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Methods of Testing Reinforced Plastics, Parts I and II

By

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of the Engineering Division, N.P.L.

Part I. Measurement of Tensile Strength

Part II. Measurement of Interlaminar Strength

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PART I. Measurement of Tensile Strength

Summary.—An experimental comparison has been made between five types of tensile tests including novel types designed to enable axial loading conditions to be approached more readily than is the case with established methods. Examination of the results of two hundred and forty tests indicates that significant differences can occur between the results of different tests and that there is also a significant variation between the properties of material cut from different parts of the same sheet.

It is concluded that the results, obtained when testing paper-base material by novel methods, are sufficiently good to justify development of a simplified apparatus of similar type for general use.

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1. *Introduction.*—Reinforced plastics are essentially non-ductile materials so that, when tested in tension, inequalities of stress due to misalignment, etc., are not relieved by local yielding of the material. Their effects on the recorded value of tensile strength are, therefore, more marked than is the case with more ductile materials and the results reported by different investigators are more likely to differ as a consequence of minor differences in testing technique.

In assessing the reliability of a given testing technique it is necessary to provide some means of discrimination between errors inherent in the test method and variations in the material itself. The experiments described below were therefore carried out in which five different types of tensile tests were repeated twenty times on two samples of material; the test pieces being cut out in an orderly arrangement to facilitate analysis.

These samples, one a paper-base material and one a fabric-base material, were selected to be representative of these two widely used classes of material and were purchased from a reputable manufacturer.

In addition to the tensile strength tests which form the subject of the report, some measurements of Young's modulus were made and are described in Appendix I. Also, because some investigators quote values for strength which are derived from bend tests, a series of bend tests was carried out as described in Appendix II.

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2. *Experimental.*—2.1. *Sampling.*—Each board measured approximately 4 ft square, the thickness of the paper-base sheet varied from 0·247 in. to 0·255 in. and the thickness of the fabric-base sheet varied from 0·248 to 0·263 in. The boards were divided into twenty sub-sections as indicated in Fig. 1. The system of numbering these sub-sections was as follows:—the first numeral refers to the horizontal rows running from 1 to 5: the second numeral refers to the vertical sub-division running from left to right in the odd-numbered rows and from right to left in the even-numbered rows: the letter which follows the numerals indicates the type of test piece cut from each sub-section as indicated in Fig. 2. These test pieces were cut from right to left in the even-numbered rows and from left to right in the odd-numbered rows but were not randomised. Whilst it was realised that randomisation was desirable it was considered that, as the test pieces had to be cut and numbered in an engineering workshop, the complication arising from randomisation might lead to errors in marking which would be avoided by adopting the regular arrangement described. As it is to be expected that variations in material would tend to be continuous it is considered that the alternation of arrangement in adjacent rows constituted an adequate safeguard against a particular fault appearing in a number of test pieces of a particular type and not in others.

2.2. *Types of Test Piece.*—The various types of test piece used are illustrated in Fig. 2. Test pieces B and C are cut according to B.S. 972–1941 and 1137–1943. Test piece K is of a type used at the National Physical Laboratory in connection with research on reinforced plastics where, for reasons of economy, only very small samples were available.

Test pieces A and L follow closely the dimensions of a test piece recommended by the Royal Aircraft Establishment. The holes are drilled before final machining and are used as reference points during the machining of the waisted portion. This ensures that the load is applied centrally.

Test piece F is adapted for use in an experimental grip devised by the author and described below.

The machined edges of all the test pieces were finished with No. 0 glass cloth, the unmachined surfaces being left in the as-received condition.

2.3. *Methods of Gripping Test Pieces.*—Test pieces B, C and F were held in wedge grips of which three types were used as illustrated in Figs. 3a, 3b and 3c. In each case a layer of No. 1 emery cloth was interposed between the test pieces and the face of the wedge grip, the abrasive side being turned towards the test piece.

The fittings used for holding Type A test pieces are illustrated in Figs. 4 and 7.

Test piece F was held in the experimental grips illustrated in Figs. 5 and 6. These grips were devised to obtain improved alignment by eliminating the uncertainties associated with wedge grips whilst avoiding the necessity for the enlarged ends of test piece type A. The principle aimed at was the elimination of all bending moments on the test piece by allowing it freedom to rotate about two horizontal axes intersecting on its centre-line, and a method was devised whereby load was applied to the shoulders of the test piece by rollers AA (Fig. 5).

It is comparatively easy to machine the waist of the test piece and the radius of the shoulders to the correct dimensions, but it is not always easy to secure that the shoulders are in the correct position relative to each other. The rollers are therefore carried in frame B which is carried in a ball-bearing at the centre so that it may swing to accommodate slight errors in the relative heights of the two shoulders. The centres of the rollers are equidistant from the pivot and lie in the same straight line so that, as far as this plane is concerned, load will be applied on the centre-line of the test piece and bending moments reduced to the negligible value determined by the friction in the ball-bearings.

Alignment in the vertical plane normal to the test piece is determined by the thickness of the test piece and the width of the rollers; frame C being pivoted so that no bending moment can be applied. At present the apparatus is suitable only for material $\frac{1}{4}$ in. thick. Initially frame C was pivoted in the same plane as frame B but this arrangement was found to be unstable and the position of the pivot was raised $\frac{3}{4}$ in. to confer stability. The main frames D were screwed into 'self-aligning' adaptors of the testing machine.

Rollers AA were cut away to form sectors so that they may be rotated to permit test pieces to be inserted. Final adjustment of their position may be made by keys inserted in the ends of the spindle.

The method of gripping test pieces of type A, Fig. 4, is open to the objection that the use of washers to centralise the test pieces is a time-consuming operation and its success is somewhat dependent on the skill and patience of the operator. Accordingly the method of gripping illustrated in Fig. 7 was devised and a special set of grips was constructed.

The apparatus is similar in appearance to the conventional type of wedge grip but differs inasmuch as load is applied by means of pin A, the function of wedges B being merely to centralise the test piece. The angle of the wedges is 60 deg, as compared with the usual 80 deg, so that the horizontal forces are correspondingly lower and the reaction of these centralising forces on the test pieces is taken through spherical washers C so that the free alignment of the test piece is not affected thereby.

2.4. *Testing Machines.*—Three testing machines, A, B and C were used in the tests. Machine A was a single-lever hand-operated testing machine of 2 tons capacity which had been in use for a number of years. Machine B was a modern multi-lever hydraulically-operated testing machine of 5,000 lb capacity so arranged that load was applied automatically at a constant rate. Machine C was a modern machine in which load was both applied and measured hydraulically and strain was applied at an approximately uniform rate. This machine could be used on four ranges of load, 1, 2, 5 and 10 tons.

2.5. *Tests Carried Out.*—Two hundred and forty tensile tests were carried out, arranged as shown in Table 1.

TABLE 1

Arrangement of Tensile Tests

Test piece (*see* Fig. 2)	Paper-base material		Fabric-base material	
	Machine	Method of gripping	Machine	Method of gripping
A	C	Fig. 4	C	Fig. 4
B	C	Fig. 3a	C	Fig. 3a
C	A*	Fig. 3c	B	Fig. 3b
F	C	Fig. 5	C	Fig. 5
K	A	Fig. 3c	A	Fig. 3c
L	C	Fig. 7	C	Fig. 7

* The loads required to break these test pieces in paper-base material were beyond the capacity of machine B.

3. *Results*.—3.1. *Analysis*.—Tables 8 and 9 give the results of tests on paper-base and fabric-base materials, respectively. The 119 independent comparisons that may be made between the results of 120 tests may be grouped as follows:—

Types of test	5
Sub-sections	19
Remainder due to error	95
	119

As was to be expected from its more ductile nature, the reproducibility of the results from the fabric-base material is better than for the paper-base material. The figures for both materials however indicate that the different types of test pieces give significantly different results and that there is a variation between the strength of material in different parts of the sheet.

Values of t have been calculated for the difference between the various tests and are given in Table 2.

TABLE 2

Values of t

Paper-base material		Fabric-base material	
Test pieces	t	Test pieces	t
F and K	0·2339	A and C	0·1958
A and L	0·2543	B and C	0·1976
C and K	0·7384	A and B	0·3983
C and F	1·211	B and F	0·5679
A and K	1·912	C and F	0·8192
A and F	1·913	B and L	0·8495
F and L	1·9714	F and L	0·9594
K and L	2·0645	C and L	1·118
L and C	2·067	A and F	1·415
B and C	2·229*	A and L	1·850
A and C	3·038	L and K	3·384*
B and K	3·203	B and K	3·590
B and F	3·566	F and K	4·152
B and A	4·183	C and K	4·563
B and L	6·232	A and K	5·504

* A value of t exceeding 2·093 indicates that the difference would be expected to occur by chance not more frequently than once in twenty trials.

Comparing the results given by different machines using the same type of test piece there is no significant difference between the two modern machines when fabric-base material is being tested. It was not possible to compare these two machines using paper-base material owing to the restricted range of the multi-lever machine. A comparison between the hydraulic and single-lever machines revealed a significant difference; the average reading of the single-lever machine being 0·53 tons/sq in. in excess of the modern machine.

Comparing three types of test piece in the same machine, Types A, B and F show no significant difference with fabric-base boards but, where paper-base boards are tested, there is no significant difference between Types A and F but B is significantly lower than both of them.

Standard errors of the mean are arranged in order of magnitude in Table 3.

TABLE 3

Standard Errors of Mean

Paper		Fabric	
Test piece	Standard error of mean	Test piece	Standard error of mean
B	0·2027	B	0·1734
K	0·1919	C	0·1647
A	0·1889	F	0·1464
C	0·1819	K	0·1463
L	0·1692	A	0·1395
F	0·1489	L	0·1291

It will be noted that B, the British Standard Type test piece tested in the modern hydraulic machine gave the greatest scatter in each case. The three improved types of test piece A, F and L gave considerably lower scatter.

Table 4 attempts to show the means obtained using the various tests and the significant differences between them. Thus in Column 1 the result on test piece A (paper-base material) is inserted and F and K are omitted as not being significantly different from A. C is the first value significantly lower than A and B is significantly lower than C. Column 2 shows that F is significantly higher than B but not significantly different from any of the other values. B is significantly lower than all the other tests. In the case of the fabric-base material K is significantly higher than all the other values but the remainder do not significantly differ among themselves.

TABLE 4

Significant Differences between Tests

Tensile Strength in tons/sq in.

Paper-base materials				Fabric-base materials					
Test piece	1	2	3	Test piece	4	5	6	7	8
A	14·075			K	9·095	9·095	9·095	9·095	9·095
L			14·023	L	8·789				
F		13·735		F		8·744			
K			13·691	B			8·689		
C	13·544			C				8·662	
B	13·015	13·015	13·015	A					8·642

3.2. *Position of Fracture.*—The position of fracture of a test piece provides some indication of the degree of self-alignment permitted by the gripping device and of the proneness of the form of the test piece to give rise to concentration of stress. Table 5 indicates the number of fractures occurring in the waist of the test piece, at the shoulders or in the grips for the various types of test piece.

TABLE 5

Number of Fractures in Different Parts of Test Pieces

	Paper-base materials			Fabric-base materials		
Test piece	Broke in parallel portion	Broke at shoulders	Broke in grips	Broke in parallel portion	Broke at shoulders	Broke in grips
A	15	1	5*	19	1	0
B	15	5	0	18	2	0
C	12	8	0	15	5	0
F	16	4	0	19	1	0
K	11	9	0	11	9	0
L	17	3†	0	9	11†	0

* One test piece broke simultaneously at hole and at centre.

† Broke at junction of radius and parallel portion.

3.3. *Causes of Variation within Boards.*—An attempt was made to trace the causes of variation in properties with position in the boards by plotting contours of tensile strength, density and thickness. Apart from the fact that fabric-base boards appeared to be stronger and denser at the centre than at the edges, no clear conclusions could be drawn and the diagrams are not reproduced.

4. *Conclusions.*—It is concluded that values obtained for the tensile strength of fabric-base material are not particularly sensitive to variation in method of test if the results obtained from an unusually small type of test piece tested in a single-lever testing machine piece are excluded.

The mean values obtained from three series of tests on novel test pieces, A, F and L, gave results which were significantly higher than those obtained from the British Standard Test Piece B tested in the same machine. The British Standard Test Piece tested in the single-lever machine gave results that were significantly higher than those derived from a similar test piece tested in a hydraulic machine. As the static calibrations of these machines were identical, the explanation of the discrepancy may lie in the effect of inertia of the beam of the former machine. This may account for the significantly high values obtained with test piece K in fabric material. Whilst there is some doubt as to whether the criterion of a good tensile test method should be attainment of a high mean strength or minimum scatter, taking all the results into account it would appear that test pieces of types A, F and L tested in a modern hydraulic machine with proper attention to alignment will yield more reliable results from paper-base materials than test pieces of the British Standard Type.

APPENDIX I

Modulus of Elasticity

Measurements of Young's Modulus of Elasticity in tension were made on test pieces of Type B (Fig. 2). The method used consisted of applying a stress of 3 tons/sq in., noting the extension with an extensometer of the 'Lindley' type and then reducing load to a nominal value. This process was repeated until the deflections noted in succeeding cycles attained a steady value. This value was used to estimate the modulus and the results are given in Table 6.

TABLE 6

Values of Young's Modulus

(Units — 10^6 lb/sq in.)

	Paper	Fabric
Maximum	3·02	1·65
Minimum	2·75	1·08
Mean	$2{\cdot}85_2$	1·42
Standard deviation	$0{\cdot}077_5$	$0{\cdot}129_5$
Standard error of mean	$0{\cdot}0622_3$	$0{\cdot}0805_5$

APPENDIX II

Cross-Breaking Test using German Apparatus

The machine illustrated in Fig. 8 had recently been received from Germany and a series of tests was made on the same materials as the series described in the paper in order to provide some basis for comparison between values of strength derived from a bending-type test and from tensile tests.

Many examples of the machine were noted during a recent visit to Germany where it appears to be part of the normal equipment of laboratories engaged on investigation of plastics. It was made by Schopper's of Leipzig and is of extremely simple construction. Load is applied by turning handle D which raises crosshead B. The test piece rests on supports, the position of which may be adjusted to the required span. The upper portions of these supports may rotate about an axis parallel to, or coincident with, the axis of the test piece, to facilitate bedding down of imperfect test pieces. The reaction applied to spindle F is taken by a helical spring in the main body of the casing so that vertical movement of the spindle is proportional to load. A rack attached to spindle F engages in a pinion connecting to the central circular scale. This scale, therefore, rotates by an amount which is proportional to the load which can, therefore, be read off from the fixed scale. The upper part of spindle F carries a screw thread which engages in a nut forming part of the boss of handwheel A. The lower part of this boss is provided with grooves around which a cord N is passed. This cord passes over pulley R and a weight which slides in tube H is attached thereto. This weight is of such a value that it will overcome the friction of the screw thread but will not overcome the friction between the boss and the seat at the top of the machine casing. Thus when load is applied and spindle F moves up carrying the boss away from the machine casing, the weight is allowed to fall causing A to rotate on the screw thread so bringing the boss back into contact with the seating on the machine casing. This acts as a maximum load device because, on the applied load falling off, spindle F is unable to return, the spring remains compressed and the pointer continues to indicate the maximum load. The combined effect of friction in the screw thread and between the boss and the seat on the machine casing is sufficient to prevent the torque applied by the small weight affecting the load recorded by the machine.

Deflection is measured by an arrangement which shows the motion of the crosshead relative to that of spindle F. Spindle t carries a rack which engages with a pinion connected to pointer L. The pitch of this rack and the diameter of the pinion is identical with the corresponding features of the load-indicating device so that, apart from elastic deflection of the apparatus, the position of the pointer relative to that of the inner (moving) scale indicates the deflection of the test piece under load. No indication of deflection was noted when load was applied with the spindle resting directly on the crosshead, so that it can be concluded that the construction of the apparatus is sufficiently stiff to prevent results being affected by elastic deflection of machine components.

The zero indication of deflection may be adjusted by turning screw K which acts through a trip plate m. The loading piece b is attached to a spindle which slides in spindle F and which is pressed downwards by a weak helical spring. During loading this spring is compressed completely and load is transferred directly from b to F. On a test piece breaking, b descends under the influence of the small spring tripping m so that, even if the crosshead is further raised, no further deflection is indicated. Spindle t is prevented from falling by friction grip e. It is thus possible to obtain a reading of the deflection at the instant when the test piece breaks. Whilst this feature is probably satisfactory for use on mouldings and other material which give a clean break it did not function satisfactorily during the present tests because fracture was never complete. The readings of deflection are, however, fairly reliable as it is easy for the operator to stop turning handle D when fracture commences.

The results of the tests are given in Table 7.

TABLE 7

Results of Cross-Breaking Tests

	Paper	Fabric
Modulus of rupture (tons/sq in.)		
Maximum	17·32	12·50
Minimum	13·90	11·27
Mean	15·56	11·97
Standard deviation	0·2655	0·2513
Standard deviation of mean	0·1152	0·1121
Deflection at break (millimetres)		
Maximum	6·31	11·91
Minimum	4·46	8·01
Mean	5·58	9·591
Standard deviation	0·4567	1·155
Standard deviation of mean	0·1518	0·7599

Fig. 9 shows typical failures of both types of material. It will be noted that the fracture in the paper-base material is complex and reveals a tendency to spread along the laminae. The failure in the fabric-base material is relatively simple and appears to consist of an initial tensile failure at the surface followed by simple secondary tearing failures.

TABLE 8

Results of Tests on Paper-Base Boards

No. of Test piece	Type of Test						
	A	B	C	F	K	L	Mean
11	14·09	12·95	13·84	14·18	14·47	14·57	14·017
12	14·88	12·65	13·21	13·25	13·41	14·22	13·603
13	14·08	13·60	13·54	13·82	14·82	14·72	14·097
14	14·48	12·75	14·17	13·82	14·44	13·97	13·605
21	12·77	12·37	12·62	12·85	12·29	13·50	12·733
22	14·13	12·51	13·48	14·09	13·39	14·14	13·457
23	14·14	13·68	12·14	13·34	14·97	14·55	13·803
24	14·84	13·93	14·15	13·97	12·85	13·81	13·925
31	14·69	10·37	14·23	13·59	13·67	12·49	13·173
32	14·50	13·72	14·02	13·12	14·02	14·11	13·915
33	13·30	14·09	14·52	14·07	13·83	13·00	13·468
34	15·04	13·58	13·97	13·65	13·90	14·01	14·025
41	13·42	13·49	13·77	14·19	13·56	14·31	13·623
42	13·65	12·87	13·99	13·31	13·86	14·12	13·633
43	13·13	12·98	13·69	13·34	13·72	13·66	13·420
44	12·95	13·56	12·53	13·97	13·96	15·00	13·662
51	14·64	12·42	13·79	14·73	13·53	14·25	13·893
52	15·13	13·45	13·51	13·73	14·03	14·30	14·025
53	14·08	12·70	13·30	13·69	12·96	13·97	13·450
54	13·55	12·62	12·41	13·98	12·13	13·76	13·075
Mean	$14{\cdot}074_5$	$13{\cdot}014_5$	$13{\cdot}544_0$	$13{\cdot}734_5$	$13{\cdot}690_5$	14·023	13·6316
Standard deviation	0·7136	0·8213	0·6619	0·4434	0·7370	0·5727	
Standard error of mean	0·1889	0·2027	0·1819	0·1489	0·1919	0·1692	

TABLE 9

Results of Tests on Fabric-Base Boards

No. of Test piece	Type of Test						
	A	B	C	F	K	L	Mean
11	7·71	7·56	7·19	7·82	7·60	8·06	7·656
12	7·98	8·01	8·47	8·03	9·21	8·37	8·345
13	8·51	8·91	8·95	8·82	9·07	8·71	8·858
14	8·72	8·47	8·11	8·52	8·73	8·28	8·472
21	8·50	8·86	8·80	8·84	8·96	8·71	8·778
22	8·93	8·89	8·07	8·95	9·56	8·90	8·883
23	8·88	9·03	8·44	8·50	9·09	8·92	8·810
24	8·82	9·18	8·45	8·55	9·56	8·63	8·865
31	8·46	7·81	8·19	8·86	9·29	8·85	8·410
32	9·00	9·04	9·53	9·00	9·63	9·25	9·242
33	9·00	9·32	9·20	8·85	9·28	8·73	9·063
34	8·86	9·27	9·31	9·19	9·30	8·69	9·103
41	9·02	8·83	9·25	9·15	9·30	9·09	9·107
42	8·96	7·30	9·05	8·62	8·88	8·86	8·612
43	8·83	9·07	8·86	8·82	9·22	8·79	8·932
44	8·86	8·61	9·06	8·58	9·32	8·54	8·828
51	8·11	8·50	8·69	8·65	8·93	8·71	8·598
52	8·69	8·98	8·42	9·22	8·88	9·49	8·947
53	8·92	9·12	8·39	9·07	8·95	9·28	8·955
54	8·07	9·01	8·81	8·81	9·13	8·92	8·792
Mean	8·641$_5$	8·688$_5$	8·662	8·744	9·094$_5$	8·789	8·7613
Standard deviation	0·3890	0·6013	0·5427	0·4234	0·4281	0·3338	
Standard error of mean	0·1395	0·1734	0·1647	0·1464	0·1463	0·1291	

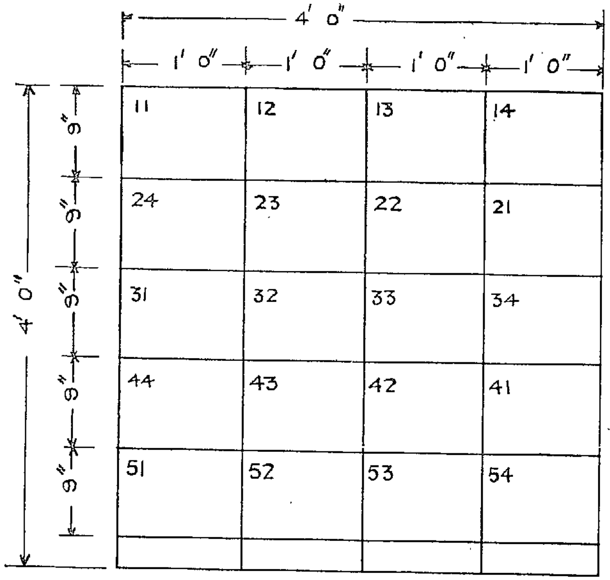


FIG. 1. Relative position of sub-sections.

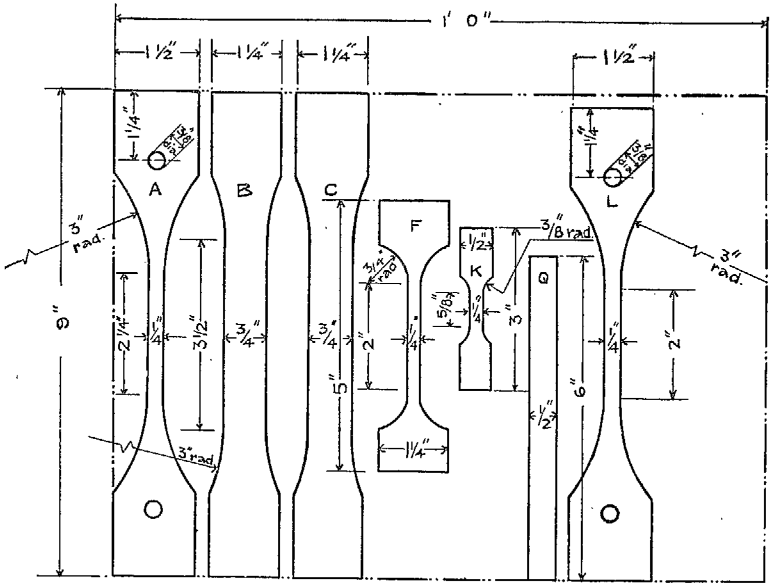


FIG. 2. Arrangement and dimensions of test pieces from each sub-section.

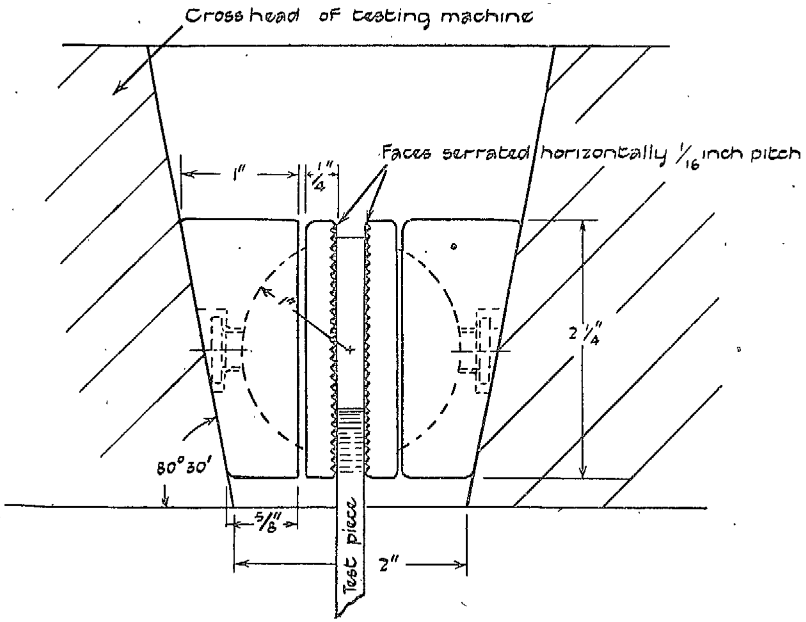


FIG. 3a. Method of gripping test pieces type B.

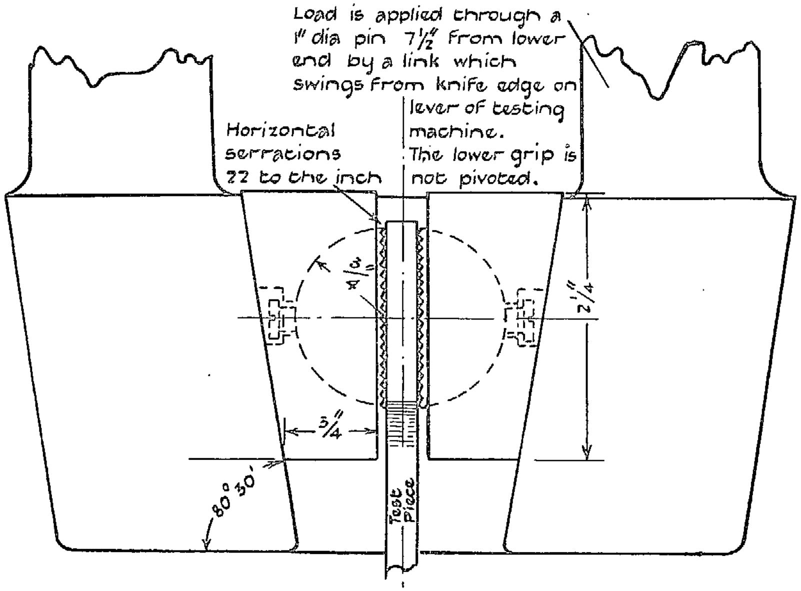
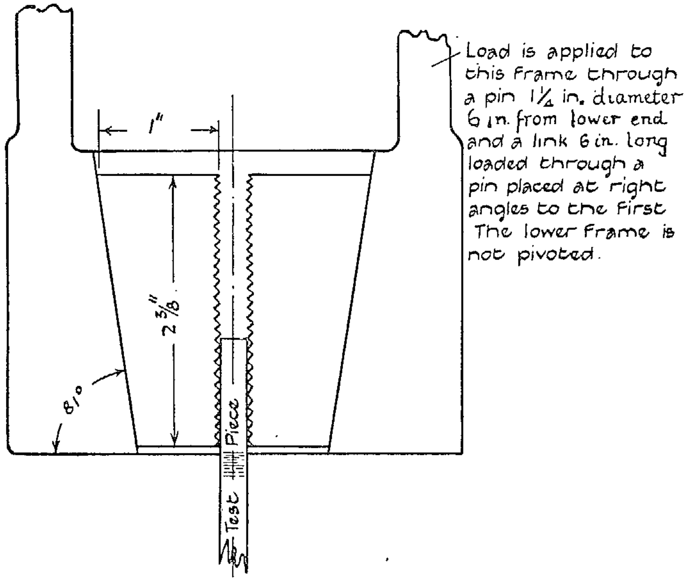
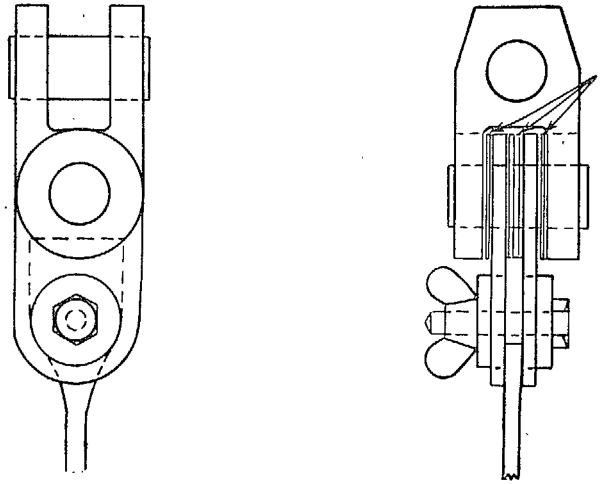


FIG. 3b. Method of gripping test pieces type C (fabric).



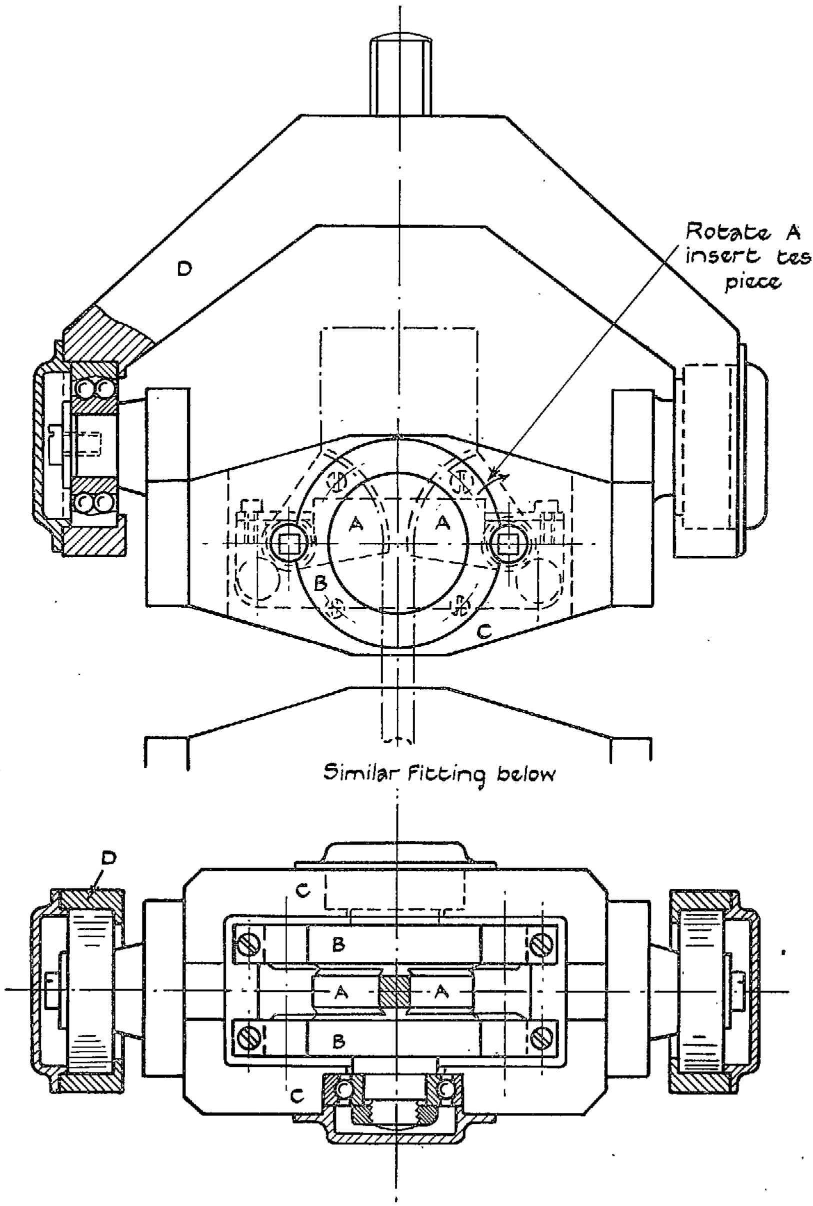
Load is applied to this frame through a pin 1¼ in. diameter 6 in. from lower end and a link 6 in. long loaded through a pin placed at right angles to the first. The lower frame is not pivoted.

FIG. 3c. Method of gripping test pieces, type K.



Washers used to secure central alignment of test pieces of various thicknesses

FIG. 4. Method of holding test pieces, type A.



Rotate A to insert test piece

Similar fitting below

FIG. 5. Experimental method.

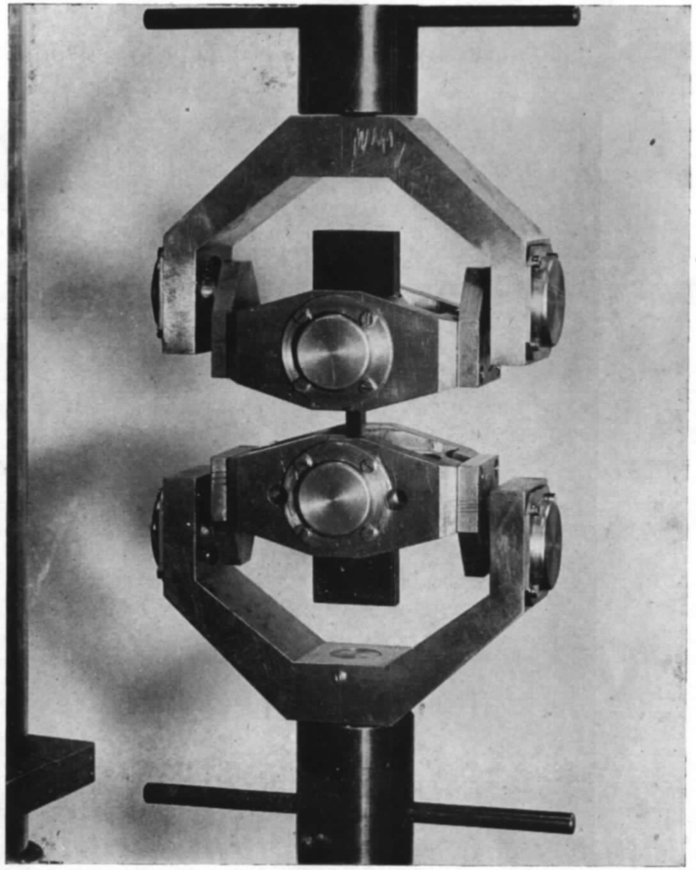


FIG. 6. Experimental grips.

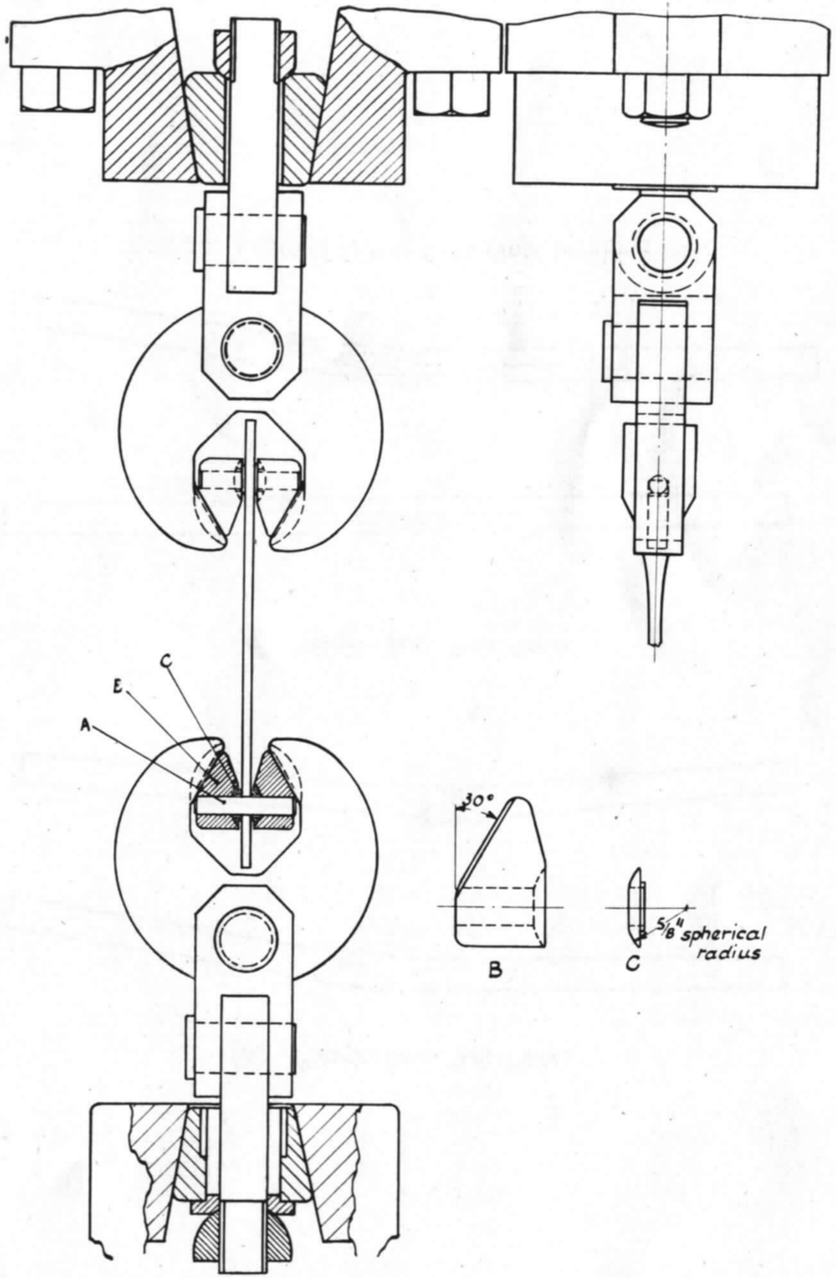


FIG. 7. Experimental self-centring grips.

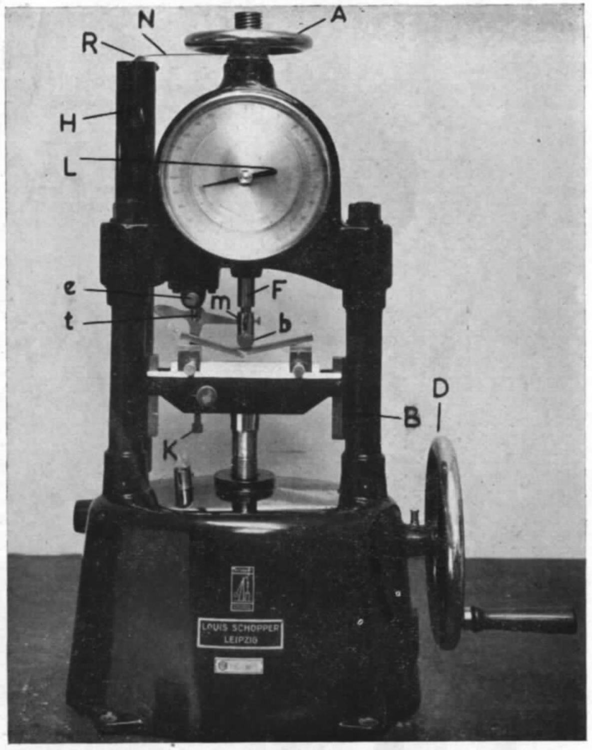
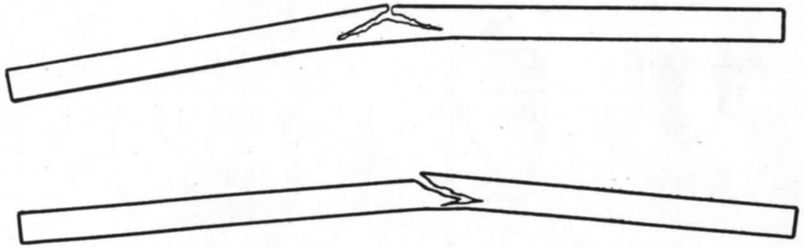


Fig. 8. Bending test machine of German origin.

(a) Fabric Base Test Pieces



(b) Paper Base Test Pieces

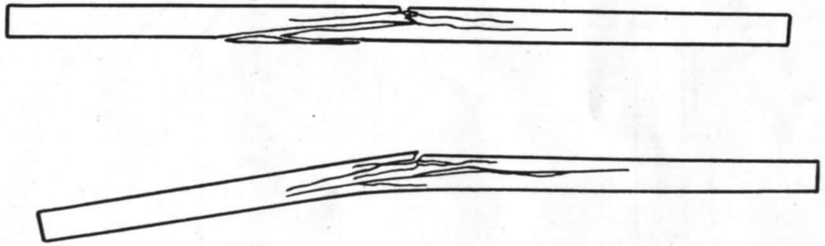


Fig. 9. Types of failure from cross-breaking test.

PART II. Measurement of Interlaminar Strength

Summary.—(a) *Purpose of Investigation.*—The strength of reinforced plastics depends almost entirely on their fibrous reinforcement and when, as in laminated plastics, this reinforcement is arranged to lie in parallel planes, there is marked interlaminar weakness. For example, the tensile strength measured in a direction at right-angles to the laminations is shown to be from one-sixth to one-ninth of the corresponding value measured in the direction of the laminations.

In spite of the obvious concern of the designer in the value of interlaminar strength and of the indication of previous research that this quantity is markedly affected by variations in manufacturing conditions, measurements of this quantity are not generally made in this country. It has been the practice in the National Physical Laboratory however to carry out certain tests of interlaminar strength and it was considered desirable to compare and to assess the accuracy of these tests together with those used in U.S.A. and Germany. Besides providing the basis for the rational interpretation of the results, it was hoped that the investigation would enable one particular type of test to be selected for further work.

(b) *Range of Investigation.*—In the first instance tests by various methods were made on a range of fabric-reinforced phenolic laminates which had been prepared for another investigation and in which, whilst the same resin and fabric had been used throughout, mechanical properties had been made to vary over a wide range by modification in resin content, pressure and other manufacturing variables. The results of these tests were distinctly encouraging inasmuch as they revealed a very high degree of correlation between the results of interlaminar shear, delamination and axial-compression tests.

The number of samples used in the above-mentioned test was insufficiently large to enable a statistical estimate of variability to be made. In order to obtain such an estimate, two large sheets of material, one of fabric and one of paper-base material, were tested, each test being replicated at least twenty times. It is shown that the variability of the material from place to place in a single sheet is considerable and estimates of the variability of the various test methods are given. The results obtained on the fabric-reinforced material provided some support for the correlation between properties revealed in the first series of tests but the relations between the results of the various tests when applied to paper-reinforced material differed quantitatively if not qualitatively from those obtained with fabric.

Finally four samples of material 1 in. in thickness were tested by the same methods as used in the previous two series of tests and further tests of interlaminar strength were made by means which had been precluded by the small thickness ($\frac{1}{4}$ in.) of the other samples. These further tests revealed an effect of size of test piece on the result of delamination tests. Interlaminar tensile tests showed only small differences between the various materials, but marked differences in mode of failure under compression were observed between paper and fabric-reinforced plastics.

Some of the apparatus used in the investigation has not been described previously and details are given in the report.

(c) *Conclusion.*—Whilst there is unmistakable evidence that the results of the various tests for interlaminar strength are related, it is not yet possible to select one test for use to the exclusion of all the others.

1. *Introduction.*—Reinforced plastics, consisting of flat sheets of paper or fabric impregnated with resin and bonded together, depend for their strength and stiffness on the cellulose or other fibres which form the paper or fabric. These are arranged in the plane of the sheet and consequently cannot contribute to the strength of the interlaminar region. Thus shearing and tensile forces acting on the plane of the laminations are limited by the strength of the resin and depend markedly on the effectiveness of the bond between the sheets. For example, it has been shown that contamination of fabric by size or natural wax has a marked detrimental effect on the interlaminar shear strength of boards prepared therefrom. (Pepper, Barwell and Hale, 1946[1]).

It will be readily understood that the relative weakness of laminated material in the direction perpendicular to the laminations is a matter of concern to the user and, because this quantity is susceptible to variations in manufacturing conditions, the provision of reliable test data is very desirable. It is surprising, therefore, that this property is not generally measured. No British Standard Specification calls for any test of interlaminar strength and the only standardised tests, known to the author, are the U.S. 'Bonding Strength Test'[2] and the German 'Spaltbarkeit' test VDE 0318 (Nitsche und Pfestorf[3]). The former consists of measuring the load on a 10-mm diameter ball required to rupture the bond when applied to the edge of a test piece 1 × 1 × $\frac{1}{2}$ in. The latter is similar in principle but employs a wedge subtending an angle of 60 deg with a radius at the crest of 0·5 mm in place of the sphere. The wedge is 18 mm long and is forced into the centre of a test piece 10 × 10 × 15 mm, being arranged with its axis parallel with the laminations. A probable reason for the lack of a bonding strength test in this country is that the sheet used is generally too thin for either of the above-mentioned tests to be applied.

For some years it has been the practice at N.P.L. to carry out shear tests on the interlaminar plane and to make comparative tests on compression pieces whose mode of failure was likely to be modified by interlaminar weakness (Pepper and Barwell, 1944[4]).

The object of the present paper is to review the results of these and other tests and to examine the possibility of standardising a method of test for interlaminar strength. The experimental work described below may be divided into four sections as follows:—

(*a*) Examination of any correlation which may exist between the results of shear, delamination and compression tests made on a series of fabric-base plastic boards.

(*b*) Evaluation of the reproducibility of such tests when replicated on two large samples of plastic sheet.

(*c*) Comparison of results of the above-mentioned tests with interlaminar tensile strength,

and (*d*) Estimation of size effect in compression and delamination tests.

2. *Examination of the Correlation between the Results of Shear, Delamination and Compression Tests in a Series of Fabric-Reinforced Plastic Boards.*—In an investigation of the factors influencing the strength of fabric-reinforced plastics, previously reported (Pepper and Barwell[4]) a number of determinations were made of shear strength parallel to the laminations and of compressive strength on a series of boards made from the same resin and fabric under a wide range of conditions of pressure, resin content, etc. These results have been examined together with the results of delamination tests made on samples cut from the same boards and are discussed below.

2.1. *Methods of Test.*—2.1.1. *Shearing tests.*—The method of measuring shear strength parallel to the laminations is illustrated in Fig. 1. The test pieces which were tested in pairs were made to fit closely into the spaces formed by recesses in the body of the testing appliance and the movable central portion. Load was applied to the central portion in a hydraulic testing machine through a sphere and the shear strength was estimated from the maximum load recorded by the machine.

2.1.2. *Compression test.*—The ends of the compression test piece were ground square and parallel in a precision grinding machine. The test pieces were then compressed lengthwise in an axial loading shackle as shown in Fig. 2. As the length of the test piece was made three times its thickness, it was somewhat slender and sensitive to lack of shear rigidity parallel with the laminations.

2.1.3. *Delamination test.*—The maximum thickness available for test was $\frac{1}{4}$ in. so that the U.S. delamination test which requires a thickness of $\frac{1}{2}$ in. could not be used. A test, therefore, was devised which was in effect a half-scale model of the U.S. test, a 5-mm ball being forced in an edgewise direction into the centre of a test piece whose dimensions were $\frac{1}{2}$ × $\frac{1}{2}$ × $\frac{1}{4}$ in. To ensure that the ball acted centrally on the test piece, brass fittings shown in Fig. 3 were made to fit on the ends of the platens of the axial loading shackle, Fig. 2; the test piece being held centrally by spring A forcing it against bracket B.

2.2. *Results of Tests.*—The results of the shear tests have been plotted against compressive strength in Fig. 4. It will be noted that, despite considerable scatter, the correlation is marked.

Fig. 5a shows the correlation between delamination value and shear strength. The calculated correlation coefficient is 0·894. Figs. 5b and 5c show respectively the correlation between delamination value and compression strength on normal material and on material which has been immersed in water for 7 days. The respective correlation coefficients are 0·908 and 0·955.

The scatter of the results is such that, without further evidence, it would be unwise to estimate the value to be expected in one type of test from the results obtained from another type of test. However, the relatively high values of coefficient of correlation obtained show that the results of the three types of test are closely related and may in fact represent the same fundamental property.

3. *Examination of Reproducibility of Tests.*—3.1. *Object of Test and Method of Sampling.*—Whereas the foregoing results afforded some evidence of the existence of a correlation between tests over a wide range of material, they provide no basis for assessing the reproducibility of the various tests. An investigation into the reproducibility of the various methods of tensile testing had been completed (Barwell, 1946[5]) and during the conduct of this investigation, opportunity had been taken to reserve samples for interlaminar and associated tests. The materials used, a paper-reinforced laminate and a fabric-reinforced laminate of commercial manufacture, were subdivided into twenty sub-sections and the method of sampling was identical with that described in Ref. 5. Test pieces were cut from each sub-section from the positions indicated in Fig. 6. The tests carried out were as follows:— Shear strength parallel to the laminations in two directions at right-angles, delamination test and compression in a direction parallel to the lamination. In addition, shearing tests normal to the laminations were made, but the results are not relevant to the subject of this report.

3.2. *Methods of Test.*—3.2.1. *Shear test parallel to the laminations.*—The removal of the sheared test pieces from the apparatus illustrated in Fig. 1 is sometimes a matter of difficulty. The possibility also exists, although the effect has not so far been detected, of the sides of the appliance tending to close in as a result of the downwards force, thereby causing a serious friction error. Therefore, a new appliance was constructed as illustrated in Fig. 7 for use in a tensile testing machine. It was so arranged that, after the test pieces had been sheared, the plunger could be pulled out sufficiently far to release the portion of the sheared test pieces by bringing them alongside cavities provided for the purpose. It will be noted that any elastic deformation as a result of the applied forces will result in the opening out of the sides of the appliance. Thus errors due to friction are less likely to be serious than in the case of the type illustrated in Fig. 1.

3.2.2. *Compression and delamination tests.*—The compression and delamination tests were carried out by the methods described in sections 2.1.2 and 2.1.3, respectively.

3.3. *Results of Tests.*—The results of the tests are given in Table 1, together with the standard deviations. It will be noted that the figures reveal no significant difference between the shear strength when the direction of shearing force within the plane of the laminations is changed through a right-angle. The compressive strengths of the paper-base and fabric-base sheets are practically identical but the shear and delamination strengths of the paper-base material are rather lower.

Plotting the mean of the results of Tables 1A (Paper) and 1B (Fabric) in Figs. 4 and 5, it will be noted that the resulting points do not correspond with the values obtained in the previous series of tests. This indicates that the relation between the results of the delamination and compression tests is not the same for all types of material and demonstrates that it would be unwise to attempt to deduce values of delamination strength from compression tests.

In the case of the fabric-reinforced material, the relation between shear and compression strength indicated in Fig. 4 may be held to be confirmed by tests on the further sample of material, but it is clear that a different relationship exists for paper-reinforced material. Fig. 5a lends some support for a general relationship between delamination value and shear strength but the conformity of the two sets of data is not good and all that can be said is that these properties are related in a manner which is less dependent on the nature of the laminate than is the relationship between compression and shear strengths or that between delamination and compression as indicated in Fig. 5b.

Consideration of the standard deviations given in Tables 1A and 1B show that the scatter is least in the compression test and greatest in the shear test. The variation is marked in every case and in the last column of Table 1B it is so great that, on the evidence of these results, one would not be justified in asserting that two samples differed unless the means of four determinations on each sample differed by over 2 tons/sq in. Analysis of the results of tensile tests on the same boards has indicated, however, that there is considerable variation in the material of one sheet. Using the results of tests L and M and P and R in each individual sub-section as a basis for estimation of variations due to test method, it is possible to analyse the total variance into two components. The result of the calculation is that the component of variance due to variation in the properties of the material is 0·103657 and that due to test method, 0·065792. This figure is based on forty tests so that the corresponding standard deviation is 0·256 and the standard error of the mean is 0·08. Therefore the probable error of the mean of twenty tests is ±0·085 and of four tests ±0·406.

Thus, whilst it may be shown that in the worst case the shear test may discriminate between materials differing by approximately 0·8 tons/sq in., four tests only being carried out, this is by no means satisfactory and the compression and delamination strengths should be taken into account in assessing a result because they provide a more accurate basis for discrimination between materials.

4. *The Transverse Tensile Test in Comparison with Other Interlaminar Strength Tests.*—The choice of tests described in sections 2 and 3 was restricted by the thickness of the material and a test in which the laminations were pulled apart in direct tension was not possible for the same reason. A limited quantity of commercially prepared material 1 in. in thickness was available and the opportunity was taken of carrying out a direct determination of interlaminar tensile strength on this material. The material comprised two grades of paper-reinforced sheet and two grades of fabric-reinforced sheet ; shear, compression and delamination tests were carried out to permit comparison of the result with those of the direct tensile test. Test pieces were cut from the material according to the pattern indicated in Fig. 8.

4.1. *Methods of Test.*—4.1.1. *Interlaminar shear strength.*—The results of shearing tests have been shown to be dependent on the method and degree of clamping of the ends of the test piece. When screw clamps are used the results depend on the degree of tightening and time is consumed in adjustments to clamps and of position of the test piece. In the type of apparatus illustrated in Figs. 1 and 7, the uniformity of clamping is determined by the care taken in machining the test pieces to fit the recesses in the appliance.

The apparatus illustrated in Fig. 9 was therefore designed to eliminate personal factors and to expedite testing. Its normal use is for transverse shear tests and the minimum length of test piece required is 1 in. Its use in the earlier part of the investigation was precluded by the small thickness of the material under test but with the thicker boards it was possible to cut test pieces 1 in. long as marked A in Fig. 8.

The apparatus is adapted for use in a tensile testing machine and is so arranged that the test piece may be automatically gripped by forces which are directly proportional to the force required to shear the material. Location and ejection of the test piece is automatic and operation is considerably simplified. Referring to Fig. 9, plunger A is connected by side links B with the lower head of a tensile testing machine. The main frame C, containing the die, is supported by pins D which form the fulcra of bell cranks E. Thus, when load is applied through the plunger to a test piece resting on C, the reaction on pin D causes the bell cranks to rotate until shoe F comes into contact with the test piece. The bell cranks are so proportioned that the load on the shoe is twice that on the plunger. The load at the upper ends of the bell cranks is taken through links G to fork H which is connected to the upper head of the testing machine.

When the test piece shears the plunger forces the central portion through the die to permit ejection through the hole provided in C.

Tests were also carried out using the appliance illustrated in Fig. 7. The test pieces for these tests B and C in Fig. 8 were cut from the sample in such a position that the planes of shear were coincident with the planes of shear in the test using the automatic apparatus.

4.1.2. *Interlaminar tensile test.*—Cylinders $\frac{3}{4}$-in. in diameter were machined from the samples in the position indicated by D, Fig. 8, and Duralumin end pieces were glued to these at each end. A special jig was used to hold the end pieces in correct alignment during glueing. The test pieces were then turned in a lathe to the form indicated in Fig. 10 and were tested in a hand-operated testing machine of 600 lb capacity.

4.1.3. *Compression tests.*—Nine 1-in. cubes, E in Fig. 8, were tested in compression in an axial loading shackle similar in principle to that illustrated in Fig. 2, but which had been designed for loads up to 20 tons. Three cubes were tested in each of three directions.

In addition, the test pieces marked F in Fig. 8 were tested in the manner described in section 2.1.2.

4.1.4. *German delamination test.*—Additional test pieces, not shown in Fig. 8, were prepared for testing by the Spaltbarkeit Test V.D.E. 0318. They measured initially 10 × 10 × 15 mm and were tested in the Schopper testing machine described in Appendix II, Part I. This machine is normally provided with a wedge which may be substituted for the curved loading contact used in cross-breaking tests. This wedge was not provided with this particular machine and one was constructed in accordance with the dimensions given in Ref. 3.

4.1.5. *Delamination tests.*—Delamination tests on test pieces marked G, Fig. 8, were carried out by the method described in section 2.1.3.

4.2. *Results of Tests.*—The results of the tests are given in Table 2.

4.2.1. *Interlaminar shear strength.*—Two pairs of shear test pieces B and C in each case were inadvertently tested in transverse shear but the results of the remaining four pairs are given in each case. It will be noted that in each case the mean of the results using the automatic clamping tool is higher than the mean of the results using the type B appliance. This difference is not significant, however, as the calculated values of t are $1 \cdot 41$, $0 \cdot 0385$, $1 \cdot 206$ and $1 \cdot 505$ respectively. The number of degrees of freedom was eight so that t would have to exceed $2 \cdot 31$ for the difference to be significant to the 5 per cent level.

The two methods appear to give rise to about the same scatter of results ; standard deviations were $0 \cdot 161$, $0 \cdot 260$, $0 \cdot 228$ and $0 \cdot 219$ for the automatic appliance and $0 \cdot 209$, $0 \cdot 196$, $0 \cdot 185$ and $0 \cdot 121$ for the type B appliance. It will be noted that these standard deviations are generally lower than the corresponding figures in Table 1 and this provides support for the contention that the scatter in that case was due to real differences in the properties of the material in different parts of the same sheet.

The fabric-reinforced materials have a higher shear strength than the paper-reinforced materials as was the case in the results given in Table 1. The means for both types are not as high however and the results are sufficiently consistent for this difference to be accounted as being real.

4.2.2. *Interlaminar tensile test.*—Considerable difficulty was experienced in obtaining a sufficiently good glued joint between the end fittings and the test piece, but a satisfactory method of bonding was finally evolved in the Chemical Research Laboratory. The results for the paper-reinforced materials show type 1 to be considerably stronger than type 2 : and to this extent the tensile test confirms the results of the shear and delamination tests. This consistency does not embrace the results obtained with the fabric-reinforced materials where the material having the highest tensile strength is not significantly higher in shear strength than that possessing the lower tensile strength. Moreover, the tensile strength of the fabric-base material is not significantly greater than that of the paper-base materials although the shear and delamination values are considerably higher.

The low absolute value of the interlaminar tensile strength, about 1·5 tons/sq in., is of considerable importance to designers. In the case of paper-base sheet this value is approximately one-ninth of the tensile strength in the plane of the sheet and in fabric-base materials one sixth. As the tensile strength in the plane is the one usually quoted, the need for caution will be appreciated.

4.2.3. *Compression tests.*—Comparison of the results of the longitudinal tests with the tests in the same direction on a cube leads to the conclusion that there is no significant difference in the case of the paper-reinforced materials but that in the fabric-reinforced materials the difference is highly significant, t values in Cases III and IV being 10 and 10·62 for seven degrees of freedom. It is clear that the slenderness of the test piece, therefore, affects the results in the fabric materials and not in the paper materials, although the interlaminar shear strength of the former is considerably higher. The dimensions of the F type test pieces were selected so that the material might fail in pure compression or as a strut, the mode of failure depending on the relative values of compressive strength and shear rigidity of the material. In the present tests, therefore, it would be inferred on this basis that the shear rigidity of the paper-base material was sufficiently high for the material to exert its full compressive strength in the slender test piece without the intervention of buckling whereas in the case of the fabric-base materials the opposite was the case and the slender test pieces failed by buckling at lower stresses than were successfully withstood in compression by the cubes. Their absolute values of compressive strength as determined on the cubes being of the same order, it is necessary to infer that the modulus of rigidity of the paper-base material was higher than that of the fabric-base material, although the interlaminar shear strength was lower. There is no reason why there should be a general relationship between modulus of rigidity and interlaminar shear strength, and therefore, no reason for a general correlation between shear strength and compression strength. It is therefore not surprising that the mean from Table 1A should fail to conform to the general pattern of the points in Fig. 4, and the general correlation for fabric-base materials indicated therein seems to imply a correlation between interlaminar shear strength and modulus of rigidity in the LT or RT planes, whichever may be appropriate to the direction of testing.

Figs. 1a and 1b show a selection of the cubical compression test pieces after failure. The three cubes shown on the left-hand side of the photographs were tested with the compressive stress acting on a plane normal to the laminations, whereas those on the right were tested with the compressive stress acting on the plane of the laminations.

Where the compressive force was applied normally to the laminations, the behaviour of the fabric- and paper-reinforced materials was similar, although failure was more violent in the case of the paper-reinforced materials. Where the compressive force acted in the direction of the lamination, the types of failure of the two classes of material differed markedly. The paper-base

where

R radius of sphere,

P applied load,

σ_1 Poisson's ratio of material of sphere,

σ_2 Poisson's ratio of material of plane,

E_1 Young's modulus of material of sphere,

E_2 Young's modulus of material of plane.

Whilst these expressions cannot be directly applied to anisotropic material, anisotrophy would primarily affect the shape of the area of contact and it is to be expected that, if failure were determined by the attainment of some limiting stress, the failing load would vary as R squared. In the delamination test the attainment of such limiting stress may be affected by the finite size of the test piece. In the experiments on size effect, therefore, each dimension of the test piece was increased in the same ratio as the diameter of the ball.

All the characteristic dimensions of the tests being in proportion, the delaminating load would be expected to vary as the square of any selected dimension. In Fig. 12, the results have been plotted logarithmically against thickness of test piece and it will be noted that the points in each case correspond well with straight lines which are parallel for the different types of material. The slope of these lines corresponds with an index of 1·8418 instead of 2, the expected value.

Examination of broken test pieces, a section of which is illustrated in Fig. 13, showed clearly that failure commenced by an interlaminar cleavage at the edge of the area of contact. The location of this cleavage suggests that the failure is tensile in character and the test may be effectively a form of interlaminar tensile test. Linear correspondence with the results of direct tensile tests is not to be expected if the Hertzian relationship, *i.e.*, that maximum tensile stress varies as the cube root of the applied load, holds. If this is the case, the delamination test should be much more sensitive to variations in material than the tensile test.

The test piece shown at the extreme left of Fig. 13 represents a type of failure frequently occurring in tests of fabric-reinforced materials. Here a core of material is forced away beneath the ball, failure being apparently by shearing. This is believed to be a secondary effect occurring after the main cleavage. This view is based on the fact that the cleavage is always displaced from the centre-line of the bush and that, whenever it has been possible to arrest a test immediately after the inception of failure, the appearance of the test piece has corresponded with the central illustration in Fig. 13.

5.2. *Results of Compression Tests.*—Referring to Table 4, it will be noted that the compressive strength determined on the largest pieces is in all cases higher than in the other two sizes. Considering the two other cases, the results obtained on each type of material differed significantly but, with both fabric- and paper-reinforced materials, one grade gave the higher result in the smaller test piece and another in the larger test piece.

It is doubtful, however, if this represents a real size effect, as the largest test pieces were not machined all over, and the possibility exists that the moulded surface and the material adjacent to it may differ mechanically from the material nearer the centre. Therefore further work is required to confirm the existence of any size effect.

Fig. 14 illustrates the difference in type of failure experienced with the two types of material. In the case of paper-reinforced material, failure occurred suddenly and the material delaminated almost completely. With fabric-reinforced material failure was less sudden and tended to commence on planes which were inclined to the laminations.

6. *Conclusions.*—Whilst there is unmistakable evidence of correlation between the results of shear, edgewise compression and delamination tests, the relation between the results of the various tests varies according to the class of material and it is not yet possible to select one test for use to the exclusion of the others.

There is considerable variation in properties in material in different parts of the same sample and, whilst the reproducibility of the various tests is not good, it is satisfactory in relation to the inherent variability of the material.

The delamination test appears to be most sensitive to variations in bonding, but it is necessary to standardize the size of ball and test piece as there exists a significant size effect.

The direct transverse tensile test has not yet been developed to the stage where it could be incorporated in a specification and it has not yet been found possible to relate the values obtained from different types of test by any theory based on elasticity or plasticity. This difficulty is mainly occasioned by the non-homogenous nature of laminated plastics and further investigation would be desirable.

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TABLE 1A

Results of Interlaminar Tests on Paper-Base Sheets ¼-in. Thick

Test section	Compressive strength (tons/sq in.)		Delamination test (tons)		Shear strength parallel to laminations (tons/sq in.)	
	G	H	I	J	L and M at 90 deg	P and R at 0 deg
11	12·57	12·33	0·150	0·146	2·78	2·32
12	12·28	12·30	0·144	0·142	2·39	2·39
13	12·39	12·42	0·149	0·140	2·06	2·37
14	12·15	12·11	0·136	0·135	1·75	2·45
21	12·15	12·21	0·136	0·143	2·89	2·48
22	12·42	12·48	0·142	0·142	2·23	2·54
23	12·21	12·39	0·156	0·154	2·38	2·37
24	12·56	12·59	0·145	0·140	2·42	2·61
31	11·97	12·46	0·145	0·133	2·82	1·99
32	12·16	12·38	0·142	0·144	2·75	2·56
33	11·95	12·26	0·154	0·143	2·57	2·38
34	10·95	11·04	0·125	0·120	2·68	2·83
41	11·94	12·12	0·135	0·136	2·54	2·39
42	11·21	12·41	0·147	0·143	2·56	2·71
43	12·28	12·41	0·139	0·144	2·48	2·30
44	10·69	10·86	0·131	0·138	2·65	2·79
51	11·95	12·09	0·146	0·135	2·31	2·52
52	12·23	12·37	0·142	0·145	2·45	2·80
53	12·04	12·01	0·142	0·139	2·58	2·50
54	12·00	11·97	0·147	0·137	2·42	2·60
Mean	12·01	12·16	0·143	0·140	2·48	2·50
Standard deviation	0·500	0·446	0·0078	0·0064	0·267	0·200
Standard error of mean	0·158	0·149	0·0198	0·0569	0·1155	0·10
0·05 limits of error of mean of 20 tests	±0·233	±0·2082	±0·0364	±0·0030	±0·1245	±0·0934
0·05 limits of error of mean of 4 tests	±1·125	±1·00	±0·0176	±0·0146	±0·600	±0·450

TABLE 1B

Results of Interlaminar Test on Fabric-Base Sheets $\frac{1}{4}$-in. Thick

Test section	Compressive strength (tons/sq in.)		Delamination test (tons)		Shear strength parallel to laminations (tons/sq in.)	
	G	H	I	J	L and M at 90 deg	P and R at 0 deg
11	11·86	12·32	0·266	0·263	2·98	2·71
12	12·20	12·01	0·267	0·286	3·93	3·98
13	12·43	11·83	0·288	0·274	4·24	4·20
14	12·04	12·01	0·250	0·263	3·92	3·08
21	11·87	11·95	0·269	0·269	4·05	4·20
22	12·61	12·17	0·292	0·275	4·12	4·59
23	12·32	11·97	0·283	0·287	4·40	4·30
24	12·28	12·43	0·276	0·284	4·07	4·18
31	12·34	11·96	0·279	0·273	4·22	4·47
32	12·37	12·65	0·295	0·266	4·53	4·25
33	12·24	12·31	0·299	0·276	4·47	4·50
34	12·19	12·03	0·277	0·272	4·20	4·36
41	11·64	12·28	0·280	0·280	4·28	4·36
42	12·05	12·37	0·273	0·287	4·41	4·49
43	12·28	12·05	0·289	0·286	4·57	4·32
44	12·24	12·36	0·284	0·255	4·30	4·34
51	11·21	11·98	0·264	0·276	4·14	4·42
52	12·04	12·38	0·263	0·290	4·64	4·41
53	12·05	12·96	0·264	0·288	4·22	4·42
54	11·64	12·02	0·246	0·257	4·20	4·40
Mean	12·10	12·18	0·275	0·275	4·19	4·20
Standard deviation	0·254	0·223	0·014	0·10105	0·348	0·470
Standard error of mean	0·113	0·106	0·0269	0·0224	0·132	0·154
0·05 limits of error of mean of 20 tests	±0·1186	±0·104	±0·007	±0·005	±0·161	±0·219
0·05 limits of error of mean of 4 tests	±0·572	±0·502	±0·032	±0·024	±0·77	±1·05

TABLE 2

Results of Tests on Boards 1-*in. Thick*

(Units — tons/sq in., except where otherwise stated)

Type of Test	Number	Paper		Fabric	
		Type I	Type II	Type III	Type IV
Shear as in Fig. 7	A1 to 6	2·17, 2·15, 2·08 2·38, 2·26, 2·49 (2·25)	2·19, 2·72, 1·99 1·94, 1·65, 2·30 (1·96)	3·29, 3·63, 3·50 2·26, 3·34, 3·48 (3·25)	3·44, 3·35, 3·25 3·00, 3·19, 3·14 (3·23)
as in Fig. 9	B, C, 1 to 4	2·28, 2·31, 2·73, 2·36 (2·42)	1·82, 1·86, 2·22, 2·12 (2·005)	3·12, 3·51, 3·44, 3·50 (3·39)	3·32, 3·21, 3·48, 3·24 (3·32)
Compression Longitudinal	F1 to 6	13·45, 13·39, 13·01 12·84, 12·97, 12·97 (13·12)	11·84, 13·70, 13·08 13·76, 11·28, 13·96 (12·94)	10·99, 10·44, 10·88 10·78, 10·48, 10·48 (10·67)	12·13, 12·37, 12·04 12·25, 12·37, 12·36 (12·25)
Cube					
0 deg	E4 to 6	12·99 13·37, 12·71 (13·02)	13·86, 13·63, 13·87 (13·79)	11·70, 11·60, 11·44 (11·58)	12·95, 13·20, 13·16 (13·10)
90 deg	E1 to 3	13·53, 13·34, 13·42 (13·43)	12·78, 12·80, 13·91 (13·16)	12·00, 11·55, 11·78 (11·78)	11·77, 12·28, 12·17 (12·07)
Perpendicular	E7 to 9	19·12, 19·08, 18·56 (18·92)	19·17, 19·26, 19·52 (19·32)	18·20, 18·21, 18·10 (18·17)	18·90, 19·04, 18·73 (18·89)
Delamination as in Fig. 3 (load in tons)	G1 to 6	0·135, 0·140, 0·136 0·140, 0·141, 0·136 (0·136)	0·135, 0·116, 0·125 0·123, 0·127, 0·128 (0·126)	0·260, 0·261, 0·245 0·245, 0·245, 0·242 (0·250)	0·225, 0·225, 0·240 0·236, 0·224, 0·237 (0·231)
German test (load in kg)	R1 to 6	225, 223, 225 211, 222, 225 (225)	214, 217, 215 207, 208, 198 (210)	greater than 250	greater than 250
Tension	D1 to 3	1·45, 1·46, 1·56 (1·49)	1·42, 1·39, 1·20 (1·34)	1·29, 1·36, 1·34 (1·33)	1·67, 1·85 (1·76)

Figures in brackets indicate mean values.

TABLE 3

Results of Tests on Size Effect in Delamination

Delamination load in tons

Size of test piece	Test No.	Paper		Fabric	
		Type I	Type II	Type III	Type IV
½ × ½ × ¼ in. (repeated from Table 2), 5-mm ball	G1	0·135	0·135	0·260	0·225
	2	0·140	0·116	0·261	0·225
	3	0·136	0·125	0·245	0·240
	4	0·140	0·123	0·249	0·236
	5	0·141	0·127	0·247	0·224
	6	0·136	0·128	0·242	0·237
	Mean	0·136	0·126	0·250	0·231
1 × 1 × ½ in. 10-mm ball	K1	0·426	0·437	0·877	0·751
	2	0·449	0·389	0·745	0·788
	3	0·402	0·392	0·778	0·806
	4	0·413	0·464	0·912	0·743
	5	0·453	0·408	0·784	0·753
	6	0·464	0·480	0·755	0·771
	Mean	0·435	0·425	0·808	0·769
2 × 2 × 1 in. 20-mm ball	L1	1·70	1·72	2·83	2·36
	2	1·66	1·63	2·74	2·50
	3	1·79	1·68	3·02	2·47
	4	1·69	1·80	2·90	2·66
	5	1·66	1·66	2·83	2·48
	6	1·70	1·52	2·80	2·58
	Mean	1·70	1·67	2·85	2·51

TABLE 4

Results of Tests on Size Effect in Compression

Stress in tons/sq in.

Size of test piece	Test No.	Paper		Fabric	
		Type I	Type II	Type III	Type IV
¾ × ½ × ¼ in. (from Table 2)	F1	13·45	11·84	10·99	12·13
	2	13·39	13·70	10·44	12·37
	3	13·01	13·96	10·88	12·04
	4	12·84	13·08	10·78	12·25
	5	12·97	13·76	10·48	12·37
	6	12·97	11·28	10·48	12·36
	Mean	13·12	12·94	10·67	12·25
	S.D.	0·2512	1·12	0·326	0·1406
1½ × 1 × ½ in.	H1	13·65	12·02	11·37	11·81
	2	13·50	12·62	10·89	11·82
	3	13·33	13·86	11·34	11·97
	4	13·61	12·55	11·55	11·65
	5	13·39	11·26	11·43	11·90
	6	13·59	13·79	11·34	12·0
	Mean	13·51	12·68	11·32	11·86
	S.D.	0·129	1·008	0·226	0·127
3 × 2 × 1 in.	J1	14·89	14·47	16·54	12·94
	2	15·03	14·62	12·83	13·14
	3	14·94	14·05	13·37	12·90
	4	14·83	14·01	11·29	12·95
	5	14·86	14·79	12·49	12·75
	6	14·79	14·29	12·83	12·80
	Mean	14·89	14·37	13·23	12·91

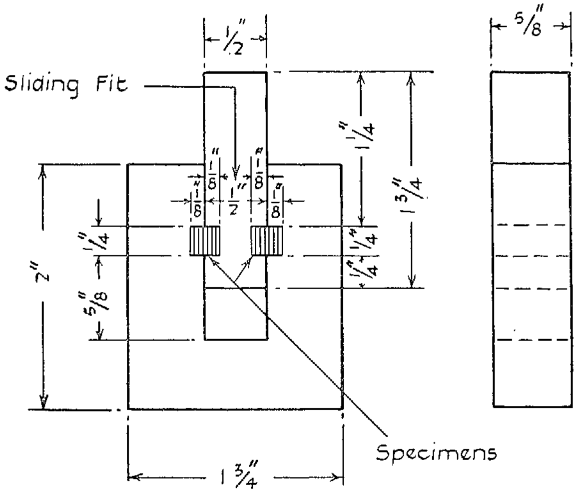


FIG. 1. Shear test apparatus (type A).

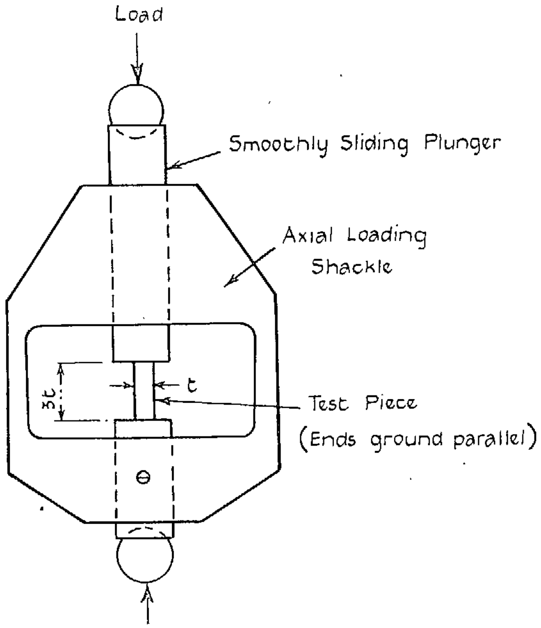


FIG. 2. Axial loading shackles as used in compression test.

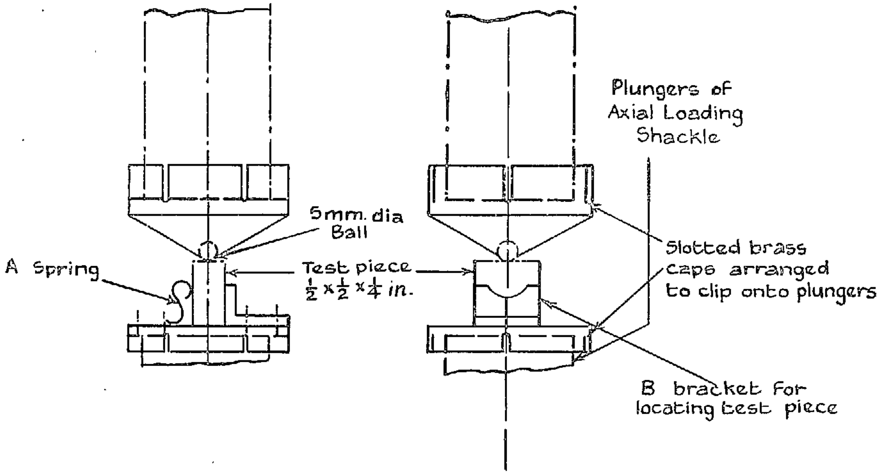


FIG. 3. Attachment for delamination test.

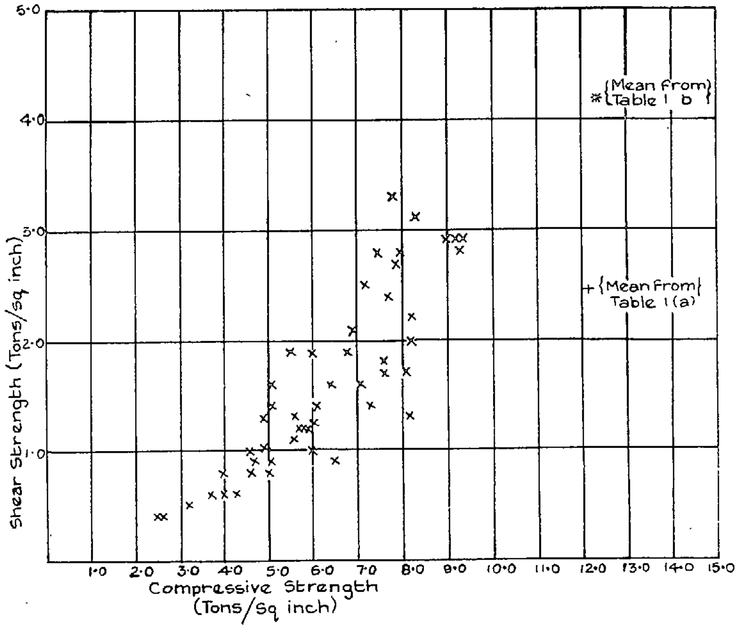


FIG. 4. Correlation between shear and compression test results.

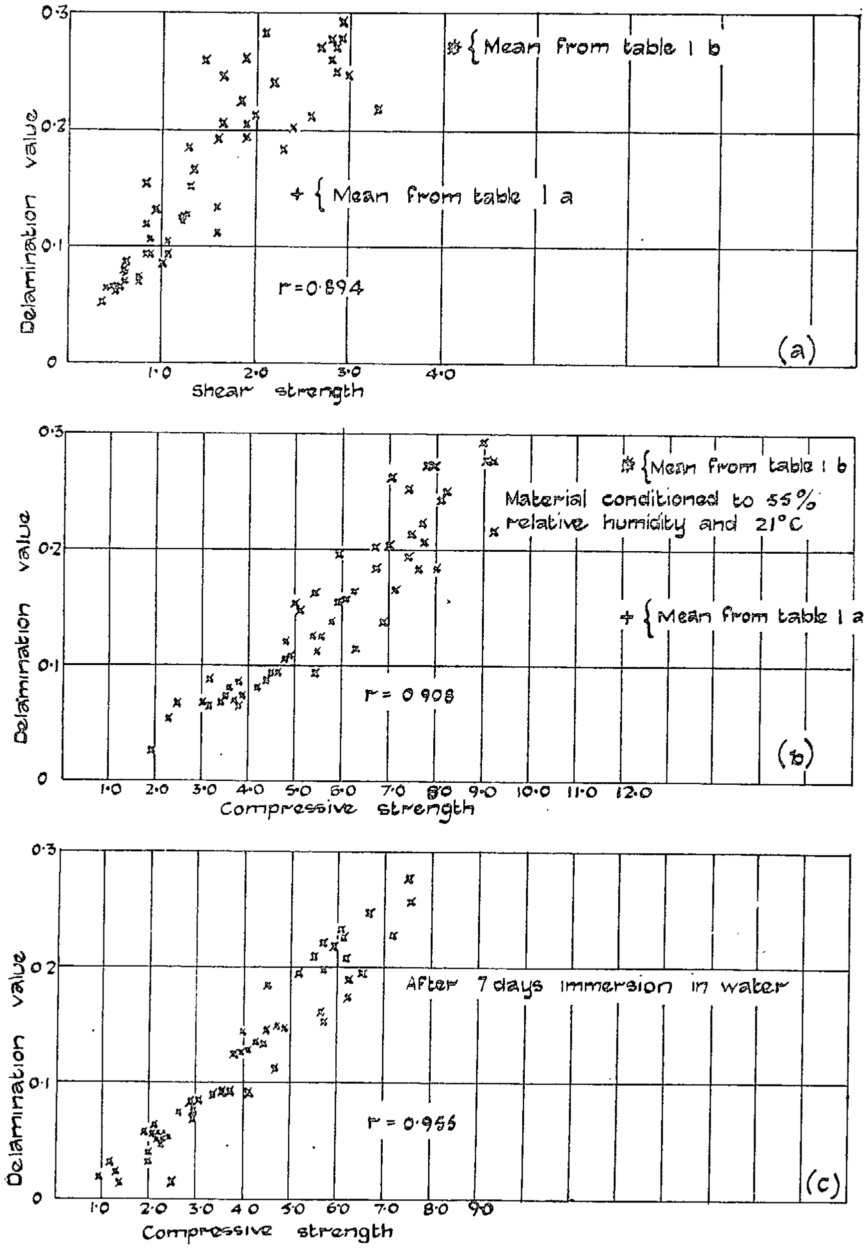
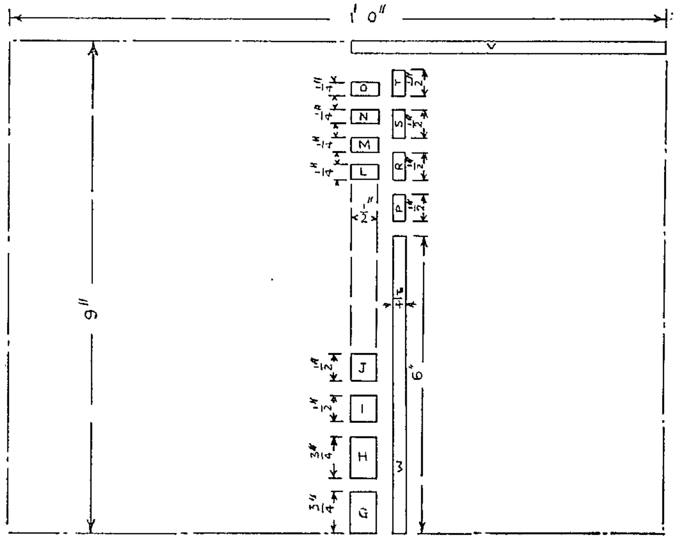
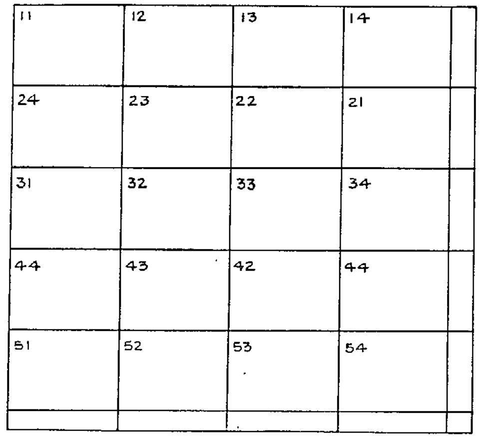


FIG. 5. Correlation between delamination value and shear and compression strength.



G,	H	Test pieces for Compression Test
I,	J	Test pieces for Delamination Test
L,	M	Test pieces for Shearing Test on Plane parallel to Laminations
N,	O	Test pieces for Shearing Test on Plane normal to Laminations
P,	R	Test pieces for Shearing Test on Plane parallel to Laminations
S,	T	Test pieces for Shearing Test on Plane normal to Laminations
V,	W	Test pieces for Shearing Test on Plane normal to Laminations

(a) Arrangement of Test pieces in each Sub-section



11	12	13	14
24	23	22	21
31	32	33	34
44	43	42	44
51	52	53	54

(b) Relative Position of Sub-sections

FIG. 6. Arrangement of test pieces.

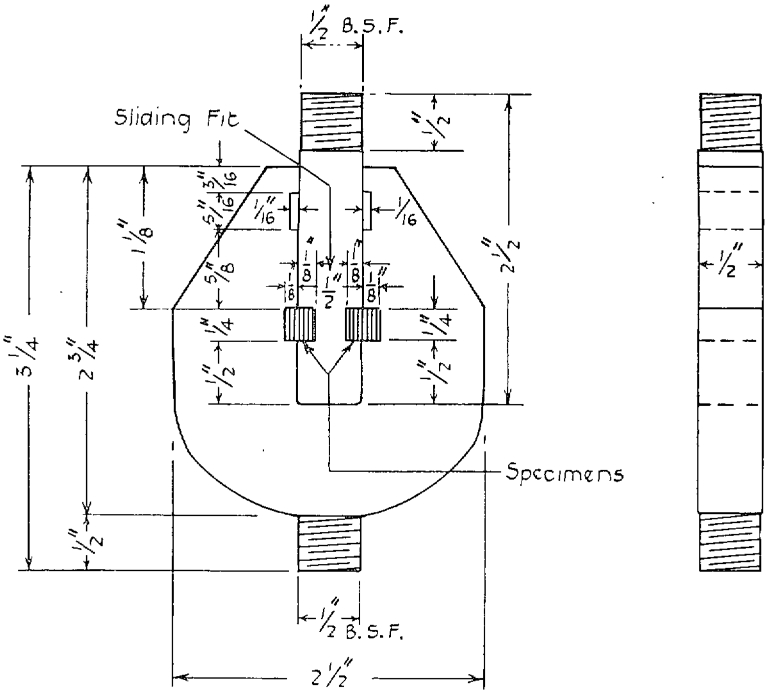


Fig. 7. Shear test apparatus (type B).

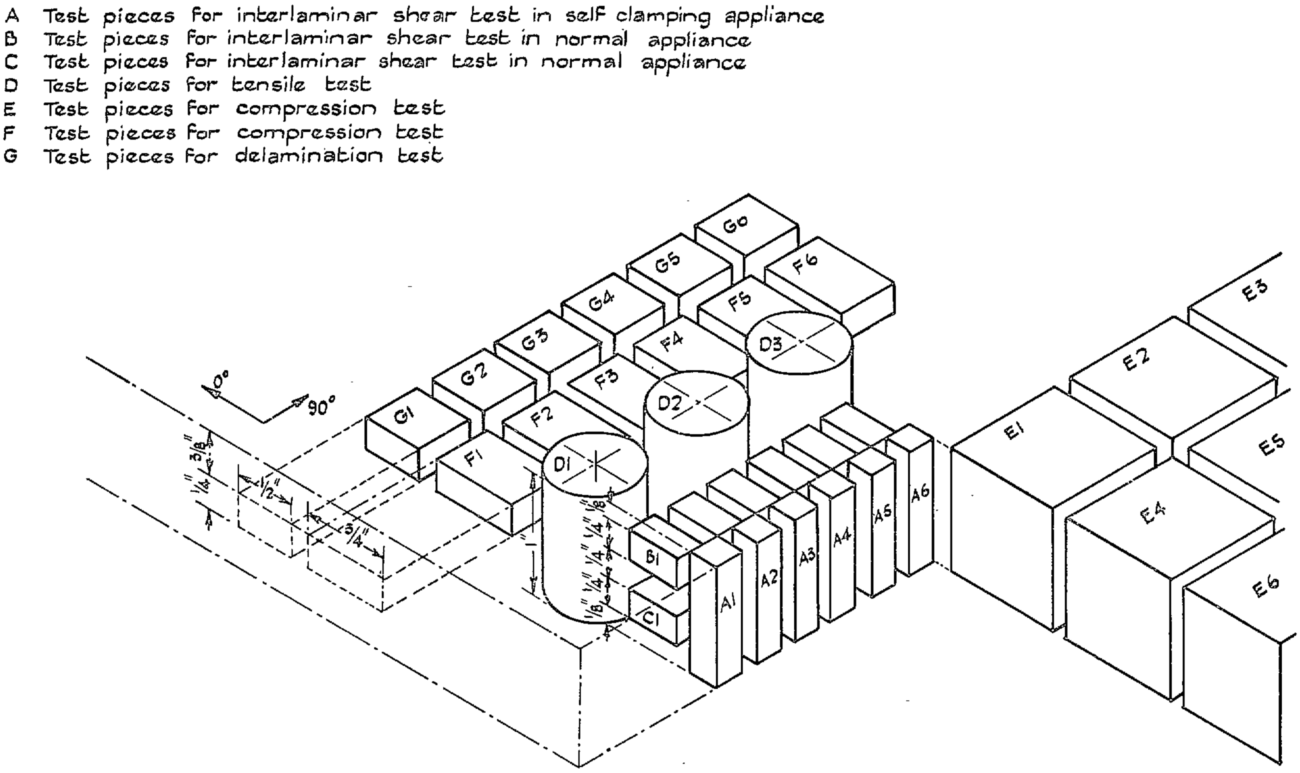


Fig. 8. Position of test pieces cut from 1-in. thick boards.

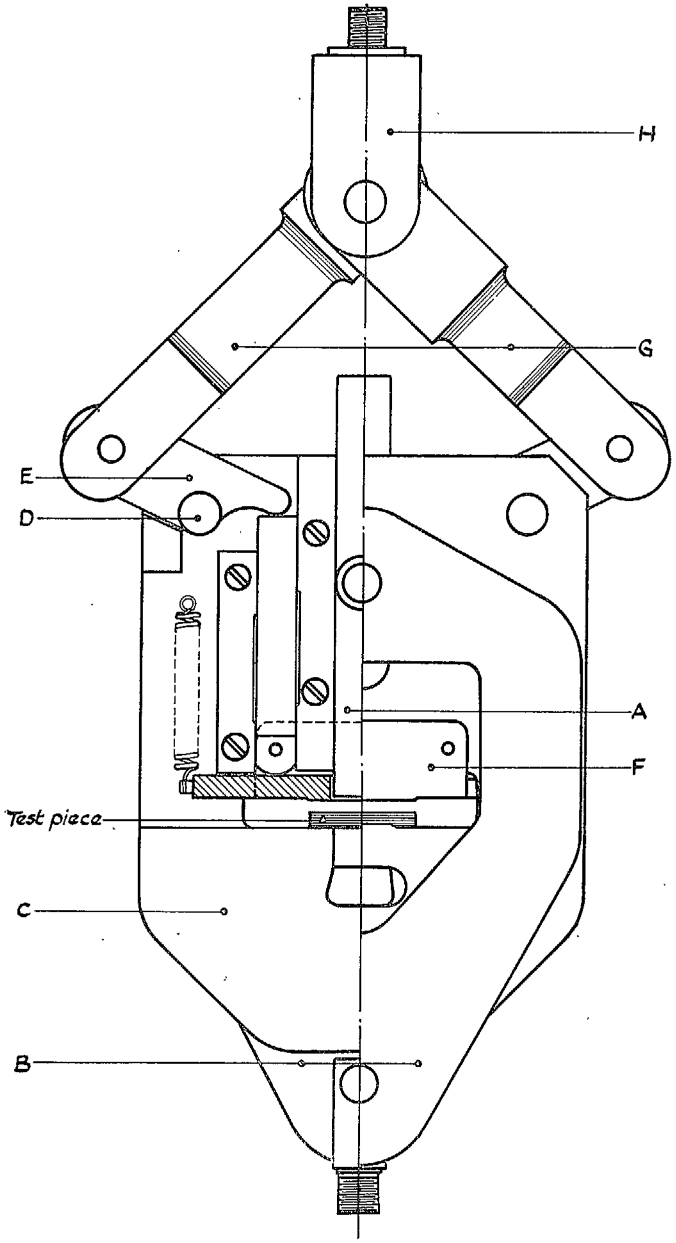


FIG. 9. Shear test appliance arranged for automatic clamping of test pieces.

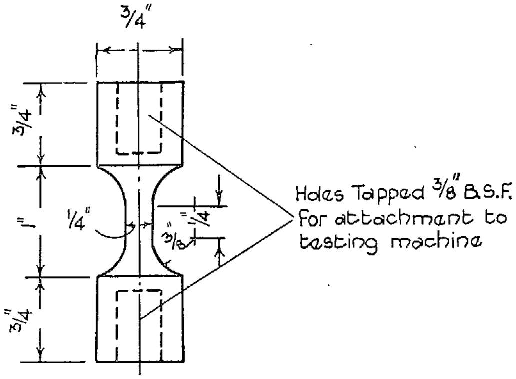
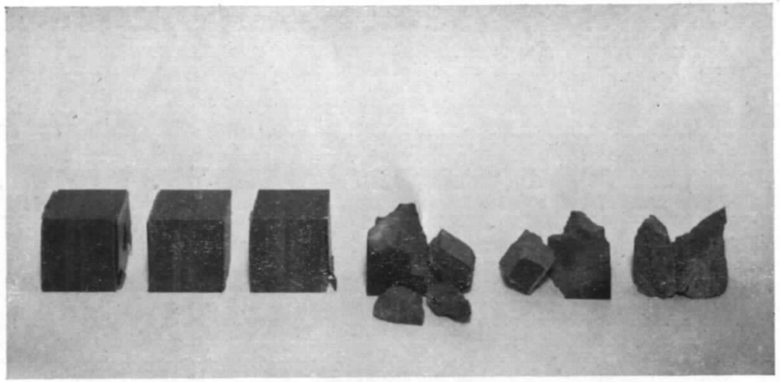
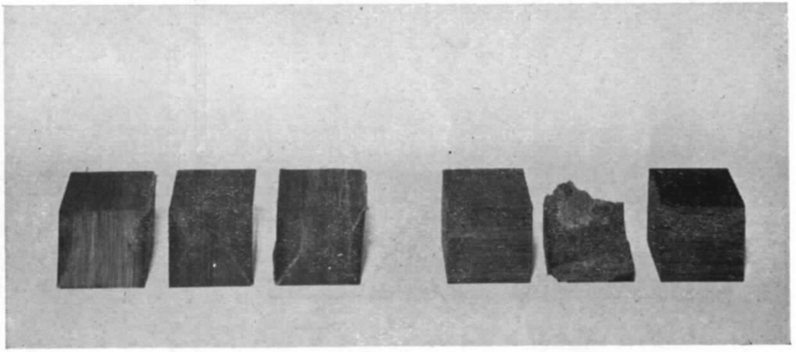


FIG. 10. Tensile test piece.



(a) Paper-reinforced test pieces.



(b) Fabric-reinforced test pieces.

FIG. 11. Compression test pieces after test.

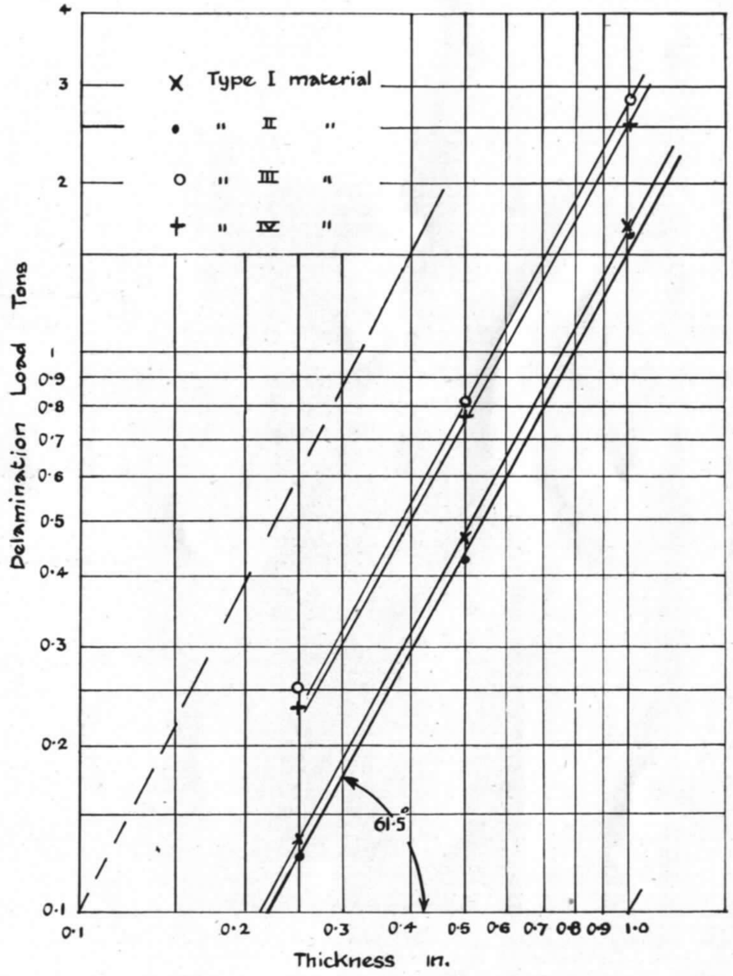


FIG. 12. Size effect in delamination tests.

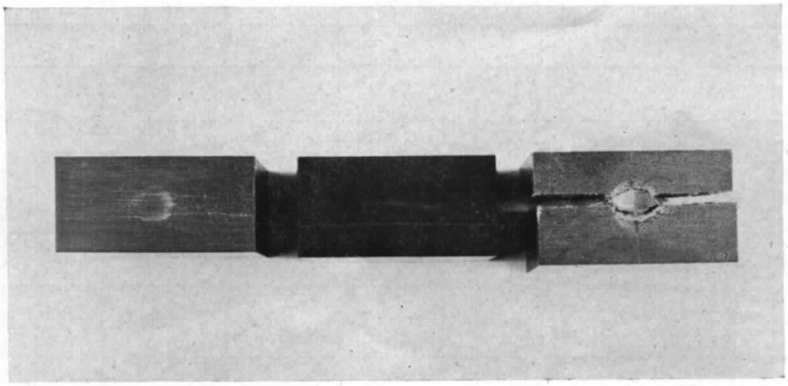


FIG. 13. Delamination test pieces after test.

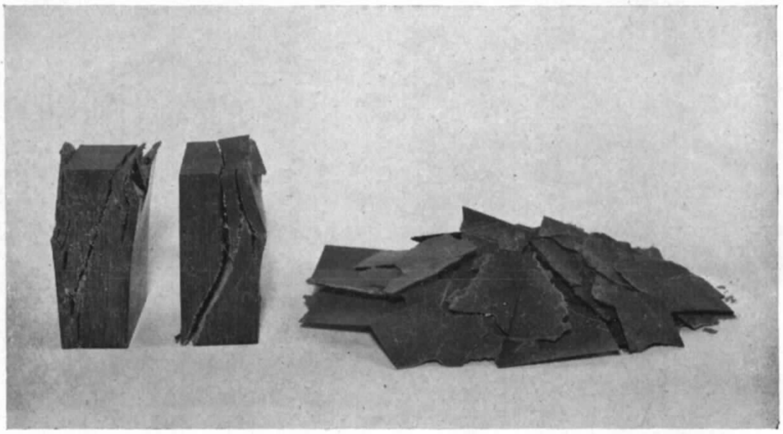


FIG. 14. Compression test pieces after test (fabric-reinforced material on left, paper-reinforced material on right).

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