N.A.E.

R. & M. No. 2658
(10,427)
A.R.C. Technical Report

MINISTRY OF SUPPLY

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

Compression Tests on Dural-Celluboard Sandwich Panels

By

K. H. V. BRITTEN, B.Sc.

LONDON : HER MAJESTY'S STATIONERY OFFICE
1952
FIVE SHILLINGS NET

Compression Tests on Dural-Celluboard Sandwich Panels

By

K. H. V. BRITTEN, B.Sc.

COMMUNICATED BY THE PRINCIPAL DIRECTOR OF SCIENTIFIC RESEARCH (AIR),
MINISTRY OF SUPPLY

Reports and Memoranda No. 2658*
November, 1946

Summary.—Results are given of compression tests made on 56 Dural-Celluboard Sandwich Panels with Birch Spruce or Whitewood centres.

These are compared with results from similar tests on Dural-Balsa sandwich and all-metal panels, and it is seen that over the range of sizes and weights considered Dural-Celluboard can be equally or more efficient for carrying end loads.

The birch Celluboard was more efficient than the spruce or whitewood and the thicker sandwiches, and those with thicker skins were more efficient than the thinner specimens. The maximum stress reached in the skin, 48,000 lb/sq in., was equal to the 0·1 per cent tensile proof stress of the material. The birch filling had also reached its maximum compression stress, 8,000 lb/sq in. The design had therefore exploited these materials to their fullest extent.

---

1. *Introduction*.—Much interest had been shown recently in sandwich construction as practical and theoretical investigations have indicated that sandwich panels can be equally or more efficient than the more conventional stringer and corrugated panels for carrying end loads.

This report describes tests made on 56 flat Dural-Celluboard panels with birch, spruce and whitewood centres, and compares the results with those obtained from Dural-Balsa and all-metal panels.

2. *Description of Specimens*.—The panels consisted of two duplicate sets—the first with birch fillings and the second with spruce or whitewood fillings. It was originally intended that all panels of the second set should have spruce fillings but as it was found impossible to obtain 0·1-in. thick plywood in spruce, whitewood was substituted.

The panels comprised a Celluboard filling between sheet dural faces. The filling consisted of 3-ply stringers 0·1 in. or 0·2 in. thick at 0·5 in., a 1·0-in. pitch and laminated balsa spacers at 4 in. pitch. The plywood was composed of two outer sheets with grain parallel to the length of the panel (0·04 in. or 0·09 in. thick) and a central sheet with grain perpendicular (0·02 in. thick). The filling thickness was 0·5 in. or 0·75 in. and the thickness of the dural varied from 0·015 in. to 0·036 in. In accordance with the recommendation of a previous report[1] a veneer of birch or whitewood, 0·031 in. thick, was glued between the dural faces and filling, as difficulty had been found in obtaining satisfactory adhesion between the metal faces and wooden filling in previous tests on sandwich panels.

---

* R.A.E. Technical Note S.M.E. 383, received 4th March, 1947.

A photograph of a section of panel cut away to show the veneer and Celluboard filling is given in Fig. 4. The glues used were liquid Micanite resin 294 between the dural and veneer and Catacol between the veneer and filling.

The panels were 12 in. or 24 in. long and approximately 6 in. wide, 2-in. strips of $\frac{1}{4}$-in. thick plywood facings were glued to the dural at the ends of each panel to provide reinforcement against local crushing. Additional reinforcement was provided by inserting wooden blocks approximately 1 in. long in the end cells. The ends of the panels were machined so that they were parallel to each other.

The dimensions and weights of individual panels are given in Tables 1 and 2. The weight per sq ft of each panel was found by cutting off the reinforced section and weighing the remainder. The weight per sq ft of the dural was taken from tables and the weight of the filling determined by difference. The density of the stringers was found from the weight per sq ft of filling by obtaining by measurement a near value for the weight per sq ft of the veneer, glue and balsa spacers. The value of E_f for the Celluboard stringers was adjusted for density variation using the formula

$$E/E^1 = (\varrho/\varrho^1)^{1 \cdot 25}.$$

3. *Method of Test.*—The panels were tested in compression up to failure. The testing machines used were a 10-ton Dennison, 50-ton Avery and 90-ton Riehle. The top and bottom plattens of these machines had machined steel faces and the panels were placed vertically between as shown in Fig. 1. Overall deflections were measured by deflection gauges placed on either side of the panel and strains in the dural were recorded by four electrical resistance strain gauges fitted across the centre-line of each panel as shown in Fig. 1. The strain gauges on the panels with spruce and white wood fillings were placed 1 in. from each edge. As explained below it was found necessary to cut down some of the panels having birch fillings after the gauges were in position and the final distance from the edges, therefore, varied between 0·3 in. and 1·0 in.

Loads were applied in increments of approximately 1,000 or 2,000 lb depending on the estimated strength of the specimen and gauge readings were taken after each addition. Close watch was kept for any signs of failure during testing, both by observation and by plotting gauge readings as the test proceeded.

Most of the panels as supplied had free edges at one or both sides. That is, the panel had been cut, so that the edge stringers were not flush with the edge of the dural sheet but were set back at distances varying up to 1 in. Two panels of the first set (04B and 08B) were tested in this condition and in both cases failure occurred at a low load and accompanied by buckling of the free edge. An attempt to overcome this difficulty was made by clamping the free edge. The clamps were arranged so that the sides of the panel were held at their original distance apart. They were used on panels 02B, 05B and 07B and the low failing load was thereby avoided to some extent. Severe buckling occurred near the clamps, however, and it was therefore decided to cut down the remaining panels where necessary to leave each edge supported by a stringer.

4. *Results.*—The panels are numbered by their length and type of filling. The 12-in. panels have 2 digit, and the 24-in. 3 digit numbers. The suffix B, S, and W indicates that the filling was birch, spruce or whitewood respectively.

In the paragraphs that follow reference will be made to the ‘ selected load ’. This was obtained from the load-strain graphs for each panel by taking the maximum load within the limit of proportionality.

Material control tests were made on 10 specimens of dural similar to that used in the panels and the results of these are shown in Table 4. The mean value of $9 \cdot 9 \times 10^6$ lb/sq in. for E_S is used in subsequent calculations.

The values taken for the weight of veneer and glue were as follows:—

Birch veneer	0·40 lb/sq ft (2 sheets)
Whitewood veneer	0·32 lb/sq ft (2 sheets)

The following details for each panel are given in columns 16 to 24 of Tables 1, 2.

Column 16—Failing load. Column 17—Selected load. Columns 18 and 19—per cent loads in dural by calculation and by strain gauge readings.—In order to check the reliability of strains recorded by the gauges these two values of the per cent load in dural of the selected load are compared. The calculated value was obtained by assuming equal strain in the dural and filling and using the values of E_f and E_s obtained as explained above. The value in column 19 was calculated directly from gauge readings at the selected load.

Columns 20 and 21—Stresses in dural and filling at failure.—The stresses in dural and filling at failure have been calculated on the assumptions that E_s/E_f remains constant up to failure and that the strains in dural and filling are equal at failure.

Column 22.—Maximum stress in compression of birch, spruce or whitewood.—Originally values were calculated for the maximum stress in compression of birch, spruce and whitewood plywood using values for plywood supplied by Forest Products Research Laboratory, but on comparing these values with the failing stress in the filling (column 21) it was found in a number of cases that the failing stress was considerably higher. Values of the maximum stress in compression of birch, spruce and whitewood have therefore been calculated ignoring the effect of the ply construction. Variations in density were allowed for by using the formula

$$S/S^1 = (\varrho/\varrho_1)^{1\cdot 25} \text{ (Columns 23, 24 Efficiency factors)} .$$

The failing load per ft width divided by the weight per sq ft has been calculated for each panel and given in column 23. This gives a measure of the panel's efficiency but does not offer a comparison between panels of different length. The value of failing load per ft width divided by strut length is therefore given in column 24.

Fig. 2 shows the efficiency figures plotted together. Similar results for other types of sandwich panels and for sheet-stringer panels made from D.T.D. 390 are included for comparison. Fig. 3 shows results for the celluboard panels separately.

The selected load and per cent load given by strain gauges are omitted for number 110W as no readings were taken when this panel was tested.

5. *Types of Failure.*—Three principal types of failure were observed: —

(a) Sudden failure in gluing between the veneer and filling, dural and veneer or both accompanied by buckling of the dural and filling.

(b) Local buckling of dural or of dural and veneer followed by final failure as described above.

(c) Euler bowing of the entire panel followed by failure in gluing and buckling of dural and filling.

Some failures did not conform exactly to these types and a more detailed description of individual failures is given in Table 5. Figs. 5 and 6 show some typical failures.

6. *Discussion of Results.*—The panels can be divided into two classes by their type of primary failure: namely, panels which failed initially as a strut (*i.e.*, bowing occurred) and panels which failed only by buckling of the dural and filling. These classes must be considered separately since bowing produces a considerable increase in stress and final failure in gluing or by buckling will therefore occur at a lower load than if the panel had not bowed.

We shall consider first the panels which did not bow. We shall omit 04B, 08B, 12B, 11S and 114S in comparing results. Of these the first two were tested with a free edge at one side as described above and gluing down the edges of the last three was noted to be unsatisfactory before testing. The following panels will therefore be considered:

01B, 02B, 03B, 05B, 06B, 07B, 09B, 10B, 11B, 14B, 102B, 104B, 106B, 01W, 02W, 03W, 04W, 05W, 06W, 07S, 08S, 09W, 10W, 12S, 13S, 14S, 102W, 105W, 106W, 108S, 110W, 111S.

Some relevant results for these panels are given in Table 3.

The following points are of interest:

(i) The maximum differences between the calculated and measured loads in the dural are:

11 per cent with birch fillings,
8 per cent with spruce fillings,
18 per cent with whitewood fillings,

provided panels 02B, 05B, 07B are excluded; the tests of these specimens are thought to be unrepresentative because the specimens were tested with free edges and fitted with clamps and local bucklings occurred some time before failure.

(ii) For panels with birch filling the failing stress in the dural is always above the limit of proportionality ($3\cdot04 \times 10^4$ lb/sq in.) with a mean value of $3\cdot87 \times 10^4$ lb/sq in.

Three panels with spruce filling show a failing stress below the limit of proportionality and the stress has a mean value of $3\cdot02 \times 10^4$ lb/sq in. Stresses in Whitewood Specimens have a mean value of $3\cdot58 \times 10^4$ lb/sq in. but four panels have a failing stress below the limit of proportionality.

(iii) Considering panels with birch filling the failing stresses in the filling are all above 70 per cent of the maximum stress in compression of birch with the exception of 09B. The mean value is 87 per cent. For panels with spruce fillings the lowest failing stresses are greater than 41 per cent of the maximum stress in compression with a mean value of 82 per cent. The mean value for whitewood filling is 87 per cent and all are within 67 per cent.

(iv) Failure occurred suddenly without preliminary buckling in all but six specimens with birch filling, the six being 01B, 02B, 03B, 05B, 07B, 102B. The percentage of the failing load at which buckling first occurred in these latter panels varied between 52 and 89. The early local buckling on 02B, 05B and 07B was probably caused by the clamps fitted to these panels. Two panels with spruce filling (08S and 108S) buckled before failure at 59 per cent and 75 per cent of the failing load respectively. Panels 03W, 09W and 102W buckled at 54, 39 and 51 per cent of the failing load respectively.

(v) A comparison of panels with similar dimensions but different filling material does not indicate any very pronounced difference in the efficiencies of the filling. The mean efficiencies for different fillings are as follows:

Birch	$2\cdot22 \times 10^4$ ft (13 panels)
Spruce	$2\cdot06 \times 10^4$ ft (7 panels)
Whitewood	$2\cdot14 \times 10^4$ ft (12 panels)

(vi) A comparison of similar panels with $0\cdot5$ in. and $0\cdot75$ in. wide fillings does not show any marked difference in efficiency. The mean efficiency figures for panels with $0\cdot5$ in. and $0\cdot75$ in. fillings are:

(all $\times 10^4$ ft)

	$0\cdot5$ in.	$0\cdot75$ in.
Birch	2·25 (6 panels)	2·20 (7 panels)
Spruce	2·33 (3 panels)	1·86 (4 panels)
Whitewood	2·04 (5 panels)	2·21 (7 panels)

(vii) A comparison of panels with similar dimensions with 0·1 in. and 0·2 in. cell walls shows that in four cases out of six, 0·1 in stringers are more efficient. The mean efficiencies for panels with 0·1 in and 0·2 in stringers are:

(all × 10^4 ft)

	0·1 in.	0·2 in.
Birch	2·13 (9 panels)	2·43 (4 panels)
Spruce	2·06 (7 panels)	
Whitewood	2·14 (12 panels)	

(viii) Plotting values of efficiency against skin thickness, it will be seen that the maximum efficiency reached for any given skin thickness increases with the skin thickness. A comparison of the mean values of efficiency for various thicknesses does not show quite such a definite increase but it must be remembered that the number of panels considered with a given sheet thickness varies from 3 to 1. The mean efficiencies are:

(all × 10^4 ft)

2·10, 2·14, 1·93, 2·26, 2·86 for 0·015 in., 0·018 in., 0·022 in., 0·028 in. and 0·036 in. skins respectively.

We shall now consider the panels which bowed, *i.e.*,

13B, 101B, 103B, 105B, 109B, 110B, 107B, 111B, 113B, 108B, 112B, 114B, 101W, 103W, 109W 104W, 107S, 113S, 112S.

Examining results as before we find that:

(i) The discrepancy between experimental and calculated per cent loads in dural is not appreciably larger than for the panels already considered. It reaches a maximum of 13 per cent for birch fillings, 7 per cent for spruce and 16 per cent for whitewood.

(ii) Two panels with birch filling show a failing stress in dural below the limit of proportionality. The failing stress has a mean value of 3·26 × 10^4 lb sq in. Two panels with spruce fillings have a failing stress below the limit of proportionality and the mean failing stress in dural is 2·89 × 10^4 lb/sq in. Two panels with whitewood fillings have failing stresses below the limit of proportionality and the mean value is 3·16 × 10^4 lb/sq in.

(iii) Failing stresses in the birch fillings are all greater than 67 per cent of the maximum stress in compression of birch. Stresses at failure in spruce and whitewood fillings are greater than 70 per cent of the maximum stress in compression.

(iv) Only one panel, 104W buckled before failure (at 75 per cent of the failing load).

(v) Again there seems to be no pronounced difference in the efficiency of the various types of filling.

The mean efficiencies are:

(all × 10^4 ft)

Birch	1·98 (12 panels)
Spruce	2·00 (3 panels)
Whitewood	1·90 (4 panels)

(vi) The mean efficiency figures for panels with 0·5 in. and 0·75 in. wide fillings are:

	0·5 in.	0·75 in.
Birch	1·98 (8 panels)	1·98 (4 panels)
Spruce	1·88 (2 panels)	2·26 (1 panel)
Whitewood	1·84 (3 panels)	2·06 (1 panel)

(vii) The number of specimens is not sufficient to make a comparison of similar panels with 0·1 in. and 0·2 in. stringers possible.

(viii) The maximum failing stress attained for any given skin thickness increases with skin thickness.

The mean efficiencies are (all × 10^4 ft) 1·67, 1·93, 1·86, 2·02, 2·01 for 0·015 in., 0·018 in., 0·022 in. 0·028 in. and 0·036 in. skin respectively. Considering the five panels 04B, 08B, 12B, 11S and 114S which were tested in unsatisfactory conditions, we see that:

(i) The failing stress in the dural is always below the limit of proportionality.

(ii) The failing stress in the filling is never higher than 61 per cent of the maximum stress in compression.

(iii) Buckling occurred before failure in 11S and 114S at 51 per cent and 68 per cent of the failing load respectively.

7. *Conclusions.*—It appears from these considerations that:

(a) The highest values of stress at failure and the highest values of the mean stress at failure in the dural are reached in panels with birch filling; also the mean efficiency of the birch panels is higher than those of spruce or whitewood. It seems, therefore, that birch celluboard provides a more efficient filling than spruce or whitewood.

(b) For the range of skin thicknesses considered the effect of increasing the thickness of dural is to raise the efficiency.

(c) Although comparison of individual specimens does not show pronounced difference in the efficiencies of panels with 0·5 in. and 0·75 in. wide filling; of the 19 panels which bowed only 6 had 0·75 in. fillings. The wider filling, therefore, provides a more efficient structure as there is less tendency to fail by Euler bowing.

In high-speed aircraft it is of particular importance that the outer surfaces should be smooth and remain undistorted under loading. It has been shown that sandwich construction can be more efficient than metal sheet-stringer panels in this respect. The efficiency of the gluing is, of course, of great importance here. Of the 51 panels tested under satisfactory conditions, 11 buckled before failure and in 3 of these cases buckling was probably due to the clamps fitted. It seems, therefore, that liquid Micanite 294 and Catacol are satisfactory glues for this type of sandwich.

The inclusion of the veneer and extra layer of glue appreciably increases the weight of the filling and only a small area of veneer is useful in providing an interface between the stringers and dural. Failure in gluing usually occurred both between the dural and veneer and between the veneer and filling and it is possible that a more efficient sandwich might be obtained without the veneer.

From Fig. 2 it can be seen that for values of ϱ/l up to 3 × 10^4 lb/sq ft the efficiencies of Celluboard panels are in general higher than those of dural and balsa. Also from results given in ‘ Compression tests on Dural Balsa Panels ’ of 24 flat dural-balsa panels tested, 12 buckled before failure. It seems, therefore, that dural-Celluboard provides a more efficient construction than dural-balsa over the greater part of the range considered.

The comparison with metal panels is more difficult as no results seem to be available for the higher values of ϱ/l. In the range where comparison is possible, however, Celluboard panels reach efficiencies in some cases 20 per cent higher than sheet-stringer panels.

REFERENCE

No.	*Author*	*Title, etc.*
1	R. G. Chapman	Compression Tests on Dural-Balsa Sandwich Panels. R. & M. 2153. June, 1945.

TABLE 1

Compression Tests on Dural Celluboard Panels with Birch Fillings

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
N°	Nominal length in.	Particulars of panel						Weights				E of filling	Cross sec. area		Failing load (lb)	Selected load (lb)	% loads in dural		Stresses at failure		Max stress in comp of birch lb/in²	Failing load/ft wt. sq ft ft × 10⁴	Failing load/ft strut length lb × 10⁴ ft²	N°
		Measured length (in.)	Measured width (in.)	Stringer thickness (in.)	Stringer spacing (in.)	Nominal filling thickness (in.)	Nominal sheet thickness (in.)	Panel lb/sq ft	Nominal sheet lb/sq ft 2 sheets	Filling lb/sq ft	Density of filling lb/cu ft	lb × 10⁶/in²	Sheet sq in.	Filling sq in.			By calculation	By strain gauges	Sheet lb/sq in	Filling lb/sq in				
01B	12	11·87	6·00	0·1	0·5	0·5	0·015	1·24	0·43	0·81	42·5	1·53	0·18	0·98	12,300	6,720	55	44	37300	5780	6,980	1·98	2·48	01B
03B		11·75	6·00				0·018	1·31	0·53	0·78	39·1	1·38	0·22	1·03	14,000	11,800	61	51	38900	5410	6,300	2·14	2·86	03B
05B		11·94	6·00				0·022	1·43	0·64	0·79	40·2	1·43	0·26	0·93	13,900	11,200	65	49	34800	5010	6,520	1·95	2·79	05B
09B		11·81	5·04				0·028	1·73	0·82	0·91	54·0	2·07	0·28	0·92	18,490	12,430	60	55	39300	8210	9,440	2·55	4·47	09B
02B		11·81	5·85			0·75	0·015	1·32	0·43	0·89	33·1	1·12	0·17	1·19	12,900	8,960	57	39	43000	4860	5,110	2·01	2·69	02B
04B		11·88	6·00				0·018	1·46	0·53	0·93	36·1	1·25	0·22	1·28	10,800	10,100	58	44	28400	3580	5,700	1·48	2·18	04B
06B		11·88	5·52				0·022	1·77	0·64	1·13	51·5	1·95	0·24	1·17	15,460	12,420	51	47	32900	6480	8,890	1·90	3·39	06B
10B		11·88	5·67				0·028	1·85	0·82	1·03	43·9	1·60	0·32	1·18	24,550	15,550	63	53	48100	7800	7,300	2·81	5·25	10B
07B		11·75	6·00	0·2	1·0	0·5	0·022	1·43	0·64	0·79	35·6	1·38	0·26	0·98	17,300	10,100	65	54	43300	6010	5,600	2·42	3·53	07B
11B		11·69	5·31				0·028	1·79	0·82	0·97	55·6	2·41	0·30	0·93	19,450	11,430	57	57	36700	8910	9,780	2·46	4·51	11B
13B		12·00	5·31				0·036	1·98	1·05	0·93	51·1	2·17	0·38	0·93	23,280	15,530	66	64	40100	8770	8,800	2·65	5·27	13B
08B		11·88	6·00			0·75	0·022	1·67	0·64	1·03	38·5	1·52	0·26	1·28	10,020	8,960	57	51	21800	3360	6,160	1·20	2·02	08B
12B		11·88	5·34				0·028	1·95	0·82	1·13	45·9	1·90	0·30	1·23	9,430	7,450	56	50	17500	3360	7,700	1·09	2·14	12B
14B		11·81	5·29				0·036	2·13	1·05	1·08	42·2	1·71	0·38	1·23	26,200	14,370	64	62	44400	7680	6,940	2·79	6·04	14B
101B	24	23·38	6·00	0·1	0·5	0·5	0·015	1·28	0·43	0·85	47·1	1·74	0·18	0·93	10,340	6,280	53	50	30400	5350	7,940	1·61	1·06	101B
103B		23·31	5·56				0·018	1·43	0·53	0·90	52·9	2·01	0·20	0·90	11,990	8,450	53	46	31600	6420	9,180	1·81	1·33	103B
105B		23·44	5·30				0·022	1·47	0·64	0·83	44·8	1·64	0·23	0·83	11,200	7,370	62	49	30300	5030	7,490	1·72	1·30	105B
109B		23·25	5·58				0·028	1·73	0·82	0·91	54·0	2·07	0·31	0·90	16,370	12,420	62	59	32700	6840	9,440	2·03	1·82	109B
102B		23·31	5·54			0·75	0·015	1·54	0·43	1·11	50·0	1·88	0·16	1·17	12,040	8,650	42	43	31700	6020	8,580	1·69	1·34	102B
104B		23·44	5·48				0·018	1·78	0·53	1·25	60·8	2·40	0·20	1·24	17,480	10,370	40	40	35000	8470	10,940	2·15	1·96	104B
106B		23·44	5·31				0·022	1·69	0·64	1·05	45·4	1·66	0·23	1·08	15,350	10,360	56	50	37400	6290	7,570	2·05	1·77	106B
110B		23·38	5·54				0·028	1·80	0·82	0·98	40·0	1·42	0·31	1·10	18,860	13,460	66	54	40100	5740	6,480	2·27	2·10	110B
107B		23·44	5·32	0·2	1·0	0·5	0·022	1·52	0·64	0·88	45·6	1·88	0·23	0·93	13,300	9,380	56	53	32400	6150	7,620	1·97	1·54	107B
111B		23·38	5·29				0·028	1·82	0·82	1·00	58·9	2·59	0·30	0·93	15,890	13,440	56	56	29400	7700	10,500	1·98	1·85	111B
113B		23·38	5·37				0·036	1·90	1·05	0·85	42·2	1·71	0·39	0·94	17,480	14,460	71	66	31800	5500	6,940	2·06	2·00	113B
108B		23·44	5·30			0·75	0·022	1·86	0·64	1·22	52·6	2·25	0·23	1·23	16,500	11,400	45	47	32400	7360	9,130	2·01	1·91	108B
112B		23·44	6·00				0·028	1·94	0·82	1·12	45·2	1·86	0·34	1·28	16,470	10,380	59	53	28400	5340	7,550	1·70	1·69	112B
114B		23·38	5·32				0·036	2·14	1·05	1·09	43·0	1·75	0·38	1·23	18,990	14,520	63	60	31600	5600	7,100	1·94	2·20	114B

TABLE 2

Compression Tests on Dural Celluboard Panels with Spruce or Whitewood Fillings

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
N^o	NOMINAL LENGTH IN.	PARTICULARS OF PANEL						WEIGHTS				E OF FILLING LB ×10⁶/IN²	CROSS-SEC. AREA		FAILING	SELECTED	% LOADS IN DURAL		STRESSES IN FAILURE		MAX. STRESS IN COMP OF SPRUCE & W.W. LB/IN²	FAILING LOAD/FT / WT/SQFT FT ×10⁴	FAILING LOAD/FT / LENGTH LB×10⁴/FT²	N^o
		MEASURED LENGTH (IN.)	WIDTH (IN.)	STRINGER THICKNESS (IN.)	STRINGER SPACING (IN.)	NOMINAL FILLING THICKNESS (IN.)	NOMINAL SHEET THICKNESS (IN.)	PANEL LB/SQ FT	NOMINAL SHEET LB/SQ FT 2 SHEETS	FILLING LB/SQ FT	DENSITY OF FILLING LB/CU FT		SHEET IN.²	FILLING IN.²	LOAD (LB)	LOAD (LB)	BY CALCULATION	BY STRAIN GAUGES	SHEET LB/IN²	FILLING LB/IN²				
01W	12	11·74	5·24	0·1	0·5	0·5	0·015	1·03	0·43	0·60	27·6	1·18	0·16	0·83	10,380	6,270	62	54	3,990	4,750	4,920	2·31	2·43	01W
03W		11·76	5·34				0·018	1·14	0·53	0·61	28·8	1·24	0·19	0·83	8,530	7,370	66	63	2,940	3,680	5,170	1·69	1·96	03W
05W		11·74	5·28				0·022	1·24	0·64	0·60	27·6	1·18	0·23	0·83	14,490	9,340	70	58	4,390	5,220	4,920	2·66	3·36	05W
09W		11·86	5·13				0·028	1·47	0·82	0·65	33·3	1·49	0·29	0·82	11,460	8,370	71	59	2,790	4,190	6,210	1·83	2·71	09W
02W		11·90	5·93			0·75	0·015	1·17	0·43	0·74	27·7	1·18	0·18	1·27	13,430	9,490	55	48	4,070	4,850	4,920	2·32	2·74	02W
04W		11·73	5·99				0·018	1·27	0·53	0·74	27·7	1·18	0·22	1·28	16,250	10,370	59	48	4,390	5,220	4,920	2·56	3·33	04W
06W		11·70	5·98				0·022	1·35	0·64	0·71	25·4	1·06	0·26	1·27	17,220	11,390	65	53	4,310	4,610	4,420	2·56	3·54	06W
10W		11·69	5·98				0·028	1·61	0·82	0·79	31·5	1·39	0·33	1·27	16,370	11,390	65	56	3,210	4,500	5,790	2·04	3·38	10W
07S		11·80	4·98	0·2	1·0	0·5	0·022	1·32	0·64	0·68	32·2	1·68	0·20	0·79	10,470	8,430	61	56	31,300	5,310	6,220	2·08	2·79	07S
11S		11·88	4·36				0·028	1·59	0·82	0·77	42·2	2·36	0·24	0·77	6,610	5,600	57	75	15,600	3,720	8,740	1·14	1·84	11S
13S		11·78	4·54				0·036	1·76	1·05	0·71	35·6	1·91	0·33	0·78	19,360	13,430	69	66	40,400	7,780	7,070	2·91	5·21	13S
08S		11·59	4·43			0·75	0·022	1·43	0·64	0·79	26·6	1·32	0·19	1·03	6,320	5,200	58	63	19,300	2,580	4,880	1·20	1·77	08S
12S		11·88	4·48				0·028	1·67	0·82	0·85	31·1	1·61	0·25	1·03	14,600	8,960	59	58	34,900	5,680	5,960	2·34	3·95	12S
14S		11·82	4·50				0·036	1·86	1·05	0·81	28·1	1·42	0·32	1·03	20,190	13,470	68	63	43,200	6,200	5,260	2·88	5·46	14S
101W	24	23·83	5·36	0·1	0·5	0·5	0·015	1·05	0·43	0·62	29·4	1·30	0·16	0·84	8,060	5,600	59	53	2,990	3,920	5,420	1·72	0·91	101W
103W		23·83	5·41				0·018	1·16	0·53	0·63	31·0	1·36	0·19	0·84	10,100	6,720	61	47	3,260	4,470	5,670	1·93	1·13	103W
105W		23·71	5·16				0·022	1·22	0·64	0·58	25·3	1·06	0·23	0·82	8,960	6,720	72	54	2,800	3,000	4,420	1·71	1·06	105W
109W		23·75	5·29				0·028	1·48	0·82	0·66	34·5	1·56	0·30	0·83	12,300	8,950	70	54	2,860	4,520	6,500	1·88	1·41	109W
102W		23·90	6·02			0·75	0·015	1·15	0·43	0·72	26·2	1·10	0·18	1·28	13,100	7,840	56	45	4,090	4,540	4,580	2·27	1·31	102W
104W		23·86	5·98				0·018	1·31	0·53	0·78	30·8	1·35	0·22	1·20	13,400	11,200	58	45	3,530	4,800	5,630	2·06	1·35	104W
106W		23·79	5·35				0·022	1·38	0·64	0·74	27·7	1·18	0·24	1·09	10,400	8,960	65	53	2,810	3,350	4,920	1·69	1·18	106W
110W		23·60	6·00				0·028	1·64	0·82	0·82	33·9	1·52	0·34	1·28	16,800	—	63	—	3,110	4,790	6,330	2·05	1·71	110W
107S		23·74	4·58	0·2	1·0	0·5	0·022	1·33	0·64	0·69	33·4	1·76	0·20	0·79	8,750	6,720	59	55	25,800	4,580	6,520	1·72	1·16	107S
111S		23·77	4·56				0·028	1·57	0·82	0·75	40·0	2·21	0·26	0·79	11,900	8,960	59	57	27,300	6,100	8,190	1·99	1·58	111S
113S		23·85	4·67				0·036	1·81	1·05	0·76	41·1	2·28	0·34	0·79	14,300	8,960	65	58	27,400	6,300	8,450	2·03	1·84	113S
108S		23·80	4·67			0·75	0·022	1·50	0·64	0·86	31·8	1·66	0·21	1·04	5,830	3,920	54	46	15,200	2,550	6,150	1·00	0·75	108S
112S		23·78	4·61				0·028	1·70	0·82	0·88	33·3	1·75	0·26	1·04	14,800	12,300	59	56	33,400	5,900	6,490	2·26	1·94	112S
114S		23·75	4·61				0·036	1·90	1·05	0·85	31·1	1·61	0·33	1·04	6,660	5,040	66	70	13300	2,170	5,960	0·91	0·88	114S

TABLE 3

Compression Tests on Dural Celluboard Panels

No.	Diff. between calc. and exp. per cent loads in dural	$\frac{\text{Failing stress in dural} \times 100}{\text{Stress at L.P.}}$	$\frac{\text{Failing stress in filling} \times 100}{\text{Max. stress in comp.}}$	$\frac{\text{Failing load /ft}}{\text{wt./ft}^2}$ ft $\times 10^4$
01B	11	123	83	1·98
02B	18	141	95	2·01
03B	10	128	86	2·14
05B	16	114	77	1·95
06B	4	108	73	1·90
07B	11	142	107	2·42
09B	5	129	48	2·55
10B	10	158	107	2·81
11B	0	121	110	2·46
14B	2	146	111	2·79
102B	1	104	70	1·69
104B	0	115	77	2·15
106B	6	123	83	2·05
01W	8	131	96	2·31
02W	8	134	99	2·32
03W	3	97	71	1·69
04W	11	145	106	2·56
05W	12	145	106	2·66
06W	12	142	104	2·56
07S	5	103	85	2·08
08S	5	63	53	1·20
09W	12	92	67	1·83
10W	9	106	78	2·04
12S	1	115	95	2·34
13S	3	133	110	2·91
14S	5	142	118	2·88
102W	11	135	99	2·27
105W	18	92	68	1·71
106W	12	93	68	1·69
108S	8	50	41	1·00
110W	—	103	76	2·05
111S	2	90	74	1·99

Panels which did not bow.

TABLE 3—*continued*

No.	Diff. between calc. and exp. per cent loads in dural	$\dfrac{\text{Failing stress in dural} \times 100}{\text{Stress at L.P.}}$	$\dfrac{\text{Failing stress in filling} \times 100}{\text{Max. stress in comp.}}$	$\dfrac{\text{Failing load /ft}}{\text{wt./ft}^2\ \text{ft} \times 10^4}$
13B	2	132	100	2·65
101B	3	100	67	1·61
103B	7	104	70	1·81
105B	13	100	67	1·72
107B	3	107	81	1·97
108B	2	107	81	2·01
109B	3	108	72	2·03
110B	12	132	89	2·27
111B	0	97	73	1·98
112B	6	93	71	1·70
113B	5	105	79	2·06
114B	3	104	79	1·94
101W	6	98	72	1·72
103W	14	107	79	1·93
104W	13	116	85	2·06
107S	4	85	70	1·72
109W	16	94	70	1·88
112S	3	110	91	2·26
113S	7	90	75	2·03

Panels which bowed.

TABLE 4

Results of Control Tests on Dural Sheeting

Specimen No.	1	2	3	4	5	6	7	8	9	10	Mean values
Stress at L.P. lb/in.^{2} ..	26,000	30,900	23,500	34,200	33,600	30,900	32,900	31,400	31,400	29,100	30,390
0·1 per cent proof stress lb/in.^{2}	40,800	43,500	45,000	45,700	46,900	48,200	45,000	44,800	49,700	48,900	45,850
Maximum stress lb/in.^{2}	59,000	61,000	64,100	65,000	63,000	63,900	63,000	63,400	65,000	65,300	63,270
E_S lb × 10^6/in.^{2} ..	9·8	10·0	9·7	9·9	9·9	10·1	10·0	9·7	9·7	10·1	9·9

TABLE 5

Method of Failure

(A) *Panels with Birch Fillings*

01B	At 10,600 lb buckling of the dural and veneer began at the edge of one side. Final failure at 12,300 lb was caused by failure in gluing between the dural and veneer and buckling of the dural and veneer.
101B	At 5,000 lb bowing began. Final failure at 10,340 lb was due to buckling of dural or of dural-veneer and failure in gluing across the centre of both faces of the panel.
02B	This panel was tested with a free edge 0·47 in. deep at one side and supported by a clamp on this edge. At 6,700 lb buckling of the dural began at the free edge above the clamp. This spread and at 12,900 lb the panel failed, buckling having occurred right across one sheet and $\frac{3}{4}$ of the width across the other.
102B	At 10,000 lb separation of the dural from the veneer occurred over approx. 2 in. midway down one edge. Failure occurred at 12,040 lb, the dural buckling across the centre of one side and a small buckle forming on the opposite side.
03B	At 9,500 lb a small buckle in the dural formed at the centre of one edge. This spread across the panel and final failure occurred at 14,000 lb.
103B	Bowing began at 8,000 lb and increased until the panel failed at 11,990 lb, the gluing failing right across the centre of the convex side.
04B	Failure occurred suddenly in the gluing ; the dural buckled halfway across one sheet above the reinforcing (gluing down the edges of this panel was noted to be unsatisfactory before testing).
104B	Similar to 04B but buckling occurred across the centre of both sides.
05B	This panel was tested with a free edge 0·31 in. deep at one side and fitted with 2 clamps at this edge. At 12,300 lb buckling began near one clamp. This spread across the panel and final failure occurred at 13,900 lb.
105B	Bowing began at 10,000 lb and increased until the panel failed at 11,200 lb, the gluing failing across the convex side near the reinforcing.
06B	Similar to 04B.
106B	Similar to 04B.
07B	This panel was tested with a 0·59 in. deep free edge and supported by two clamps. At 13,400 lb buckling began by one clamp and separation of the dural from the end reinforcing occurred. As the load increased severe buckling occurred near both clamps and this spread across the panel on one side at 17,300 lb.
107B	Similar to 101B. Bowing began at 12,000 lb and buckling occurred across the concave face at the centre at 13,300 lb.
08B	This panel was tested with a free edge 0·6 in. deep at one side. Failure occurred suddenly at 10,020 lb, the dural buckling half way across both faces near the reinforcing.
108B	Similar to 101B. Bowing began at 14,000 lb and final failure was at 16,500 lb.
09B	Similar to 04B.
109B	Bowing began at approx. 12,000 lb and increased to 16,370 lb without failure in gluing. No further load was applied.
10B	Similar to 04B. Failure at 24,550 lb.
110B	Similar to 109B. Bowing began at 16,000 lb and increased to 18,860 lb without buckling.
11B	Similar to 04B. Failure at 19,450 lb.
111B	Similar to 101B. Bowing began at 9,450 lb and buckling occurred across the concave face at 15,890 lb.
12B	Similar to 04B. Failure at 9,430 lb.
112B	Bowing began at 10,380 lb and at 15,010 lb separation of the dural from the veneer occurred on the convex side. This spread across the panel and final failure was at 16,470 lb.
13B	Similar to 101B. Bowing began at 20,510 lb and final failure was at 23,280 lb.

TABLE 5—*continued*

113B	Bowing began at 13,000 lb and separation of the dural from the veneer also occurred on the concave side. This spread across the panel and buckling also occurred on the convex face above the reinforcement at 17,480.
14B	Similar to 04B. Failure at 26,200 lb.
114B	Similar to 101B. Bowing at 16,000 lb and failure at 18,990 lb.

(B) *Panels with Spruce and Whitewood Filling*

01W	Similar to 04B. Failure at 10,380 lb.
101W	Similar to 101B. Bowing at 5,600 lb and final failure at 8,060 lb.
02W	Similar to 04B. Failure at 13,430 lb.
102W	Buckling of the dural occurred at 6,700 lb and spread half way across the panel at 13,100 lb when failure occurred.
03W	At 4,600 lb buckling of the dural began at one side. Final failure occurred at 8,530 lb, the dural, or dural and veneer, buckling across the opposite side.
103W	Similar to 101B. Failure at 10,100 lb.
04W	Similar to 04B. Failure at 16,250 lb.
104W	Bowing began at 10,100 lb and buckling occurred down one edge. At 13,400 lb buckling spread across both faces of the panel.
05W	Similar to 04B. Failure at 14,490 lb.
105W	Similar to 04B. Failure at 8,960 lb.
06W	Similar to 04B. Failure at 17,220 lb.
106W	Similar to 04B. Failure at 10,400 lb.
07S	Similar to 04B. Failure at 10,470 lb.
107S	Similar to 101B. Bowing at 7,800 lb and gluing failure on the convex side at 8,750 lb.
08S	At 3,700 lb buckling occurred near the reinforcing way across one face. Failure occurred at 6,320 lb with buckling across both faces.
108S	At 4,370 lb a small buckle formed at the centre of one edge. This spread across the panel and failure occurred at 5,830 lb.
09W	At 4,500 lb buckling of the dural away from the veneer occurred at the centre of one side. Final failure was at 11,460 lb, when buckling spread across the centre of both faces.
109W	Similar to 101B. Bowing began at 8,960 lb and failure in gluing occurred across the convex side at 12,300 lb.
10W	Similar to 04B. Failure at 16,370 lb.
11S	Similar to 04B. Failure at 6,610 lb. Gluing down the edge of this panel was noted to be unsatisfactory before testing.
111S	Similar to 04B. Failure at 11,900 lb.
12S	Similar to 04B. Failure at 14,600 lb.
112S	Similar to 101B. Bowing began at 11,200 lb and buckling occurred across both faces at 14,800 lb.
13S	Similar to 04B. Failure at 19,360 lb and buckling.
113S	Similar to 101B. Bowing began at 4,480 lb and buckling occurred across both sides at 14,300 lb.
14S	At 20,190 lb the dural and veneer or dural suddenly separated from the filling over the whole unsupported surface of both faces.
114S	At 4,490 lb buckling occurred at the centre of one edge. This spread across the panel in all directions and final failure occurred at 6,660 lb with extensive separation of the dural and veneer from the filling. Gluing down the edges of this panel was noted to be unsatisfactory before testing.

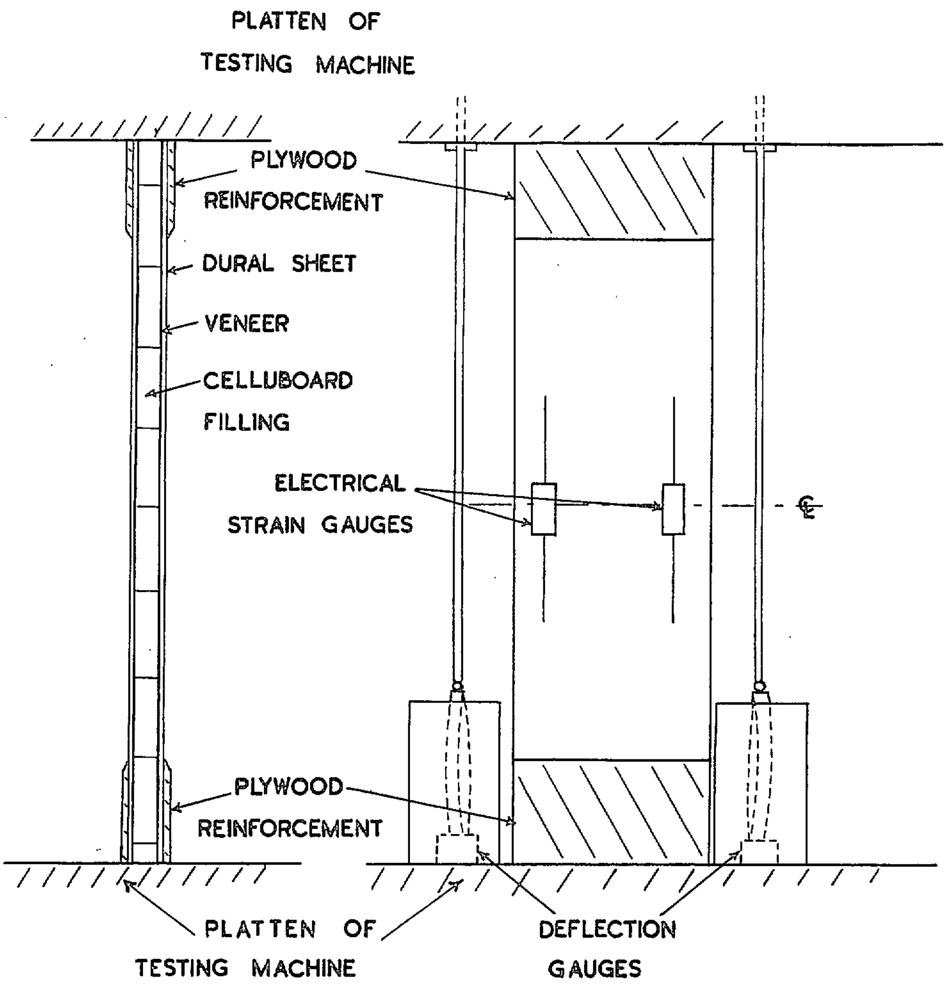


Fig. 1. Compression Tests on Dural-Celluboard Panels. Arrangement of Panel under Test.

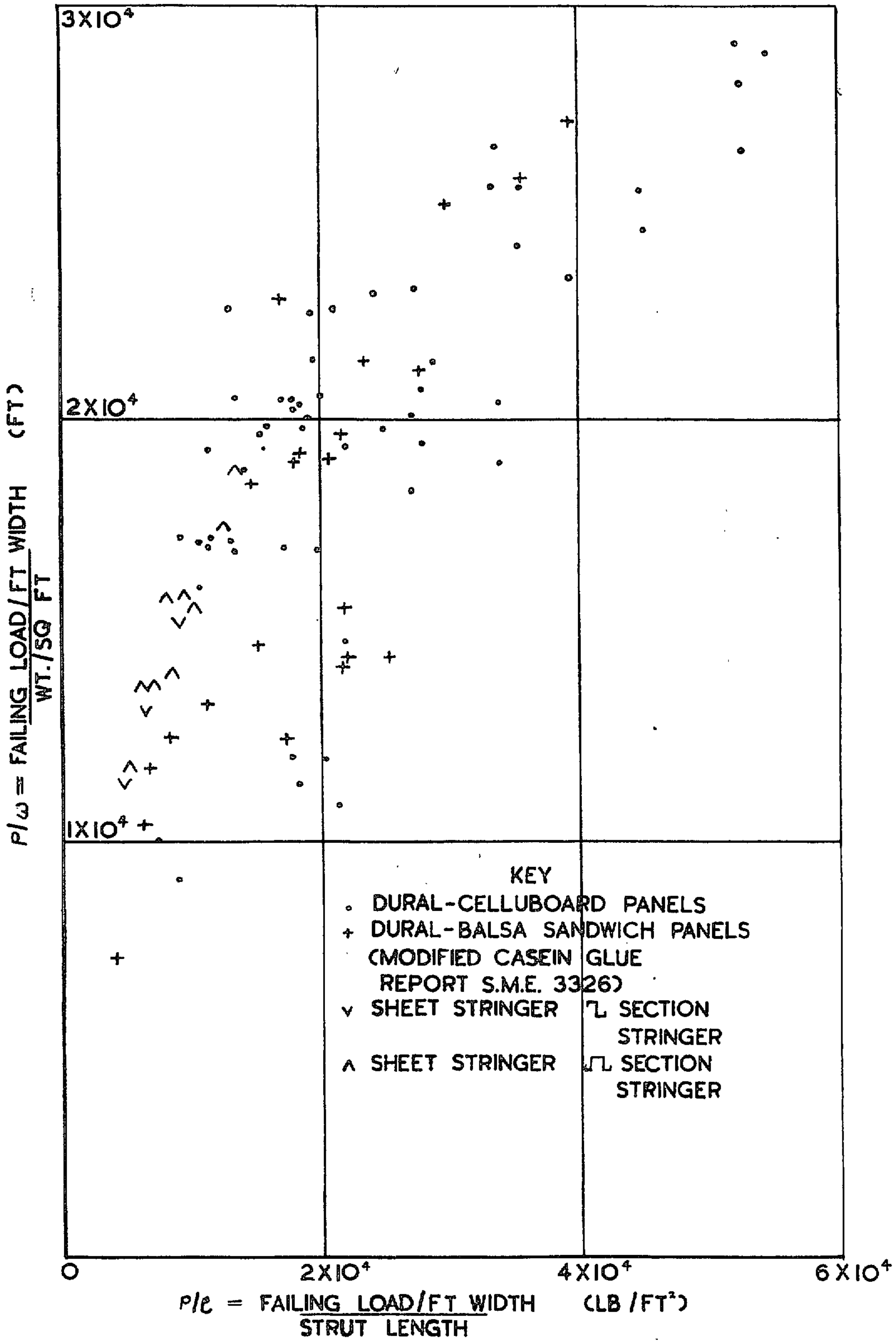


Fig. 2. Comparative Efficiencies of Dural-Celluboard and other Types of Construction.

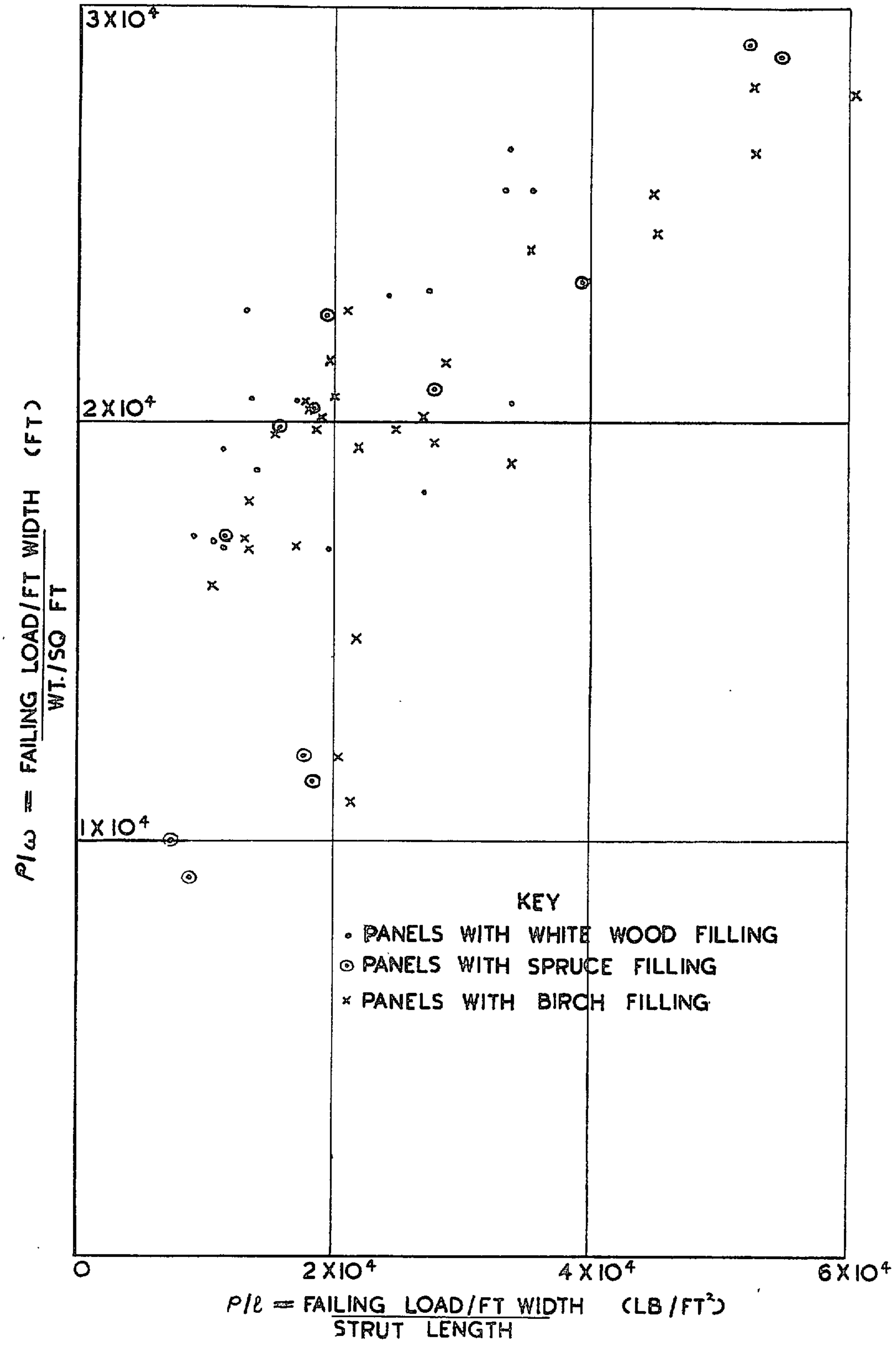


FIG. 3. Strength-Weight Efficiency Graph for Dural-Celluboard Panels.

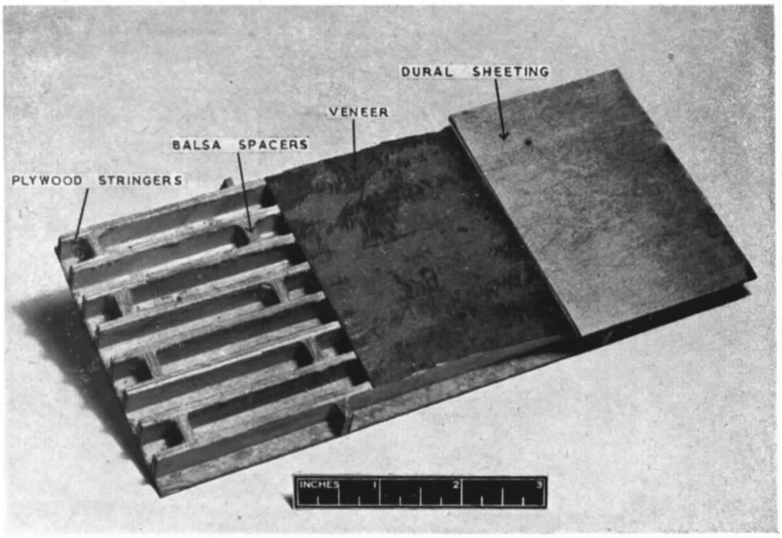
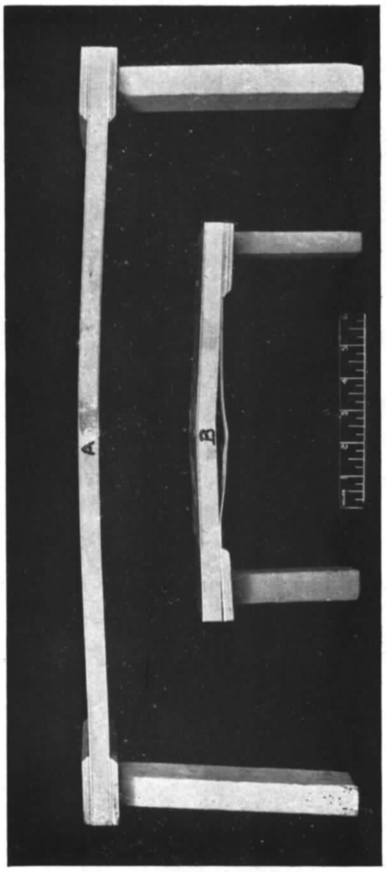
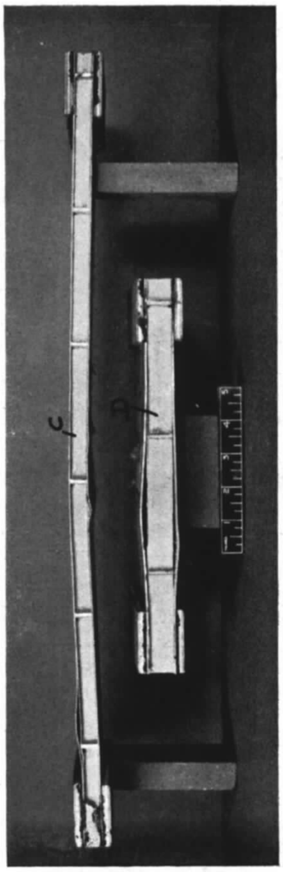


FIG. 4. Dural-Celluboard Panels.



(A) Euler bowing.
(B) Euler bowing and buckling of dural.



(C) Euler bowing and buckling of dural and veneer. Secondary failure near end reinforcement.
(D) Buckling of dural across both faces.

FIG. 5. Typical Failures. Dural-Celluboard Panels.

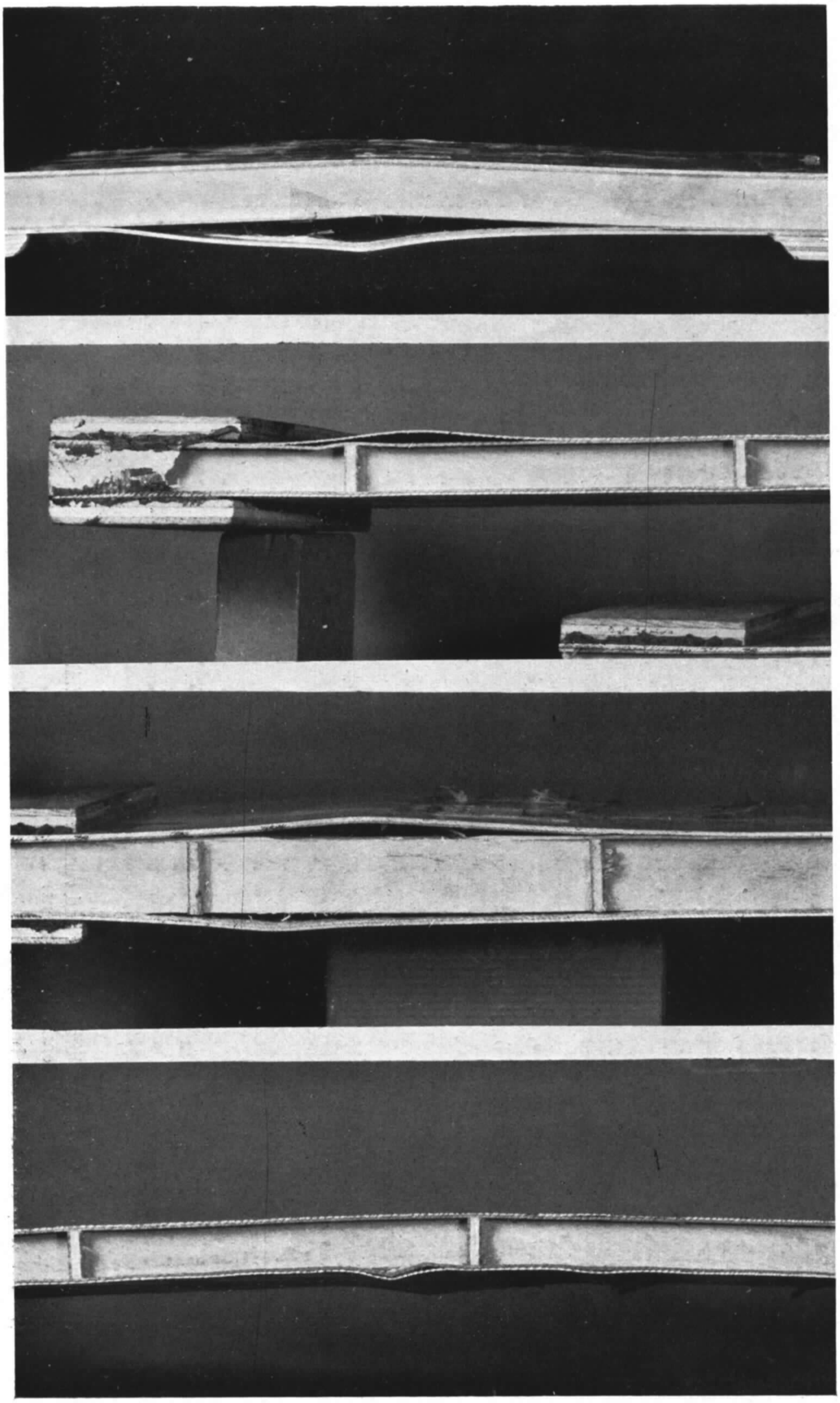


FIG. 6. Typical Failures. Dural-Celluboard Panels.

(96755) Wt. 14/655 K5 10/52 Hw.

PRINTED IN GREAT BRITAIN

R. & M. No. 2658
(10,427)
A.R.C. Technical Report

Publications of the Aeronautical Research Council

ANNUAL TECHNICAL REPORTS OF THE AERONAUTICAL RESEARCH COUNCIL (BOUND VOLUMES)—

1934–35 Vol. I. Aerodynamics. *Out of print.*
Vol. II. Seaplanes, Structures, Engines, Materials, etc. 40*s*. (40*s*. 8*d*.)

1935–36 Vol. I. Aerodynamics. 30*s*. (30*s*. 7*d*.)
Vol. II. Structures, Flutter, Engines, Seaplanes, etc. 30*s*. (30*s*. 7*d*.)

1936 Vol. I. Aerodynamics General, Performance, Airscrews, Flutter and Spinning. 40*s*. (40*s*. 9*d*.)
Vol. II. Stability and Control, Structures, Seaplanes, Engines, etc. 50*s*. (50*s*. 10*d*.)

1937 Vol. I. Aerodynamics General, Performance, Airscrews, Flutter and Spinning. 40*s*. (40*s*. 10*d*.)
Vol. II. Stability and Control, Structures, Seaplanes, Engines, etc. 60*s*. (61*s*.)

1938 Vol. I. Aerodynamics General, Performance, Airscrews. 50*s*. (51*s*.)
Vol. II. Stability and Control, Flutter, Structures, Seaplanes, Wind Tunnels, Materials. 30*s*. (30*s*. 9*d*.)

1939 Vol. I. Aerodynamics General, Performance, Airscrews, Engines. 50*s*. (50*s*. 11*d*.)
Vol. II. Stability and Control, Flutter and Vibration, Instruments, Structures, Seaplanes, etc. 63*s*. (64*s*. 2*d*.)

1940 Aero and Hydrodynamics, Aerofoils, Airscrews, Engines, Flutter, Icing, Stability and Control, Structures, and a miscellaneous section. 50*s*. (51*s*.)

Certain other reports proper to the 1940 volume will subsequently be included in a separate volume.

ANNUAL REPORTS OF THE AERONAUTICAL RESEARCH COUNCIL—

1933–34	1*s*. 6*d*. (1*s*. 8*d*.)
1934–35	1*s*. 6*d*. (1*s*. 8*d*.)
April 1, 1935 to December 31, 1936.	4*s*. (4*s*. 4*d*.)
1937	2*s*. (2*s*. 2*d*.)
1938	1*s*. 6*d*. (1*s*. 8*d*.)
1939–48	3*s*. (3*s*. 2*d*.)

INDEX TO ALL REPORTS AND MEMORANDA PUBLISHED IN THE ANNUAL TECHNICAL REPORTS, AND SEPARATELY—

April, 1950	R. & M. No. 2600.	2*s*. 6*d*. (2*s*. 7½*d*.)

INDEXES TO THE TECHNICAL REPORTS OF THE AERONAUTICAL RESEARCH COUNCIL—

December 1, 1936 — June 30, 1939.	R. & M. No. 1850.	1*s*. 3*d*. (1*s*. 4½*d*.)
July 1, 1939 — June 30, 1945.	R. & M. No. 1950.	1*s*. (1*s*. 1½*d*.)
July 1, 1945 — June 30, 1946.	R. & M. No. 2050.	1*s*. (1*s*. 1½*d*.)
July 1, 1946 — December 31, 1946.	R. & M. No. 2150.	1*s*. 3*d*. (1*s*. 4½*d*.)
January 1, 1947 — June 30, 1947.	R. & M. No. 2250.	1*s*. 3*d*. (1*s*. 4½*d*.)

Prices in brackets include postage.

Obtainable from
HER MAJESTY'S STATIONERY OFFICE
York House, Kingsway, LONDON, W.C.2 423 Oxford Street, LONDON, W.1
P.O. Box 569, LONDON, S.E.1
13a Castle Street, EDINBURGH, 2 1 St. Andrew's Crescent, CARDIFF
39 King Street, MANCHESTER, 2 Tower Lane, BRISTOL, 1
2 Edmund Street, BIRMINGHAM, 3 80 Chichester Street, BELFAST
or through any bookseller.

S.O. Code No. 23-2658