Wood Science and Technology Vol. 10 (1976) p. 57–68

Plywood Properties Influenced by the Glue Line

By M. Okuma*
Faculty of Agriculture, University of Tokyo, Japan

Summary. The effect of the number and the location of glue lines in the cross section on the bending properties has been studied on plywood bonded with tannin–formaldehyde adhesive. The thickness of glue line has also been investigated. By comparing the theoretical equations with the empirical ones, we can get the thickness of the glue line of wattle tannin adhesive plywood to be 0.15 mm. As for Young's modulus in bending of the glue line in the plywood, it is calculated to be 219 800 kg/cm^2 and is larger than that of the glue line of phenolic resin bonded plywood. In relation to the veneer, Young's modulus of the veneer under the condition of plywood assembly seems to be slightly larger than that of the veneer under the free condition.

Introduction

Many studies have been carried out on the relationship between mechanical properties of plywood and its construction of veneers [Curry 1954; Sawada 1959; Asano 1963]. The effect of the glue line has been largely overlooked though it cannot be neglected in the following cases:

1. The glue line is very thick.
2. The number of glue lines in unit thickness of the plywood is large.
3. The glue line differs much from the surrounding veneers in mechanical and physical properties.

In this report, the effect of the number and the location of glue lines in the cross section on the bending property of plywood has been studied on plywood bonded with tannin-formaldehyde adhesive. The thickness of glue line has also been investigated.

CSIRO of Australia has carried out research on adhesive properties of tannin for a period of about 20 years and tannin adhesive developed by it has been used commercially by the plywood industry for some years in that country. It becomes necessary to compare the glue line properties of tannin bonded plywood with that of urea and phenolic resin bonded plywood.

Materials and experimental procedure

Veneer

Rotary cut Hoop pine (*Araucaria cunninghamii*) veneers of 0.76 and 1.84 mm thickness were used. Density in the air dry condition was 0.535 g cm^{-3} (average).

* The author wishes to express his gratefulness to CSIRO of Australia for a Fellowship during the tenure of which this research was carried out. The direction and cooperation of Mr. K. F. Plomley, Dr. P. Grossman and Mr. P. Collins, CSIRO of Australia are gratefully acknowledged

Adhesive

The adhesive used was wattle tannin-formaldehyde, and its components were as follows [Plomley 1966]:

	Parts by weight
Wattle tannin extract	100*
Water	113
Wood flour	10
Walnut shell flour	10
Paraformaldehyde	10

* Based on oven dry weight

pH of the glue mixture was adjusted to 7.1 with sodium hydroxide. The glue was spread with a roller spreader and the glue spread was 400 g m^{-2}, double glue line.

Veneer construction

Plywood panels of 9 different constructions were prepared. 3 sheets of plywood (40 cm x 40 cm) were made for each construction. The various constructions are shown in Table 1.

Pressing conditions

Pressing conditions were as follows:

Cold press: 880 kPa, 10 min.
Closed assembly time: 50 min.
Hot press: 980 kPa, 140 °C.
Pressing time: shown in Table 1.

Table 1. Veneer construction

Plywood No.	Veneer construction									n	T
1				0.76	0.76	0.76				3	5.5
2				1.84	1.84	1.84				3	6.5
3				1.84	0.76	1.84				3	6.5
4			0.76	1.84	1.84	1.84	0.76			5	7.5
5			1.84	0.76	0.76	0.76	1.84			5	7.0
6			0.76	0.76	0.76	0.76	0.76			5	6.25
7			0.76	1.84	0.76	1.84	0.76			5	7.0
8		0.76	0.76	0.76	0.76	0.76	0.76	0.76		7	6.5
9	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	9	7.5

n: Number of plies
T: Hot pressing time (min)
0.76, 1.84: Thickness of matched veneer (mm)

Test specimens

The prepared plywood sheets were kept in a conditioning room for ten days prior to being cut into bending specimens. The specimens were then left in the laboratory for more than a month before testing.

Measurement of density

To obtain the density of the plywood, the sizes and weights of the bending specimens were measured. Moisture content of the specimens was about 12% at that time.

Measurement of Young's modulus in bending

The bending test (centre point loading) to obtain Young's modulus was carried out using an Instron testing machine. The ratio of the span to the thickness of the specimen was always 24 and the loading speed was 2 mm/min.

Method of indicating veneer construction

The method used to indicate the veneer construction of the plywood is shown in Fig. 1 and is for the case where n = 5, i. e. 5-ply.
In relation to the glue line, it may be assumed that there is no independent glue layer in the cross section of the plywood. The portion of the veneer where glue penetrates is considered to be the glue line.

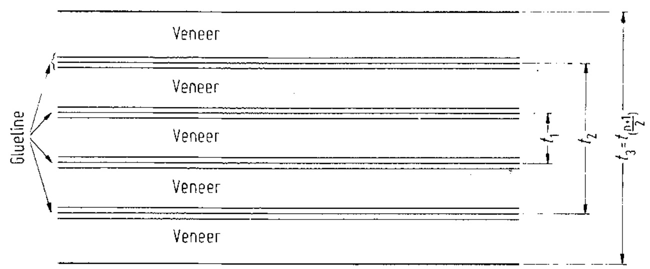

Fig. 1. Cross section of plywood, showing t_i and glue line, in the case of n = 5 (5 plies)

Experimental results and discussions

Density of plywood

The density of plywood, ρ_p, will depend on the density of the veneer, the compression of the veneer during hot pressing [Lyngcoln, Gottstein 1967] and the amount of the glue spread. If it is assumed that the decrease in thickness of the veneers making up the plywood is the same for each veneer and the depth of glue penetration into each veneer is always the same, then the following equation is applied (cf. Appendix).

$$\rho_p = \rho_v + (\rho_r - \rho_v)\, t_r K_1 , \qquad (1)$$

$$K_1 = \frac{n-1}{t} , \qquad (2)$$

where n: number of plies
t: thickness of the plywood
t_r: thickness of the glue line
ρ_p, ρ_v, ρ_r: respectively, density of the plywood, density of the veneer in the plywood (under the condition of making up the plywood) and density of glue line.

K_1 shows the number of glue lines in unit thickness of the plywood, i. e. K_1 is a coefficient of plywood with respect to the veneer construction and is calculated from Eq. (2).

Table 2. Experimental results of the density of plywood

	Plywood No. 1	2	3	4	5	6	7	8	9
t_0	2.28	5.52	4.44	7.04	5.96	3.80	5.96	5.32	6.84
t	2.15	5.24	4.30	6.68	5.59	3.58	5.56	4.92	6.34
K_1	9.28	3.85	4.64	6.01	7.15	11.10	7.09	12.16	12.78
ρ_p	0.643	0.593	0.595	0.615	0.623	0.654	0.643	0.687	0.690

t_0: Total thickness of the assembled veneers (mm)
t: Thickness of plywood (mm)
K_1: Coefficient with respect to veneer construction, cf. Eq. (2) (cm^{-1})
ρ_p: Density of plywood ($g\,cm^{-3}$)

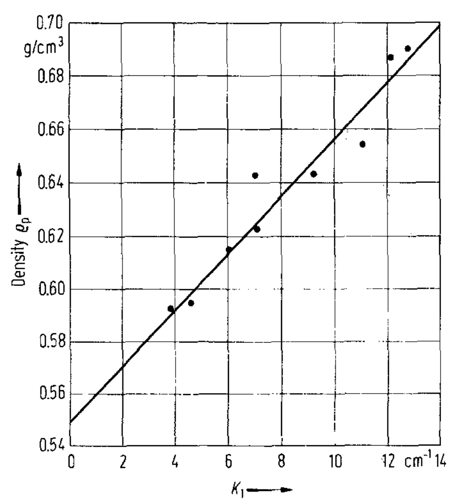

Fig. 2. Relationship between density of the plywood ρ_p and K_1. K_1: Coefficient with respect to veneer construction, cf. Eq. (2)

We also have experimental results of the density of plywood, as shown in Table 2. Then, by plotting these experimental results together with K_1, we obtain the graph as shown in Fig. 2. The following empirical equation is then derived.

$$\rho_p = 0.550 + 0.0107 K_1 \text{ (g cm}^{-3}\text{)} . \quad (3)$$

Now, we can get the values of t_r and ρ_v by comparing the constants of both equations against each other. Comparing the constants, we find the values of $(\rho_r - \rho_v) t_r$ and ρ_v are

$$(\rho_r - \rho_v) t_r = 0.0107 = a = \text{constant} \text{ (g cm}^{-2}\text{)} , \quad (4)$$

$$\rho_v = 0.550 \qquad \text{(g cm}^{-3}\text{)} . \quad (5)$$

The density of the glue line ρ_r, should be known in order to calculate t_r. In the case where no glue is applied, there are two equations relating C and ρ_u, where ρ_u is the veneer density of the area anticipated to be the glue line. C is the ratio of the void area in the anticipated glue line to the total area of the anticipated glue line.

$$C = 1 - 0.641 \rho_u \qquad (3.5) , \quad (6)$$

$$\rho_r = C \rho_0 \alpha + \rho_u \quad (7)$$

where ρ_0: density of the cured glue
α: ratio of the glue penetration into the void of veneer
0.641: the reciprocal of the estimated density of wood substance.

From Eqs. (6) and (7), Eq. (8) is derived.

$$\rho_r = (1 - 0.641 \rho_u) \rho_0 \alpha + \rho_u . \quad (8)$$

Then Eq. (9) is gained from Eqs. (4) and (8).

$$\{(1 - 0.641 \rho_u) \rho_0 \alpha + \rho_u - \rho_v\} t_r = a . \quad (9)$$

On the other hand, the total weight of whole veneers before hot pressing is equal to the weight of the wooden portion in the manufactured plywood; then we can get Eq. (10).

$$t' \rho'_v = \{t - (n - 1) t_r\} \rho_v + (n - 1) t_r \rho_u , \quad (10)$$

where n: number of plies
ρ'_v: density of the veneer (under the free condition)
t': total thickness of assembled veneers.

Now, from Eqs. (9) and (10), Eq. (11) is gained.

$$t_r = \frac{a - \frac{1}{n-1} (1 - 0.641 \rho_0 \alpha) (t' \rho'_v - t \rho_v)}{(1 - 0.641 \rho_v) \alpha \rho_0} . \quad (11)$$

We can calculate from Eq. (11) the thickness of the glue line of wattle tannin adhesive plywood to be 0.015 cm, using a = 0.0107, ρ_v = 0.550, α = 0.75 (value of W. T. Curry's thesis [Curry 1957], ρ_0 = 1.407 (experimental datum) and other data from Table 2.

In the past, many attempts to determine the thickness of the glue line have been carried out, however, most of them were done by observation of the glue lines with a microscope. In this case, it is rather difficult to know the limit of the glue penetration into the veneer and it needs many observations to gain an average thickness of glue line. W. T. Curry obtained the value of 0.012–0.018 cm for urea resin bonded plywood by calculation of the amount of glue in the glue line and the compression of veneers during hot pressing [Curry 1957]. The author has obtained the value of 0.017 cm for phenolic resin bonded plywood by this density method. It is a little larger than the value for the wattle tannin glue line. However, we may consider the average thickness of wattle tannin glue line in the plywood to be approximately 0.015 cm.

In relation to the density of the veneer in the plywood (under the condition of making up the plywood), the value of 0.550 g cm^{-3} has been obtained. This is a little larger than the value under the free condition (ρ_v' = 0.535 g cm^{-3}) and was probably caused by the compression of veneers during hot pressing. The density of the veneer in the plywood is different from that of the free veneer.

Young's modulus in bending of the plywood

Calculating equation

We have the following equation when regarding the bending of plywood as the bending of the combined beam,

$$E = \frac{\Sigma (e_j I_j)}{I'} \qquad (12)$$

where, E: Young's modulus of the plywood
e_j: Young's modulus of j layer (veneer or glue line)
I_j: moment of inertia to the neutral axis of the plywood of j layer,
I': moment of inertia of the plywood.

Now, when we apply Eq. (12) to n-ply plywood and neglect the terms of t_r^2 and t_r^3 (they are very small), the following equations are derived (cf. Appendix):

$$E_1 = e_1 - (e_1 - e_2) K_2 + 3 t_r (2 e_r - e_1 - e_2) K_3 , \qquad (13)$$

$$E_2 = e_2 + (e_1 - e_2) K_2 + 3 t_r (2 e_r - e_1 - e_2) K_3 , \qquad (14)$$

$$K_2 = \frac{\sum_{i=1}^{\frac{n-1}{2}} (-1)^{\frac{n-1+2i}{2}} t_i^3}{t^3_{\left(\frac{n+1}{2}\right)}} , \qquad (15)$$

$$K_3 = \frac{\sum_{i=1}^{\frac{n-1}{2}} t_i^2}{t^3_{\left(\frac{n+1}{2}\right)}} \tag{16}$$

where, E_1, E_2: Young's modulus of the plywood, where the grain of the face veneer is respectively parallel and perpendicular to the span direction.

e_1, e_2: Young's modulus of the veneer in the plywood, under the condition of assembly of the plywood, in which the grain is respectively parallel and perpendicular to the span direction.

e_r: Young's modulus of the glue line in the plywood.

$t_1 \ldots t_2 \ldots t_{\left(\frac{n+1}{2}\right)}$: cf. Fig. 1.

K_2 and K_3 are the coefficients of the plywood with respect to the veneer construction and can be calculated when the veneer construction of the plywood is fixed. The values of K_2 and K_3 of the prepared plywood sheets are shown in Table 3.

Table 3. Results of bending test

	Plywood No. 1	2	3	4	5	6	7	8	9
K_2	0.032	0.037	0.005	0.469	0.054	0.204	0.415	0.291	0.334
K_3	0.52	0.21	0.07	1.03	0.29	0.90	1.02	1.46	1.64
E_1	141.4	145.6	132.3	89.4	143.8	124.0	95.3	131.1	118.0
E_2	14.3	13.3	6.4	80.7	15.7	40.2	77.0	61.0	65.4
$E_1 + E_2$	155.7	158.9	138.7	170.1	159.5	164.2	172.3	192.1	183.4
$E_1 - E_2$	127.1	132.3	125.9	8.7	128.1	83.8	18.3	70.1	52.6

K_2, K_3: Coefficients of plywood with respect to veneer construction, cf. Eqs. (15) and (16). Unit K_3: cm^{-1}

E_1, E_2: Young's modulus in bending, when grain of the face veneer is respectively parallel and perpendicular to the span ($10^2\,N\,mm^{-2}$)

From Eqs. (13) and (14)

$$E_1 + E_2 = e_1 + e_2 + 6(2e_r - e_1 - e_2)\,t_r K_3\,, \tag{17}$$

$$E_1 - E_2 = (e_1 - e_2)(1 - 2K_2)\,. \tag{18}$$

These equations show that $E_1 + E_2$ has a linear relationship to the coefficient K_3 and $E_1 - E_2$ also has a linear relationship to its coefficient K_2.
On the other hand, experimental results are shown in Table 3 and Figs. 3 and 4 represent the relationships between $E_1 + E_2$ and K_3, $E_1 - E_2$ and K_2. Then, the following empirical equations are derived:

$$E_1 + E_2 = 145\,500 + \;\; 26\,000\,K_3 \;\; (kg\,cm^{-2})\,, \tag{19}$$

$$E_1 - E_2 = 138\,500 - 269\,000\,K_2 \;\; (kg\,cm^{-2})\,. \tag{20}$$

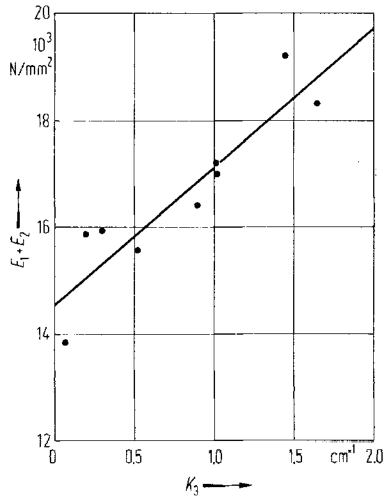

Fig. 3. Relationship between $E_1 + E_2$ and K_3. K_3: Coefficient of plywood with respect to veneer construction, cf. Eq. (16); E_1, E_2: Young's modulus, when grain of the face veneer is respectively parallel and perpendicular to span

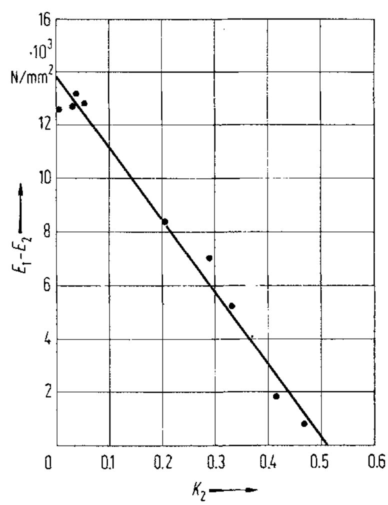

Fig. 4. Relationship between $E_1 - E_2$ and K_2. K_2: Coefficient of plywood with respect to veneer construction, cf. Eq. (15)

These equations become

$$E_1 = 142\,000 - 134\,600\,K_2 + 13\,000\,K_3\ (\mathrm{kg\,cm^{-1}})\,, \tag{21}$$

$$E_2 = 3500 + 134\,600\,K_2 + 13\,000\,K_3\ (\mathrm{kg\,cm^{-1}})\,. \tag{22}$$

We can now calculate Young's modulus of the wattle tannin plywood for all kinds of veneer constructions using Eqs. (21) and (22).

The coefficients K_2 and K_3

In the process of deriving Eqs. (13) and (14), we get an equation without the term of K_3 when the existence of glue lines is ignored. This means that K_3 is a coefficient which has some relationship to the effect of the glue line on Young's modulus in bending. The value of K_3 becomes larger as the plywood increases in the number of glue lines and also with the location of glue lines closer to the surface of the plywood.

Up to now, the effect of the glue line on the mechanical properties of the plywood has been neglected in most cases [Curry 1956; Kollmann 1951; Sawoda 1959; Asano 1963]. As mentioned before, if the glue line is ignored, Eq. (17) becomes Eq. (23).

$$E_1 + E_2 = e_1 + e_2 \, . \tag{23}$$

Eq. (23) means that $E_1 + E_2$ is always constant, even if the veneer construction changes ($e_1 + e_2$ = constant). However, as shown in Fig. 3, $E_1 + E_2$ increases distinctly with K_3. So it seems that it is impossible to ignore the existence of the glue line in some cases.

On the other hand, K_2 is a coefficient which is related to the effect of the combination of veneer to Young's modulus in bending. From Eq. (18) we get $K_2 = 0.5$ in the case of $E_1 = E_2$, i. e. the plywood with coefficient K_2 equal to 0.5 is isotropic. For example, in the case of 3 ply-plywood, $K_2 = t_1^3/t_2^3 = 0.5$ leads to $t_1/t_2 = 0.8$.

This means that the plywood, of which the thickness of the core veneer is 80% of the total thickness, has the same Young's modulus in perpendicular and parallel direction to the grain of the face veneer.

Young's modulus of the glue line and the veneer

By comparing the theoretical Eqs. (13) and (14) with the empirical Eqs. (21) and (22), we can get Young's modulus in bending of the glue line and the veneer in the plywood (under the condition of plywood assembly). The results are shown in Table 4. The results of phenolic plywood, which the author obtained in the previous test by the same method [Okuma 1967] are also quoted in the Table. In the case of phenolic resin bonded plywood, rotary cut Bagtikan (*Parashorea malaanonan* Merr.) veneers of 1.05 mm and 2.05 mm thickness were used. Air dry density was 0.555 g cm^{-3} (average). The results are summarized as follows:

In relation to the veneer, the value of e_1 is much larger than that of e_2 and we may be able to neglect e_2 in some cases in calculating Young's modulus of the plywood. e_1 is Young's modulus of the veneer under the condition of plywood assembly and E_w is Young's modulus of the solid wood, Hoop pine [Bolza, Kloot 1963] and Bagtikan [Sudo 1965], under the free condition. E_w seems to be very close to Young's modulus of the veneer when the loading direction is parallel to the grain direction.

Table 4. Young's modulus of glue line and veneer in the plywood

Glue	Young's modulus (10^2 Nmm^{-2})			
	e_1	e_2	e_r	E_w
Tannin-formaldehyde	140.9	4.7	219.8	132.0*
Phenol-formaldehyde	134.9	5.3	185.5	124.0**

e_1, e_2: Young's modulus of the veneer (under the condition of assembly of the plywood) of which grain is respectively parallel and perpendicular to the span direction
e_r: Young's modulus of the glue line
E_w: Young's modulus of the solid wood, of which grain direction is parallel to the load direction

* Hoop pine
** Bagtikan

Then, comparing e_1 with E_w, e_1 is slightly larger than E_w. The reason may be that the density of the veneer in the plywood becomes larger by compression during hot pressing [Lyngcoln, Gottstein 1967].
As mentioned before, the glue line consists of wood and adhesive. Young's modulus of the glue line e_r is larger than moduli of both components (Young's modulus of the moulded phenolic resin is about 1.0 Nmm^{-2} [Anonymus 1950]. The reason for this fact is not clear at present. However, Van Vlack [1964] points out that the mixture of two materials, such as wood flour and resin, carbon and rubber, sand and tar etc., is stronger than either alone. In the first example, the wood flour prevents shear slip in the resin and maximum strength is developed with intermediate compositions, with the two phases strengthening each other.
Young's modulus of the glue line may have some relation to this interactive property. However, Young's modulus of the glue line of wattle tannin plywood is very large and is larger than that of phenolic resin bonded plywood.

Appendices

Derivation of Eq. (1)

The volume of the veneer is proportional to $t - (n - 1)\,t_r$, the volume of the glue line to $(n - 1)\,t_r$. The weight of the plywood equals the sum of the weights of the veneers and the glue lines, so that for a unit area of sheet

$$\rho_p t = \rho_v [t - (n - 1)\,t_r] + \rho_r (n - 1)\,t_r$$

which rearranged gives Eq. (1).

Derivation of Eqs. (13)–(16)

E_1 and E_2 can be calculated as follows when we fix the notation of the cross section of plywood as shown in Fig. 1.

In the case of 5-ply,

$$E_1 = \frac{\Sigma(e_j I_j)}{I'} = \frac{12}{b t_3^3}\left[\frac{b(t_1 - t_r)^3}{12} \cdot e_1 + \frac{2b}{3}\left\{\left(\frac{t_1 + t_r}{2}\right)^3 - \left(\frac{t_1 - t_r}{2}\right)^3\right\} e_r + \right.$$
$$+ \frac{2b}{3}\left\{\left(\frac{t_2 - t_r}{3}\right)^3 + \left(\frac{t_1 + t_r}{2}\right)^3\right\} e_2 + \frac{2b}{3}\left\{\left(\frac{t_2 + t_r}{2}\right)^3 + \left(\frac{t_2 - t_r}{2}\right)^3\right\} e_r +$$
$$\left. + \frac{2b}{3}\left\{\left(\frac{t_3}{2}\right)^3 - \left(\frac{t_2 + t_r}{2}\right)^3\right\} e_1\right] = \frac{1}{t_3^3}[e_1 \{t_3^3 - t_2^3 + t_1^3 - 8 t_r (t_2^2 + t_1^2) +$$
$$+ 3 t_r^2 (t_1 - t_2) - 2 t_r^3\} + e_2 \{t_2^3 - t_1^3 - 3 t_r (t_2^2 + t_{12}) + 3 t_r^2 (t_2 - t_1) - 2 t_r^3\} +$$
$$+ e_r \{6 t_r (t_2^2 + t_1^2) + 4 t_r^3\}]$$

neglecting the terms of t_r^2 and t_r^3 (which are very small compared with t_1, t_2).

$$E_1 = e_1 - (e_1 - e_2)\frac{t_2^3 - t_1^2}{t_3^3} + 3 t_r (2 e_r - e_1 - e_2)\frac{t_2^2 + t_1^2}{t_3^3} .$$

Similarly,

$$E_2 = e_2 + (e_1 - e_2)\frac{t_2^3 - t_1^3}{t_3^3} + 3 t_r (2 e_r - e_1 - e_2)\frac{t_2^2 + t_1^2}{t_3^3} .$$

Then, in the case of n-ply,

$$E_1 = e_1 - (e_1 - e_2)\frac{\sum_{i=1}^{\frac{n-1}{2}} (-1)^{\frac{n-1+2i}{2}} t_i^3}{t^3_{\left(\frac{n-1}{2}\right)}} + 3 t_r (2 e_r - e_1 - e_2)\frac{\sum_{i=1}^{\frac{n-1}{2}} t_i^2}{t^3_{\left(\frac{n-1}{2}\right)}} =$$

$$= e_1 - (e_1 - e_2) K_2 + 3 t_r (2 e_r - e_1 - e_2) K_3 . \qquad (13)$$

Similarly,

$$E_2 = e_2 + (e_1 - e_2) K_2 + 3 t_r (2 e_r - e_1 - e_2) K_3 . \qquad (14)$$

Where

$$K_2 = \frac{\sum_{i=1}^{\frac{n-1}{2}} (-1)^{\frac{n-1+2i}{2}} \cdot t_i^3}{t^3_{\left(\frac{n+1}{2}\right)}} , \qquad (15)$$

$$K_3 = \frac{\sum_{i=1}^{\frac{n-1}{2}} t_i^2}{t^3_{\left(\frac{n+1}{2}\right)}} . \qquad (16)$$

References

Anonymus. 1950. Modern plastic encyclopedia and engineer's handbook. p. 1056
Asano, I. 1963. Some anisotropic properties on the strength of the plywood. J. Society of Materials Science, 12: 761–768
Bolza, E.; Kloot, N. H. 1963. The mechanical properties of 174 Australian timbers. CSIRO Div. For. Prod. Technol. Pap. No. 25
Curry, W. T. 1954. The strength properties of plywood. (2) Effect of the geometry of construction. Forest Prod. Res. Bull. No. 33
Curry, W. T. 1957. The strength properties of plywood. (3) The influence of the adhesive. Forest Prod. Res. Bull. No. 39
Kollmann, F. 1951. Technologie des Holzes und der Holzwerkstoffe 1. Band. 624–636. Berlin 1951: Springer
Lyngcoln, K. J.; Gottstein, J. W. 1967. Compression of Hoop pine assemblies during hot pressing. CSIRO Plywood and Gluing Doc. 103
Okuma, M. 1967. Studies on the mechanical properties of plywood. Bull. of the Tokyo Univ. Forests (63): 1–56
Plomley, K. F. 1966. Tannin-formaldehyde adhesives for wood. (2). CSIRO, Div. For. Prod. Technol. Pap. No. 39
Sawada, M. 1959. Studies on the elasticity of plywood. J. Japan Wood Research Society 5: 45–49, 131–137
Sudo, S. 1965. Tropical wood. 1000 Species. 108–109
Van Vlack, L. H. 1964. Elements of materials science. 2nd Ed., pp. 303, 304, Reading, Mass.: Addison – Wesley

(Received March 25, 1975)

Dr. M. Okuma
Faculty of Agriculture, University of Tokyo
1 Yayoi, Bunkyo-ku, Tokyo 113, Japan