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.

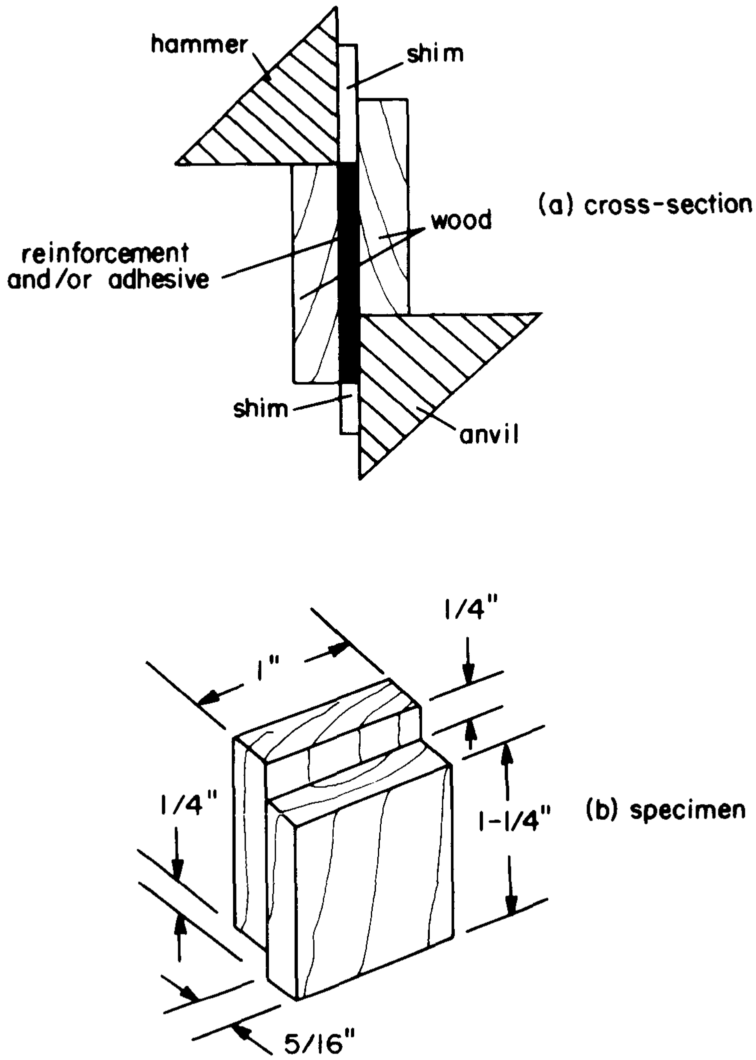

FIG. 1. ASTM D 905-49(76) shear test.

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	525	1,546^{W3}	1,401^{W}	1,671^{W}	1,643^{W}	1,510^{W}	1,663	1,213	2,040^{W}
	(17)[4]	(35)	(135)	(162)	(67)	(94)	(82)	(26)	(74)	(97)
Heavy weave glass B238	759	695	1,508^{W}	1,141^{W}	1,689^{W}	1,644^{W}	1,585^{W}	1,667	639	1,727^{W}
	(80)	(60)	(110)	(92)	(44)	(44)	(61)	(57)	(71)	(78)
Light weave glass-auto	—	938	1,897	1,817^{W}	—	—	—	—	—	—
	—	(129)	(28)	(46)	—	—	—	—	—	—
Kevlar®										
Uni-Kevlar® 417	1,219	1,196^{W}	1,503	1,731	1,114	1,251	1,437	1,636	1,275^{W}	1,743^{W}
	(54)	(129)	(61)	(79)	(69)	(167)	(94)	(152)	(120)	(83)
Heavy weave Kevlar® 1035	519	536	1,076	1,179	1,093	1,164	1,134	1,211	789	1,634^{W}
	(30)	(19)	(50)	(15)	(50)	(50)	(104)	(40)	(113)	(48)
Light weave Kevlar® 500	826	776	1,327	1,353	—	—	—	—	—	—
	(40)	(28)	(144)	(143)	—	—	—	—	—	—
Graphite										
Unigraphite 417	1,229^{W}	1,300^{W}	1,497^{W}	1,353^{W}	1,625^{W}	1,645^{W}	1,408^{W}	1,162^{W}	1,313^{W}	1,864^{W}
	(83)	(167)	(67)	(84)	(45)	(66)	(72)	(125)	(86)	(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.

TABLE 5. *Shear strengths[1,2] of reinforced maple using hot-pressed[3] resorcinol- and phenol-resorcinol-formaldehyde adhesives.*

Adhesive	Resorcinol formaldehyde				Phenol resorcinol formaldehyde	
	RS-126		G1131		G4411	
Cure pressure reinforcement	100	65	100	50	100	50
	lb/in.²					
A260 glass ≡[4]			[5]1,814	2,778	1,558	2,383
			(431)	(427)	(412)	(516)
B238 glass #[6]			1,600	1,574	1,216	1,461
			(196)	(257)	(172)	(216)
417 Kevlar® ≡	1,527	1,938	2,243	3,056	1,805	2,731
	(196)	(188)	(335)	(255)	(324)	(449)
1033 Kevlar® #	857	1,099	973	1,190	613	891
	(106)	(120)	(168)	(65)	(77)	(110)
417 graphite ≡			2,673	3,187	3,337	3,620
			(399)	(293)	(280)	(439)

[1] There were no wood failures.
[2] All results average of 12 tests.
[3] All assemblies had open time of 5–7 min, close time of 40–50 min (except G4411 which was 2 hr), and hot-pressed for 6–7 min with platens at 275 F.
[4] ≡ denotes unidirectional reinforcement.
[5] Standard deviations in parentheses.
[6] # denotes bidirectional reinforcement.

woven materials. Elevated-temperature cures with pressures no greater than 50 lb/in.², and room-temperature cure pressures of no more than 100 lb/in.², appear advantageous.

In addition to the individual adhesives and reinforcements of Tables 2–6, glass-, Kevlar®-, and graphite-woven prepreg reinforcements using phenol-formaldehyde were also evaluated. Information on the prepregs used in this evaluation is contained in Appendix II. This is the first known application of uncured preim-

TABLE 6. *Shear strengths[1] of reinforced maple using hot-pressed[2] Isobind 100 and epoxy adhesives.*

Adhesive	Shear strength (standard deviation) (lb/in.²) — Reinforcement: 417 Glass ≡[3]	417 Kevlar® ≡	417 Graphite ≡	A260 Glass ≡	B238 Glass #[4]	1033 Kevlar® #	None
Dow epoxy	3,750[W5]	3,927[W]	3,765	4,085[W]	1,364	1,317	
(75/25/10)	[6](175)	(161)	(170)	(132)	(340)	(374)	
Ciba epoxy	4,223[W]	4,185[W]	4,215[W]				4,085[W]
	(127)	(76)	(53)				(334)
Isocyanate	2,086	2,140	2,372	1,915	844		2,006
(Isobind)	(416)	(331)	(173)	(286)	(428)		(334)

[1] All results are average of at least 6, and normally 13, tests.
[2] All assemblies had an open time of 2 min, a closed time of 40–45 min, a press time of 20–17 min, platen temperatures of 280 F, and all but the Isobind isocyanate cured A-260 glass, B-238 glass, and unreinforced maple (which had curing pressure of 100 lb/in.²) were cured under 50 lb/in.² pressure.
[3] ≡ denotes unidirectional reinforcement.
[4] # denotes bidirectional reinforcement.
[5] Superscript W denotes dominated by wood failures.
[6] Standard deviations in parentheses.

TABLE 7. *Shear strength of preimpregnated fiber (phenol-formaldehyde resin) reinforced maple.*

Prepreg	Cure cycle			Shear strength[1]
	Platen temperature	Cure time	Cure pressure	
	°F	*min*	*lb/in.²*	*lb/in.²*
Glass	275	25	150	[2]1,090 (346)[A3]
Glass	275	25	50	2,043 (476)[A]
Glass	275	60	150	3,683 (251)[W]
Glass	275	60	50	3,822 (119)[B]
Glass[4]	275	60	50	2,614 (429)[A]
Glass	365	25	50	3,087 (384)[A]
Glass	365	25	15	1,975 (658)[A]
Graphite	365	25	50	1,465 (890)[A]
Graphite	365	25	15	366 (157)[A]
Graphite	280	60	150	1,129 (711)[A]
Graphite	280	60	50	1,634 (434)[A]
Kevlar®	365	25	50	1,640 (286)[A]
Kevlar®	365	25	15	1,855 (338)[A]
Kevlar®	280	60	50	1,573 (297)[A]
Kevlar®	280	60	15	2,195 (665)[A]

[1] Results are typically the average of 12 specimens from a common assembly.
[2] Standard deviations in parentheses.
[3] Superscript A denotes mostly adhesive failures (0–20%), B denotes significant wood failures (20–80%), and W denotes dominant wood failures (80–100%).
[4] Phenol-formaldehyde (Plenco P-650) added to wood surfaces prior to inserting prepreg.

pregnated fibers to wood. Preimpregnated reinforcements were hot-pressed between maple adherends and the specimens loaded in shear (ASTM D 905-49). Observed shear strengths and curing details are presented in Table 7. Glass reinforcement again shows superior performance; the strengths of all but the first case (1,090 lb/in.^{2}) exceed that of Douglas-fir (1,500 lb/in.^{2}).

The following generalizations can be made regarding the adhesive-reinforcement systems: (a) Strengths obtained with the prepreg reinforcements (Table 7) are vastly superior to those obtained using P-650 (Table 3). (b) The prepregs outperformed the bidirectional materials (glass or Kevlar®) bonded with resorcinol formaldehyde, phenol resorcinol formaldehyde, epoxy, or isocyanate. (c) The woven-glass prepreg material produced a shear strength approaching the best demonstrated by the unidirectional reinforcements. (d) Glass prepreg, and unidirectional glass, Kevlar®, or graphite cured with epoxy adhesives all produced an interface shear strength as great as that of maple, and greater than that of Douglas-fir. (e) The reinforcement of wood by unidirectional prepreg material should be evaluated. (f) Preimpregnated fiber reinforcements are exceedingly easy to use. However, their cure times are longer than those for resorcinol formaldehyde, phenol resorcinol formaldehyde, or epoxy adhesives. Also, failed specimens that had been reinforced by prepreg materials suggest insufficient resin for optimum performance (Rowlands et al. 1981).

DURABILITY OF REINFORCEMENT SYSTEM

Numerous shear specimens (ASTM D 905 test) were subjected to an accelerated exposure environment (ASTM D 2559, cycle 1) to evaluate the durability of various glass-adhesive systems. Results are presented in Table 8. Six of 12 matched

TABLE 8. *Comparison of shear strengths of accelerated aged and dry specimens.*[1]

Adhesive	Accelerated Aged Shear strength	Accelerated Aged Wood failure	Dry Shear strength	Dry Wood failure	Retention in strength (aged/dry) × 100
	lb/in.²	%	*lb/in.²*	%	%
Phenol-formaldehyde	2,716	24	2,763	6	98
Prepreg glass	[2](161)	(25)	(204)	(12)	
G1131	1,480	9	2,653	4	56
(resorcinol formaldehyde)	(839)	(11)	(185)	(5.8)	
G4411	1,763	0	2,671	<1	66
(phenol resorcinol formaldehyde)	(529)	—	(122)	—	
Dow epoxy	1,630	2	3,216	49	51
	(81)	2.6	(168)	(24)	
RS-216	1,580	<1	2,809	0	56
(resorcinol formaldehyde)	(485)	—	(234)	—	
Isobind 100	640	0	1,880	0	34
	(173)	—	(216)	—	
Ciba epoxy	1,285	4	2,993	23	43
(cured at 120 lb/in.²)	(254)	(2.3)	(119)	(20)	
Ciba epoxy	1,214	2	3,210	42	38
(cured at 50 lb/in.²)	(362)	(3.9)	(82)	(19)	

[1] All maple adherends contained style-417 unidirectional glass except the phenol-formaldehyde resin which contained style-181 bidirectional glass (prepreg).
[2] Standard deviations in parentheses.

specimens were subjected to the vacuum-pressure-soak (VPS) accelerated-environment cycle, while the other six specimens were not and thus served as a control comparison. All specimens were initially conditioned at 80 F and 65% RH to achieve an equilibrium MC of 12%. Applied shear stress and the fiber reinforcement were again parallel to wood grain. Processing and curing details of Table 8 are contained in Rowlands et al. (1981).

Table 8 indicates that aging significantly affects the durability of most glass-adhesive combinations tested. The phenol-formaldehyde prepreg and G1131 (resorcinol formaldehyde) have a higher percentage of wood failures in the aged condition than in the virgin state, suggesting the maple adherends degraded more

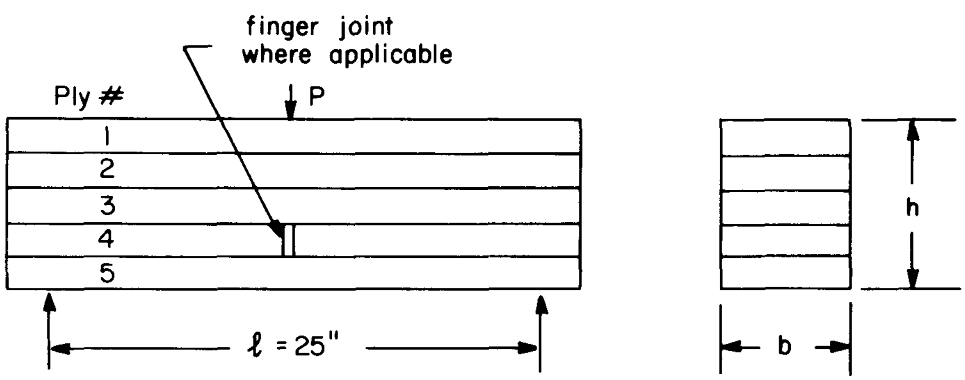

FIG. 2. Ply designation of Douglas-fir laminated beams subjected to three-point bending.

FIG. 3. Beam under three-point loading.

than the adhesives. The Kopper's G4411 (phenol resorcinol formaldehyde), Borden's RS-216 (resorcinol formaldehyde), and Isobind 100 (isocyanate) exhibited virtually no wood failures in either the virgin (dry) or aged condition.

The epoxies were again superior in the virgin state to the other adhesives, confirming the data of Table 6. However, the epoxies lose over half of their strength upon aging. The Ciba epoxy, which performs so well in the virgin situation (Tables 6 and 8), is particularly deteriorated by aging (Table 8). Phenol-formaldehyde glass prepreg continues to perform well, even upon aging. It is the only adhesive-reinforcement system tested that retains an aged interface shear strength (2,716 lb/in.^{2}) comfortably above that of dry Douglas-fir ($\sim$1,500 lb/in.^{2}). On the other hand, Isobind 100 again performs badly. The G1131, G4411, Dow epoxy, and

TABLE 9. *Laminated Douglas-fir beam dimensions.*

Case	Average thickness of wood plies 1 and 5	Average thickness of wood plies 2, 3, and 4	Average glue-line or glass-adhesive thickness	Width b	Depth h
			in.		
A	0.197	0.197	0.009	0.860	1.022
B	0.198	0.198	0.007	0.846	1.020
C	0.201	0.180	0.032	0.856	1.070
D	0.196	0.182	0.036	0.853	1.081

Note: Reinforced laminated beams C and D contain double plies of 417-glass reinforcement. All wood and reinforcement bonded with RS-216.

TABLE 10. *Results of laminated Douglas-fir beams tested under three-point bending.*

Specimen	Ultimate load P (lb)	Flexural stiffness EI ($\times 10^3$ lb/in.^{2})	Description
A-1	283	153	Laminated Douglas-fir
A-2	235	139	
A-3	224	132	
A-average	247	141	
B-1	247	129	Laminated Douglas-fir with a finger joint
B-2	266	136	
B-3	257	140	
B-average	257	135	
C-1	381	170	Reinforced laminated Douglas-fir
C-2	359	174	
C-3	405	170	
C-average	382	171	
D-1	370	165	Reinforced laminated Douglas-fir with a finger joint
D-2	374	166	
D-3	293	157	
D-average	346	163	

Note: All plies and reinforcement bonded with RS-216.

RS-216 continue to behave similarly to each other. The standard deviations of Table 8 indicate the low level of variance of the Dow epoxy system.

Table 8 data must be interpreted cautiously until results of such accelerated-aging methods are correlated with inservice environments. Use of excessively severe aging tests could include a decision to bypass an adhesive reinforcement having superior dry strength, but reduced strength upon aging.

FLEXED BEAM TESTS

Five-ply glass-reinforced Douglas-fir beams, with and without finger joints, were tested in three-point bending. Ply designation, constituent details, and individual dimensions are contained in Fig. 2 and Table 9. All beams were cured at room temperature for 24 hours at 50 lb/in.^{2}. The joints of the finger-jointed plies were bonded with RS-216 and fully cured prior to bonding such plies as part of an overall laminated beam. Three identical specimens of each of the four cases were prepared. The beams were centrally loaded at the rate of 0.1 inch per minute, and mid-span deflection δ and load P recorded. Results are contained in Table 10 where the elastic stiffness EI is computed from (Biblis 1965; Wangaard 1964)

TABLE 11. *Results of solid Douglas-fir beams tested under three-point bending.*

Specimen	Width b	Depth h	Ultimate load, P	E (10^6 lb/in.^{2})	EI ($\times 10^3$ lb/in.^{2})	σ^u
	in.	*in.*	*lb*			*ksi*
1	0.629	1.011	227	2.27	123	13.24
2	0.627	1.010	231	2.38	128	13.54
3	0.629	1.009	236	2.36	127	13.82
4	0.628	1.010	236	2.32	125	13.81
5	0.629	1.010	214	2.26	122	12.51
Average	0.628	1.010	229	2.32 (0.053)	125 (2.25)	13.38 (0.54)

$$EI = \frac{P\ell^3}{48\delta}\left[1 + 1.2\left(\frac{h}{\ell}\right)^2\frac{E}{G}\right] \quad (1)$$

and E/G = 16 (Wood Handbook 1974). Figure 3 illustrates a beam being tested.

Recognizing that beam failure always initiated in the bottom tensile ply, it is not surprising that the presence or absence of a finger joint had little effect on the strengths in Table 10. A finger joint similarly introduced only a small (5%) decrease in beam stiffness EI. However, the glass increased stiffness by 20% and strength by as much as 50%.

Five solid, Douglas-fir beams were also tested under three-point bending. Average results, together with standard deviations, are included in Table 11. Values of maximum stress σ^u were obtained from

$$\sigma = \frac{3P\ell}{2bh^2} \quad (2)$$

Using the glass-reinforced beam dimensions (0.856 in. × 1.07 in.) of case C (Tables 9 and 10), strength (P_D) and elastic stiffness (EI_D) of the solid Douglas-fir beams (Table 11) were computed (Rowlands et al. 1981) by Eq. (1) and (2) to be

$$P_D = 350 \text{ pounds}$$
$$EI_D = 203 \times 10^3 \text{ lb/in.}^2 \quad (3)$$

Comparison of these results with those for reinforced laminated beams (case C, Table 10) would indicate only a 9% increase in strength, and a structural stiffness EI decrease due to the addition of the reinforcement. These results suggest the shear contribution in the reinforced beams may be greater than that expressed by the second term of Eq. (1) with E/G = 16, and that the actual values of EI for cases C and D are greater than reported in Table 10. This would produce a stiffness enhancement due to a reinforcement greater than the 20% indicated. The increased transverse shear effect of flexed laminated composites is well recognized (Jones 1975).

The flexural modulus (E_D) of the Douglas-fir (Table 11) is 2.3×10^6 lb/in.^{2}, while tensile coupons subsequently cut from the undamaged ends of these same beams gave a tensile modulus of 2.4×10^6 lb/in.^{2}. Other results (Eq. 5) suggest that the Douglas-fir modulus may be as low as 1.9×10^6 lb/in.^{2}. Based on $E_D = 2.3 \times 10^6$ lb/in.^{2} and $E_C = 4.4 \times 10^6$ lb/in.^{2} for the glass RS-216 reinforcements, the reinforced wood beams of case C have a computed stiffness of 227×10^3 lb/in.^{2} compared with the measured value of 171×10^3 lb/in.^{2} from Table 10. Table 12 contains values of EI_D predicted (Rowlands et al. 1981) for several combinations of moduli.

If the laminated beam of case C (no finger joints) was reinforced with graphite ($E_c = 2.7 \times 10^6$ lb/in.^{2}) instead of glass, the predicted beam stiffness would be 292×10^3 lb/in.^{2} rather than the 227×10^3 lb/in.^{2} predicted in Table 12 for glass. Since the graphite used is not significantly stronger than the glass composite, and because failure of internally reinforced beams tends to initiate at the outside tensile wood ply, flexed beams are probably more effectively reinforced with additional glass plies than with the more expensive graphite. The structural stiffness of beams is enhanced as the composite plies are moved away from the neutral axis.

TABLE 12. *Predicted flexural stiffness (EI_D) of laminated wood beams (case C of Table 10) with Douglas-fir modulus (ED) and reinforcement modulus (EC).*

Douglas-fir modulus E_D (10^6 lb/in.^{2})	Reinforcement layer modulus E_C (10^6 lb/in.^{2})	Flexural stiffness EI_D ($\times 10^3$ lb/in.^{2})
1.9	4.4	197
1.9	2.5	173
2.1	4.4	219
2.1	2.5	188
2.3	4.4	227
2.3	2.5	203
2.3	9.7	292
2.3	2.3	200
2.0	2.0	170

MATERIAL PROPERTIES

Strength and modulus of the constituent wood and reinforcement were determined using both bending and tensile specimens. From Eq. (1) and (2), and results of Table 11, the modulus E_D and strength $\sigma_D{}^u$ are

$$\begin{aligned} E_D &= 2.3 \times 10^6 \text{ lb/in.}^2 \\ \sigma_D{}^u &= 13{,}380 \text{ lb/in.}^2 \end{aligned} \tag{4}$$

These quantities assume linear response. E_D of Eq. (4) was determined from the linear portion slope of the load-displacement profiles of tested solid-wood beams and is thus valid theoretically. The load-deformation behavior of these beams became nonlinear at 70% of maximum load, implying the calculated Douglas-fir strength of 13,380 lb/in.^{2} may be high.

Dog-bone tensile specimens (12 in. long, 2½-in. test section, Fig. 4) were subsequently machined from the undamaged ends of the broken beams of Tables 10 and 11. At least six specimens were tested from each of the solid Douglas-fir (Table 11), the nonreinforced laminated Douglas-fir and the reinforced, laminated Douglas-fir (Table 10) beams. The tensile values of $\sigma_D{}^u$ = 13,540 lb/in.^{2} and E_D = 2.4 × 10^6 lb/in.^{2} (Table 13) compare favorably with the quantities $\sigma_D{}^u$ = 13,380 lb/in. and E_D = 2.3 × 10^6 lb/in.^{2} obtained from flexure. On the other hand, $\sigma_D{}^u$ = 9,570 lb/in.^{2} and E_D = 1.96 × 10^6 lb/in.^{2} from nonreinforced laminated tensile specimens (based on wood cross-sectional area only) are comparatively low. The elastic modulus E_D computed from the equivalent cross section of nonreinforced laminated beams (case A, Table 10) and the measured structural stiffness EI = 141,000 lb/in.^{2} is

$$E_D = 1.9 \times 10^6 \text{ lb/in.}^2 \tag{5}$$

FIG. 4. Failed laminated tensile coupon.

TABLE 13. *Strength and stiffness of tensile coupons machined from undamaged sections of the beams of Tables 11 and 12.*

Property	Solid fir	Cases A and B	Case C[1]	Case D[1]
$\sigma_D{}^u$ (ksi)[2]	[3]13.54 (2.3)			
E_D ($\times 10^6$ lb/in.^{2})[2]	2.40 (0.15)			
$\sigma_T{}^u$ (ksi)[2]		9.26 (2.77)		
E_T ($\times 10^6$ lb/in.^{2})[2]		1.89 (0.18)		
$\sigma_D{}^u$ (ksi)		9.57 (2.86)		
E_D ($\times 10^6$ lb/in.^{2})		1.96 (0.19)		
$\sigma_T{}^u$ (ksi)			17.13 (1.5)	19.83 (0.77)
E_T ($\times 10^6$ lb/in.^{2})			2.42 (0.16)	2.65 (0.16)
$E_c{}^*$ ($\times 10^6$ lb/in.^{2})[4]			4.46 (0.94)	5.34 (0.84)
$E_c{}^{**}$ ($\times 10^6$ lb/in.^{2})[5]			3.00 (0.94)	4.10 (0.84)

[1] Case C contained 17% glass by volume while case D contained 19%.
[2] $\sigma_T{}^u$ and E_T based on total area (wood plus reinforcement and/or adhesive). $\sigma_D{}^u$ and E_D based on wood only.
[3] Standard deviations in parentheses.
[4] $E_c{}^*$ prediction based on $E_D = 2 \times 10^6$ lb/in.^{2}.
[5] $E_c{}^{**}$ prediction based on $E_D = 2.3 \times 10^6$ lb/in.^{2}.

For Douglas-fir (Wood Handbook 1974),

$$\sigma_D{}^u = 6{,}800 \text{ lb/in.}^2 \text{ to } 13{,}000 \text{ lb/in.}^2$$

therefore (6)

$$E_D = 1.2 \times 10^6 \text{ lb/in.}^2 \text{ to } 1.96 \times 10^6 \text{ lb/in.}^2$$

Tensile material coupons were also tested for each of the cured glass-RS-216, graphite-RS-216, and Kevlar®-RS-216 417-style reinforcements. Longitudinal

FIG. 5. Tensile testing of reinforcement materials.

TABLE 14. *Strength of modulus of cured 417 glass-RS-216, 417 graphite, RS-216 and 417 Kevlar®, RS-216 reinforcement materials as obtained from tensile tests.*

Material	Wood adherends machined away			Cured between wax paper		
	σ^u (ksi)	E (10^6 lb/in.^{2})	Thickness (t)	σ^u (ksi)	E (10^6 lb/in.^{2})	Thickness
			in.			*in.*
1-ply glass	[1]54.7 (7.97)	4.23 (0.66)	0.015	—	—	—
2-ply glass	60.1 (6.35)	4.43 (0.5)	0.024	34.2 (6.2)	2.50 (0.14)	0.032
1-ply graphite	38.3 (13.8)	6.34 (1.38)	0.015	20.2 (9.6)	4.57 (1.0)	0.020
2-ply graphite	62.8 (8.78)	9.70 (2.48)	0.025	25.8 (6.9)	5.17 (0.56)	0.039
2-ply Kevlar®	=	=	=	85.6 (12.3)	7.87 (0.37)	0.034

[1] Standard deviations in parentheses.

strains were measured with an extensometer (Fig. 5). Single- and double-ply coupons were cured between either maple adherends or wax paper. The wood of those specimens formed between maple was subsequently machined away in the test region to provide a double dog-bone shaped, cured fiber-resin tensile coupon having maple tabs. Such specimen preparation represents the situation in practice more realistically as some adhesive is expected to penetrate the wood, thereby influencing the fiber volume fraction. Wood end tabs were subsequently bonded to the flat coupons cured between wax paper for loading. These material specimens had a cure cycle essentially identical to that of the laminated beams described previously. As expected, the corresponding fiber-resin ply thickness, t′, is smaller (indicative of higher fiber-volume fraction) when cured between wood adherends. Where wood was machined away from the reinforcement (Table 14), the two-ply results are considered more reliable since any machining degradation would have proportionally less influence. Based on the above, the most representative reinforcement material properties are

$$\begin{aligned} &\textit{glass-RS-216:}\ E_c = 4.4 \times 10^6 \text{ lb/in.}^2 \text{ and } \sigma_c{}^u = 60 \text{ ksi} \\ &\textit{graphite-RS-216:}\ E_c = 9.7 \times 10^6 \text{ lb/in.}^2 \text{ and } \sigma_c{}^u = 63 \text{ ksi} \end{aligned} \tag{7}$$

Tensile coupons were also cut from undamaged sections of the previously tested laminated beams. Test data from these specimens, together with the rule of mixtures, provide additional information on material properties. Results of these tensile tests are contained in Table 13, including values of the composite (E_c) as computed from the rule of mixtures (Jones 1975),

$$E = \frac{E_T A_T - E_D A_D}{A_c} \tag{8}$$

and for two values of the wood modulus. The measured per-ply thickness of the glass reinforcements (t′ = 0.016 in. and 0.018 in.) of the laminated beams (cases C and D) of Table 13 exceeds that of the double-ply tensile material coupons of Table 14 (t′ ~ 0.012 in.), indicating that the former could be expected to have a lower fiber content and thus a reduced modulus. The lower reinforcement moduli computed in Table 13 are therefore the more reasonable of these two cases, implying that the Douglas-fir is exhibiting a stiffness in the neighborhood of 2.2 to 2.3 × 10^6 lb/in.^{2}. This is close to that demonstrated by the solid Douglas-fir (Table 11).

Adding 18% by volume of glass reinforcement increases the strength up to 45% over the solid Douglas-fir (Table 13). Moreover, comparison of nonreinforced and reinforced laminated data (Table 14) shows increases of tensile strength of 110% and tensile modulus up to 40% by adding the glass. Graphite, while more expensive than glass reinforcement, would again further improve stiffness without loss of strength enhancement. These results exhibit an appreciably greater strength and stiffness enhancement due to the glass addition than observed previously under flexural testing.

SUMMARY AND CONCLUSIONS

The technical feasibility of internally reinforcing wood laminates with synthetic fibers has been evaluated. Ten adhesives (three epoxy resins, two resorcinol formaldehydes, two phenol resorcinol formaldehydes, two isocyanates, and one phenol-formaldehyde) and numerous reinforcements (uni- and cross-woven glass, Kevlar®, and graphite fibers; plus glass, Kevlar®, and graphite preimpregnated with phenol-formaldehyde) were assessed. The effects of various processing parameters are included, as is the behavior of the fiber-reinforced wood under both dry-ambient and severe-weather (aging) conditions. Reinforced laminates were tested in tension and flexure, with and without internal finger joints. Constituent properties were measured.

At least under normal dry conditions, the epoxies (Dow, Ciba) exhibited superb performance with all three fiber materials (glass, Kevlar®, graphite). Resorcinol formaldehyde (RS-216, G1131) and phenol resorcinol formaldehyde (G4411) also appear totally adequate under these conditions with glass and graphite, although marginal with Kevlar®. Neither the isocyanates nor the phenol-formaldehyde (P-650) proved suitable as employed, and their potential with synthetic reinforcements should be investigated further. The epoxies deteriorated significantly under a severe moisture cycle, although the practicality of the environment used may be questionable. Preimpregnated (phenol-formaldehyde) glass-reinforced maple showed virtually no degradation due to excessive aging in a wet environment, and retained a shear strength well in excess of Douglas-fir itself. Particularly for elevated-temperature curing, the relatively inexpensive phenol resorcinol formaldehyde performs essentially as well as resorcinol formaldehyde. Although bidirectional reinforcements cured with a separate adhesive typically provided less strength enhancement than did the unidirectional reinforcements, the cross-woven glass prepreg performed almost as well after severe weathering as did the unidirectional glass-epoxy reinforcement under normal, dry conditions. Sufficient adhesive must be provided to ensure adequate wetting of the fibers, as reduced strength can otherwise result from a resin-poor bond. This is especially critical with bidirectional reinforcements.

Adding fiber reinforcement to wood increases strength, stiffness, and engineering toughness, while potentially decreasing mechanical variability. Fiber reinforcement could be very advantageous in regions of stress concentration (bolted joints, etc.), as well as with tensile and flexural members. Of the reinforcements considered, glass is technically and economically superior for wood (Laufenberg et al. 1984). Glass-fiber reinforced Douglas-fir (18% glass by volume) produced a 40% stiffness enhancement and doubled the strength over similar unreinforced wood. Graphite reinforcement will further stiffen wood but provides little strength enhancement beyond glass. The cost, strength, and stiffness of Kevlar® lie between the corresponding values for glass and graphite fibers.

Preimpregnated cloth of high-strength synthetic fiber works very well in concert with wood substrates. The fabrication process and economics could be improved by preheating the wood and preimpregnated reinforcement to minimize cure time. Reinforced veneer products could then be manufactured on a production basis using simple equipment and unskilled personnel. The advantages of fiber-reinforced wood justify further pursuit.

ACKNOWLEDGMENTS

The technical assistance of E. A. Okkonen and B. H. River of the Forest Products Laboratory, and A. L. Godding and D. D. Spaith of the University of Wisconsin is appreciated. Borden Chemical Co., Dow Chemical, Plastics Engineering Co., Proform Co., Reichhold Chemical, Ren Adhesive Products, and Koppers Co., Inc., provided samples of material. Early drafts of the manuscript were typed by Mrs. M. Lynch of the University of Wisconsin. The research was funded by the USDA Forest Service, Forest Products Laboratory, Madison, Wis.

REFERENCES

BIBLIS, E. J. 1965. Analysis of wood-fiberglass beams within and beyond the elastic region. For. Prod. J. 15(2):81–88.

BOEHME, C. 1976. Behavior under load of GFK (glass-fiber reinforced plastic reinforced wood-based materials). Holz Roh-Werkst. 34:155–161.

———, AND V. SCHULZ. 1974. Behavior of GFK (glass-fiber reinforced plastic)—wood sandwiches. Holz Roh-Werkst. 32:250–256.

BOHANNAN, B. 1962. Prestressing wood members. For. Prod. J. 12(12):596–602.

BORGIN, K. B., G. F. LOEDOLFF, AND G. R. SAUNDERS. 1968. Laminated wood beams reinforced with steel strips. J. Struct. Div., ASCE 94(ST7):1681–1705.

BULLEIT, W. M. 1980. A theory for reinforced particleboard in flexure. WSU Report 12-136. For. Prod. Lab., Madison, WI.

CURTIS, J. O. 1972. Steel reinforced wooden beams. Trans. ASAE. pp. 552–555.

HOYLE, R. J. 1975. Steel-reinforced wood beam design. For. Prod. J. 25(4):17–23.

JONES, R. M. 1975. Mechanics of composite materials. McGraw-Hill, NY.

KRUEGER, G. P., L. B. SANDBERG, T. L. LAUFENBERG, D. S. LARSEN, AND R. E. ROWLANDS. 1986. Reinforced butt joints in parallel-laminated veneer (PLV). (To be submitted to Journal of the Institute of Wood Science.)

LANTOS, G. 1964. Test results on mild steel reinforced glulam timber beams. Civil Eng. and Public Works Review 54:1261–1264.

———. 1970. The flexural behavior of steel reinforced laminated timber beams. Wood Sci. 2(3): 136–143.

LAUFENBERG, T. L., R. E. ROWLANDS, AND G. P. KRUEGER. 1984. The economic feasibility of synthetic fiber reinforced parallel-laminated veneer. For. Prod. J. 34(4):15–22.

MARK, R. 1961. Wood-aluminum beams within and beyond the elastic range. For. Prod. J. 11(10): 477–484; and 11(11):508–516.

PETERSON, J. L. 1965. Wood beams prestressed with bonded tension elements. J. Struct. Div., ASCE 91(ST1):103–119. Paper 4218.

ROWLANDS, R. E., G. P. KRUEGER, R. P. VAN DEWEGHE, D. S. LARSEN, AND T. L. LAUFENBERG. 1981. The economic and technical feasibility of producing synthetically reinforced parallel laminated veneer material. UW Report. For. Prod. Lab., Madison, WI.

SAUCIER, J. R., AND J. A. HOLMAN 1976. Structural particleboard reinforced with glass fiber—progress in its development. For. Prod. J. 25(9):69–72.

SLIKER, A. 1962. Reinforced wood laminated beams. For. Prod. J. 12(2):91–96.

SPAUN, F. D. 1981. Reinforcement of wood with fiberglass. For. Prod. J. 31(4):26–33.

THEAKSTON, F. H. 1965. A feasibility study for strengthening timber beams with fiberglass. Canadian Agric. Eng. Pp. 17–19.

WANGAARD, F. F. 1964. Elastic deflection of wood-fiberglass composite beams. For. Prod. J. 14(6): 256–260.

WOOD HANDBOOK. 1974. Handbook No. 72. U.S. Department of Agriculture, Forest Service, For. Prod. Lab., Madison, WI

APPENDIX I. ADHESIVES[4]

1. Everfix epoxy—Domestic adhesive used for repairing automobiles, boats, etc.
2. Dow epoxy—75% by weight of DER 331 + 25% by weight of DER 736 to 10% by weight of DEH 24. This is a room-setting adhesive.
3. Ciba epoxy—RP-136 mixed 100:40 by weight with H-994 (polyamide plus aliphatic polyamine) hardener. The manufacturer recommends a 48-hour cure at room temperature, 10 minutes at 212 F or 5 minutes at 250 F.
4. RS-216 resorcinol formaldehyde (Borden Chemical Co.)—RS-216 mixed 100:20 by weight with FM60M hardener. Basically a room-setting adhesive.
5. G1131 resorcinol formaldehyde (Koppers Co., Inc.)—Pressure time of 8–10 hours at room temperature, decreasing to 3 minutes at a glueline temperature of 180 F.
6. LT-68D phenol resorcinol formaldehyde (Borden Chemical Co.)—LT-68D combined 5:1 by weight with FM124D hardener. Typically an elevated-temperature-cure adhesive.
7. G4411 phenol resorcinol formaldehyde (Koppers Co., Inc.)—Cure time of 20 hours at room temperature, decreasing to 2–3 minutes at 200 F.
8. EP65-58 isocyanate (Ashland Chemical Co.)—EP65-58 mixed 100:20 by weight with EP65-A59 hardener. Room-temperature-cure adhesive.
9. Isobind 100 isocyanate (Upjohn Chemical Co.).
10. Plenco P-650 phenol-formaldehyde (Plastics Engineering Co., Sheboygan, WI)—Cures in a few minutes at 200–400 F.

APPENDIX II. REINFORCEMENTS[4]

Glass

Type 417 unidirectional E-glass (Hi-Pro-Form-Fabrics, Inc., Newark, DE 19711)—Volan finish; 0.013 in. thick and weighs 8.5 oz/yd^2.

Type A-260 nonwoven unidirectional glass roving (Proform Co., Sequin, TX 78155)—amino-silane finish; 0.08 in. thick and weighs 26 oz/yd^2.

Type B-238 bidirectionally woven glass roving (Proform Co., Sequin, TX 78155)—0.08 in. thick and weighs 23.8 oz/yd^2.

Auto fiberglass (body shop or boat suppliers)—cross-woven cloth—0.03 in. thick and weighs 6 oz/yd^2.

Glass prepreg (Fiberite Corp., Orange, CA 92669)—phenol-formaldehyde impregnated cross-woven S-glass roving.

Kevlar®

Type 417 unidirectional Kevlar® (Hi-Pro-Form-Fabrics, Inc., Newark, DE 19711)—0.013 in. thick and weighs 8.5 oz/yd^2.

Type 500 cross-woven cloth (Hi-Pro-Form-Fabrics, Inc., Newark, DE 19711)—0.009 in. thick and weighs 4.8 oz/yd^2.

Type 1033 heavy cross-woven roving material (Hi-Pro-Form-Fabrics, Inc., Newark, DE 19711)—0.026 in. thick and weighs 13.8 oz/yd^2.

Kevlar® prepreg (Fiberite Corp., Orange, CA 92669)—phenol-formaldehyde impregnated cross-woven fabric.

---

[4] Additional details contained in Rowlands et al. (1981).

Graphite

Type 417 unidirectional graphite (Hi-Pro-Form-Fabrics, Inc., Newark, DE 19711)—0.013 in. thick and weighs 7.8 oz/yd^2.

Graphite prepreg (Fiberite Corp., Winona, MN 55987)—phenol-formaldehyde impregnated woven graphite fabric.