

# Plywood and Plastics—III

## Basic Design Factors and Stress Data for Plywood Structures : The Simple Plywood Fuselage : Moulded Plywood Design

By W. NICHOLS, A.R.Ae.S.

THE previous article concluded with an approach to the subject of tangential and radial shrinkage of wood. It was stated that all woods shrink more tangentially (parallel to the growth rings) than radially (perpendicular to the growth rings). It was pointed out that the ideal wood for aircraft purposes would be one in which a low percentage of shrinkage was combined with a low ratio between the amount of shrinkage in either direction, the optimum ratio being 1.0, a condition never found in practice. The ratio for various species is shown in Fig. 10.

From Table 12 it will be seen this ratio varies from 1.28 in yellow birch to 2.16 in beech. In the manufacture of veneers these shrinkage values may be emphasised, depending on the method of cutting. With rotary-cut stock, the broad surface is all tangential wood, and this shrinks a great deal more laterally than in thickness.

In quarter-sliced stock only the radial face is in evidence, and the whole piece is more stable. In flat-sliced stock the predominating flat surface is radial, and this is also more uniform than rotary-cut veneer. It is this fact which accounts for the greater amount of "buckle" in rotary veneers.

### Moisture Content

Obviously panels made of rotary-stock woods having a high ratio, as indicated in Table 12, are much more apt to develop internal stresses due to shrinking than are panels made of quartered or sliced stock, particularly on the thin panels commonly used for aircraft purposes.

One of the first and most important characteristics to be understood in connection with wood veneer is the moisture content, a wrong value of which can make an otherwise perfect piece of wood worthless. Wood will always absorb or give out moisture until it is in equilibrium with the humidity of the surrounding atmosphere. At the same time there will be a corresponding change of dimensions. Wood, as already explained, is made up of a substance, mostly cellulose and lignin, expanded by virtue of its cellular structure to a specific gravity usually below that of water. Change of dimensions will occur, due to the absorption of water in this substance, and not in the pores of the wood, which, incidentally, does not cause appreciable swelling. Dense woods, therefore, will swell more than light porous woods, due to the greater amount of wood substance in a given volume of dense wood

than light wood, a point to be remembered in air design. As wood becomes drier, the majority of its strength characteristics are rapidly increased, thus the obvious conclusion is to use exceptionally dry woods and to utilise a protective coating on the surface to maintain this moisture content as low as possible. Experience has shown, however, that the stress or the proportional limit increases at a greater rate than does the modulus of rupture or the modulus of elasticity.

The material appears to lose ductility in a dried-out condition, and there is a limited plastic flow range before failure takes place. A starved-glued joint is liable to occur in gluing if the moisture content is too low. Also, if the moisture content of one ply is greater than that of another there will be a tendency for the panel to buckle or warp, because the content of each ply will tend to balance under any humidity conditions of the air. It has been determined that a moisture content of 7 per cent. to 9 per cent. is the most efficient in affording a good bond between the veneers, which are usually kept stored at this content by holding the relative humidity of normal temperatures within a range of approximately 30 per cent. to 40 per cent. at 60 deg. F., as

shown on the chart, Fig. 11. In moulded plywood construction, for example, if the moisture content of the veneers is fairly high, a longer period under the application of heat would be needed during the moulding process. This would result in boiling out of moisture from the cellular structure of the wood, with a consequent low ductility and an exceedingly brittle material.

Tensile strength apparently is not affected. It has been shown, in tests made on European woods by Gerngross at the Technical University of Berlin, that the effect of heating to 284 deg. F. for varying periods of time had little

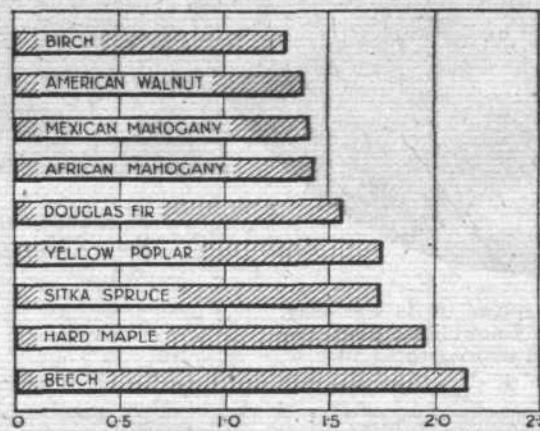


Fig. 10. Ratio of tangential to radial shrinkage of various woods.

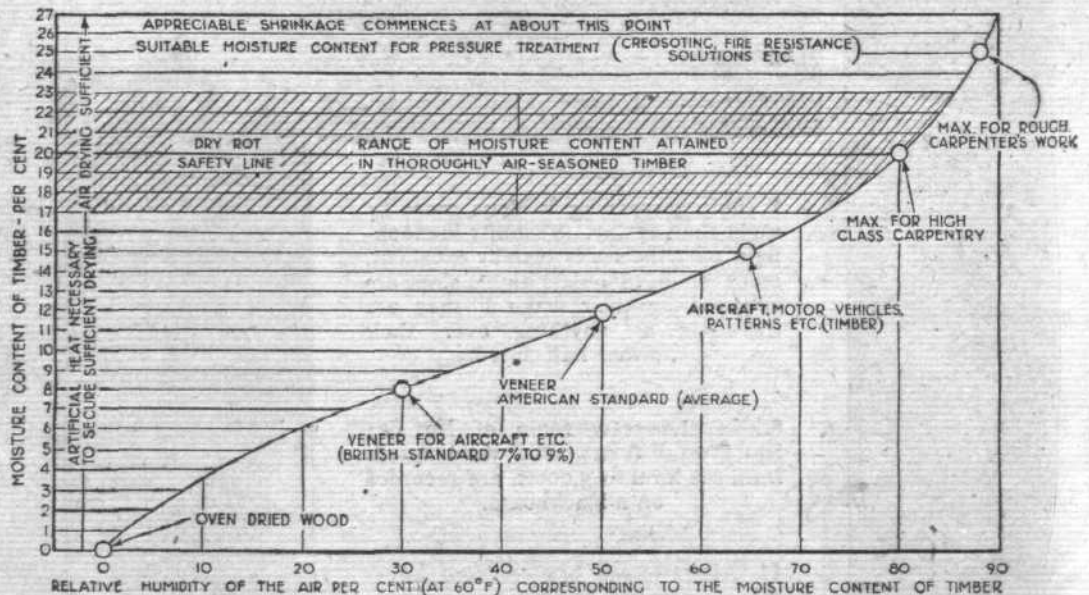


Fig. 11. Range of moisture content, seasoned timber.

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applied to unit area can be one of the decisive factors in determining the quality of a glued joint.

Mr. Thomas Perry, an authority upon plywood manufacture in America, has provided this simple rule: The glue spread in pounds per thousand sq. ft. is numerically equal to the weight in grams, plus 10 per cent. of the weight in grams of the glue on the two sides of a square foot of veneer. Thus, by taking a square foot of veneer and obtaining the weight of it in grams, then passing it through the glue spreader and obtaining the weight again in grams, the difference in weight obviously is the weight of glue on the two sides of the veneer. Assuming the difference to be 30 grams, then, according to the Perry rule, glue spread in pounds of a thousand sq. ft. will be 33 lb. (i.e., 30, plus one-tenth of 30), or 3.3 lb. per 100 sq. ft.

Aero-Research, Ltd., have recently prepared a useful chart for converting weight of glue in grams on 2 sq. ft. into glue spread in lb. per 100 sq. ft. This is reproduced in Table 13. Normally, about 3 lb. per 100 sq. ft. is correct for smooth, hard veneers, such as good-quality birch, etc., and in any case it is rarely necessary to exceed 4½ lb. per 100 sq. ft.

So far, the various characteristics of wood veneer and modern adhesives have been dealt with at some length; and, though much of this information may appear to apply mainly from a practical standpoint, it has been deliberately

TABLE 13  
TABLE FOR CONVERTING WEIGHT OF GLUE IN GRAMS ON TWO SQUARE FEET INTO GLUE SPREAD IN POUNDS ON A HUNDRED SQUARE FEET

Grams/2 sq. ft. Lb./100 sq. ft.	20 2.20	21 2.31	22 2.42	23 2.54	24 2.65	25 2.76	26 2.87
Grams/2 sq. ft. Lb./100 sq. ft.	27 2.98	28 3.09	29 3.20	30 3.31	31 3.42	32 3.53	33 3.64
Grams/2 sq. ft. Lb./100 sq. ft.	34 3.75	35 3.86	36 3.97	37 4.08	38 4.19	39 4.30	40 4.41
Grams/2 sq. ft. Lb./100 sq. ft.	41 4.52	42 4.63	43 4.74	44 4.85	45 4.96	46 5.07	47 5.18
Grams/2 sq. ft. Lb./100 sq. ft.	48 5.29	49 5.40	50 5.51	51 5.62	52 5.73	53 5.84	54 5.95
Grams/2 sq. ft. Lb./100 sq. ft.	55 6.06	56 6.17	57 6.28	58 6.39	59 6.50	60 6.61	61 6.72

included for the reason that the design of any structure must essentially be based upon a clear understanding of the various characteristics of the material being used.

The simplest use to which plywood can be put in aircraft construction is bracing by flat panels against shear loads, and in this respect it has been used extensively in the fuselage construction of light aircraft, solid timber being used to advantage wherever its properties are superior to those of plywood, such as for longerons, stiffeners, struts, etc. Investigations into a fuselage of this construction

were conducted by Aero-Research Ltd., in the past, and results published by them are of interest in leading to the more modern and complicated design problems of moulded plywood construction.

The apparent purpose of the plywood panel to act as a shear resistant web when no stiffeners are present is mis-

leading, due to the considerable depth of the fuselage side and the correspondingly large area of unsupported ply which result in the material being unable to take appreciable compression. Actually in this application the plywood acts

similarly to a large number of parallel wires. As these extend under load along one diagonal there is a corresponding contraction along the other diagonal, with the result that the plywood begins to buckle.

Providing the ultimate tensile strength has not been exceeded, this buckling disappears when the load is removed and is not necessarily a sign of imminent failure. Such a structure, however, is weak; the tension in the ply is high, due to the bad angle of the tension lines, and the tendency is for the longerons to be pulled together. With the absence of stiffeners to give support the longeron soon fails in compression through instability; therefore stiffeners become necessary.

As will be seen from the sketch, Fig. 14, the addition of stiffeners results in a great improvement, both in the angle of the tension lines of the ply and the longerons in compression, as the latter are now fairly well supported. The stiffeners are spaced to divide the side of the fuselage into approximately square panels and the tension lines in the ply run from corner to corner at approximately 45 deg. An interesting point is that adding further stiffeners to this spacing does not improve the angle of tension, and so far as the plywood is concerned, nothing is gained by such an increase over that sufficient to divide the surface into square panels.

Determining Size of the Stiffeners

At sections where the bending moment is high, however, the ratio of spacing to fuselage depth must be increased to support the compression longeron against buckling before its ultimate compressive strength is reached. These conditions are realised very simply in practice by maintaining a constant separation between the stiffeners and by reducing the depth of the fuselage towards the tail.

Assuming that there are enough stiffeners to place the tension lines at 45 deg., then from the diagram in Fig. 15, if P be the force applied to one end of the fuselage, the component acting at 45 deg. will be P/√2, and the cross-sectional area of ply of thickness t cut by the tension lines will be ht/√2. The tensile stress, in lb./sq. in. will therefore be  $f = 2P/ht$ . Forces in the compression and tension longerons comprise those due to the bending moment produced by P, and additional forces due to the horizontal component of the tension in the plywood; thus

$$HT = \frac{Px}{h} - \frac{P}{2} \text{ and } H_c = \frac{Px}{h} + \frac{P}{2}$$

Tension in the ply increases the force in the compression longeron and reduces the tension in the tension longeron.

The force in each stiffener is the vertical component of the tension in the plywood and is given by  $V = P \frac{d}{h}$ . To determine the size of the stiffeners it is only necessary to ensure that the stress as given does not exceed about 5,000 lb./sq. in. for spruce. This procedure is safe because it neglects the contribution to the compressive strength from the plywood in the immediate vicinity of the stiffener. Covering the top and bottom of a box fuselage with plywood is recommended.

From tests of loading to destruction it has been shown that longerons can collapse by buckling sideways at a comparatively small load and can be appreciably stabilised by these plywood panels; torsional rigidity is also much increased by this means. A small gap may be left between

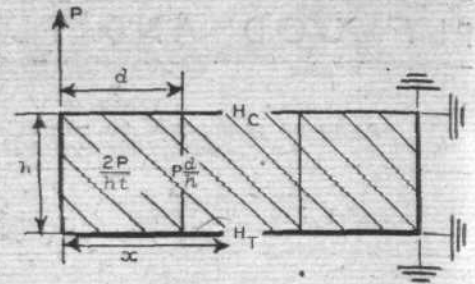


Fig. 15. Stress diagram. Tension lines in plywood show at 45 deg.

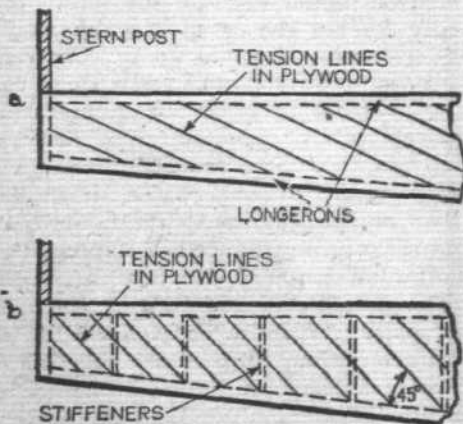


Fig. 14. Tension lines in plywood skin (a) without stiffeners; (b) with stiffeners.

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stiffeners and longerons without ill-effects. Shear forces in the fuselage side panels are greatest between the wing spars, therefore thicker plywood must be used in this region than suffices elsewhere. As this ply can take compression it should be made to do so by adding stiffeners where test shows them to be advantageous. In this instance the simple analysis given above, in which tension forces only are assumed to be acting in the ply, is no longer valid.

A fuselage of this type supplied by Aero-Research Ltd., was bought by the Air Ministry for investigation, and measurements of the deflections of the fuselage under bending and torsional loads were obtained. Notes from these investigations will be now dealt with, the overall dimensions of the rear portion submitted to test being illustrated in Fig. 16. If such a fuselage is regarded purely as a plywood tube, the torsional deflection in radians can be calculated from Bredt's or Batho's formula :

$$\theta = \frac{Tl}{4A^2G} \int \frac{dp}{t}$$

where T = torque  
 dp = element of perimeter  
 l = length of tube  
 A = area enclosed by tube  
 G = rigidity modulus of material.

In the graph Fig. 17 is shown the torsional twist in degrees under a torque of 10,000 lb.-in., applied at the stern post, assuming the value of G for plywood to be  $1.53 \times 10^5$ . The experimentally determined points are shown, and it will be seen that except at the extreme end the agreement is good.

It is stated that in a fuselage of this type the skin buckles under load, and is subjected only to diagonal tension stress ; the skin has no rigidity against shearing stresses. In these circumstances the conception of a rigidity constant becomes meaningless, and G must be replaced by some other modulus. Consequently the use of Bredt's formula in the above form is open to objection.

The deflection of a shear resistant panel is given by

$$\delta_s = \frac{Pl}{Gth}$$

where P = applied load  
 l = length of panel  
 h = depth of panel  
 t = thickness of panel

The deflection of a panel under diagonal tension is

$$\delta_t = \frac{\Delta Pl}{Eth}$$

where E = Young's modulus along the tension lines.

Therefore in the derivation of Bredt's formula  $\delta_t$  is substituted for  $\delta_s$  giving the modified equation

$$\theta = \frac{Tl}{A^2E} \frac{dp}{t}$$

From this it will be seen that when the tube is so thin that it is in a state of diagonal tension G must be replaced by

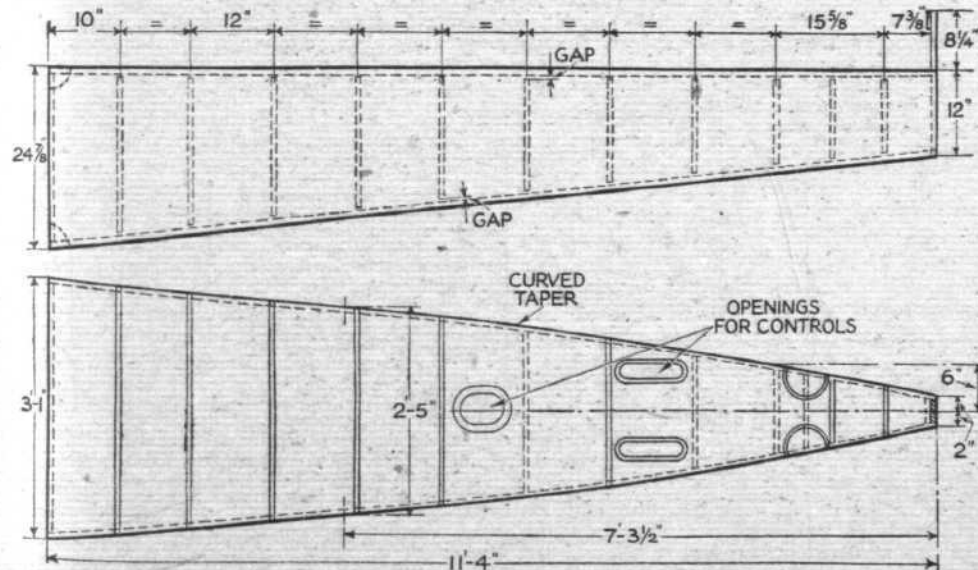


Fig. 16. Overall dimensions of the rear fuselage submitted to test.

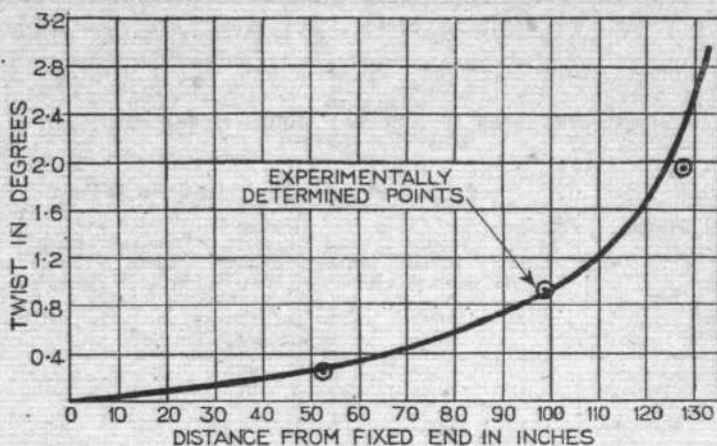


Fig. 17. Torsional twist in degrees under torque load applied at sternpost.

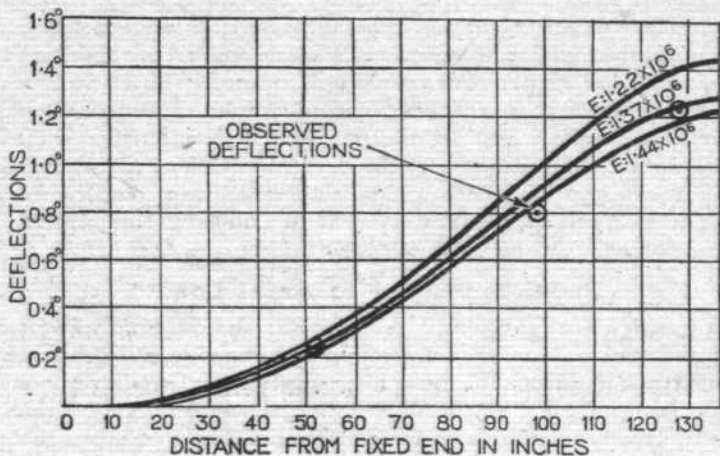


Fig. 18. Deflections of the fuselage under test.

E/4. The value of Young's modulus for birch plywood with Bakelite adhesive at 45 deg. to the grain is about  $.5 \times 10^6$  lb./sq. in. The value of E/4 should, therefore, be  $1.25 \times 10^5$  which, in view of the difficulties in obtaining consistent results in measuring the deflections, may be said to be in good agreement with the value  $1.53 \times 10^5$  used previously.

Curves are also shown in Fig. 18 for the computed deflections of the fuselage under an up-load of 1,000 lb. at the stern post, using three different values of E and assuming that the deflection is due to pure bending and is resisted by four longerons only, without assistance from the skin. The three values of E correspond to the mean and two extreme values for the spruce used. The observed deflections are also shown and are rather below the computed curves, due to the fact that a small portion of the plywood on the compressive side and a larger portion on the tension side does assist the longerons to resist bending.

Moulded Plywood Construction

Having briefly dealt with these aspects for the most simple type of fuselage incorporating plywood construction, the recent development of moulded plywood construction will be considered.

One of the first things an engineer must know about any material is the modulus of elasticity. In this respect wood is a little more difficult than other materials since each species has a different value parallel and perpendicular to the direction of the grain. To calculate the modulus of elasticity for any construction of plies and species, Gassner, in the *Journal of the Aeronautical Sciences*, March, 1942, offers a means of working backwards from test data on three-ply panels to

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TABLE 14  
BASIC STRENGTHS OF AIRCRAFT WOODS 12 PER CENT.  
MOISTURE CONTENT

Species	Parallel to Grain			Perpendicular to Grain		
	Mod. of Elast. 1,000 lb./sq. in.	Tension Stress lb./sq. in.	Comp. Stress lb./sq. in.	Mod. of Elast. 1,000 lb./sq. in.	Tension Stress lb./sq. in.	Comp. Stress lb./sq. in.
Birch ...	2,180	16,600	8,170	106.5	810	399
Spruce ...	1,367	10,200	5,610	51.4	384	211
Red Gum ...	1,535	11,900	5,800	56.9	442	215
Basswood ...	1,160	8,700	4,730	36.8	276	150
Yellow Poplar ...	1,511	9,200	5,290	54.6	393	191
African Mahogany	1,335	10,700	5,670	101.6	855	432

determine from these the apparent modulus of the single veneer.

Space available forbids the inclusion of this lengthy analysis, but values obtained have been grouped in \*Table 14 corrected for 12 per cent. moisture content. These values may be checked for accuracy from values obtained from multi-ply panels. Having the modulus of elasticity of each veneer in a composite panel the determination of the apparent modulus for bending characteristics can readily be made, but care must be exercised in choosing the correct modulus for the loading applied.

Panel Subjected to Axial Load

Consider for simplicity a three-ply panel compressed of the same species of veneers subjected to an axial load; the strain in the panel must necessarily equal the strain in each component, i.e., the face and core veneers. Also the total force required to strain the panel must be equal to the total of the forces in the component parts; therefore it can be shown that

$$E_{pa} \Delta_p t_p = t_f E_f \Delta_f + t_c E_c \Delta_c$$

where  $E_{pa}$  = Modulus of elasticity of the panel

$\Delta_f$  = Strain of the face veneers

$\Delta_c$  = Strain of the core veneers

$t_f$  = Total thickness of face veneers

$t_c$  = Total thickness of core veneers

$t_p$  = Thickness of panel

but since  $\Delta_p = \Delta_f = \Delta_c$

$$E_{pa} = \frac{t_f}{t_p} E_f + \frac{t_c}{t_p} E_c$$

Employing the same reasoning that the deflection of each veneer in a panel must be equal to the deflection of the panel, and assuming elastic properties of veneers up to failure, a simple method may be applied to a panel to determine

\* From paper presented at the Semi-Annual A.S.M.E. Meeting by G. B. Parsons, Cleveland, U.S.A. June 8th-10th, 1942.

TABLE 15.  
PLYWOOD PANELS OF RECTANGULAR CROSS SECTION.

Computation of Moment of Inertia and Section Modulus.		
Moment of Inertia $I = (K_1 B)/12$		Section Modulus $R = (K_1 B)/(6K_2)$
Grain of Face Plies Parallel to Span.		
No. of plies in panel.	$K_1$	$K_2$
3	$D_1^3 - a^3$	$D_1$
5	$D_2^3 - (a+2b)^3 + a^3$	$D_2$
7	$D_3^3 - (a+2b+2c)^3 + (a+2b)^3 - a^3$	$D_3$
9	$D_4^3 - (a+2b+2c+2d)^3 + (a+2b+2c)^3 - (a+2b)^3 + a^3$	$D_4$
Grain of Face Plies at Right Angles to Span.		
No. of plies in panel.	$K_1$	$K_2$
3	$a^3$	$a$
5	$(a+2b)^3 - a^3$	$(a+2b)$
7	$(a+2b+2c)^3 - (a+2b)^3 + a^3$	$(a+2b+2c)$
9	$(a+2b+2c+2d)^3 - (a+2b+2c)^3 + (a+2b)^3 - a^3$	$(a+2b+2c+2d)$

allowable tension and compression stresses for the separate veneers. Assuming that all veneers in the panel are of the same species and where

$\Delta_L$  = deflection of veneers with grain longitudinal or in direction of applied load

$\Delta_T$  = deflection of veneers with grain transverse or perpendicular to direction of load

$f_p$  = stress in panel

$f_L$  = stress in longitudinal veneers

$f_T$  = stress in transverse veneers

$t_L$  = total thickness of longitudinal veneers

$t_T$  = total thickness of transverse veneers

$t_p$  = total thickness of panel

$E_L$  = modulus of elasticity of longitudinal veneers

$E_T$  = modulus of elasticity of transverse veneers

Then  $f_p t_p = f_L t_L + f_T t_T$ , but  $f_L = \Delta_L E_L$  and  $f_T = \Delta_T E_T$ , solving for a relationship between  $f_L$  and  $f_T$  since  $\Delta_L = \Delta_T$

$$\frac{f_L E_L}{f_T E_T} \text{ Therefore } f_p t_p = f_L t_L + f_L \frac{E_T}{E_L} t_T$$

The above reasoning is due to Parsons, who states that the assumption that elastic qualities hold up to failure should not cause too great an error since the elastic limit of wood is quite close to the ultimate. Also the ratio of  $E_L/E_T$  appears to be greater than the ratio of modulus of rupture longitudinally to modulus of rupture transversely.

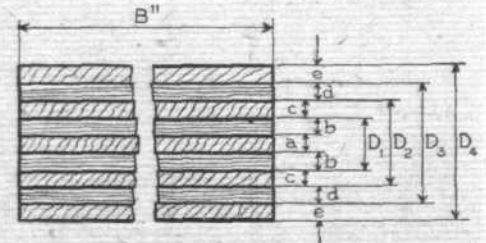
If the construction of the panel is such that the longitudinal veneers are of different species, the strength of the panel is evidently dependent upon the strength of the weaker species, and the allowable strength of the stronger veneer must be reduced so that  $f_L = (E_L/E_T) f_T$ .

Computation of the moment of inertia and section modulus of plywood panels of a rectangular cross-section are given in Fig. 19.

Tests on plywood with various grain angles to the direction of load have demonstrated that the effect of grain angle is pronounced and must be considered in calculating fuselage section properties. The subject is dealt with by L. J. Marhoefer, Chief Engineer, Vidal Research Corporation.† In the graph, Fig. 20, the variation of E with grain angle is presented as a start towards the evaluation of such data.

The concluding article in this series will be published next week.

† Design considerations for Plywood Structures—III. L. G. Marhoefer. Aviation, Jan. 1943.



Cross-section of plywood panel with plane of plies at right angles to direction of load.

$D_1$  = Thickness of 3-ply panel in inches.  
 $D_2$  = Thickness of 5-ply panel in inches.  
 $D_3$  = Thickness of 7-ply panel in inches.  
 $D_4$  = Thickness of 9-ply panel in inches.

Fig. 19. Diagram for Table 15. Computation of moment of inertia and section modulus.

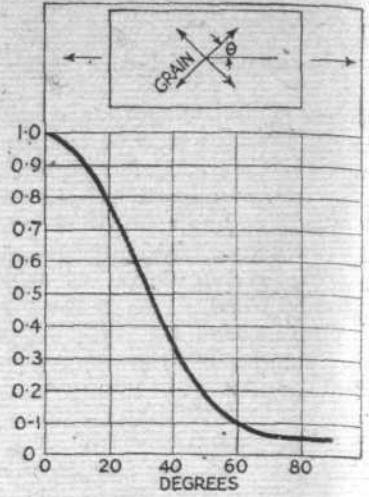


Fig. 20. Variation of mod. of elasticity with grain angle.