FLEXURAL BEHAVIOR OF GLASS FIBER REINFORCED HARDBOARD[1]

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ABSTRACT

The flexural stiffness and strength of a dry-process hardboard matrix were significantly improved by internal reinforcement with continuous glass fibers. The dynamic and static moduli of elasticity and the modulus of rupture of glass fiber reinforced hardboard increased with increasing reinforcement volume fraction. When modelled as a sandwich construction, the static flexural modulus of elasticity of the composite could be accurately predicted from the modulus of elasticity of the wood fiber matrix, and the tensile modulus of elasticity and volume fraction of the glass fiber reinforcement. Excellent linear correlation among the dynamic modulus of elasticity, the static modulus of elasticity, and the modulus of rupture allowed for estimation of the composite failure stress from flexural properties that were determined nondestructively. The results of this study will assist in the design of glass fiber reinforced hardboard composites.

Keywords: Hardboard, reinforced wood composite, wood fiber, glass fiber, mechanical properties.

SUBSCRIPTS AND SYMBOLS

Subscripts

c	composite
f	glass fiber reinforcement
m	wood fiber matrix

Symbols

a	distance between support and point load (in.)
b	width (in.)
d	depth (in.)
E	true modulus of elasticity (psi)
E′	dynamic modulus of elasticity (psi)
f_r	fundamental resonant frequency of vibration (sec^{-1})
G	in-plane modulus of rigidity (psi)
I	moment of inertia about neutral axis ($in.^4$)
l	test span (in.)

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[1] The authors are, respectively, Assistant Professor of Wood Science at the University of Massachusetts and former graduate assistant at Virginia Tech, and Professor of Wood Science at Virginia Tech. This paper is based on an entry by the first author that won the 1986 Wood Award.

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L	total specimen length (in.)
MOE	apparent modulus of elasticity (psi)
MOR	modulus of rupture (psi)
n	ratio of E/G
N	shear stiffness (lb)
P	load (lb)
v	volume (in.^{3})
V	volume fraction
w	total specimen weight (lb)
y	midspan deflection (in.)
α	level of statistical significance

INTRODUCTION

In spite of an annual domestic production of nearly 6 billion square feet (⅛-inch basis), hardboard sees sparing use in structural applications. The high edgewise shear stiffness and strength of tempered hardboard permit its use where stresses will act in the plane of the panel, as in the shear-web of box and I-beams (Lundgren 1969; Chan 1979; McNatt 1980). Limited flexural stiffness and strength, and excessive creep deflection, however, constrain its use where stresses will act normal to the plane of the panel. Significant enhancement of the flexural properties of solid and laminated wood beams (Wangaard 1964; Biblis 1965; Theakston 1965; Spaun 1981; Rowlands et al. 1986), plywood (APA 1972; Boehme and Schulz 1974; Boehme 1976a, b), and particleboard (Boehme and Schulz 1974; Saucier and Holman 1975; Boehme 1976a, b; Bulleit 1981) has been accomplished by bonding glass fiber reinforced polymer overlays to their surfaces. While no improvement in the flexural properties of wet-process hardboard has been realized when chopped glass fibers were dispersed in the furnish (Cavlin and Back 1968; Nishikawa et al. 1974, 1975), significant flexural strengthening of dry-process hardboard has been achieved with continuous glass fibers (Steinmetz 1977). A technique for enhancing hardboard's flexural properties without increasing panel thickness could broaden its structural use-spectrum.

The objective of this study was to examine the effect of reinforcement volume fraction on the elastic flexural behavior of a dry-process hardboard matrix internally reinforced with continuous glass fibers. The static flexural modulus of elasticity (MOE), modulus of rupture (MOR), and the dynamic modulus of elasticity (E′) of the wood fiber/glass fiber composite were experimentally determined. These data were used 1) to verify a predictive equation relating constituent properties and composite MOE, and 2) to identify empirical relationships between flexural properties obtained from nondestructive dynamic and destructive static test methods. The results of this study will assist in the design of glass fiber reinforced hardboard composites.

MATERIALS AND METHODS

Composite fabrication

Commercial thermomechanical wood fiber at 6% moisture content, and consisting of mixed hardwood fibers and 2.5% phenolic resin and petrolatum additives, was used to produce 12-inch by 12-inch by ¼-inch dry-process hardboard

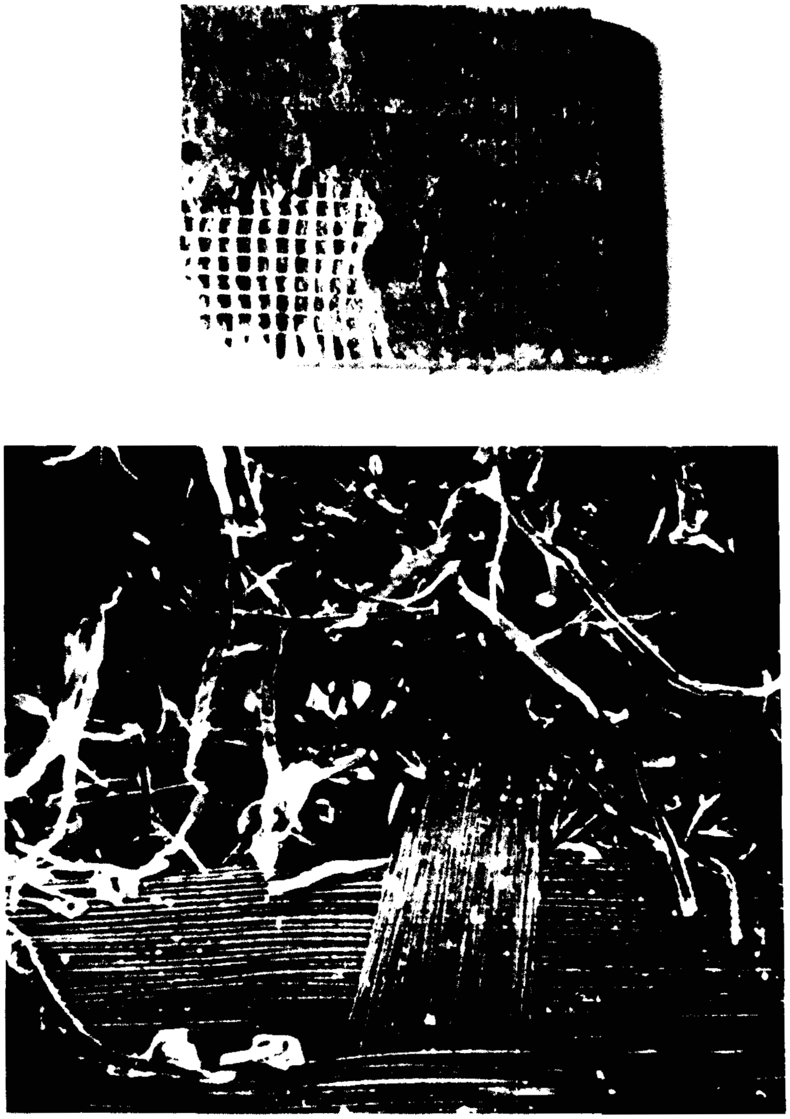

FIG. 1. Glass fiber reinforced hardboard with reinforcement in situ. Upper: actual size. Lower: SEM 120×.

panels at a specific gravity of 0.95. In addition to nonreinforced controls, hardboard panels reinforced with 1, 2, or 3 plies of a woven glass fiber fabric at 0.01 inch intervals below each surface were produced (Fig. 1). Thirty percent powdered phenol-formaldehyde adhesive by weight of glass fiber was used to bond the reinforcement to the matrix. Glass fiber fabric and adhesive details are given in the Appendix.

Panels were laid up in a forming box by the air-felting of wood fiber drawn across a wire screen, and manual placement of adhesive-coated glass fiber plies. The thickness of the wood fiber layer separating glass fiber plies was controlled

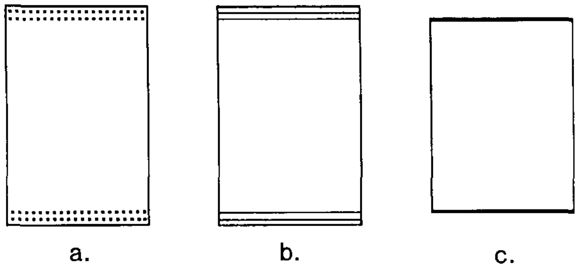

FIG. 2. (a) Glass fiber reinforced hardboard cross section (effective reinforcement volume fraction equals 0.0158). (b) Glass fiber yarns modelled as laminae of equal cross-sectional area. (c) Glass fiber reinforced hardboard modelled as a sandwich construction.

by felting the necessary weight of wood fiber as calculated from panel target dimensions and specific gravity, wood fiber moisture content, and glass fiber volume. After a cold prepressing, the felted mat was consolidated in a hot press at 405 F under a maximum 475 psi for 5 minutes. Following conditioning to equilibrium at 65% relative humidity and 70 F, specimens were cut from only the central portion of each panel to eliminate edge effects.

Matrix and reinforcement properties

The true flexural moduli of elasticity (E_m) and rigidity (G_m) of the hardboard matrix were estimated from load and deflection at proportional limit data for beams deflected under two complementary loading arrangements. The midspan deflection of a simply supported homogeneous beam under a point load at midspan or two equal point loads symmetric about the midspan, as derived by elastic strain energy methods is, respectively (Timoshenko and Gere 1972):

$$y = \frac{Pl^3}{48E_mI} + \frac{0.3Pl}{bdG_m} \tag{1}$$

$$y = \frac{Pa(3l^2 - 4a^2)}{48E_mI} + \frac{0.6Pa}{bdG_m} \tag{2}$$

The former term in each equation represents deflection due to bending moment; the latter, deflection due to shear. The ratio of material properties, E_m/G_m, was assumed to be equal to a constant, n. Estimates of E_m and G_m were obtained by making the appropriate substitution into Eqs. (1) and (2), and solving for n, E_m and G_m. It is important to note that Eqs. (1) and (2) apply to isotropic materials. This restriction has not been rigorously imposed in this study for reasons of practicality.

The tensile modulus of elasticity of the glass fiber fabric reinforcement (E_f) was computed directly from tension test load/deformation data obtained from 1-inch-wide adhesive-coated fabric strips over a 3-inch gauge length. The tests were conducted by the supplier according to an in-house procedure in which the specimen grips were separated at a rate of 2 inches per minute.

Flexural dynamic modulus of elasticity

The flexural dynamic modulus of elasticity of glass fiber reinforced hardboard was determined from its fundamental resonant frequency of vibration observed

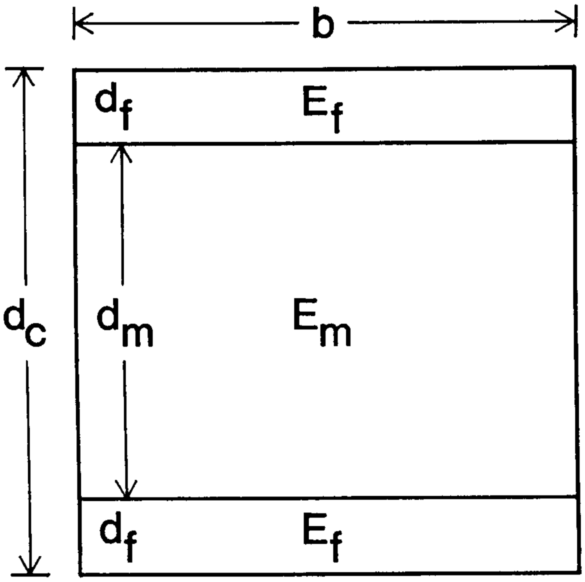

FIG. 3. Sandwich construction cross section.

under conditions of forced oscillation. Nine replications were conducted for each reinforcement volume fraction.

A composite beam simply supported at its nodal points was excited in transverse vibration with an audio signal of known frequency. The motions produced by flexural compressive and tensile strains induced in the beam's surface were transduced into an electric signal by a piezoelectric crystal resting upon it. At constant audio signal gain, the amplitude of the transduced signal was monitored as the exciting frequency was varied. Maximum signal amplitude was attained when the beam was driven at its fundamental resonant frequency. Test theory, procedure, and apparatus have been described in detail by Jayne (1959).

The dynamic modulus of elasticity of an isotropic free-free rectangular beam vibrating at its fundamental resonant frequency is computed as (Read and Dean 1978):

$$E' = \frac{0.00245 f_r^2 w L^3}{b d^3} \tag{3}$$

(The constant in Eq. (3) has units of s^2 in.$^{-1}$.)

TABLE 1. *Glass fiber reinforcement and hardboard matrix properties.*

	E (psi)	G (psi)	Stress at failure (psi)	Strain at failure (in. in.$^{-1}$)
Glass fiber reinforcement	3,272,000*	—	135,600	0.041
Hardboard matrix	450,900**	34,700	3,360	0.012

* Tension.
** Flexure.

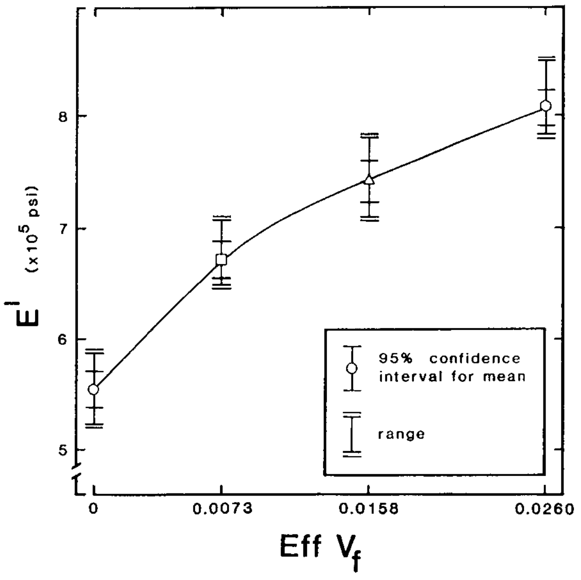

FIG. 4. Influence of effective reinforcement volume fraction (Eff V_f) on the flexural dynamic modulus of elasticity (E') of glass fiber reinforced hardboard.

Flexural static MOE and MOR

Subsequent to nondestructive dynamic evaluation, the static flexural MOE and MOR of the 9 composite beams were determined as per ASTM D 1037 (ASTM 1981). Twenty-four additional specimens were tested, increasing the number of replications at each reinforcement volume fraction to 15.

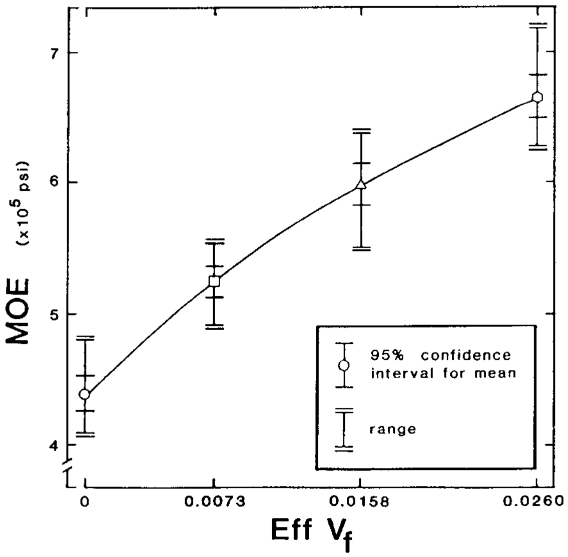

FIG. 5. Influence of effective reinforcement volume fraction (Eff V_f) on the flexural modulus of elasticity (MOE) of glass fiber reinforced hardboard.

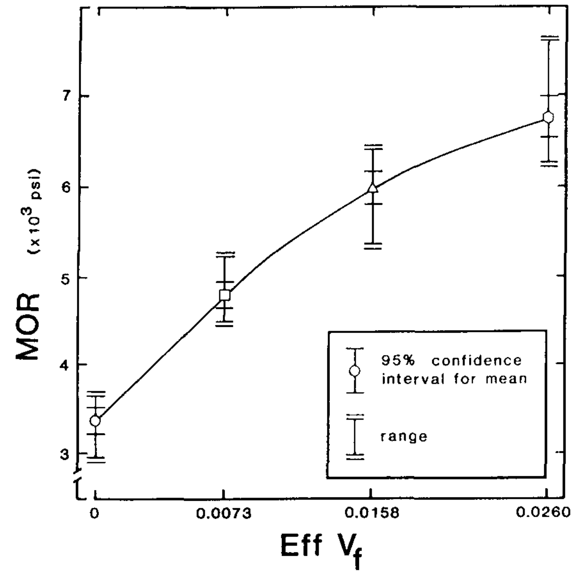

FIG. 6. Influence of effective reinforcement volume fraction (Eff V_f) on the flexural modulus of rupture (MOR) of glass fiber reinforced hardboard.

THEORETICAL RELATIONSHIPS

Prediction of composite static flexural MOE

When modelled as a sandwich construction, the true flexural modulus of elasticity of the composite (E_c) could be expressed as a function of the true flexural modulus of elasticity of the wood fiber matrix, and the tensile modulus of elasticity and volume fraction of the glass fiber reinforcement.

When viewed in cross section, the composite was not by strict definition of sandwich construction (Fig. 2a). Several assumptions were invoked in modelling the composite as a true sandwich. Individual yarns of the woven fabric were considered *en masse,* and were modelled as a solid lamina of glass fiber of identical cross-sectional area acting in the same plane (Fig. 2b). Wood fiber composing the composite surface and the 0.01-inch-thick layers separating glass fiber plies was

TABLE 2. *Observed and predicted properties of glass fiber reinforced hardboard.**

	Observed			Predicted	
Effective V_f	E′	MOE	MOR	E	MOE
0	554,300 (20,520)	439,500 (23,360)	3,360 (270)	450,900	439,400
0.0073	671,200 (20,950)	524,900 (21,260)	4,800 (280)	512,100	501,400
0.0158	741,000 (23,840)	597,300 (28,800)	5,970 (330)	582,700	570,900
0.0260	808,600 (23,520)	664,800 (29,780)	6,740 (410)	665,000	652,000

* All values in psi; (SD).

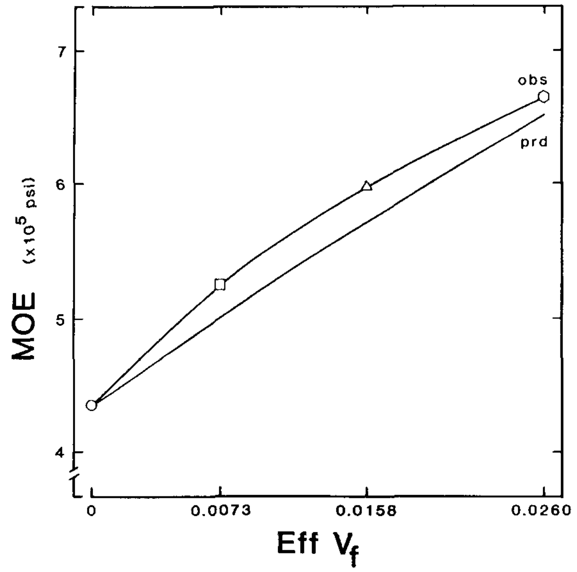

FIG. 7. Influence of effective reinforcement volume fraction (Eff V_f) on the observed and predicted flexural modulus of elasticity (MOE) of glass fiber reinforced hardboard.

ignored. The wood fiber matrix thickness was unchanged, and glass fiber plies acted directly upon its surface (Fig. 2c).

An effective reinforcement volume fraction that accounted for the omission of a slight volume of wood fiber, and not the actual reinforcement volume fraction, therefore, was used in all instances in this study. The effective reinforcement volume fractions based on the model sandwich cross section of Fig. 2c for 1, 2, or 3 plies of glass fiber at each surface were 0.0073, 0.0158, and 0.0260, respectively. Only those glass fibers stressed parallel to their length were considered; those oriented perpendicular to the direction of stress were ignored. Perfect bonding between wood fiber and glass fiber was assumed so that matrix and reinforcement at the interface experienced equal strain.

Three assumptions from ordinary bending theory were also applied: 1) no shifting of the neutral axis occurred; 2) the composite E-moduli in tension and compression were equal; and 3) strain was linearly proportional to stress.

A theoretical expression for predicting E_c was derived beginning with the expression used to calculate the stiffness of a sandwich beam symmetric about its neutral axis (Fig. 3) (Kuenzi 1959):

$$E_cI_c = E_m\frac{bd_m^3}{12} + E_f\frac{b(d_c^3 - d_m^3)}{12} \tag{4}$$

With $I_c = bd_c^3/12$, Eq. (4) reduces to:

$$E_c = E_m\frac{d_m^3}{d_c^3} + E_f\left(1 - \frac{d_m^3}{d_c^3}\right) \tag{5}$$

Equation (5) can be expressed in terms of the volume fraction occupied by the reinforcing faces by recognizing that:

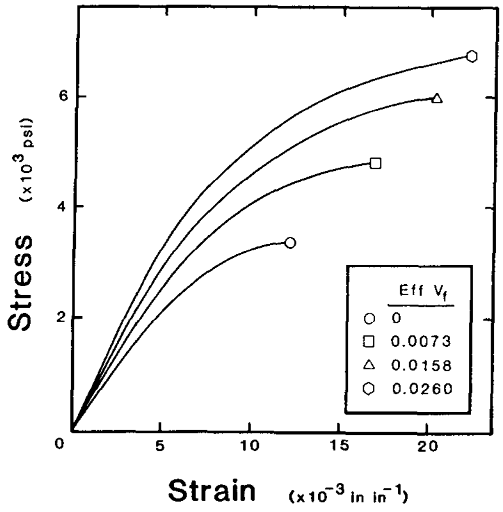

FIG. 8. Influence of effective reinforcement volume fraction (Eff V_f) on the flexural stress-strain response of glass fiber reinforced hardboard.

$$V_m = \frac{v_m}{v_c} = \frac{d_m}{d_c} \tag{6}$$

and

$$V_m + V_f = 1 \tag{7}$$

Substituting Eqs. (6) and (7) into Eq. (5) yields an expression for predicting the composite modulus based on the moduli of the components and the volume fraction of reinforcement:

$$E_c = E_f + (1 - V_f)^3(E_m - E_f) \tag{8}$$

The true flexural modulus of elasticity of the composite, however, can be determined experimentally only when it is deflected under the ideal condition of pure bending moment. In ordinary or static bending, the applied bending moment induces shear forces that produce additional deflection. The total deflection thus comprises both bending and shear components, and the modulus computed is not the true modulus of elasticity, but rather an apparent modulus of elasticity, MOE. It is advantageous to use the predicted E_c in conjunction with the shear modulus to compute a predicted apparent MOE, which can be compared directly with the experimentally observed MOE.

The total deflection of a simply supported sandwich beam under a point load at its midspan is (Kuenzi 1959):

$$y = \frac{Pl^3}{48E_cI_c} + \frac{Pl}{4N} \tag{9}$$

Shear stiffness, N, is equal to:

$$N = \left(\frac{d_c + d_m}{2}\right)bG_m \tag{10}$$

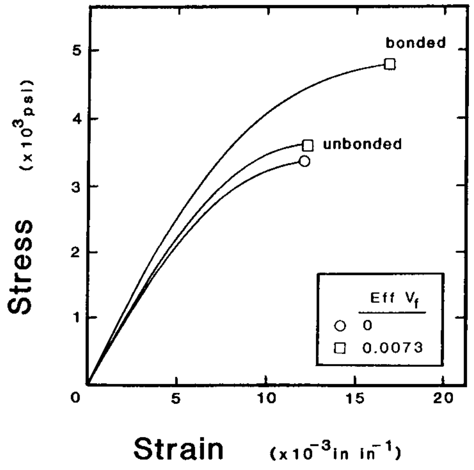

FIG. 9. Influence of bonded and unbonded glass fiber on the flexural stress-strain response of glass fiber reinforced hardboard at an effective reinforcement volume fraction (Eff V_f) of 0.0073.

The predicted apparent MOE is estimated by inserting the values for G_m and predicted E_c into Eq. (9), and using the resulting total deflection, the beam dimensions and the observed load at proportional limit in the customary expression:

$$\text{MOE} = \frac{Pl^3}{48I_c y} \tag{11}$$

RESULTS AND DISCUSSION

Properties of the hardboard matrix and the glass fiber reinforcement are shown in Table 1.

Effect of reinforcement volume fraction on composite E', MOE and MOR

The flexural dynamic modulus of elasticity, the static flexural modulus of elasticity and the modulus of rupture of glass fiber reinforced hardboard increased with increasing effective reinforcement volume fraction (Figs. 4–6; Table 2). The mean observed E', MOE and MOR at each effective reinforcement volume fraction was statistically unique at $\alpha = 0.01$ using analysis of variance and Duncan's multiple range test.

Prediction of composite static flexural MOE

Excellent agreement existed between the predicted and mean observed values of MOE of glass fiber reinforced hardboard when modelled as a sandwich construction (Table 2). When expressed as a percentage of the observed value, the predicted MOE underestimated the mean observed MOE by less than 5% over all effective reinforcement volume fractions (Fig. 7).

Two probable effects were cited in explanation of the conservative nature of predicted values. First, wood fiber composing the composite surface and that separating glass fiber plies was ignored in the model. Its contribution to the stiffness of the composite, however small, was thus unaccounted for. Second, it was tacitly

TABLE 3. *Observed properties of glass fiber reinforced hardboard with bonded and unbonded glass fiber.**

	Effective V_f		
	0	0.0073 unbonded	0.0073 bonded
MOE	439,500 (23,360)	459,200 (19,700)	524,900 (21,260)
MOR	3,360 (270)	3,590 (250)	4,800 (280)

* All values in psi; (SD).

assumed that each component acted within the composite as it would alone. Counter to this assumption, a wood fiber/adhesive/glass fiber synergy was proposed. Two possible factors were acknowledged. First, the specific gravity profile that normally exists in hardboard—higher at the surface and lower in the core—may have been accentuated by the presence of the subsurface glass fiber. Second, the adhesive used to bond reinforcement to matrix may have stiffened wood fiber at the interface. Both phenomena would have occurred at the composite's surface where their combined effect would have exerted the greatest influence on composite stiffness.

Composite failure

At all effective reinforcement volume fractions, the composite failed by tensile fracture of the extreme fiber of the hardboard matrix. The adjacent wood fiber/glass fiber interface remained viable, indicating good interfacial adhesion. Upon dissolving the matrix with concentrated sulfuric acid, the glass fiber fabric was recovered intact, with no tensile failure evident. The observed failure mode was due to a strain at maximum stress for the hardboard matrix that was significantly less than that of the glass fiber reinforcement: 0.012 in. in.^{-1} versus 0.041 in. in.^{-1}. Steel-fiber-reinforced concrete and glass-fiber-reinforced gypsum plaster are two additional brittle matrix composites that exhibit similar behavior (Aveston et al. 1972).

The MOR of a composite with a matrix of low strain at failure increases with increasing reinforcement volume fraction even though the reinforcement never fails. This arises because the work per unit volume performed in deforming the composite is distributed as strain energy among its components. The proportion of total strain energy owing to the reinforcement increases as its volume fraction increases. The matrix will fail at the same strain regardless of whether it is a homogeneous beam, or part of a composite. Thus, a greater applied stress is required to develop the necessary fracture strain in the matrix when it is part of a composite (Fig. 8).

Stress transfer

A viable adhesive bond between reinforcement and matrix is paramount to enhanced property development in composite materials. Transfer of an applied stress from matrix to reinforcement is effected by the development of shear stress at the matrix/adhesive/reinforcement interface. Significant stress transfer has the greatest probability of occurrence when the reinforcement and matrix are linked

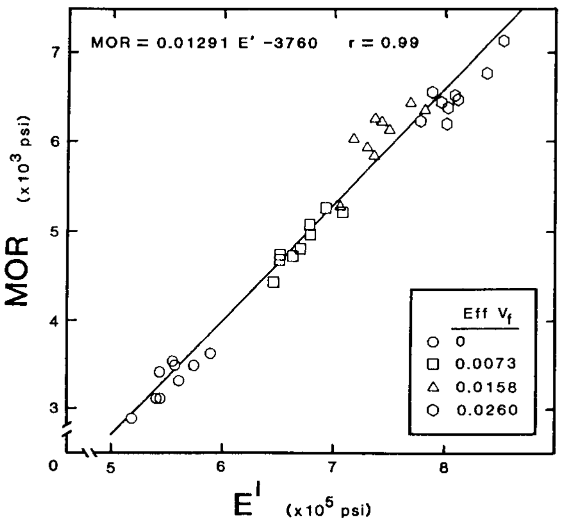

FIG. 10. Relationship between the static bending modulus of rupture (MOR) and the dynamic modulus of elasticity (E') of glass fiber reinforced hardboard by effective reinforcement volume fraction (Eff V_f).

by an interfacial zone of intermediate modulus. This zone serves to minimize the development of localized stress concentrations that could initiate their separation.

The powdered phenolic adhesive used to bond glass fiber to wood fiber was effective in promoting stress transfer (Fig. 9). When no adhesive was applied to the reinforcement, the MOE and MOR of the composite were only slightly greater

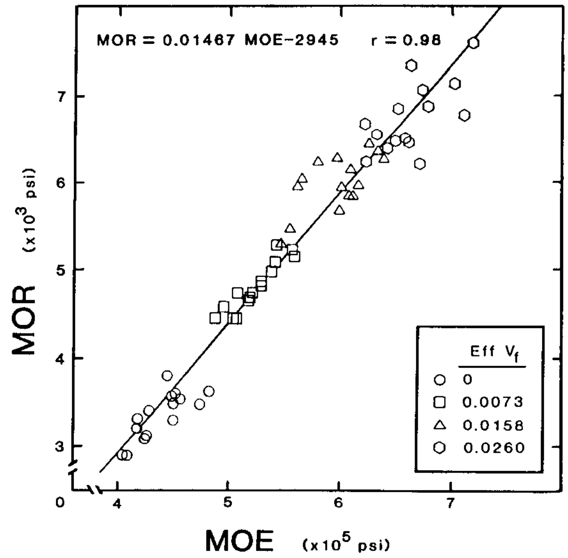

FIG. 11. Relationship between the static bending modulus of rupture (MOR) and the static bending modulus of elasticity (MOE) of glass fiber reinforced hardboard by effective reinforcement volume fraction (Eff V_f).

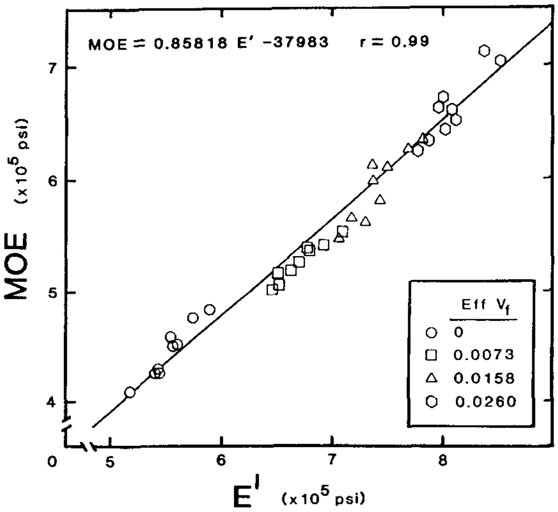

FIG. 12. Relationship between the static bending modulus of elasticity (MOE) and the dynamic modulus of elasticity (E') of glass fiber reinforced hardboard by effective reinforcement volume fraction (Eff V_f).

than that of the nonreinforced control (Table 3). The difference in both properties was significant at $\alpha = 0.05$. Frictional forces and minimal autoadhesion between glass fiber and wood fiber are likely responsible. When the same reinforcement volume fraction was bonded in situ, however, a substantial increase in the composite stress at failure was realized.

Correlation of composite dynamic and static flexural properties

Unlike the MOE, the stress at which the composite will fail cannot be predicted using the sandwich model. The model is appropriate only for linear elastic behavior; the stress-strain response of the composite to failure was decidedly nonlinear. In response, empirical correlations between paired values of E' and MOR, MOE and MOR, and E' and MOE were identified using the method of least squares. The nominal failure stress, MOR, can thus be estimated from either the theoretical MOE, or the nondestructively determined E' or MOE.

Excellent correlation was found among the dynamic modulus of elasticity, the static modulus of elasticity, and the modulus of rupture of glass fiber reinforced hardboard. A slight overlapping of the range of values about each mean occurs at its extremes for all effective reinforcement volume fractions. Strong linear association among the properties is due to the mutual dependence of each on the effective reinforcement volume fraction. The MOR can be reliably estimated from E' and MOE using empirical equations shown in Figs. 10 and 11, respectively. The MOE can be reliably estimated from E' in the same manner (Fig. 12).

On average E' was 25% greater than the MOE. The departure is conceivably due to a rate of loading in dynamic testing 10,000 times faster than that used in static testing. Limited support for this supposition was found in the data of McNatt (1970, 1975), who reported that the bending MOE of particleboard increased by an amount equal to approximately 6% of the MOE determined at the ASTM standard rate of loading for each tenfold decrease in time to failure. Moslemi (1967), however, determined E′ for both wet- and dry-process hardboard using a vibrating cantilever specimen and found it to be approximately equal to the static bending MOE. The lack of agreement between investigators indicates the need for further study.

SUMMARY AND CONCLUSIONS

Significant enhancement of the flexural stiffness and strength of a dry-process hardboard matrix was achieved by internal reinforcement with continuous glass fiber. The E′, MOE, and MOR of glass fiber reinforced hardboard increased with increasing effective reinforcement volume fraction. The failure of the composite occurred as a tensile fracture of the extreme fiber of the hardboard matrix, and was due to a strain at failure for the matrix that was significantly less than that of the reinforcement. Excellent linear correlation between MOE and MOR, E′ and MOR, and MOE and E′ allowed for estimation of the composite failure stress from nondestructively determined flexural properties.

When modelled as a sandwich construction, the flexural MOE of glass fiber reinforced hardboard was a function of the flexural MOE of the hardboard matrix, and the tensile MOE and effective volume fraction of the glass fiber reinforcement. Shear deflection of the hardboard matrix must be accounted for. Excellent agreement was found between observed values of MOE and those predicted by the model. Simplifying assumptions made in the modelling process, and a possible wood fiber/adhesive/glass fiber synergy may account for the slight undervaluation of the predicted MOE.

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APPENDIX

Style 1659 is a leno-weave bidirectional E-glass fiber fabric manufactured by Burlington Glass Fabrics Company, Altavista, Virginia. The fabric weighs 1.64 ounces per square yard, and has 20 warp and 10 fill yarns per inch (10 × 10 visual). Each warp yarn contains 408 individual glass filaments 3.6×10^{-4} inches in diameter. Fill yarns are composed of 816 filaments of identical diameter. Warp yarns alternatively pass over and under fill yarns so that proper spacing is maintained. As a result, fabric tensile strength in the fill direction is slightly greater. A starch size was applied to the fabric by BGF to improve its processability.

PARAC® GP-5520 powdered resin is a two-step phenol-formaldehyde novolac resin manufactured by Georgia-Pacific Corporation, Peachtree, Georgia.