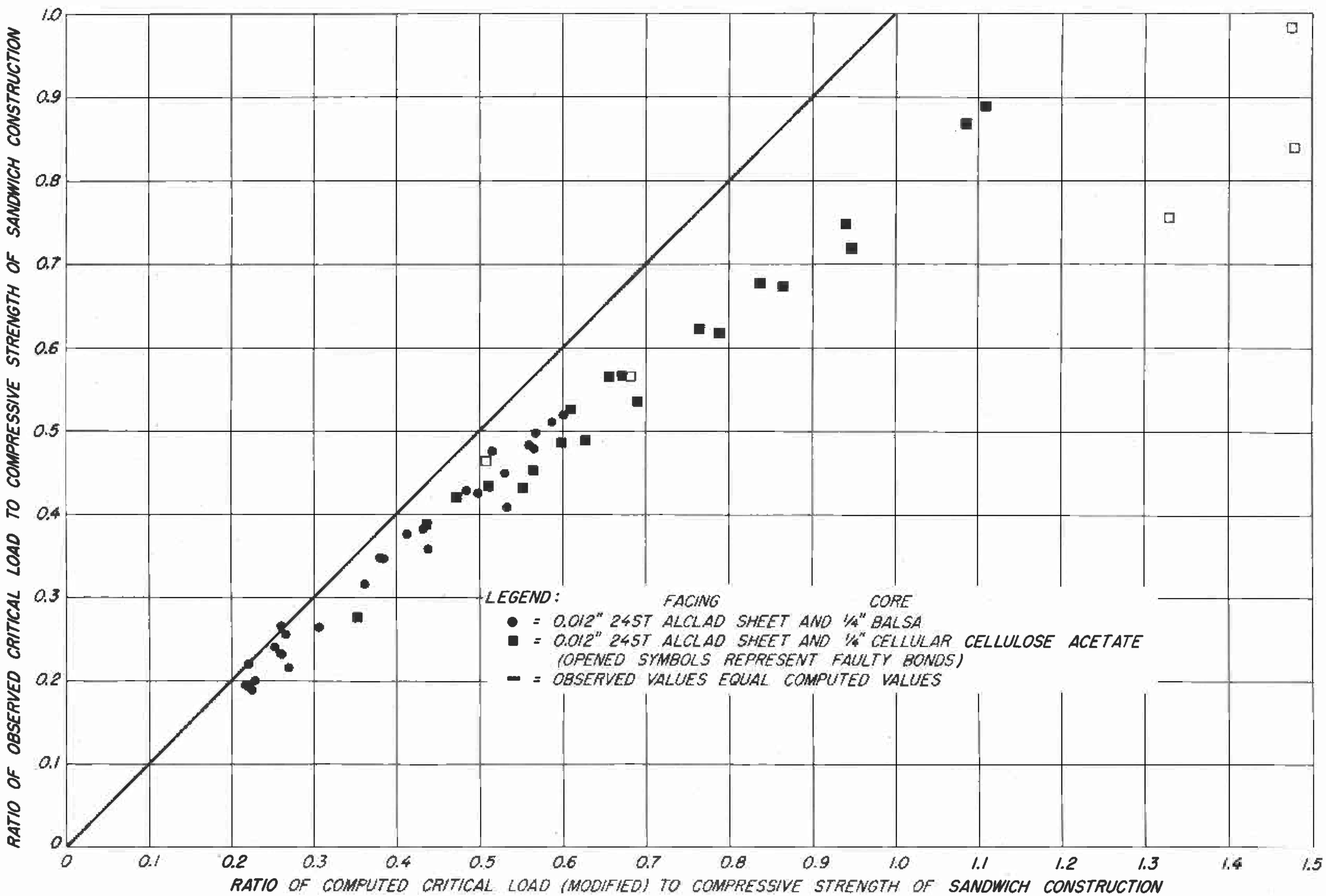

Figure 41.--Observed critical load plotted against the computed critical load (modified for reduced modulus and shear); both expressed as ratios of the compressive strength of the sandwich construction. Critical buckling of panels faced with aluminum and clamped on all four edges.

Z M 74257 F

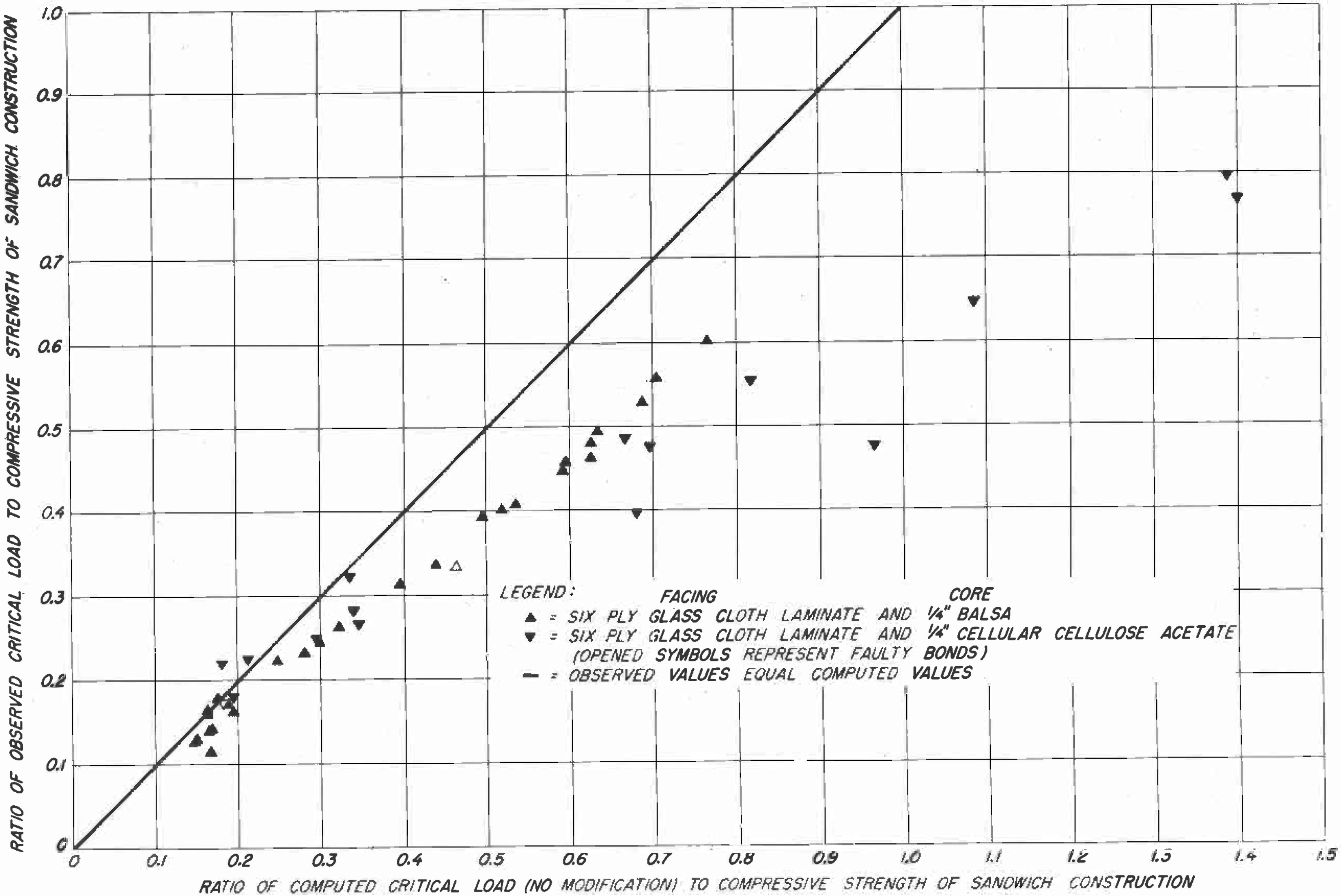

Figure 42.—Observed critical load plotted against the computed critical load (no modifications); both expressed as ratios of the compressive strength of the sandwich construction. Critical buckling of panels faced with glass cloth laminate and clamped on all edges.

Z M 74258 F

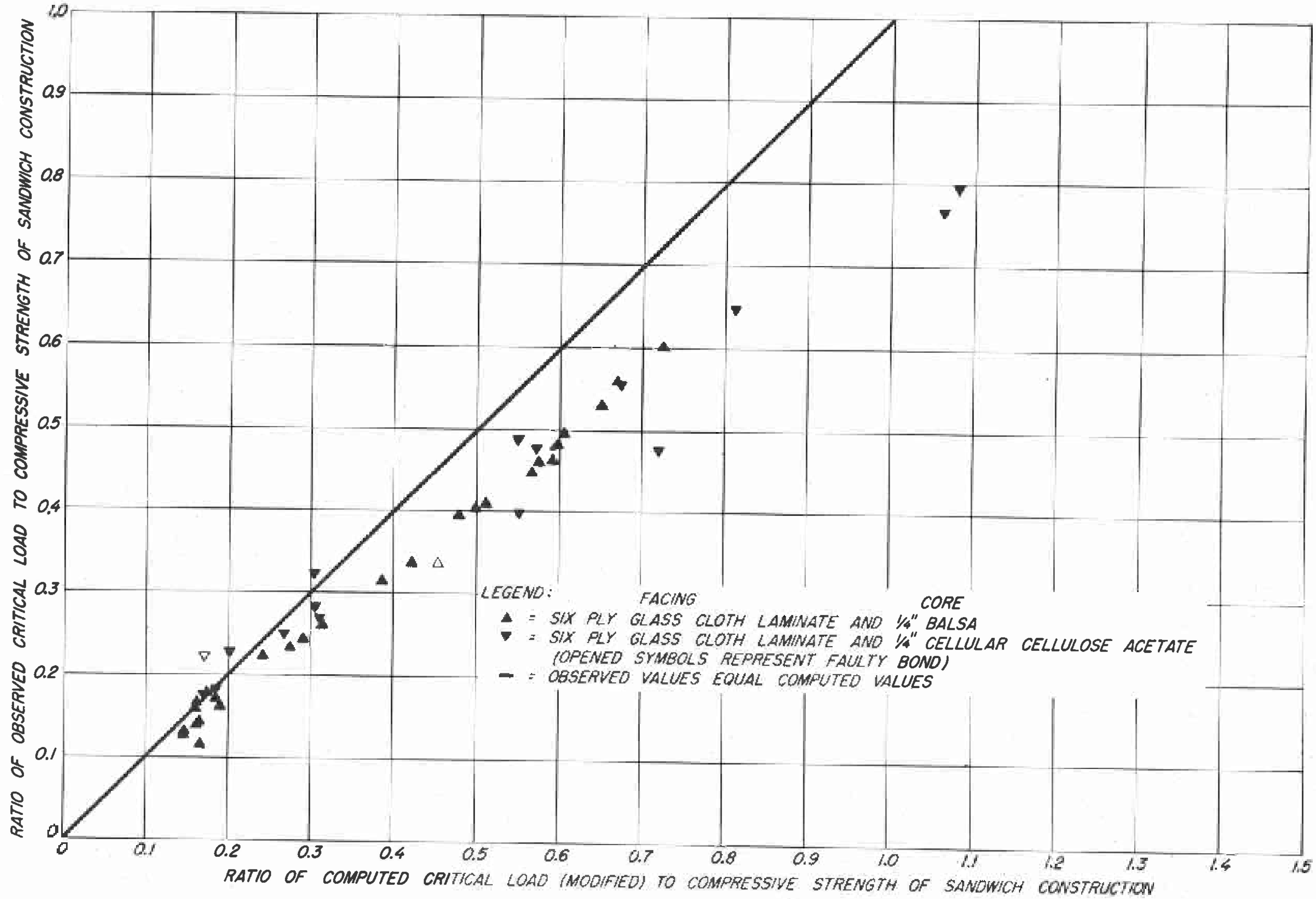

Figure 43.--Observed critical load plotted against computed critical load (modified for shear); both expressed as ratios of the compressive strength of the sandwich construction. Critical buckling of panels faced with glass cloth laminate and clamped on all edges.

Z M 74259 F

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