

# AN ANALYSIS OF FLEXURAL ELASTIC BEHAVIOR OF 3-PLY SOUTHERN PINE PLYWOOD<sup>1</sup>

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## ABSTRACT

Two methods for predicting deflections of 3-ply plywood have been verified experimentally and compared. Both methods can predict accurately the total deflection, pure bending deflection and shear deflection even at a span-to-depth ratio 14:1 of 3-ply southern pine plywood. The approximate method predicts deflections with as much accuracy as the exact theoretical method. The approximate method has the advantage of being simpler in application, and it does not require the knowledge or determination of Poisson's ratios and values of pure modulus of elasticity for the core ( $E_{TR}$ ) required by the exact method. Both methods require accurate values of modulus of rigidity in "rolling shear" and/or an accurate value of the ratio  $G_{TR}/G_{LR}$ . It is suggested that values of  $G_{TR}$  for all commercial species, used for production of structural plywood, be determined by an accurate method.

This paper presents partial results of a larger study that concerns flexural properties of southern pine plywood including plywood overlaid with fiberglass reinforced plastics. More specifically, this paper presents two experimentally verified theories by which the flexural stiffness of 3-ply southern pine plywood can be predicted accurately at short span-to-depth ratios. A previous paper (Biblis 1969) presented: 1) experimentally obtained values of effective moduli of elasticity of 3-ply plywood strips at five span-to-depth ratios smaller than 48:1; and 2) actual values of pure bending and shear deflection determined by considering the plywood cross section to be homogeneous. In this study, deflection at short span-to-depth ratios of the same 3-ply plywood specimens is predicted by two independent methods.

## BACKGROUND

Plywood, particularly 3-ply plywood, is a simple form of sandwich construction. The 90° alternation in grain orientation between face plies and core causes large differences in strength and elastic properties. Ratios of tensile wood properties

between parallel and perpendicular to grain can be as high as 40 to 1 (Biblis 1966;

Wangaard 1950). Shear strength perpendicular to grain (rolling shear strength) varies from 0.19 to 0.61 of shear strength parallel to grain (Biblis and Fitzgerald 1969; Munte and Ethington 1968). The modulus of rigidity  $G_{TR}$  in "rolling shear" ranges from 0.025 to 0.66 of rigidity modulus  $G_{LT}$  parallel to grain (Biblis and Fitzgerald 1969; Munte and Ethington 1968; March 1936).<sup>2</sup>

For testing plywood in flexure, ASTM Standards specify a 48:1 span-to-depth ratio for specimens with face grain parallel to grain. Apparently, it is assumed that deflection caused by shear is negligible at this ratio even for 3-ply plywood since no distinction is made for plywood with different number of plies. In a previous study the author (Biblis 1969) has shown that the percentage of midspan shear deflection of 3-ply southern pine plywood with face grain parallel to span is approximately 7.5% of the total deflection. Flexure properties of plywood (stiffness and strength) at a 48:1 span-to-depth ratio have been predicted

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<sup>2</sup> In designation of modulus of rigidity  $G$ , and Poisson's ratio  $\mu$ , the subscripts L, T and R refer to longitudinal, tangential and radial directions in wood respectively.  $G_{LT}$  is associated with shear deformations in the LT plane.  $G_{TR}$  is associated with shear deformations in the TR plane along the tangential direction.

accurately in the U.S. Forest Products Laboratory (FPL-059, 1964) by a theoretical method derived by March in 1936. March's method, however, can be applied also to plywood strips with relatively small span-to-depth ratios. Deflection caused by shear can be considerable, even exceeding the deflection caused by pure bending at small span-to-depth ratios. It has been shown by both March (1936) and Biblis (1969) that the percentage of shear deflection of plywood strips with face grain parallel to span is higher in 3-ply than in 5-ply plywood. This is caused by the influence of an extremely low modulus of rigidity in "rolling shear" that occurs in transverse plies. In these plies, with grain direction perpendicular to span, shear strains are relatively very large. In 3-ply plywood, the ply with the smaller resistance to shear deformation is located in the area of maximum shear stress. For plywood strips with face grain perpendicular to span, the percentage of shear deflection is higher in 5-ply than in 3-ply plywood strips (Biblis 1969).

#### *An Exact Theoretical Method for Predicting Deflection*

March (1936) has developed a theoretical method by which the effective stiffness of plywood strip even at relatively small span-to-depth ratios can be predicted accurately. March, in developing the method, first used a differential equation for a flat plate of plywood, and thus the midspan deflection of a centrally loaded strip of plywood was determined by treating the strip as a thin plate.

Derivation of the differential equation for deflection of a thin plate is based on the assumption that transverse shearing stresses are negligible when compared with stress parallel to the plane of the plate. This assumption, however, becomes increasingly inaccurate as the span-to-depth ratio of the plate decreases. In this case it becomes necessary to include the additional deflection caused by shear deformation which was neglected by the thin plate theory.

March (1936) derived an expression for total deflection that included a correction for shear deformation by considering the rectangular plywood strip centrally loaded as before, but made up of two cantilevers fixed at their junction at the center  $x = L/2$  and under the action of load  $P/2$ . Thus, he suggested the following equation for the total deflection  $y$  of a centrally loaded rectangular strip of plywood:

$$y = \frac{PL^3(1 - \mu_{LT}\mu_{TL})B}{48E_1I} \left( 1 + e \frac{d^2}{L^2} \right), \quad (1)$$

where:  $y$  = midspan deflection

$L$  = span

$E_1$  = effective modulus of elasticity

$I$  = moment of inertia of entire section =  $bd^3/12$

$\mu_{L,T}$  and

$\mu_{T,L}$  = Poisson's ratios<sup>3</sup>

$B$  = function of strip width

$d$  = total thickness of strip.

The factor  $(1 - \mu_{L,T}\mu_{T,L})B$  is a corrective factor for the effect of anticlastic curvature. March reported that the quantity  $(1 - \mu_{L,T}\mu_{T,L})B$  approaches unity for moderately long and narrow strips. When the effect of anticlastic curvature is neglected, then the midspan deflection for the strips described is given by the equation:

$$y = [PL^3/(48E_1I)] \left( 1 + e \frac{d^2}{L^2} \right). \quad (2)$$

The factor  $\left( 1 + e \frac{d^2}{L^2} \right)$  is a correction for the effect of shear deformation. The term  $e$  is a function of the appropriate Poisson's ratios and modulus of rigidity  $G$ . A special formula is required to calculate values of  $e$  for plywood of different number of plies.

March and Smith (1944) used the same mathematical treatment and derived equations to predict the effective stiffness of a strip of sandwich construction centrally loaded and freely supported at the ends.

<sup>3</sup> The  $\mu_{L,T}$  represents the numerical value of the ratio of the strain along the T direction to the strain along the L direction caused by a stress parallel to the L direction.

For sandwich beams with faces of equal thickness, March and Smith derived the following equation:

$$y = [PL^3/(48D)](1 + nd^2/L^2), \quad (3)$$

where a simplified equation for term  $n$  is

$$n = [3/(2a_1G_c)](c/d)(1 - c^2/d^2), \quad (4)$$

where  $a_1 = (1/E_f)(1 - \mu_{LT}\mu_{TL})$  (5)

$E_f$  = pure modulus of elasticity of faces (with grain parallel to span  $E_{LT}$ )

$G_c$  = modulus of rigidity of core (rolling shear modulus  $G_{TR}$ )

$c$  = thickness of core.

In equation (3) for sandwiches with faces of equal thickness, the term  $D$  can be calculated by the following equation:

$$D = [b/(12a_1)](d^3 - c^3 + pc^3), \quad (6)$$

where  $p = \frac{a_1}{a_c} = \frac{E_c(1 - \mu_{LT}\mu_{TL})}{E_f(1 - \mu_{TL}\mu_{LT})} = \frac{E_c}{E_f}$ ; (7)

therefore

$$D = \frac{b}{12a_1} \left( d^3 - c^3 + \frac{E_c}{E_f} c^3 \right),$$

and  $D = E_f I_f + E_c I_c$ , (8)

where  $E_c$  = pure modulus of elasticity of core (grain perpendicular to span  $E_{TR}$ )

$I_f$  = moment of inertia of faces

$I_c$  = moment of inertia of core.

The first term in eq. (3)  $PL^3/(48D)$  represents deflection caused by pure bending; the second term  $[PL^3/(48D)](nd^2/L^2)$  represents deflection caused by shear.

#### *An Approximate Method for Predicting Deflection*

According to this method, the cross section of a 3-ply plywood is transformed into a hypothetical cross section of a homogeneous I-beam with grain direction parallel to span. The transformation is made by reducing the width of the core ply by the ratio of modulus of rigidity perpendicular to grain (rolling shear) to that parallel to grain  $G_{TR}/G_{LR}$ . The ratio of the moduli of rigidity was chosen as the transformation

factor instead of the corresponding ratio of moduli of elasticity ( $E_{TR}/E_{LR}$ ) because in 3-ply plywood the weak core occupies an area of maximum shear stress and causes large shear deformation, particularly in small span-to-depth ratios. It has been shown by the author (Biblis 1967) in such cases that the transforming factor of the ratio of moduli of rigidity is more appropriate than the ratio of moduli of elasticity.

Elastic properties of the hypothetical homogeneous I-beam, when subjected to bending, correspond only to those parallel to grain i.e.  $E_{LR}$  and  $G_{LR}$ . Bending deflection of such an I-beam, when centrally loaded and freely supported at the ends, is calculated by the following equation derived by Newlin and Trayer (1942).

$$y = PL^3/(48EI_t) + (K^1 PL/G). \quad (9)$$

The first term  $PL^3/(48EI_t)$  represents deflection caused by pure bending. The second term  $K^1 PL/G$  represents shear deflection. The  $G$  is modulus of rigidity parallel to grain  $G_{LT}$  or  $G_{LR}$  (depending on orientation of annual rings). For calculating the term  $K^1$ , Newlin and Trayer (1942) suggested the following simplified equation:

$$K^1 = 1 + \frac{\frac{3}{2}(K_2^2 - K_1^2)K_1}{K_2^3} \left( \frac{t_2}{t_1} - 1 \right) \frac{K_2^2}{10I_t}, \quad (10)$$

where:

$K_2$  = distance neutral axis to extreme fiber

$K_1$  = distance neutral axis to flange

$t_2$  = width of flange

$t_1$  = thickness of web

$I_t$  = moment of inertia of I-section or transformed section with respect to neutral axis.

#### PROCEDURE

Detailed experimental procedure describing fabrication and test of the 3-ply plywood and calculation of its effective stiffness can be found in a previous paper by the author (Biblis 1969). However, a summary of this procedure is presented here.

Grade A rotary-cut veneer of southern yellow pine was used exclusively. Veneer was selected carefully in the mill to exclude all visible defects. Three panels of 3-ply plywood ( $\frac{1}{10}$  in. faces and  $\frac{1}{8}$  in. core) were glued with extended phenolic resin in a plywood mill. Three static bending specimens with face grain parallel to span and with dimensions as specified by ASTM Standards were machined from each panel. Each specimen was tested in static bending at the following span-to-depth ratios: 48, 28, 18, 14, and 11. After each test, specimens were trimmed to the shorter length and relaxed for 24 hr in a conditioning room before being retested at the shorter span. The load applied to each span was only  $\frac{1}{3}$  of the estimated proportional limit load for each specimen. Specimens were supported freely at the ends and centrally loaded, using an Instron testing machine. Loading speeds used for each span were according to ASTM Standards. Deflections were measured with an electric deflectionometer attached to the core at mid-span and recorded simultaneously with the corresponding loads on X-Y recorder.

#### Shear Deflection from Test Data

Values of pure moduli of elasticity  $E$  and moduli of rigidity  $G$  for plywood of each panel were determined by the method used by Preston (1954), Wangaard (1964), and Biblis (1965). Actual test values of mid-span total deflection were separated into pure bending deflection and shear deflection by the following equation:

$$y = (PL^3/48EI) + (0.3PL/AG), \quad (11)$$

where:

- $y$  = total deflection at mid-span
- $L$  = span of specimen
- $E$  = pure modulus of elasticity of plywood (free of shear deformations)
- $I$  = moment of inertia plywood cross section =  $bd^3/12$
- $A$  = cross section area of plywood =  $bd$
- $G$  = modulus of rigidity of the entire cross section of plywood in the direction of span.

#### Shear Deflection Calculated by the Exact Method

The simplified equation (3) derived by March and Smith (1944) for predicting the deflection of a sandwich construction beam was used for predicting deflections of 3-ply plywood. This method was chosen, rather than the method derived by March especially for plywood, for the following reasons: (a) it is simpler and does not assume several conditions to be applied (see March 1936); (b) 3-ply plywood indeed is a simple form of sandwich construction, especially when faces are of equal thickness as in this case.

Poisson's ratios  $\mu_{LT}$  and  $\mu_{TL}$  required in eq. (5) together with the other four ratios  $\mu_{LR}$ ,  $\mu_{RL}$ ,  $\mu_{TR}$ ,  $\mu_{RT}$  were determined experimentally for loblolly pine by a method described by Doyle, Drow, and McBurney (1968). For this, three types of loblolly pine specimens (2 inches  $\times$  2 inches  $\times$  8 inches) were tested in compression—one in compression parallel to grain, the other two perpendicular to grain. The load was applied on the tangential surface in one of the perpendicular-to-grain specimens and on the radial surface of the other. Specimens tested perpendicular to grain were laminated from smaller sections to obtain the desired grain orientation as shown in Fig. 1. Axial and lateral strains were measured simultaneously during loading by SR-4 strain gages attached to specimens (Fig. 2). Values obtained for the six Poisson's ratios are as follows:

$$\begin{array}{ll} \mu_{LT} = 0.4030 & \mu_{TL} = 0.0203 \\ \mu_{LR} = 0.4560 & \mu_{RL} = 0.0370 \\ \mu_{TR} = 0.3720 & \mu_{RT} = 0.5980 \end{array}$$

Values of pure moduli of elasticity of faces  $E_f$  (grain direction parallel to span) and of core  $E_c$  (grain direction perpendicular to span) were determined experimentally from 3-ply unidirectionally laminated veneer strips of the same thickness with those of plywood. Laminated veneers were matched to those of plywood, and both plywood and laminated veneer panels were manufactured simultaneously with the same process. Values of pure  $E_f$  and  $E_c$  for equations (5)

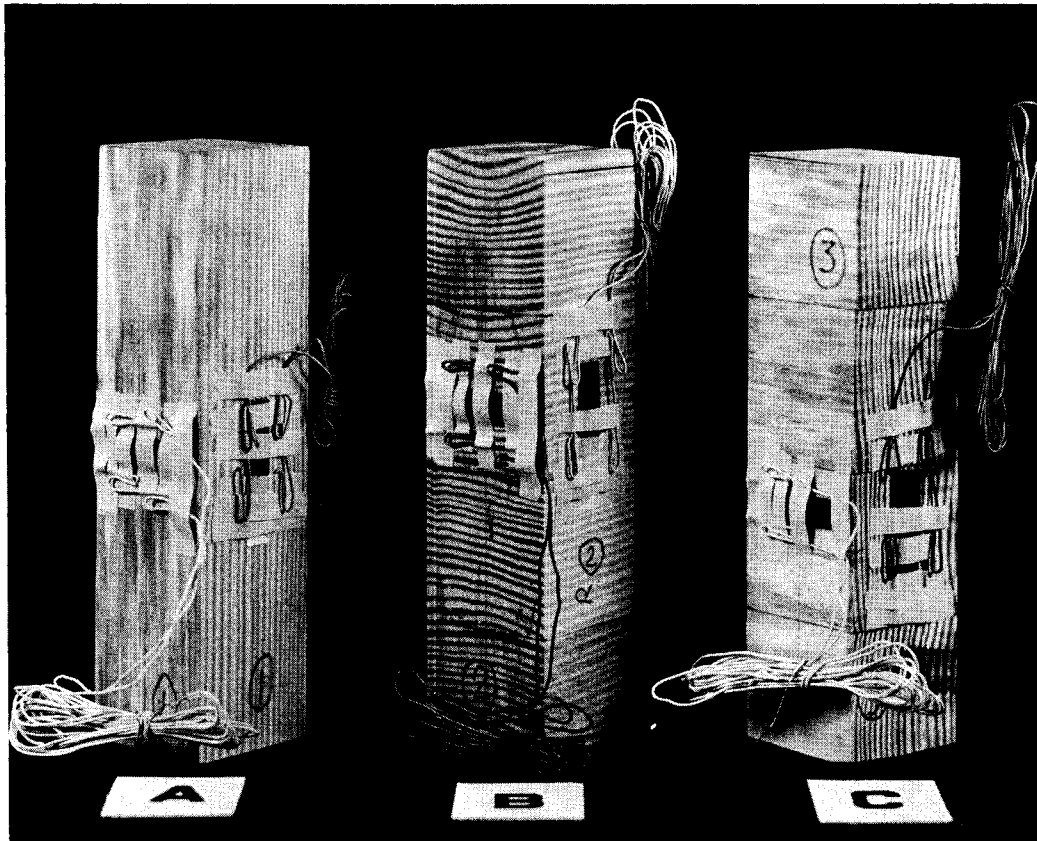


FIG. 1. Compression specimens of loblolly pine tested for determination of Poisson's ratios; (A) solid specimen for compression parallel to grain; (B) and (C) glued specimens for compression perpendicular to grain, tangential and radial respectively.

and (8) were determined (3) by the method used by Preston (1954).

Although a value of modulus of rigidity of core  $G_c$  (rolling shear modulus  $G_{TR}$ ) was determined experimentally by testing unidirectionally laminated veneer strips with grain perpendicular to span at various span-to-depth ratios, values obtained were considered unreasonably low and were not used. Instead, a value for  $G_{TR}$  was derived from the value of  $G_{LR}$  and a proper value of the ratio  $G_{TR}/G_{LR}$ . After considering values for the ratio obtained by other investigators, a value of 0.23 was accepted and used in eq. (4). (American Plywood Association 1966; Fitzgerald 1968; Palka 1967; Munte and Ethington 1968). Total deflection, pure bending deflection, and shear deflection were calculated with eq. (3).

#### *Shear Deflection Calculated by the Approximate Method*

Equation (9) was used for determining the mid-span deflection by this method. A value of pure  $E$  was determined experimentally by testing unidirectionally laminated veneer strips with grain parallel to span. Value at the proportional limit load was used for  $P$ . The value of 0.23 for the ratio  $G_{TR}/G_{LR}$  (transformation factor) was used. Total deflection, pure bending deflection, and shear deflection were calculated with eq. (9).

#### RESULTS AND DISCUSSION

Amounts of total deflection, pure bending deflection, and shear deflection at mid-span of 3-ply plywood were predicted by

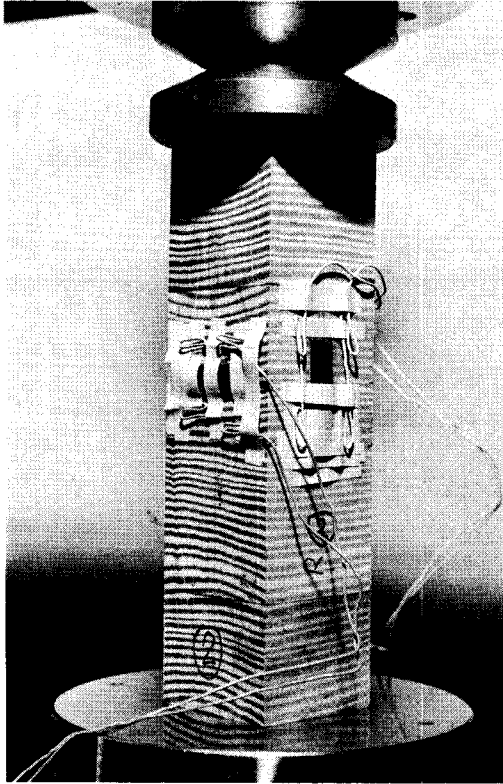


FIG. 2. Compression specimen under loading perpendicular to grain (tangential surface); strains parallel and perpendicular to direction of applied load were measured simultaneously by SR-4 strain gages attached to the specimens.

two methods at the following span-to-depth ratios: 48, 24 and 14. Deflections for the same span-to-depth ratios were calculated also from test data and compared separately with results obtained from each prediction method.

Comparisons between actual deflections and those predicted by the exact method are shown in Table 1. Percentage difference is considered positive when the predicted value is larger than the actual. Predictions of pure bending deflection are in good agreement with actual values. Values for specimens from panels 1 and 3 were predicted with an error of less than 0.45%. Average percentage differences between predicted and actual values is less than 1.85.

Predictions of shear deflections are in good agreement with actual values except for specimens of one panel, where the percentage difference is 14.87. The percentage difference for specimens from the other two panels is less than 2.0. The rather large variations between percentage differences of specimens from different panels are due to the fact that predictions were based on average values of pure  $E$  and  $G$ , while actual values of individual panels exhibit variations because of natural variability.

Predictions of total deflection are also in good agreement with actual values. Percentage differences between actual and predicted vary from  $-0.13$  to  $+6.58$  among specimens of different panels. The average percentage difference between actual and predicted total deflection even at 14:1 span-to-depth ratio is only 3.21. The exact method can predict total deflection of a 3-ply plywood strip with good accuracy even at a span-to-depth ratio of 14. The average actual percentage of shear deflection to the total deflection at 14 span-to-depth ratio is 48.83 and was predicted with 1% accuracy.

Comparisons between actual and predicted deflections by the "approximate method" are shown in Table 2. Separate predictions of pure bending and shear deflections are in good agreement with corresponding actual values. Average pure bending deflection was predicted with less than 1.0% error, and average shear deflection was predicted with less than 3.5% error. Predictions of total deflections were in excellent agreement with actual values. Percentage errors for predicted total deflections varied from  $-4.82$  to  $+3.90$ .

Predictions of pure bending deflection, shear deflection, and total deflection obtained by the approximate method are as good as those obtained by the exact method. The approximate method has an advantage of being simpler in application, and it does not require the knowledge of the Poisson's ratios and values of pure modulus of elasticity for the core  $E_c$  required by the exact method.

TABLE 1. Actual and predicted midspan deflections<sup>1</sup> by an exact theoretical method for 3-ply southern pine plywood strips

Designation of specimen <sup>2</sup>	Span to depth ratio	Pure bending deflection			Shear deflection			Total deflection			Percentage of shear deflection to the total	
		Actual in.	Predicted in.	Difference %	Actual in.	Predicted in.	Difference %	Actual in.	Predicted in.	Difference %	Actual %	Predicted %
1-P	48	0.51701	0.51879	+0.34	0.04405	0.04340	-1.48	0.56106	0.56219	+0.20	7.86	7.72
1-P	24	0.12925	0.12968	+0.33	0.04405	0.04340	-1.48	0.17330	0.17308	-0.13	25.42	25.08
1-P	14	0.04414	0.04429	+0.34	0.04405	0.04340	-1.48	0.08819	0.08769	-0.57	50.13	49.49
2-P	48	0.48998	0.51879	+5.87	0.04256	0.04340	+1.97	0.53254	0.56219	+5.57	7.99	7.72
2-P	24	0.12250	0.12968	+5.86	0.04256	0.04340	+1.97	0.16506	0.17308	+4.86	25.79	25.08
2-P	14	0.04184	0.04429	+5.86	0.04256	0.04340	+1.97	0.08440	0.08769	+3.90	50.43	49.49
3-P	48	0.52113	0.51879	-0.45	0.03778	0.04340	+14.87	0.55892	0.56219	+5.85	6.72	7.72
3-P	24	0.13028	0.12968	-0.46	0.03778	0.04340	+14.87	0.16807	0.17308	+2.98	22.48	25.08
3-P	14	0.04450	0.04429	-0.47	0.03778	0.04340	+14.87	0.08228	0.08769	+6.58	45.92	49.49
Av.	48	0.50937	0.51879	+1.85	0.04146	0.04340	+4.83	0.55084	0.56219	+2.06	7.52	7.72
Av.	24	0.12734	0.12968	+1.84	0.04146	0.04340	+4.83	0.16881	0.17308	+2.53	24.56	25.08
Av.	14	0.04349	0.04429	+1.84	0.04146	0.04340	+4.83	0.08496	0.08769	+3.21	48.83	49.49

<sup>1</sup> Deflections correspond at proportional limit load.<sup>2</sup> Number designates plywood panel.TABLE 2. Actual and predicted midspan deflections<sup>1</sup> by an approximate method for 3-ply southern pine plywood strips

Designation of specimen <sup>2</sup>	Span to depth ratio	Pure bending deflection			Shear deflection			Total deflection			Percentage of shear deflection to the total	
		Actual in.	Predicted in.	Difference %	Actual in.	Predicted in.	Difference %	Actual in.	Predicted in.	Difference %	Actual %	Predicted %
1-P	48	0.51701	0.51319	-0.74	0.04405	0.04012	-8.92	0.56106	0.55331	-1.38	7.86	7.25
1-P	24	0.12925	0.12830	-0.74	0.04405	0.04012	-8.92	0.17330	0.16842	-2.82	25.42	23.82
1-P	14	0.04414	0.04382	-0.73	0.04405	0.04012	-8.92	0.08819	0.08394	-4.82	50.13	47.80
2-P	48	0.48998	0.51319	+4.74	0.04256	0.04012	-5.73	0.53254	0.55331	+3.90	7.99	7.25
2-P	24	0.12250	0.12830	+4.73	0.04256	0.04012	-5.73	0.16506	0.16842	+2.03	25.79	23.82
2-P	14	0.04184	0.04382	+4.73	0.04256	0.04012	-5.73	0.08440	0.08394	-0.55	50.43	47.80
3-P	48	0.52113	0.51319	-1.52	0.03778	0.04012	+6.19	0.55892	0.55331	-1.00	6.72	7.25
3-P	24	0.13028	0.12830	-1.52	0.03778	0.04012	+6.19	0.16807	0.16842	+0.21	22.48	23.82
3-P	14	0.04450	0.04382	-1.53	0.03778	0.04012	+6.19	0.08228	0.08394	+2.02	45.92	47.80
Av.	48	0.50937	0.51319	+0.75	0.04146	0.04012	-3.33	0.55084	0.55331	+0.45	7.52	7.25
Av.	24	0.12734	0.12830	+0.75	0.04146	0.04012	-3.33	0.16881	0.16842	-0.23	24.56	23.82
Av.	14	0.04349	0.04382	+0.75	0.04146	0.04012	-3.33	0.08496	0.08394	-1.22	48.83	47.80

<sup>1</sup> Deflections correspond at proportional limit load.<sup>2</sup> Number designates plywood panel.

## CONCLUSIONS

- 1) Two methods, an exact and an approximate, have been verified experimentally. Both methods can predict accurately the total deflection, pure bending deflection, and shear deflection even at the span-to-depth ratio of 14:1 of 3-ply southern pine plywood.
- 2) The approximate method predicts deflections as accurately as the exact method. The approximate method has the advantage of being simpler in application and does not require the knowledge or determination of Poisson's ratios and values of pure modulus of elasticity for the core  $E_c$  required by the exact method.
- 3) Both methods require accurate values of modulus of rigidity in "rolling shear" and/or an accurate value of the ratio  $G_{TR}/G_{LR}$ . It is suggested that values of  $G_{TR}$  for all commercial species, used for production of structural plywood, be determined by an accurate method.

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