THREE-PLY AND ITS USES IN AIRCRAFT CONSTRUCTION.

Abstract of Paper read by Captain R. N. Liptrot, B.A., A.F.R.Ae.S., Member, before the Institution at the Engineers' Club, Coventry Street, W.1, on 26th October, 1923. Mr. W. O. Manning in the chair.

The CHAIRMAN, in introducing the lecturer reminded the audience that Captain Liptrot held an important position at the Air Ministry, and was fully qualified to speak on his subject.

CAPTAIN LIPTROT said :—

PHYSICAL PROPERTIES OF PLYWOOD.

As a material for use where strength combined with lightness are essential, wood, if it were of homogeneous structure, would be unexcelled. It has, however, very different physical properties, when considered in directions parallel with the grain, and perpendicular to the grain.

The object aimed at in using timber in the form of plywood, is to equalise the strength in directions at right angles. This object is attained by cutting the wood into thin sheets, which are then glued together, in such a way that the grain in any sheet is at right angles to the grain in adjoining sheets.

Where more than three sheets are used, the additional sheets are added in equal numbers on each side of the core, each successive sheet having its grain at right angles to that in adjoining sheets.

This construction not only tends to equalise the strength of the wood in different directions, but also reduces the tendency to shrink or warp, when the moisture content of the panel changes.

Symmetry is the first principle governing the construction of plywood. There must always be an equal number of plies on either side of the core, and both such corresponding plies on each side must be of the same variety of wood, of the same thickness, and cut in the same manner. In addition, the grain of the corresponding plies on each side of the core must be running in the same direction.

SHRINKAGE AND PREVENTION OF WARPING.

When plywood undergoes a change in moisture content stresses will always be set up, or released, owing to the great difference in the shrinkage of wood, in directions parallel and perpendicular to the grain. For instance, in the simplest plywood panel, of only three layers, if the moisture content increases the core will tend to expand transversely, but the transverse expansion of the core is checked, since the face plies do not deform appreciably in a direction parallel to the grain. As a result the face plies are put in tension. Similarly the face plies tend to expand at the same time, at right angles to the grain, but are restrained by the core. All plies are therefore put in tension along the grain, and in compression at right angles to the grain.

So long as all opposite pairs of plies are of exactly the same thickness and density, and have their grain running in the same direction, the total stress on each side of the core will be the same, and no distortion of the panel as a whole can take place.

It is an essential for good plywood that the grain of each ply be as nearly as possible at right angles to that in adjacent plies, and it is also desirable that the moisture content of the panel, as it leaves the press, should be as nearly as possible the same as it will be in service.

EFFECT OF THE NUMBER OF PLIES.

The larger the number of plies the more homogeneous will be the panel as a whole.

The strength, both in bending and in tension, in the direction of the face plies, becomes less as the number of plies is increased, and the strength perpendicular to the grain of the face plies increases until the two are nearly equal. Thus, whenever greater strength is required in one direction than in another, three-ply panels are best, but even in three-ply, by suitably proportioning the thicknesses, the strength in the two directions can be very fairly equalised. In resistance to splitting, however, three-ply is very inferior to that made of a large number of plies.

Where a panel is required to retain a very flat surface, it is advisable to use a large number of thin plies, as the shrinkage in various directions will be equalised.

The relation between the strength of plywood in directions parallel and perpendicular to the grain can be adjusted by suitable proportioning of the thickness of the faces to that of the core, and depends on the use to which the finished panel is to be put.

For the same tensile strength in both directions the core should be one-half the total thickness of the panel, but if equal strength in bending in the two directions is required, then the core should be about 0.7 of the total thickness.

N.B.—When speaking of multi-ply panels, the " core " refers to all the intermediate panels whose grain is perpendicular to that of the face plies.

The character of the core does not influence the strength of the panel, when it is subject to tensile stresses parallel to the grain of the face plies, but it is

TIMBER USED FOR CORES.

of great importance where column or bending strength is required, or where flat panels are essential.

Experiment has shown that plywood in carrying axial compression acts like a slender column, its strength in compression being proportional to its moment of inertia about its axis of least radius of gyration.

It follows, therefore, that, for greatest column strength for equal weight, we should use a low-density core such as poplar or basswood and thereby increase the spacing of the outer plies.

As a general rule the face plies should be thin and of tough, strong wood such as birch, which is capable of taking high stresses, and they should be spaced as far apart as possible.

In the case of panels constructed of different woods in combination, the properties in the direction in which the load is applied depend entirely on the plies which have their grain parallel to the direction of the load. Thus, if the face plies are of strong, tough wood, the column strength and tensile strength are large, irrespective of whether the core is of high or low density, provided the core thickness is the same. On the other hand, where we have a low strength core, and the panel is subjected to a load perpendicular to the grain of the face plies, all its properties will be as low as if all plies were of the same material as the core.

Figures for use in Design.

A very large amount of data on the strength and other properties of the common varieties of wood, when made up into plywood, have been collected by the American Forest Products Laboratory, and the figures given in the tables which follow have been taken from their reports.

Column Bending Modulus.

The column bending modulus is calculated by the formula.

$$s = P/A + \frac{6\,M}{(bd)}\,2$$

where s = column bending modulus.

P = load at maximum bending moment.

A = area of cross section.

M = maximum bending moment.

= P x minimum deflection.

b = width of panel.

d = thickness of panel.

Like the modulus of rupture in the standing bending test, the column bending modulus is not a true indication of the maximum fibre stress at the instant of failure, but is only a measure of the comparative strengths of the various plywoods in resisting external bending moments.

Table 1 gives the strength figures for the plywoods of various timbers which have been used for plywood. All the plywood tested was three-ply, with all plies in the same panel of the same timber and of the same thickness.

The specific gravity given is on oven dry weight.

Table 2 gives the results of a series of tests made on panels of yellow birch plywood, of more than three plies.

Table 3 gives the thickness of a sheet of veneer of the various woods necessary to give the same weight as a unit thickness of yellow birch veneer. The thickness factors in column 6 of this table are used in estimating the thickness of a panel to give the same strength in bending as a yellow birch panel. In using these figures, it should be noted that the ratio of core to total thickness must be the same for both the yellow birch panel, and also for the panel which is being estimated.

Table 4 gives the weight in ounces per square foot, for various thicknesses of the woods used in three-ply manufacture.

Three-ply fuselage construction as at present employed may be divided into three general classes.

I. The true Monocoque.

II. The semi-Monocoque.

III. The three-ply braced fuselage.

The plywood fuselage possesses considerable advantages over the ordinary box-girder type, and when properly constructed is considerably stronger in proportion to its weight than the wire-braced truss.

One great advantage of the plywood construction is that it lends itself readily to streamlining, whereas the box girder in its simplest and strongest form is a square or paralellogram in cross section, and has to be brought up to a reasonably good aerodynamic form by means of elaborate fairings. It also retains its alignment almost permanently, and is not permanently deformed by any load short of the elastic limit of the material used.

The monocoque types can be designed to resist the torsion of the tail unit, more easily and more economically than the box girder, since the material is continuous, and is disposed as far away from the axis as possible. In the wire-braced structure on the other hand, the longerons and struts have not the best section and disposition for resisting torque.

A point of the utmost importance in the manufacture of three-ply fuselages is that the plywood must be properly protected especially if the aircraft is to operate in tropical climates where wide variations in temperature and humidity are experienced. The best method of protection is to cover the plywood with a layer of glued-on fabric which is given one coat of grey undercoating paint followed by one coat of aluminium paint. It is particularly important that all exposed edges should be protected by taping, as separation of the plies and ultimate failure of the panel always starts at the edges.

I. The True Monocoque.

The true monocoque fuselage consists essentially of a plywood skin, which carries the whole of the load, except at the forward end, where engine-bearers are built into the shell.

Method of Manufacture.

The method adopted in the manufacture of the L.W.F. is as follows :—

A collapsible mould is used, over which the skin is laid on layer by layer.

The first operation is to set up the mould, and to stretch over it a layer of fabric. This is given a coat of size, and then spruce veneer 1/16 in. thick is laid on spirally, in strips about 6 in. wide, glue being applied to both fabric and veneer, at the same time. The spiral is such that one complete turn is made in the length of the body, which is 23 feet long. After this operation, the work is allowed to dry.

Glued muslin tape, $2\frac{1}{4}$ ins. wide, with a strength of about 125 lbs. per inch, is then wrapped round the fuselage, each turn overlapping the preceding by about $\frac{1}{4}$ in., and a second layer of spruce strips laid on with the spiral opposite to that in the first layer. The work is allowed to dry as before, and another winding of glued muslin tape put on. Following this the third and last layer of spruce is laid on, but with the grain running longitudinally, and the whole structure is dried for four days at a temperature of 90° F. to 100° F.

The mould is collapsed and removed, and the fuselage finished by painting and varnishing.

The obvious disadvantage of the true monocoque construction is the time required to complete, and also the fact that each mould is in use for some seven days, before it can be used for another fuselage.

The type, however, gives a very light and rigid structure, and can have a perfect streamline shape, but the time taken, and the large number of moulds required, appear to preclude its adoption for quantity production.

The function of the skin in carrying the bending moment due to the vertical loads, makes it necessary that the face plies should have their grain longitudinal, with respect to the length of the fuselage, and the grain of the core should be transverse.

II. Semi-Monocoque.

The semi-monocoque type combines the principal advantages of the true monocoque and box girder, and consists essentially of four longerons (with sometimes subsidiary longerons and stringers), with light multi-ply or box-pattern bulkheads spaced along the fuselage, the whole skeleton being covered with a thin skin of plywood, which is glued and screwed to the longerons and bulkheads.

A simple and probably correct view of the functions of the various members is that the longerons and plywood panels top and bottom take up bending moments, whilst the plywood sides resist shear, as does the wire truss of the box-girder type. The bulkheads provide for the attachment of lift wires, tail surfaces, etc., and help to maintain the shape of the fuselage, and also prevent buckling of the sides under compression. This type of fuselage is exemplified by the Albatross, Parnall Panther, and Pfalz D III fuselages.

The chief differences observed amongst members of the type are in the method of laying on the skin.

(a) *Moulded Skin.*—In this type, which has been experimented with in America, the skin is put in five moulded sections, two for the top, one for the bottom, and one for each side.

Large cast-iron dies are made of the form to which the various sections of the skin are to be moulded. These dies are hollow and steam-heated. The panel of three-ply to be moulded is first trimmed to the proper outline, and then boiled for three hours, after which it is pressed in the die, and dried out by steam heat.

Assembly.—The bulkheads, which are of multi-ply board, are clamped in an assembly jig, and the longerons glued in position. The moulded sections of the skin are placed over the framework, and secured by glueing and screwing, to the longerons and bulkheads. The same method is followed for the attachment of the side panels.

The moulding method can only be employed where the grain in the face plies is circumferential, but experience has shown that in order to withstand the tensile and compressive stresses along the fuselage, the grain in the face plies must run longitudinally.

Another objection to this method is that the boiling and subsequent steam drying of the panels in the dies, tends to bake the panels, giving a case-hardening effect.

Another method of moulding which has been tried, in order to get the face grain longitudinal, was to use a wooden mould, of the shape of the full-length section of the skin. The sections of plywood were drawn down over the mould by tightly-fitting, heavy canvas covers.

With this method also, the plywood must be boiled for about $2\frac{1}{2}$ hours, before putting over the mould, and great difficulty is experienced in making the sharp bends required at some points of the fuselage.

(b) *Use of small unmoulded panels.*—In the Albatross and " Panther " fuselages, the framework consists of the same longerons and bulkheads, but whereas in the Albatross the bulkheads are of multi-ply fretted out to shape, in the " Panther " they are of box section, being built up of two flanges of ash with two webs of three-ply.

The skin is formed in small sections, directly over the framework without the necessity for any previous moulding. All joints in the skin, both longitudinal and transverse, should be of the plain-scarf type, overlapping about 2 ins. This gives a strong water-proof connection, especially if the whole be covered by a layer of fabric glued on. If the whole fuselage is not fabric-covered, all joints in the plywood should have cover strips of glued fabric.

This process, in which the skin is laid on in a large number of small unmoulded panels, is probably the best so far developed, and lends itself admirably to quantity production.

(c) *Skin wrapped on spirally.*—In the case of the Pfalz, the skin is put on spirally over the framework of formers and longerons. It consists of two layers of three-ply, each about 1 m/m. thick, which is laid on in strips about 4 ins. wide. The first layer is bent diagonally round the framework, being attached by glueing and tacking to the longerons and formers, and the second layer is laid on top, but in the reverse direction, so that the grain is roughly at right angles to the grain of the first layer. The inside layer is reinforced in the front portion of the body, by glued tape wound on over the joints between adjoining strips of plywood.

General Notes on Semi-Monocoques.

Spruce veneer has been used with good results for semi-monocoque fuselages, especially in designs of fairly good depth, but for fuselages of heavy construction some wood such as birch is better. In many cases it is found that a combination of birch faces and poplar core gives the best results.

Since the bending moment increases rapidly forward of the rear cockpit it is more economical to use more plies in this section, than in the rear.

Where the skin is put on in small panels, spliced along the longerons, it is also possible to use somewhat heavier plywood for the top and bottom panels, which are more heavily stressed, than for the sides. In general for fuselage work, the core used is 50 per cent. of the total thickness of the panel.

Multi-ply wood for Bulkheads.—Fairly heavy construction is necessary for the bulkheads in the forward part of the fuselage, which support the main concentrated loads and take the loads from the lift wires. These are often of the order of 1 in. thick, and to secure homogeneity are made up of a number of plies each 1/16 in. thick. Where great strength is required birch is used, but spruce has been used for lighter work. As a rule, in multi-ply, the same wood is used for all plies which are of the same thickness.

It should be realised that in the rear portion the bulkheads only take secondary stresses, and their principal duty is to act as stiffening rings, and to stabilise the skin. It is thus possible to make them comparatively light.

III. Three-ply Braced Fuselages.

Many aeroplane fuselages are now made by a method which has been used with great success in the De Havilland machines, and which is more or less a combination of the girder and three-ply shell types. In this design, instead of using the usual struts and cross-bracing wires in the sides, the latter are made as N girders and covered with three-ply, which is glued and screwed to the longerons and struts. In this case, the N girder is itself sufficiently strong to take the entire load, the three-ply side being employed to stabilise the members in compression, and to strengthen the structure against bending and torsion.

Where plywood is attached in this way to a fuselage truss, it is important that it should not buckle. This tendency is more pronounced when the plywood has to lie flat than when curved, and in order to prevent any distortion the core should be made relatively thick, and of low-density wood such as poplar, whilst the faces are of birch.

Fuselages of this type are exceedingly strong for a moderate weight, and are very permanent.

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TABLE 1.

STRENGTHS OF VARIOUS SPECIES OF 3-PLY PANELS.

SPECIES.	Average Specific Gravity of Ply-wood.	Average Percentage Moisture	COLUMN BENDING MODULUS. Load parallel to Grain of Faces. Pounds per sq. in.	COLUMN BENDING MODULUS. Load perpendicular to Grain of Faces. Pounds per sq. in.	TENSILE STRENGTH. Parallel. Pounds per sq. in	TENSILE STRENGTH. Perpendicular. Pounds per sq. in.	MODULUS OF ELASTICITY. Parallel. Pounds per sq. in. in bending.	MODULUS OF ELASTICITY. Perpendicular Pounds per sq. in. in bending.
Yellow Birch	.67	8.5	16,000	3,200	13,200	7,700	2,259,000	197,000
Ash, Black	.47	9.2	7,360	1,620	6,200	3,940	1,028,000	87,000
Ash, White	.61	10.6	9,980	2,440	6,540	4,330	1,422,000	144,000
Basswood	.41	9.6	6,520	1,540	6,300	4,100	1,213,000	85,000
Beech	.67	8.6	15,390	2,950	13,000	7,260	2,149,000	167,000
Cedar	.41	13.3	6,460	1,480	5,200	3,340	1,032,000	84,000
Cotton Wood	.48	9.5	8,110	1,660	7,540	4,500	1,461,000	110,000
Mahogany, African	.52	12.7	8,070	2,000	5,370	3,770	1,261,000	144,000
Mahogany, American	.53	10.7	10,160	2,310	10,670	5,990	1,820,000	169,000
Poplar, Yellow......	.50	9.0	8,900	1,920	7,380	4,520	1,501,000	114,000
Sycamore	.56	10.0	10,920	2,390	8,840	5,480	1,642,000	135,000
Walnut	.58	9.7	11,850	2,660	7,640	5,100	1,664,000	144,000
Spruce	.41	8.0	7,280	1,540	5,180	3,150	1,176,000	98,000

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TABLE 2.

COMPARISON OF STRENGTH OF THREE, FIVE AND SEVEN-PLY YELLOW BIRCH. ALL PLIES OF SAME THICKNESS IN ANY ONE PANEL.

No. of Plies.	Average Specific Gravity.	Average Percentage Moisture.	Column Bending Modulus. lbs. per sq. inch.		Tensile Strength in lbs. per sq. inch.		Average Splitting Resistance compared to three-ply Birch in percentage of three-ply.
			Parallel to Grain of Face Plies.	Perpendicular to Grain of Face Plies.	Parallel to Grain of Face Plies.	Perpendicular to Grain of Face Plies.	
3	.68	6.1	19,100	3,700	14,400	7,900	100
5	.67	6.6	14,700	6,800	13,100	8,600	143
7	.70	7.1	14,300	7,900	12,900	9,300	212

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TABLE 3.

THICKNESS FACTORS FOR VENEER.

Giving Column 6.—Veneer thickness for same bending strength as Birch.
„ 7.— „ „ for same weight as Birch.

SPECIES. 1	Average Specific Gravity of Species. 2	Specific Gravity of Glued Plywood as tested. 3	Unit bending Strength compared with Birch in percentage of Birch. 5	Thickness Factor for same Total Bending Strength as Birch. 6	Thickness Factor for same weight as Birch. 7	Percentage Moisture in Plywood as tested. 4
Birch, Yellow	.63	.67	100	1.00	1.00	8.5
Ash, Black	.50	.48	47	1.46	1.26	9.2
Ash, White	.58	.61	66	1.23	1.09	10.6
Basswood	.38	.41	42	1.54	1.66	9.6
Beech	.63	.67	96	1.02	1.00	8.6
Cedar	.34	.41	41	1.56	1.85	13.3
Cotton Wood	.43	.48	51	1.40	1.47	9.5
Mahogany, African	.46	.52	53	1.37	1.37	12.7
Mahogany. American	.57	.53	65	1.24	1.11	10.7
Poplar, Yellow	.41	.50	56	1.33	1.54	9.0
Sycamore	.50	.56	69	1.20	1.26	10.0
Spruce	.38	.41	46	1.47	1.66	8.0
Walnut	.57	.58	76	1 15	1.11	10.2

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TABLE 4.

WEIGHT IN OUNCES PER SQ. FOOT OF ONE PLY VENEER OF VARIOUS SPECIES.

SPECIES.	Specific Gravity Oven dry Based on volume air dry.	Air Dry Moisture Content in percentage.	THICKNESS IN INCHES. $\frac{1}{100}$	$\frac{1}{80}$	$\frac{1}{64}$	$\frac{1}{60}$	$\frac{1}{55}$	$\frac{1}{48}$	$\frac{1}{40}$	$\frac{1}{32}$	$\frac{1}{28}$	$\frac{1}{24}$	$\frac{1}{20}$	$\frac{1}{16}$	$\frac{1}{12}$	$\frac{1}{10}$	$\frac{1}{8}$	$\frac{1}{6}$	$\frac{3}{16}$	$\frac{1}{4}$
Ash, Black	.50	10.4	.42	.52	.65	.69	.78	.87	1.04	1.30	1.49	1.74	2.08	2.60	3.47	4.16	5.20	6.94	7.81	10.41
Ash, White	.64	8.7	.53	.67	.83	.89	.97	1.11	1.33	1.67	1.9	2.22	2.66	3.33	4.44	5.3	6.66	8.88	10.00	13.32
Birch, Yellow	.63	9.6	.52	.66	.82	.87	.95	1.09	1.31	1.64	1.87	2.19	2.62	3.28	4.37	5.24	6.56	8.74	9.84	13.12
Basswood	.38	8.4	.32	.40	.49	.53	.58	.66	.79	.99	1.13	1.32	1.58	1.98	2.64	3.16	3.96	5.28	5.94	7.92
Beech	.63	11.2	.52	.66	.82	.87	.95	1.09	1.31	1.64	1.87	2.19	2.62	3.28	4.37	5.24	6.56	8.74	9.84	13.12
Cedar	.34	7.3	.28	.35	.44	.47	.51	.59	.71	.88	1.01	1.18	1.42	1.77	2.36	2.83	3.54	4.72	5.31	7.08
Cottonwood	.43	4.7	.36	.45	.56	.60	.65	.75	.90	1.12	1.28	1.49	1.79	2.24	2.98	3.58	4.47	5.97	6.71	8.96
Mahogany, African	.46	5.6	.38	.48	.60	.64	.70	.80	.96	1.20	1.37	1.60	1.92	2.39	3.19	3.83	4.79	6.38	7.18	9.58
Mahogany, American	.49	7.9	.41	.51	.65	.68	.75	.85	1.02	1.28	1.46	1.70	2.04	2.55	3.50	4.08	5.10	6.80	7.66	10.20
Poplar, Yellow	.41	6.1	.34	.43	.53	.57	.62	.71	.85	1.07	1.22	1.42	1.71	2.13	2.84	3.41	4.27	5.69	6.40	8.54
Sycamore	.50	9.2	.42	.52	.65	.69	.76	.87	1.04	1.30	1.49	1.73	2.08	2.60	3.47	4.16	5.20	6.94	7.82	10.41
Spruce	.38	8.9	.32	.40	.49	.53	.58	.66	.79	.99	1.13	1.32	1.58	1.98	2.64	3.16	3.96	5.28	5.94	7.92
Walnut	.57	4.8	.47	.59	.74	.79	.86	.99	1.19	1.48	1.70	1.98	2.37	2.97	3.96	4.75	5.94	7.92	8.91	11.87

In estimating glued-up Panels allow { 0.3 oz. per sq. foot for Blood Albumin / 0.4 oz. per sq. foot for Casein Cements } For each Glued Surface.

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