AN ANALYSIS OF FLEXURAL RIGIDITY OF 7-PLY SOUTHERN PINE PLYWOOD STRIPS AT SHORT SPANS PARALLEL TO FACE GRAIN[1]

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ABSTRACT

Two methods for predicting deflection of 7-ply plywood strips in small span-to-depth ratios have been developed and presented together with experimental verification. These methods first require transformation of the cross section of 7-ply plywood into a hypothetical homogeneous cross section with grain direction of all plies parallel to span. With one method, shear deflection is calculated by equating the internal work with the external work of the transformed cross section. With the other method, shear deflection is calculated with an equation based on the assumption that shear deflections in any two similarly loaded beams of the same length, height, and moment of inertia are proportional to the summations of the shear stresses on their respective vertical sections.

Shear and total deflections of 7-ply plywood at short spans, predicted by both methods, are in good agreement with deflections obtained from actual tests.

This paper presents partial results of a study that concerns flexural properties of southern pine plywood. More specifically, it presents an experimentally verified method by which the flexural stiffness of 7-ply southern pine plywood strips can be predicted accurately at short spans parallel to face grain.

It has been shown by March (1936), Biblis (1969), and Biblis and Chiu (1970) that shear deflections at midspan of 3-ply and 5-ply plywood strips at a 24:1 span-to-depth ratio are approximately 26% and 18%, respectively, of the total. Since the use of structural plywood involves the above span-to-depth ratio, shear deflections should be considered in design.

March (1936) developed a theoretical method by which the effective stiffness of a plywood strip with any number of plies and with relatively small span-to-depth ratios can be predicted accurately. March's method, however, requires values of Poisson's ratios in addition to those of moduli of elasticity and rigidity of faces and core (E_f, E_c, G_{LR}, G_{TR}). For most species, including southern yellow pine, values of Poisson's ratios are not known.

March's theoretical treatment for predicting shear deflection assumes plywood with plies of equal thickness. For plywood with veneer plies of unequal thickness, March's equation for shear deflection must be rederived.

Biblis and Chiu (1969 and 1970) developed and verified a simplified method that predicts accurately total deflection of 3-ply and 5-ply pine plywood strips with face grain parallel to span, even at a span-to-depth ratio of 14. In the case of a 5-ply plywood strip, its cross section was transformed into a homogeneous double-I-beam and shear deflection was calculated by equating the internal work with the external work of the hypothetical double-I-beam in flexure. This method predicted total deflections with an average error of less than 6% at a span-to-depth ratio of 24.

This work presents an analysis that is an expansion of the method employed for 5-ply plywood in calculating shear deflection.

A METHOD FOR PREDICTING DEFLECTION OF 7-PLY PLYWOOD STRIPS WITH FACE GRAIN PARALLEL TO SPAN

Total deflection y of a centrally loaded 7-ply plywood strip of rectangular cross sec-

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tion consists of a portion caused by pure bending Y_1, and additional deflection Y_2 caused by sheer stresses.

Pure bending deflection

The deflection caused by pure bending at midspan of a 7-ply plywood strip can be calculated by:

$$Y = \frac{PL^3}{48EI}, \qquad (1)$$

where: P = load within the elastic region, lbs
L = span of plywood strip, inches
I = moment of inertia of the entire cross section with respect to the neutral axis
E = pure modulus of elasticity of plywood strip.

$$EI = \sum_{i=1}^{n} E_i I_i = E_T I_T + E_L I_L, \qquad (2)$$

where:
E_T = pure modulus of elasticity of veneer perpendicular to grain direction (crossbands),
E_L = pure modulus of elasticity of veneer in the longitudinal direction (faces),
I_T = moment of inertia of plies with grain perpendicular to span, with respect to neutral axis of the strip, and
I_L = moment of inertia of plies with grain parallel to span, with respect to neutral axis of the strip.

Equation (2) can be rewritten as:

$$EI = (rI_T + I_L)E_L, \qquad (3)$$

where r is the ratio E_T / E_L. Thus, equation (1) can be considered as obtained by transforming the transverse plies into parallel plies with the same pure modulus of elasticity E_L. The transformation is obtained by reducing width of the transverse plies by the ratio E_T/E_L.

For a 7-ply plywood strip with all plies of the same thickness, EI may be calculated by the following simple formula:

$$EI = \left(\frac{99r + 244}{343}\right) E_L I \qquad (4)$$

Shear deflection

(A) Elastic strain energy method

In this method, the cross section of a 7-ply plywood strip is transformed into a hypothetical homogeneous cross section with grain direction of all plies parallel to span. Transformation is made by reducing the width of transverse plies by the ratio of G_{TR}/G_{LR} modulus of rigidity perpendicular to span to that parallel to span.

Thus, the plywood strip is transformed into a homogeneous beam with a modulus of rigidity G_{LR}. The transformed cross section and the assumed parabolic distribution of shear stress along the depth are shown in Fig. 1. Shear deflection is calculated as follows by equating internal work to external work that causes shear distortion.

Let τ = unit shear stress
G_{LR} = modulus of rigidity parallel to grain
b_1 = reduced width of transverse plies (web) = $(G_{TR}/G_{LR})b_2$
b_2 = actual width of plywood strip (flange)
H_1, H_2, H_3, and H_4 = distances from the neutral axis as shown in Fig. 1.
V = total vertical shear = $P/2$
Y = distance from neutral axis
I_t = moment of inertia of the transformed cross section with respect to neutral axis.

The internal work per unit volume is:

$$\left(\frac{\tau}{2}\right)\left(\frac{\tau}{G_{LR}}\right) dA \cdot dx = \left(\frac{\tau^2}{2G_{LR}}\right) dA \cdot dx,$$

where $dA = b \cdot dy$

for a beam of length L, loaded at center with a load P, the external work is equal to $PY_2/2$. Since the external work equals the internal work then:

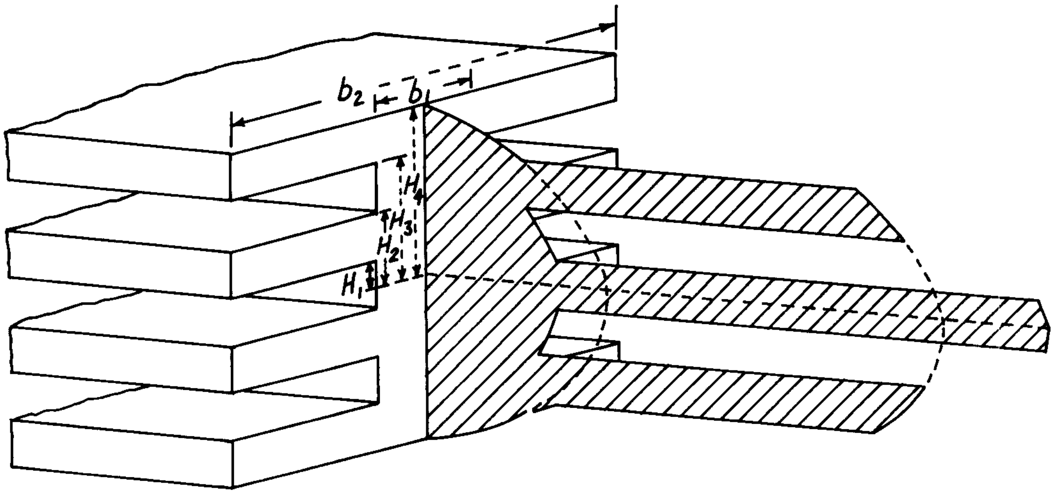

FIG. 1. Distribution of shear stresses along the depth of the transformed cross section.

$$\frac{PY_2}{2} = 2\left(\frac{L}{2G_{LR}}\right)\int_0^H \tau^2 \cdot b \cdot dy \quad \text{or}$$

$$\frac{PY_2}{2} = \frac{L}{G_{LR}}\left[\int_{H_3}^{H_4}\tau_1^2\, b_2\, dy + \int_{H_2}^{H_3}\tau_2^2\, b_1\, dy + \int_{H_1}^{H_2}\tau_3^2\, b_2\, dy + \int_0^{H_1}\tau_4^2\, b_1\, dy\right]. \qquad (5)$$

Where the unit shear stress τ_1, between H_3 and H_4 is equal to:

$$\tau_1 = \frac{V}{I_f b_2}\int_y^{H_4} b_2\, y\, dy = \frac{P}{4I_f}\left(H_4^2 - Y^2\right), \qquad (6)$$

the unit shear stress τ_2 between H_2 and H_3 is:

$$\tau_2 = \frac{P}{4I_f b_1}\left[b_2\left(H_4^2 - H_3^2\right) + b_1\left(H_3^2 - Y^2\right)\right]. \qquad (7)$$

Similarly, the unit shear stress τ_3 between H_1 and H_2, and τ_4 between O and H_1 are:

$$\tau_3 = \frac{P}{4I_f b_2}\left[b_2\left(H_4^2 - H_3^2 + H_2^2 - Y^2\right) + b_1\left(H_3^2 - H_2^2\right)\right] \qquad (8)$$

$$\tau_4 = \frac{P}{4I_f b_1}\left[b_2\left(H_4^2 - H_3^2 + H_2^2 - H_1^2\right) + b_1\left(H_3^2 - H_2^2 + H_1^2 - Y^2\right)\right]. \qquad (9)$$

Thus, substituting equations (6), (7), (8), (9) into equation (5), the following equation for the external work on the entire beam is derived:

$$\frac{PY_2}{2} = \frac{P^2L}{16I_f^2G_{LR}}\Big[b_2\Big(\frac{8}{15}H_4^5 - H_4^4H_3 + H_4^4H_2$$
$$- H_4^4H_1 + 2H_4^2H_3^3 + 2H_4^2H_2^3 + 2H_4^2H_1^3 -$$
$$4H_4^2H_3^2H_2 + 4H_4^2H_3^2H_1 - 4H_4^2H_2^2H_1 - \frac{23}{15}H_3^5$$
$$+ 3H_3^4H_2 - 3H_3^4H_1 - 2H_3^2H_2^3 - 4H_3^2H_1^3 +$$

$$6 H_3^2 H_2^2 H_1 + \frac{8}{15} H_2^5 - 3 H_2^4 H_1 + 4 H_2^2 H_1^3 - \frac{23}{15} H_1^5 \Big)$$

$$+ \; b_1 \Big(2 H_4^2 H_3^2 H_2 - 2 H_4^2 H_3^2 H_1 - 2 H_4^2 H_2^3 + 2 H_4^2 H_2^2 H_1$$

$$+ \frac{8}{15} H_3^5 - 3 H_3^4 H_2 + 3 H_3^4 H_1 + 4 H_3^2 H_2^3 - 6 H_3^2 H_2^2 H_1$$

$$+ \; 2 H_3^2 H_1^3 - \frac{23}{15} H_2^5 + 3 H_2^4 H_1 - 2 H_2^2 H_1^3 + \frac{8}{15} H_1^5 \Big)$$

$$+ \; \frac{b_2^2}{b_1} \Big(H_4^4 H_3 - H_4^4 H_2 + H_4^4 H_1 - 2 H_4^2 H_3^3 \; +$$

$$2 H_4^2 H_3^2 H_2 - 2 H_4^2 H_3^2 H_1 + 2 H_4^2 H_2^2 H_1 - 2 H_4^2 H_1^3 + H_3^5$$

$$- \; H_3^4 H_2 + H_3^4 H_1 - 2 H_3^2 H_2^2 H_1 + 2 H_3^2 H_1^3 + H_2^4 H_1 + H_1^5$$

$$- 2 H_2^2 H_1^3 \Big) + \frac{b_1^2}{b_2} \Big(H_3^4 H_2 - H_3^4 H_1 - 2 H_3^2 H_2^3$$

$$+ \; 2 H_3^2 H_2^2 H_1 + H_2^5 - H_2^4 H_1 \Big) \Big] \qquad (10)$$

By denoting the expression in the bracket with factor K_1, we have

$$\frac{P Y_2}{2} = \frac{P^2 L}{16 I_f^2 G_{LR}} \left(K_1 \right) ,$$

and shear deflection is equal to:

$$Y_2 = \left(P L / 8 I_f^2 G_{LR} \right) \left(K_1 \right) . \qquad (11)$$

The above formula is developed by assuming a parabolic distribution of shear stresses on the transformed cross section of the plywood beam. Shear deflection is determined by the ordinary method of equating external work to internal work. In the development of equation (10), high powers and numerous factors are involved. When the number of plies increases, higher powers and more factors will be involved. Thus, a second, simpler formula is developed here.

(B) Proportional stress area method

In this method the same transformation of cross section is made. The same shear stress distribution is considered as in the first method. The fundamental assumption in this simple method is that shear deflections in any two beams of the same length L, height H, and moment of inertia I that are similarly loaded are proportional to the summation of shear stresses on their respective vertical sections. The principle of this method was first used by Newlin and Trayer (1924) for determining shear deflection of I-beams.

Shear stress distributions along the depth of the transformed cross section were established from equations (6), (7), (8), and (9) and are shown in Fig. 1 as shaded area. For a beam of rectangular cross section with the same length L, depth H, and of width b to make its moment of inertia equal to that of the transformed section, shear deflection is 0.3 PL/bHG_{LR}. Assuming that shear deflection for each beam will be proportional to the areas under stress curve, shear deflection of the plywood strip can be determined by multiplying 0.3 PL/bHG_{LR} by the ratio of the area under the shear stress curve of the beam with rectangular cross section.

From Fig. 1, the upper half of the shaded area above the neutral axis under the stress distribution curve of the transformed cross section is:

$$\frac{V H_4^3}{3 I} + \frac{V}{2 I} \Big[\left(H_4^2 - H_3^2 \right) \left(H_3 - H_2 + H_1 \right) \left(\frac{b_2}{b_1} - 1 \right)$$

$$+ \left(H_3^2 - H_2^2 \right) \left(H_2 - H_1 \right) \left(\frac{b_1}{b_2} - 1 \right) \; +$$

$$\left(H_2^2 - H_1^2 \right) \left(H_1 \right) \left(\frac{b_2}{b_1} - 1 \right) \Big] .$$

The upper half of the area under the shear stress distribution curve of the rectangular beam with the same length, height, and moment of inertia is:

$$\frac{2}{3} H_4 \left(\frac{V H_4^2}{2I} \right) = \frac{V H_4^3}{3I} .$$

Therefore, shear deflection of the transformed cross-sectional beam is:

$$Y_2 = \frac{0.3 PL}{A_r G_{LR}} \left\{ 1 + \frac{3}{2 H_4^3} \left[\left(H_4^2 - H_3^2 \right) \left(H_3 - H_2 + H_1 \right) \left(\frac{b_2}{b_1} - 1 \right) + \left(H_3^2 - H_2^2 \right) \left(H_2 - H_1 \right) \left(\frac{b_1}{b_2} - 1 \right) + \left(H_2^2 - H_1^2 \right) \left(H_1 \right) \left(\frac{b_2}{b_1} - 1 \right) \right] \right\} , \quad (12)$$

where $A_r = bH$ is the area of the rectangular cross section beam with equivalent I of the transformed section. Since the moment of inertia of the rectangular beam is the same as the moment of inertia of the transformed cross section beam, $A_r = 3I_t/H^2_4$. Therefore, shear deflection Y_2 is:

$$Y_2 = \frac{P L H_4^2}{10 I_t G_{LR}} \left\{ 1 + \frac{3}{2 H_4^3} \left[\left(H_4^2 - H_3^2 \right) \left(H_3 - H_2 + H_1 \right) \left(\frac{b_2}{b_1} - 1 \right) + \left(H_3^2 - H_2^2 \right) \left(H_2 - H_1 \right) \left(\frac{b_1}{b_2} - 1 \right) + \left(H_2^2 - H_1^2 \right) \left(H_1 \right) \left(\frac{b_1}{b_2} - 1 \right) \right] \right\} . \quad (13)$$

For 7-ply plywood with plies of equal thickness, equation (13) can be simplified to:

$$Y_2 = \frac{P L H^2}{40 I_t G_{LR}} \left[\frac{25}{49} + \frac{120}{343} \frac{b_2}{b_1} + \frac{48}{343} \frac{b_1}{b_2} \right] , \quad (14)$$

where H is total thickness of the plywood and I_t is the moment of inertia of the transformed cross section.

Defining $g = G_{TR}/G_{LR} = b_1/b_2$, then, for 7-ply plywood with plies of equal thickness,

$$I_t = (g)(I_T) + I_L = \left(\frac{99}{343} g + \frac{244}{343} \right) I , \quad (15)$$

where I is moment of inertia of actual total cross section of plywood. And equation (14) can be further simplified to:

$$Y_2 = \frac{0.3 PL}{A G_{LR}} \left(\frac{48 g^2 + 175 g + 120}{99 g^2 + 244 g} \right) \quad (16)$$

By denoting the factors in parentheses as K_2, we have

$$Y_2 = \left(\frac{0.3 PL}{A G_{LR}} \right) \left(K_2 \right) , \quad (17)$$

where $A = b_2H$ and the factor (K_2) as shown depends on the G_{TR}/G_{LR} ratio and on the plywood construction.

EXPERIMENTAL DESIGN FOR VERIFICATION OF PROPOSED METHODS

For experimental verification of the proposed analyses, 7-ply plywood was constructed and specimens therefrom were tested in static bending. Actual stiffness was calculated and compared with values predicted by the proposed analyses. Additional tests also were conducted to obtain certain elastic constants (E_L, E_T, G_{LR}, G_{TR}) of 7-ply unidirectionally laminated veneer used for predicting deflections of the plywood strips according to equations (1), (11), and (17).

Experimental 7-ply panels were constructed exclusively from grade A rotary-cut veneer of southern yellow pine. All veneer was selected carefully in a plywood mill to exclude visible defects. Initially, a 5-ply panel (4 × 8 ft) was constructed in the plywood mill with veneer of equal thickness (⅛ inch) and bonded with extended phenolic adhesive. One-half of the 5-ply panel was made into plywood while the other one-half was made into unidirectionally laminated veneer. This arrangement was made by a 90° rotation of grain direction of one-half of the cross bands. The 7-ply plywood and 7-ply unidirectionally laminated veneer used in this study were obtained by bonding a ⅛-inch veneer on each face of the 5-ply panel. This bonding was made at room temperature with a resorcinol formaldehyde adhesive. Thus the 7-ply plywood and unidirectionally laminated veneer sections were matched with respect to veneer properties and manufacturing process.

Nine test specimens, 2.0 inches in width and 45.0 inches in length, were cut from each of 7-ply plywood and of 7-ply unidirectionally laminated veneer panels, with face grain parallel to span. In addition, nine test specimens, 2.0 inches (wide) and 24.0 inches (long) were cut from each of 7-ply plywood and unidirectionally laminated veneer sections, with face grain perpendicular to span. All specimens were tested nondestructively in static bending with central loading. Specimens with face grain parallel to span were tested at the following span-to-depth ratios: 48, 32, 24, 14, and 11, while specimens with face grain perpendicular to span were tested at 24, 18, 14, 11, and 8 span-to-depth ratios. Loading speeds used for each span were according to ASTM Standards (1968). The load applied to each span, was only one-third of the estimated load at the proportional limit. Tests were conducted with an Instron testing machine. Deflections were measured with an electric deflectometer attached to the core at midspan and recorded simultaneously with the corresponding loads on an X-Y recorder. After each test, specimens were trimmed to the next shorter span by trimming off an equal portion from each end and relaxed 24 hr in a conditioning room before being retested at that shorter span.

The following properties were calculated from tests of specimens described above:

(1) Actual modulus of elasticity of each specimen at each span was calculated by the formula $E = PL^3/48\,YI$; where Y is observed midspan total deflection corresponding at load P and span L.

(2) Values of pure moduli of elasticity and moduli of rigidity for each group of specimens were determined by a method used originally by Preston (1954) and later by Biblis (1965).

Values of the above elastic constants are shown in the tabulation below:

Specimen group	Face grain with respect to span	Modulus of elasticity at 48:1 span-to-depth ratio (psi)	Pure modulus of elasticity (psi)	Modulus of rigidity (psi)
Plywood	Parallel	1,648,800	1,715,660	19,960
Uni-lam.[1]	Parallel	2,485,830	2,539,200	49,550
Uni-lam.	Perpendicular	92,720	95,970	5,220

[1] Designates unidirectionally laminated veneer.

Actual deflections of 7-ply plywood calculated from observed total deflection

Average observed test values of midspan total deflection of 7-ply plywood strips with face grain parallel to span at span-to-depth ratios 48, 24, and 14 were separated into pure bending deflection and shear deflection by the first and second terms, correspondingly, of the following equation:

$$Y = \frac{PL^3}{48EI} + \frac{0 \cdot 3PL}{AG}, \quad (18)$$

where Y = observed total deflection at midspan

P = load corresponding to deflection Y

E = pure modulus of elasticity of 7-ply plywood with face grain parallel to span

I = moment of inertia of plywood cross section
A = cross section area of plywood
G = modulus of rigidity of 7-ply plywood with face grain parallel to span
L = span of specimen.

Predicted deflections of 7-ply plywood

Deflection caused by pure bending at midspan was predicted by equation (1). Values of E_L and E_T were determined experimentally from 7-ply unidirectionally laminated veneer strips.

Shear deflection at midspan was predicted by equation (11), and also by the simpler equation (17). For transforming the cross section of 7-ply plywood into a hypothetical homogeneous cross section with grain direction of all plies parallel to span, the value of 0.23 for G_{TR}/G_{LR} was used as in the previous work concerning 3-ply and 5-ply southern pine plywood (Biblis and Chiu 1970). Values of G_{LR} were determined experimentally from unidirectionally laminated veneer by the method described previously.

RESULTS AND DISCUSSION

The relationship between effective moduli of elasticity and span/depth ratios of 7-ply plywood with face grain parallel to span is shown in Fig. 2.

Comparisons between actual deflections and those predicted by equations (1) and (11) are shown in Table 1. Comparisons between actual deflections and those predicted by equations (1) and (17) are shown in Table 2. Percentage difference is considered positive when the predicted value is higher than the actual. Shear deflection predicted by the stress energy method was 3.9% higher than the actual, while those predicted by the stress area method was 6.9% higher. Since the pure bending deflection was predicted 6.9% lower, the total deflection at 24 span-to-depth ratio was predicted with an error of approximately 5% by either method. Although predictions of shear and total deflections by either method are in very good agreement with the actual deflections, the stress area method is simpler and easier to apply.

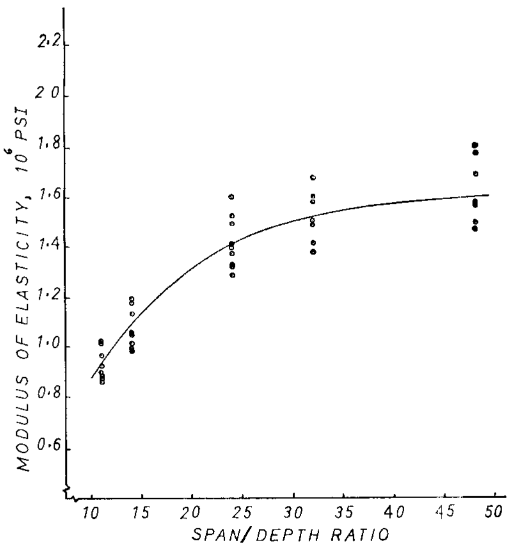

FIG. 2. Effective moduli of elasticity of 7-ply southern pine plywood flexure specimens (0.875-inch total thickness) with face grain parallel to span at five span-to-depth ratios.

Shear deflection as percentage of total at 48, 24, and 14 span-to-depth ratios of 7-ply plywood are 4.79, 16.76, and 37.17, respectively.

SUMMARY AND CONCLUSION

Two methods for predicting deflection of 7-ply plywood strips in small span-to-depth ratios have been developed and presented together with experimental verification. These methods first require transformation of the cross section of 7-ply plywood into a hypothetical homogeneous cross section with grain direction of all plies parallel to span. Then pure bending and shear deflections are calculated. With one method, shear deflection is calculated by equating the internal work with the external work of the transformed cross section. With the other method, shear deflection is calculated with an equation based on the assumption that shear deflections in any two similarly loaded beams of the same length, height, and moment of inertia are proportional to

TABLE 1. *Actual and predicted midspan deflections*[1] *by the elastic stress energy method for 7-ply plywood strips*

Span-to-depth ratio	Pure bending deflection			Shear deflection			Total deflection			Percentage of shear deflection to the total	
	Actual inches	Predicted inches	Difference %	Actual inches	Predicted inches	Difference %	Actual inches	Predicted inches	Difference %	Actual %	Predicted %
48	1.21438	1.13597	-6.90	0.05350	0.05559	+3.90	1.26788	1.19156	-6.41	4.22	4.67
24	0.30360	0.28399	-6.90	0.05350	0.05559	+3.90	0.35710	0.33958	-5.16	15.75	16.37
14	0.10329	0.09662	-6.90	0.05350	0.05559	+3.90	0.15679	0.15221	-3.01	34.12	36.52

[1] Deflections correspond at proportional limit load.

TABLE 2. *Actual and predicted midspan deflections*[1] *by the proportional stress area method for 7-ply plywood strips*

Span-to-depth ratio	Pure bending deflection			Shear deflection			Total deflection			Percentage of shear deflection to the total	
	Actual inches	Predicted inches	Difference %	Actual inches	Predicted inches	Difference %	Actual inches	Predicted inches	Difference %	Actual %	Predicted %
48	1.21438	1.13597	-6.90	0.05350	0.05717	+6.86	1.26788	1.19314	-6.26	4.22	4.79
24	0.30360	0.28399	-6.90	0.05350	0.05717	+6.86	0.35710	0.34116	-4.67	15.75	16.76
14	0.10329	0.09662	-6.90	0.05350	0.05717	+6.86	0.15679	0.15379	-1.95	34.12	37.17

[1] Deflections correspond at proportional limit load.

the summations of the shear stresses on their respective vertical sections.

Shear and total deflections of 7-ply plywood at short spans predicted by both methods are in very good agreement with deflections obtained from actual tests.

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EFFECT OF GAMMA RADIATION, WET-HEAT, AND ETHYLENE OXIDE STERILIZATION OF WOOD ON ITS SUBSEQUENT DECAY BY FOUR WOOD-DESTROYING FUNGI

Errata

Underscoring of means in the following six lines should be corrected to read as follows:

60.14	62.74	62.89	63.01	63.02
42.88	44.93	45.37	45.52	48.91
41.86	43.30	43.54	43.60	46.06
0.005	0.009	0.020	0.020	0.021
0.001	0.008	0.011	0.015	0.018
31.69	33.47	33.62	33.96	36.06

Wood and Fiber, **2**(4): 360–361, Table 4, by Roger S. Smith and Christine V. Sharman.