FIBER-REINFORCED WOOD COMPOSITES

R. E. Rowlands

Professor of Engineering Mechanics
University of Wisconsin
Madison, WI 53706

R. P. Van Deweghe[1]

Graduate Assistant
Mechanics Department, University of Wisconsin
Madison, WI 53706

T. L. Laufenberg

Engineer
Forest Products Laboratory,[2] P.O. Box 5130
U.S. Department of Agriculture, Forest Service
Madison, WI 53705

and

G. P. Krueger

Former Dean of Engineering
Michigan Technological University
Houghton, MI 49931

(Received June 1984)

ABSTRACT

The technical feasibility of producing internally reinforced laminated wood is evaluated experimentally. Numerous fiber reinforcements and adhesives are assessed, and effects of several processing and environmental parameters are included. Results demonstrate the increased strength and stiffness to be achieved under both tension and flexure by adding fiber reinforcement. Glass reinforcement is particularly suitable.

Keywords: Fiber-reinforced, composites, wood, laminated-veneer lumber, glass, graphite, Kevlar®, adhesives, mechanical properties.

SYMBOLS

A	adhesive failure, as a superscript
B	significant wood failure, as a superscript
b	beam width
c	reinforcement-adhesive composite system, as a subscript
D	Douglas-fir, as a subscript
E	elastic modulus

[1] Now engineer, Trane Co., LaCrosse, WI.

[2] Maintained at Madison, WI, in cooperation with the University of Wisconsin. The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture of any product or service to the exclusion of others that may be suitable.

Wood and Fiber Science, 18(1), 1986, pp. 39–57

G	shear modulus
h	beam depth
I	area moment of inertia
ℓ	beam span
P	load
t'	per-ply thickness
t	total thickness of reinforcement
T	based on total area, as a subscript
u	ultimate, as a superscript
VPS	vacuum-pressure-soak cycle
w	predominately wood failure, as a superscript
δ	deflection
σ	stress

INTRODUCTION

Advances in fiber-reinforced plastics motivate one to evaluate the feasibility of producing high-performance synthetically reinforced wood. Strong and/or stiff fiber-reinforced wood components could substitute for larger and heavier all-wood members, thereby using less wood and minimizing mechanical property variability. Acceptable reinforcement systems and processes would also permit structural use of poorer quality wood, including short lengths. Additional advantages and savings could be realized by reinforcing and thereby strengthening mechanical fasteners, regions of stress concentration, and finger and butt joints.

The authors are unaware of any prior wood reinforcement with uncured preimpregnated materials, or internal reinforcement with graphite or Kevlar®.[3]

Numerous investigations have considered reinforced wood. Most of these pursuits have involved metal reinforcement (Bohannan 1962; Borgin et al. 1968; Curtis 1972; Hoyle 1975; Lantos 1964, 1970; Mark 1961; Peterson 1965; Sliker 1962), while fewer investigations have been concerned with nonmetallic synthetic fiber reinforcement (Boehme 1976; Boehme and Schulz 1974; Bulleit 1980; Saucier and Holman 1976; Spaun 1981; Theakston 1965).

The results of reinforcing laminated Douglas-fir and maple components are reported here. Ten adhesives (epoxies, resorcinol formaldehydes, phenol resorcinol formaldehydes, isocyanates, and a phenol-formaldehyde) and numerous types of fiber reinforcement (unidirectional and cross-woven glass, graphite, and Kevlar®) are evaluated. Effects on performance of different cure cycles and weathering are included. The extremely strong glass reinforcements could be helpful in joints, windmill blades, pallets, trusses, and scaffolds, while the stiff graphite contribution would be advantageous in roof, floor, and deck systems. An economic study of manufacturing fiber-reinforced wood (Laufenberg et al. 1984) and a study of the potential for strengthening butt joints with graphite reinforcement (Krueger et al. 1984) utilize the results reported in this paper.

ADHESIVES

The ten adhesives evaluated are listed in Appendix I. Although the eventual intent was to reinforce Douglas-fir laminates, the various adhesives were also

[3] Kevlar is a trademark of E. I. DuPont.

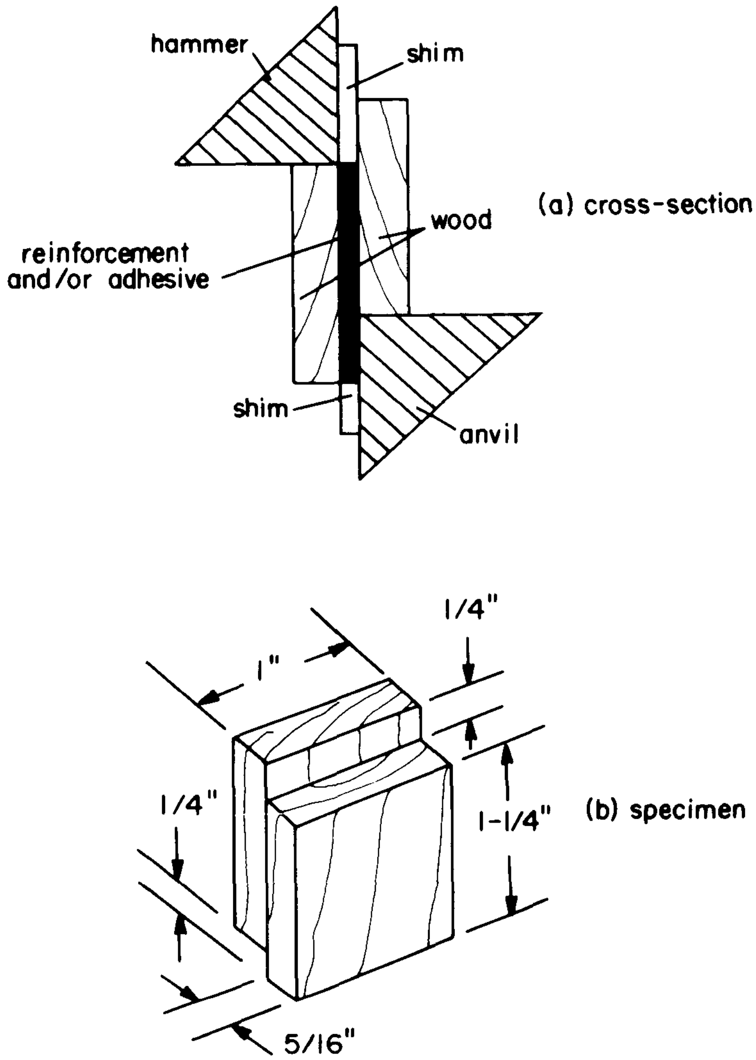

FIG. 1. ASTM D 905-49(76) shear test.

evaluated with maple because of its superior strength. Both shear (ASTM D 905-49, Fig. 1) and tensile (ASTM 1344-72) strengths of adhesives were measured. While epoxies have not been popular wood adhesives, they are used extensively with fiber-reinforced materials.

The measured shear (parallel to the grain) and tensile strengths (standard deviations in parentheses) of the various adhesives (no reinforcement) are listed in Table 1. Unless noted otherwise, these adhesives were cured at room temperature. As indicated by the W superscript (wood failure) in Table 1, all adhesives performed at least as well in shear as the Douglas-fir adherends. Moreover, all bonded Douglas-fir tensile specimens failed in the wood except those bonded with either the Plenco P-650 or the Dow epoxy. Douglas-fir typically has a shear strength (parallel to the grain) of 1,000–1,500 lb/in.[2] (Wood Handbook 1974), which agrees

TABLE 1. *Shear and tensile strengths of various adhesives with maple and Douglas-fir adherends–room-temperature cures.*

Adhesive	Shear strength[1]		Tensile strength[1]	
	Maple	Douglas-fir	Maple	Douglas-fir
	lb/in.^{2}			
Ashland isocyanate	2,693[A]	1,546[W]	814[B]	264[W]
(EP65-A58/A59)	(247)[2]	(87)	(156)	(56)
Upjohn isocyanate[3]	1,850[W]	—	—	—
(Isobind 100)	(430)			
Kopper's G1131	3,447[B]	1,468[W]	460[A]	252[W]
(resorcinol formaldehyde)	(122)	(105)	(35)	(15)
Borden's RS-216	2,739[A]	1,521[W]	498[A]	259[W]
(resorcinol formaldehyde)	(285)	(78)	(35)	(39)
Kopper's G4411	2,418[A]	1,583[W]	373[A]	225[W]
(phenol resorcinol formaldehyde)	(167)	(143)	(53)	(49)
Borden's LT-68-D	2,186[A]	1,454[W]	—	—
(phenol resorcinol)	(287)	(116)		
Plenco P-650[3]	2,892[W]	1,450[W]	697[B]	250[B]
(phenol-formaldehyde)	(595)	(74)	(121)	(90)
Dow epoxy	2,994[B]	1,465[W]	268[A]	209[B]
(DER 736 + DER 331 + DEH24)	(245)	(74)	(27)	(62)
Everfix epoxy	1,812[A]	1,497[W]	304[A]	308[W]
	(228)	(136)	(81)	(65)
Ciba epoxy[3]	4,085[W]	—	—	—
(RP136 + H-994)	(108)			

Failure—A, dominated by adhesive failure (0–10% wood failure). B, significant wood failure (20–80% wood failures). W, dominated by wood failure (80–100% wood failures).

[1] Unless otherwise stated, all wood specimens tested were conditioned at 80 F and 65% RH to achieve a 12% MC. All wood surfaces were passed through a jointer within 24 hr of gluing to provide a clean, smooth surface. Cured specimens were again returned to the conditioning room (80 F and 65% RH) for at least a week prior to testing.

[2] Standard deviations in parentheses.

[3] Cured at elevated temperature.

with the wood shear failures for this material (Table 1). Sugar maple has a shear strength of 1,500–2,300 lb/in.^{2} (Wood Handbook 1974).

The average shear strengths in Table 1 are based on a minimum of 5 specimens from each of 2 bonded wood layups, for a minimum of 10 specimens. All tensile strengths in Table 1 are averages of 8 specimens from each of 2 bonded assemblies, for a total of 16 tests.

For the room-temperature-cured adhesives (other than Isobind-100, Plenco P-650, and Ciba epoxy) of Table 1, the maple specimens were cured at 200 to 225 lb/in.^{2}, while the Douglas-fir specimens were cured at 100 to 150 lb/in.^{2}. Room-temperature-pressurized cure time was at least 20 hours (Rowlands et al. 1981).

The elevated-temperature curing of the glued specimens was achieved by pressing between hot platens. In actual production it may be advantageous to use the latent heat of preheated wood to aid curing.

REINFORCEMENT SYSTEMS

Several different forms of glass-, Kevlar®-, and graphite-fiber reinforcements were evaluated. Unidirectional and cross-woven nonimpregnated materials were

TABLE 2. *Shear strength (lb/in.^{2}) of room-temperature-cured reinforced Douglas-fir.*[1,2]

	Adhesive and cure pressure (lb/in.^{2})									
	Ashland isocyanate		RS-216		G1131		G4411		Dow epoxy	
Reinforcement	150	100	150	100	150	100	150	100	150	75
Glass										
Uniglass A-260	740 (17)[4]	525 (35)	1,546^{W}[3] (135)	1,401^{W} (162)	1,671^{W} (67)	1,643^{W} (94)	1,510^{W} (82)	1,663 (26)	1,213 (74)	2,040^{W} (97)
Heavy weave glass B238	759 (80)	695 (60)	1,508^{W} (110)	1,141^{W} (92)	1,689^{W} (44)	1,644^{W} (44)	1,585^{W} (61)	1,667 (57)	639 (71)	1,727^{W} (78)
Light weave glass-auto	— —	938 (129)	1,897 (28)	1,817^{W} (46)	— —	— —	— —	— —	— —	— —
Kevlar®										
Uni-Kevlar® 417	1,219 (54)	1,196^{W} (129)	1,503 (61)	1,731 (79)	1,114 (69)	1,251 (167)	1,437 (94)	1,636 (152)	1,275^{W} (120)	1,743^{W} (83)
Heavy weave Kevlar® 1035	519 (30)	536 (19)	1,076 (50)	1,179 (15)	1,093 (50)	1,164 (50)	1,134 (104)	1,211 (40)	789 (113)	1,634^{W} (48)
Light weave Kevlar® 500	826 (40)	776 (28)	1,327 (144)	1,353 (143)	— —	— —	— —	— —	— —	— —
Graphite										
Unigraphite 417	1,229^{W} (83)	1,300^{W} (167)	1,497^{W} (67)	1,353^{W} (84)	1,625^{W} (45)	1,645^{W} (66)	1,408^{W} (72)	1,162^{W} (125)	1,313^{W} (86)	1,864^{W} (50)

[1] Each result average of five tests.
[2] ¾-in.-thick Douglas-fir adherends.
[3] Superscript W denotes mostly wood failure.
[4] Standard deviations in parentheses.

TABLE 3. *Shear strength of reinforced Douglas-fir adherends hot-cured*[1,2] *with phenol-formaldehyde (Plenco P-650).*

Reinforcement	Strength
Glass	*lb/in.²*
Uniglass A-260	498 (136)[3]
Heavy weave glass B238	748 (172)
Kevlar®	
Uni-Kevlar® 417	886 (185)
Heavy weave Kevlar® 1033	494 (155)
Graphite	
Uni-graphite 417	1,954 (79)[W4]

[1] Cured for 45–70 min at 70 lb/in.² with platens at 335 F.
[2] ¾-in.-thick Douglas-fir adherends.
[3] Standard deviations in parentheses.
[4] Superscript W denotes mostly wood failure.

tested, as were biwoven products impregnated with phenol-formaldehyde (Appendix II).

The suitability of reinforcing wood with the fiber systems in Appendix II, and using the adhesives of Appendix I, was evaluated on the basis of the shear tests (ASTM D 905-49) of the interface between Douglas-fir and maple adherends. Tables 2 and 3 contain data for Douglas-fir adherends, while Tables 4–6 contain data for maple adherends. The adhesives of Tables 2 and 4 were cured at room temperature; those of Tables 3, 5, and 6 were hot-pressed. The reinforcements and loadings of the specimens of Tables 2–6 were both parallel to the wood grain. Effects of cure pressure from 50 to 150 lb/in.² are included.

The resorcinol formaldehydes (RS-216 and G1131) generally performed well with glass and graphite reinforcements (Tables 2, 4, 5). Most adhesives performed well with the graphite (Tables 2–5), and the Dow epoxy bonded well to all reinforcements, particularly at the lower curing pressure of 75 lb/in.² (Tables 2 and 6). The Ciba system performs well in unreinforced and reinforced specimens (Tables 1 and 6). Unidirectional glass or graphite cured with either of the epoxies (Dow, Ciba), resorcinol formaldehydes (RS-216, G1131), or phenol resorcinol formaldehyde (G4411) provides an interface shear strength at least equal to that of Douglas-fir, suggesting their suitability for reinforcing that material. Although glass and graphite perform excellently, the Kevlar® is not as good. Unidirectional reinforcements exhibit shear strengths (parallel to the fibers) superior to those of

TABLE 4. *Shear strengths*[1] *of unidirectionally reinforced maple using room-temperature-cured*[2] *resorcinol formaldehyde (G1131).*

Reinforcement	Strength
	lb/in.²
417 glass	3,265 (175)[3]
417 Kevlar®	2,045 (374)
417 graphite (2-ply)	3,072 (437)

[1] Adhesive failures throughout.
[2] All assemblies had an open time of 2 min, a closesd time of 45 min, a press time of 24 hr at 74 F and 100 lb/in.².
[3] Standard deviations in parentheses.