DURABILITY OF STRUCTURAL LUMBER PRODUCTS AT HIGH TEMPERATURES. PART I. 66°C AT 75%RH AND 82°C AT 30%RH

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ABSTRACT

Background. The effect of temperature on properties can be separated into reversible and permanent effects. The National Design Specification (NDS) provides factors (C_t) for reducing properties for reversible effects but provides little guidance on permanent effects.

Objectives. The primary objective of this paper is to evaluate the effect of prolonged heating (permanent effect) on the flexural properties of solid-sawn and composite lumber products exposed at 66°C and 75% relative humidity (RH) and at 82°C and 30% RH. A second objective is to determine how to estimate total effects.

Procedures. Solid-sawn lumber, laminated veneer lumber (LVL), and laminated strand lumber (LSL) were heated continuously for up to 6 years. After each exposure period, the lumber was conditioned to room temperature at the specified RH and then tested on edge in third-point bending. Some lumber was also tested hot at 66°C after 48 h of exposure and after 3 years of exposure.

Results. After 3 years of continuous exposure at 66°C and 75% RH, solid-sawn Spruce–Pine–Fir (SPF) and Douglas-fir retained about 72% of their original modulus of rupture (MOR) and southern pine about 47%. For the first 2 to 3 years of exposure, changes in MOR of LVL were similar to that of solid-sawn SPF and Douglas-fir. After almost 6 years of exposure, SPF retained about 67% MOR and LVL 26% to 49%. The MOR of LSL was more sensitive to duration of exposure than was the MOR of either solid-sawn lumber or LVL, with a residual MOR of 47% after 28 months. After 21 months at 82°C and 30% RH, solid-sawn lumber retained 50% to 55% MOR, LVL 41%, and LSL 45%. For all products, modulus of elasticity was less sensitive to thermal degradation than was MOR.

Conclusions. The effect of temperature on MOR of solid-sawn lumber is independent of grade. Composite lumber is more sensitive than solid-sawn to change in strength due to thermal degradation. The difference in MOR between species and product types may be less at low humidity

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levels than at high. The total effect of temperature on MOR can be estimated by adding the reversible plus the permanent effects. Available literature suggests that the wood used in attics of residential construction is not likely to experience significant accumulation of exposure at temperatures ≥66°C over the life of the structure.

INTRODUCTION

Durability of wood may be defined as the ability to resist environmental stresses over long periods. Dry wood, at moderate temperatures, is remarkably durable. However, wood may be subjected to decay in damp conditions and to thermal degradation during fire. The durability of wood can also be affected by exposure to high temperatures over long periods. Current design philosophy in the United States assumes that exposure of untreated wood to temperatures up to 66°C (150°F) causes no permanent loss in properties unless the exposure is for prolonged periods (AF&PA 1997). The National Design Specification for Wood Construction (NDS) provides factors (C_t) for adjusting properties for short-term temperature exposures. The *Wood Handbook* (Forest Products Laboratory 1987) provides only limited guidance on the length of time that wood can be exposed to high temperatures before permanent loss in properties might occur. Virtually all the research on which this guidance is based was obtained from limited exposure of small clear specimens, generally less than 25.4 by 25.4 mm (1 by 1 in.) in cross section. Neither the NDS nor the *Wood Handbook* addresses the durability of composite lumber products when exposed to high ambient temperatures.

The primary objectives of this paper are to review the basis for current recommendations on the effect of thermal degradation on lumber properties and to present results on the permanent loss in flexural properties of nominal 2- by 4-in. (standard 38- by 89-mm) solid-sawn and structural composite lumber when exposed at 66°C (150°F) and 75% relative humidity (RH) and 82°C (180°F) at 30% RH over long periods. A second objective is to determine how to combine reversible and permanent effects to estimate total effects. This study is part of a comprehensive study of lumber properties in extreme environments. Other exposure conditions in the duration of temperature portion of this study are 66°C (150°F) at 25% RH and 82°C (180°F) at 80% RH. Information on these other exposure conditions, as well as analytical models for predicting beam performace, will be published as the study progresses.

BACKGROUND

In general, the mechanical properties of wood decrease when heated and increase when cooled. Up to about 100°C (212°F), at constant moisture content, the temperature–property relationship is linear and seems reversible. Thus, this ''reversible'' effect (also called immediate effect) of temperature implies that the property will essentially return to the value at the original temperature if the temperature change is rapid. This effect is the result of a transitory change in the internal energy level of the wood. In addition to this reversible effect, there may also be a permanent, or irreversible, effect when wood is heated at elevated temperatures for extended periods. This permanent effect is a result of degradation of one or more chemical constituents of the cell wall: hemicelluloses, cellulose, or lignin (Fengel and Wegener 1984). The extent of the property loss depends on the stress mode, temperature, duration of exposure, moisture content, heating medium, and species of wood (Forest Products Laboratory 1999).

Effect of heating on mechanical properties of clear wood

The NDS (AF&PA 1997) states that tabulated design values shall be multiplied by a temperature factor (C_t) for structural members

TABLE 1. *Temperature factor* C_t *for adjusting lumber properties for reversible effect of temperature.*[a]

| Design values[b] | In-service moisture conditions | C_t | | |
		$T \leq 100°F$	$100°F < T \leq 125°F$	$125°F < T \leq 150°F$
F_t, E	Wet or dry	1.0	0.9	0.9
F_b, F_v, F_c, $F_{c\perp}$	Dry	1.0	0.8	0.7
	Wet	1.0	0.7	0.5

[a] Source: AF&PA 1997. 100°F = 38°C, 125°F = 52°C, 150°F = 66°C.
[b] F_t is allowable tensile strength parallel to grain; E, modulus of elasticity; F_b, allowable bending strength; F_v, allowable shear strength parallel to grain; F_c, allowable compressive strength parallel to grain; $F_{c\perp}$, allowable compressive strength perpendicular to grain.

that will experience sustained exposure to temperatures up to 66°C (150°F) (Table 1). The term "sustained exposure" might lead one to conclude that the C_t factors account for permanent effects of temperature. However, the discussion in the NDS Commentary (AF&PA 1993) indicates that the C_t factors are for the reversible effects of temperature. According to the Commentary, prolonged exposure to temperatures above 66°C (150°F) should be avoided; when such exposures do occur, reductions in allowable properties should be made for both the permanent and reversible effects of temperature. Furthermore, permanent effects should be based on the cumulative time the members will be exposed to temperature levels over 66°C (150°F) during the life of the structure and the strength losses associated with these levels. For additional information on temperature effects, the Commentary refers to the 1987 edition of the *Wood Handbook* (Forest Products Laboratory 1987). Although the exact method for adjusting properties for the permanent effect of temperature is somewhat vague, it is clear that 66°C (150°F) is the reference temperature.

The selection of 66°C (150°F) as a reference temperature with respect to the structural serviceability of wood originated with the research of J. D. MacLean in the 1940s and 1950s. MacLean (1951) evaluated the weight loss of 10 domestic hardwood and softwood species when heated in water, steam, or air. All tests were conducted on 25.4- by 25.4-mm (1- by 1-in.) specimens, 152.4 mm (6 in.) in

length. Four specimens were used for each combination of species, heating medium, and temperature. All specimens were oven-dried prior to exposure. From these studies, Mac-Lean concluded that heating in water or steam results in faster weight loss than does heating in an oven. He noted that within certain heating periods some species withstand heating better than others, but he thought that this difference was less important when wood is heated over long periods. MacLean reasoned that because temperatures that are harmful to one species will be harmful to another, the only difference is that a somewhat longer heating period may be required to cause the same amount of degradation of one species than of another.

Three additional observations may be made about MacLean's data (Table 2). First, when heated in water, hardwoods were always more sensitive than softwoods for all temperatures. Second, when heated in an oven, hardwoods were not always more sensitive than softwoods. Third, in both media, southern pine was the most sensitive of the softwoods tested. Later studies (MacLean 1954, 1955) showed that when hardwoods were heated in water, bending strength was reduced more than that of softwoods. However, when hardwoods were heated in an oven, they were not necessarily more sensitive to thermal degradation than were softwoods (Green and Evans 2001).

MacLean (1951) also discussed the extent of specimen charring with respect to the length of heating. He noted that charring had been observed in wooden walls, floors, and doors in dry kilns at the Forest Products Laboratory at temperatures as low as 77°C to 93°C (170°F to 200°F) after periods equivalent to about 1.5 years of commercial operation. MacLean concluded that "if good service life is desired, wood should not be exposed under service conditions where temperatures appreciably higher than 66°C (150°F) will be encountered." The 1955 edition of the *Wood Handbook* (Forest Products Laboratory 1955) states that "when wood is exposed to temperatures of 66°C (150°F) or more for extended periods

TABLE 2. *Relative ranking of weight loss for species heated at indicated temperatures and times.*[a]

| | Heated in water | | | | Heated in oven | | | |
Species	200°F 5,080 h	250°F 418 h	300°F 141 h	350°F 30 h	200°F 5,080 h	250°F 418 h	300°F 141 h	350°F 30 h
Basswood	1	3	3	2	6	1	1	1
White oak	2	4	4	3	2	3	2	9
Yellow birch	3	1	1	1	4	2	3	5
Yellow-poplar	4	2	5	4	4	5	5	8
Hard maple	5	6	2	6	8	7	4	2
Sweet gum	6	5	6	5	3	4	9	4
Southern pine	7	7	7	7	1	8	6	3
White pine	8	9	8	8	6	9	7	10
Douglas-fir	9	8	9	10	9	10	10	7
Sitka spruce	10	10	10	9	10	6	8	6

[a] Weight loss ranked from most (1) to least (10). Source: MacLean 1951. 200°F = 93°C, 50°F = 120°C, 300°F = 150°C, 350°F = 175°C.

of time, it will be permanently weakened.'' This recommendation was subsequently incorporated in the NDS (AF&PA 1993) and has remained a guidepost for durability when wood is exposed to high ambient temperatures.

Millett and Gerhards (1972) conducted an ''accelerated aging'' study of four softwood and two hardwood species. Their objective was to develop an Arrhenius equation to predict the effect of duration of temperature exposure on flexural properties. The 12.7- by 6.4- by 165-mm (0.50- by 0.25- by 6.5-in.) specimens were preconditioned to 26.7°C (80°F) prior to heating in an oven for varying times at temperatures ranging from 115°C to 175°C (239°F to 347°F) (Table 3). There were approximately 10 specimens per species, temperature, and time. Following treatment, the specimens were reconditioned prior to testing. The average moisture content of the exposed specimens was approximately 4.6% at time of test; average moisture content of the unheated controls was 7.9%. As expected, modulus of rupture (MOR) was much more sensitive to temperature than was modulus of elasticity (MOE). As in MacLean's studies on heating wood in an oven (MacLean 1951, 1955), the two hardwoods were not necessarily the most sensitive species (Table 4). Again, for MOR, southern pine was the most sensitive of the softwood species.

More recently, studies have been conducted at the Forest Products Laboratory to understand the effect of fire-retardant treatments on the mechanical properties of wood. Some of these studies have included exposure of untreated clear 16- by 35- by 305-mm (⅝- by 1⅜- by 12-in.) long specimens of solid-sawn southern pine at 54°C (130°F) and 73% RH, 66°C (150°F) and 75% RH, and 82°C (180°F) and 50% RH (LeVan et al. 1990; Winandy 1995). These three exposures would be expected to produce equilibrium moisture content (EMC) values of 12%, 12%, and 6.5%, respectively, under short-term exposure. The specimens were tested in center-point bending. After exposure, all specimens were equilibrated at 22.8°C (73°F) and 67% RH (nominal 12% moisture content) prior to testing. There were approximately 25 specimens per exposure group. The results are shown in Table 5. The exposure at 54°C (130°F) resulted in a loss in MOR of about 2% (0.98 retention) and was probably too short an exposure to produce meaningful results for untreated wood. After 4 years exposure at 66°C (150°F) and 75% RH, residual MOR of untreated southern pine was 0.35, while residual MOE was 0.82. At 82°C (180°F) and 50% RH, the retention in MOR was 0.85 after 5.3 months and the residual MOE was 0.97. These MOR retentions are only slightly lower than those at 66°C (150°F) for the equivalent exposure.

TABLE 3. *Average residual property for clear wood heated in oven.*[a]

Temperature °F (°C)	Time (days)	Western redcedar	Douglas-fir	Ponderosa pine	Southern pine	Red oak	Sugar maple
				Modulus of rupture			
289 (115)	64	0.82	0.87	0.93	0.83	0.88	0.86
	128	0.71	0.89	0.83	0.75	0.73	0.76
	192	0.69	0.80	0.74	0.65	0.70	0.67
	255	0.64	0.74	0.74	0.56	0.62	0.64
275 (135)	16	0.77	0.92	0.87	0.80	0.85	0.86
	34	0.67	0.79	0.73	0.64	0.67	0.65
	48	0.64	0.73	0.67	0.52	0.59	0.61
	64	0.55	0.73	0.65	0.52	0.53	0.56
311 (155)	4	0.76	0.82	0.80	0.74	0.74	0.80
	8	0.65	0.76	0.68	0.61	0.60	0.62
	12	0.58	0.67	0.60	0.54	0.53	0.58
	16	0.51	0.65	0.55	0.45	0.48	0.48
347 (175)	1	0.79	0.84	0.81	0.76	0.74	0.76
	2	0.67	0.70	0.64	0.62	0.58	0.61
	3	0.58	0.65	0.60	0.53	0.56	0.52
	4	0.46	0.58	0.50	0.44	0.49	0.48
				Modulus of elasticity			
239 (115)	64	0.99	0.98	1.05	1.00	1.09	1.03
	128	0.95	1.01	1.00	1.03	1.03	1.03
	192	0.92	0.93	0.97	0.97	1.05	0.96
	255	0.90	0.93	1.00	0.97	1.06	1.02
275 (135)	16	0.98	1.01	1.01	1.03	1.07	1.02
	34	0.93	0.95	0.98	0.97	1.06	1.02
	48	0.91	0.89	0.95	0.93	1.05	1.01
	64	0.87	0.92	0.97	0.97	1.03	1.02
311 (155)	4	0.97	0.97	0.98	0.99	1.06	1.02
	8	0.91	0.93	0.98	0.97	1.01	1.01
	12	0.88	0.89	0.95	0.94	1.01	1.01
	16	0.85	0.88	0.92	0.92	0.97	0.93
347 (175)	1	0.99	0.98	1.04	1.07	1.03	1.02
	2	0.94	0.91	0.93	0.95	0.98	0.98
	3	0.89	0.91	0.93	0.95	1.00	0.97
	4	0.78	0.88	0.89	0.88	0.95	0.89

[a] Source: Millett and Gerhards 1972. Values are relative to property of unheated control.

TABLE 4. *Relative ranking of change in flexural properties for species heated in oven at indicated temperatures and times.*[a]

Species	Modulus of rupture				Modulus of elasticity			
	239°F 255 days	275°F 64 days	311°F 16 days	347°F 4 days	239°F 255 days	275°F 64 days	311°F 16 days	347°F 4 days
Southern pine	1	1	1	1	3	3	3	2
Red oak	2	2	2	4	6	6	6	6
Western redcedar	3	3	4	2	1	1	1	1
Sugar maple	3	4	2	3	5	5	5	4
Ponderosa pine	5	5	5	5	4	3	3	4
Douglas-fir	5	6	6	6	2	2	2	2

[a] Changes in flexural properties ranked from most (1) to least (6). Source: Millett and Gerhards 1972. 239°F = 115°C, 275°F = 135°C, 311°F = 155°C, 347°F = 175°C

TABLE 5. *Average residual properties of clear Southern pine heated in air at various exposures and tested after equilibration at 22.8°C (73°F), 67% RA.*[a]

Exposure	Duration of heating (months)	Modulus of rupture	Modulus of elasticity	Moisture content at test (%)
54°C, 73% RH	0.0	1.000	1.000	10.5
(130°F, 73% RH)	0.2	0.954	0.969	10.6
	0.7	0.975	0.949	10.5
	2.0	0.989	0.973	9.8
	5.3	0.979	0.980	9.9
66°C, 75% RH	0.0	1.000	1.000	10.5
(150°F, 75% RH)	0.7	0.928	1.021	10.5
	2.0	0.997	1.081	10.7
	5.3	0.889	0.986	10.8
	9.5	0.925	1.042	10.9
	18.5	0.787	1.072	10.9
	36.0	0.662	1.066	12.1
	48.0	0.347	0.817	11.5
82°C, 50% RH	0.0	1.000	1.000	10.5
(180°F, 50% RH)	0.2	1.019	0.984	9.0
	0.7	1.013	1.035	8.7
	2.0	0.968	0.988	8.0
	5.3	0.854	0.971	7.9

[a] LeVan et al. 1990; Winandy 1995, 2001.

Chemical changes in wood during thermal degradation

For temperate species, wood is composed of about 40% to 50% cellulose, 20% to 35% lignin, and 12% to 35% hemicellulose, plus extractives (Petterson 1984) (Table 6). When heated for up to 48 h, these components are relatively stable at temperatures up to about 100°C (212°F) (Fengel and Wegener 1984). Chemical acid hydrolysis is the most typical degradation mechanism, with the hemicelluloses being more sensitive to thermal degradation than is cellulose or lignin (Fengel and Wegener 1984). Because the hemicelluloses are composed of shorter chains of molecules and have a more branched structure, they are generally easier to hydrolyze by acids than is cellulose. Of the hemicelluloses, arabinose and galactose have been found to be especially sensitive to thermal degradation (LeVan et al. 1990; Winandy 1995). As the wood is degrading, acetyl groups being lost from the chemical structure combine with available water to form acetic acid. This acid acts as a catalyst to further speed the rate of degradation.

As evident from the work of MacLean, thermal degradation is a function of not only temperature but also the length of the heating period, moisture content of the wood, and type of heating medium. There are only small differences between hardwoods and softwoods in the total amount of hemicellulose present, and hardwoods actually have less arabinose and galactose than the other hemicelluloses (Table 6). Thus, the amount of hemicellulose present would not appear to be the cause of the greater sensitivity of hardwoods to boiling in water. However, hardwoods do have more acetyl groups than do softwoods. Thus, hardwoods generally have more "acid-forming potential" than do softwoods. Heating wood in water would also cause the wood to swell (or to remain swollen) and thus allow freer movement of the acids generated during decomposition. The presence of liquid water would ensure plenty of water to combine with the acetyl groups being lost and would facilitate movement of the acid generated. The greater temperature sensitivity of southern pine compared with other softwoods is harder to explain, although perhaps the generation of resinous acids during decomposition is a factor.

TABLE 6. *Summary of chemical composition of wood.*[a]

Component	Average (% by weight)		Range (% by weight)	
	Softwood	Hardwood	Softwood	Hardwood
Glucose	44.5	45.8	41–47	38–52
Lignin	29.5	22.6	26–33	19–24
Hemicellulose				
Arabinose	1.4	0.5	0.5–2.7	0.3–0.8
Galactose	2.0	1.1	1.0–4.7	0.1–2.2
Xylose	6.4	17.1	2.8–10	12–26
Mannose	10.6	2.4	8.0–13	1.8–3.6
Acetyl group	1.4	3.8	0.8–2.2	2.9–5.5
Uronic anhydride	4.1	4.4	2.8–5.4	3.5–5.1

[a] Source: Petterson 1984.

PROCEDURES

All lumber used in this study was 38 by 89 mm (nominal 2 by 4 in., standard 1.5 by 3.5 in.; hereafter called 2 × 4) obtained from commercial production. Two grades of solid-sawn Spruce–Pine–Fir (SPF) lumber were obtained from a mill in Vancouver, BC. The machine-stress-rated (MSR) grades were 2100f–1.8E and 1650f–1.5E. The solid-sawn Douglas-fir was 1800F–1.8E and 2400F–2.0E MSR lumber obtained from a mill in central Oregon. The solid-sawn southern pine was taken from existing stocks at the Forest Products Laboratory and was a mixture of several MSR grades with assigned MOE values between 1.6E and 2.0E. Three species of laminated veneer lumber (LVL) were sampled: Douglas-fir, southern pine, and yellow-poplar (see Appendix C for species names). All the LVL was 2.0E grade and was manufactured with a phenol-formaldehyde adhesive. Two species of laminated strand lumber (LSL) were sampled: aspen (1.3E grade) and yellow-poplar (1.5E). Both species of LSL were manufactured using an isocyanate-based adhesive. After lumber was conditioned at 23°C (73°F) and 65% RH, nominal 12% moisture content, the flatwise MOE of each piece was obtained by transverse vibration (E_{TV}) (Ross et al. 1991).

For the duration of exposure portion of the study, each grade of MSR lumber was sorted into 10 groups of approximately 30 pieces per group, and each species of LVL and LSL was sorted into 10 groups of approximately 15 pieces per group. This was accomplished by ranking E_{TV} values from high to low and then randomly assigning the first 10 pieces to a treatment group. The next group of 10 pieces was then assigned to a treatment group until all pieces were assigned. Additional groups, matched by E_{TV}, were also obtained for later studies in this program.

Two conditioning chambers were used for this phase of the study. A Forma Scientific chamber with approximate dimensions of 3.0 by 6.0 by 2.7 m (10 by 20 by 9 ft) was used to maintain the specimens to be exposed at 66°C (150°F) and 75% RH. A second chamber with approximate dimensions of 3.7 by 3.7 by 3.0 m (12 by 21 by 10 ft) was used for the specimens to be conditioned at 82°C (180°F) and 30% RH. Specimens to be heated were placed on stickers in the appropriate conditioning room. At 66°C (150°F), solid-sawn and LVL 2 × 4s were conditioned up to 68 months (5.7 years), with groups of samples removed periodically for testing. To avoid total loss of data from excessive degradation, the LSL groups were heated for a shorter period. For aspen LSL, the total heating period was 28 months (2⅓ years) and for yellow-poplar LSL, 32 months (2⅔ years). At 82°C (180°F), most specimens were exposed for approximately 21 months. The yellow-poplar LSL tests were terminated at the same time as the aspen tests, but lumber for the yellow-poplar tests was placed in the heating chamber at a later date because the material was not initially avail-

able. Following exposure, the lumber from the 66° chamber was removed from the heating chamber and equilibrated at 23°C (73°F) and 65% RH prior to testing. Control specimens were placed in a room-temperature chamber (23°C (73°F)) at 65% RH and held for testing until the first group of heated specimens was tested. Two groups of solid-sawn SPF lumber of each grade and two groups of each species of LVL were also tested hot. One group of each type was also tested hot at 66°C (150°F) after about 36 h exposure and the other after 3 years' exposure (Appendix A). Lumber from the 82° chamber was reconditioned at 23°C and 25% RH prior to testing.

Modulus of elasticity of equilibrated specimens was determined by transverse vibration (E_{TV}), with the specimens in flatwise orientation and supported at their ends (Ross et al. 1991). Edgewise MOR was determined by ASTM D198 (ASTM 1999) using quarter-point loading and a span-to-depth ratio of 21:1. Quarter-point loading was chosen to increase the constant moment region over what it would have been for the more traditional third-point loading. The rate of loading was approximately 51 mm (2 in.) per minute. This rate was chosen because some groups in the larger study were to be tested hot and a faster rate of loading would minimize cooling of the specimens during testing.

The testing equipment was located close to the chamber maintained at 66°C (150°F). The lumber to be tested hot was positioned inside the chamber near a small door so that pieces could be removed one piece at a time and quickly tested. A record was kept of the elapsed time from removal of the lumber from the chamber until the maximum load was reached. In addition, one 2.4-m (8-ft) solid-sawn SPF 2 × 4 and one 2.4-m (8-ft) Douglas-fir LVL 2 × 4 were each instrumented with a thermocouple a few microns under the surface and another thermocouple in the middle of the cross section to determine approximately how quickly the lumber cooled when removed from the chamber. The pieces were placed in the chamber for 17 h and then removed to observe cooling (only about 1.5 h was required for a dry, room-temperature 2 × 4 to reach 66°C (150°F)). The temperature in the room outside the conditioning chamber was about 21°C (70°F).

After testing, oven-dry moisture content and specific gravity based on oven-dry weight and oven-dry volume were determined from sections taken near the failure region (ASTM D2395 and D4442, ASTM 1999). Specimens were also cut from near the failure region for chemical analysis. To prepare for chemical analysis, several randomly selected pieces from each treatment group were ground to material fine enough to pass a 30-mesh (0.547-μm) screen. Chemical analysis for sugars, acid soluble lignin, and Klason lignin was conducted generally following the procedures of Petterson and Schwandt (1991), TAPPI Method 250 (TAPPI 1982), and Effland (1977). Individual chemical components were determined as a percentage of the total weight of the wood. Acidity was determined using a pH meter on a water and wood flour solution.

RESULTS

Exposure at 66°C (150°F), 75% RH

Table 7 summarizes the properties of solid-sawn lumber tested over the course of the study; Table 8 presents the properties of composite lumber products. Because of the small sample sizes, the absolute values may or may not be representative of the populations from which they were obtained. Furthermore, the E_{TV} value might be expected to be slightly higher than the value that would have been obtained by static measurement. However, we believe that the relative change in properties following exposure is typical of what might be expected of the lumber types tested and that the change in E_{TV} relative to the original will be the same for different flexural modes. Although not addressed in the study reported here, a recent study demonstrated that the percentage of change in flatwise dynamic MOE and edgewise static MOE is virtually identical

TABLE 7. *Properties of solid-sawn 2 × 4 lumber tested at 23°C (73°F) and 65% RH after exposure at 66°C (150°F) and 75% RH for indicated periods.*[a]

Species and grade	Exposure (months)	*n*	Moisture content (%)	Specific gravity (OD/OD)	E_{TV} Mean (10^6 lb/in²)	(GPa)	COV (%)	MOR Mean (10^3 lb/in²)	(MPa)	COV (%)
					Spruce–Pine–Fir					
1650f-1.5E	0	31	11.0	0.42	1.571	10.83	11.5	7.005	48.30	26.6
	6	31	9.6	0.42	1.629	11.23	15.8	6.402	44.14	33.2
	12	31	9.0	0.42	1.554	10.71	11.7	6.389	44.05	29.6
	24	30	9.6	0.41	1.618	11.16	12.5	5.139	35.43	32.0
	36	30	9.2	0.42	1.599	11.03	12.8	4.769	32.88	34.7
	48	31	8.8	0.41	1.574	10.85	12.0	4.702	32.42	31.9
	68	32	10.1	0.41	1.505	10.38	12.3	4.952	34.14	34.8
2100f-1.8E	0	30	11.5	0.45	1.868	12.88	8.9	8.975	61.88	25.8
	6	30	10.0	0.45	1.895	13.07	10.8	8.491	58.50	25.1
	12	30	8.7	0.45	1.852	12.77	9.8	7.423	51.18	36.5
	24	30	9.5	0.45	1.898	13.09	8.7	6.366	43.89	31.8
	36	30	9.4	0.45	1.917	13.22	11.7	6.575	45.33	31.5
	48	29	8.9	0.44	1.954	13.47	10.2	6.047	41.69	27.5
	68	30	10.3	0.45	1.824	12.58	10.3	5.623	38.77	35.2
					Douglas-fir					
1800f-1.8E	0	29	11.6	0.46	1.968	13.57	13.5	6.647	45.83	27.7
	36	15	11.8	0.47	1.961	13.52	17.9	4.885	33.68	34.7
	48	15	8.7	0.44	1.975	13.62	14.1	4.658	32.12	46.3
2400f-2.0E	0	29	11.8	0.54	2.524	17.40	11.4	10.040	69.23	27.6
	36	15	11.7	0.54	2.525	17.41	13.3	7.587	52.31	36.4
	48	15	8.6	0.51	2.565	17.69	12.0	7.422	51.17	30.8
					Southern pine					
MSR	0	52	10.9	0.64	2.428	16.74	20.2	12.146	83.75	29.9
	36	52	11.6	0.61	2.269	15.64	22.4	5.686	39.20	36.4

[a] Note: Properties were measured in English units.

for the reversible effect of temperature on properties (Green et al. 1999).

For solid-sawn lumber, average EMC of the exposed specimens was sometimes slightly lower than that of their respective controls. This primarily occurred with the SPF lumber. This decrease in hygroscopicity is a well-known effect of heating wood over long periods (Stamm 1964). The effect was less noticeable for LVL and LSL, probably because the wood sustained significant heating as part of the manufacturing process. The decrease in hygroscopicity probably also explains the lower EMC of LVL and LSL compared with that of the solid-sawn lumber. The data showing the unexpected increase in EMC for the heated LSL, which were actually obtained several years after the initiation of the study on solid-sawn and LVL lumber, may be partly a result of some problems encountered with the room-temperature conditioning chamber. Because it is expected that heated lumber and composite lumber products might reach a lower EMC for the same set of exposure conditions, properties were not adjusted to a common moisture content, as MacLean (1954, 1955) and Millett and Gerhards (1972) chose to do.

For solid-sawn lumber, little change in E_{TV} occurred over the entire exposure period (Table 7). Over 68 months' exposure, E_{TV} of Douglas-fir LVL was reduced about 20% and E_{TV} of southern pine and yellow-poplar LVL about 24% (Table 8). The E_{TV} of yellow-poplar LSL was reduced about 13% after 18 months' exposure, and the E_{TV} of aspen LSL was reduced about 8% after 28 months. Note

TABLE 8. *Properties of composite 2 × 4 lumber tested at 23°C (73°F) and 65% RH after exposure at 66°C (150°F) and 75% RH for indicated periods.*

Species and grade	Exposure (months)	n	Moisture content (%)	Specific gravity (OD/OD)	E_{TV} Mean (10^6 lb/in^2)	E_{TV} Mean (GPa)	E_{TV} COV (%)	MOR Mean (10^3 lb/in^2)	MOR Mean (MPa)	MOR COV (%)
					LVL					
DF 2.0E	0	15	8.7	0.52	2.370	16.34	5.1	8.957	61.76	12.9
	6	15	9.3	0.51	2.322	16.01	5.1	8.244	56.84	10.4
	12	15	8.9	0.53	2.468	17.02	5.1	8.495	58.57	13.1
	24	15	10.0	0.51	2.267	15.63	6.0	6.500	44.82	10.7
	36	15	9.6	0.51	2.226	15.35	8.5	5.855	40.37	11.6
	48	14	8.8	0.49	2.352	16.22	5.9	4.171	28.76	14.6
	68	14	10.3	0.52	1.894	13.06	6.1	3.134	21.61	15.3
SP 2.0E	0	16	9.3	0.62	2.926	20.17	5.7	11.391	78.54	9.9
	6	16	9.6	0.63	2.442	16.84	5.1	10.349	71.36	9.5
	12	16	8.7	0.62	2.600	17.93	6.4	10.431	71.92	10.7
	24	16	9.8	0.61	2.483	17.12	7.8	8.096	55.82	13.1
	36	15	9.4	0.60	2.366	16.31	5.0	7.749	53.43	8.8
	48	15	9.1	0.61	2.352	16.22	5.9	6.608	45.56	12.1
	68	18	9.9	0.62	2.218	15.29	6.2	5.554	38.29	11.2
YP 2.0E	0	16	8.5	0.50	2.174	14.99	5.8	10.678	73.62	7.1
	6	17	9.7	0.49	1.996	13.76	5.4	9.975	68.78	9.1
	12	15	8.4	0.49	2.059	14.20	4.9	10.430	71.91	8.5
	24	16	9.3	0.48	2.028	13.98	6.7	7.990	55.09	12.5
	36	15	8.8	0.49	1.958	13.50	4.5	6.888	47.49	12.6
	48	13	7.9	0.48	1.965	13.55	5.1	4.415	30.44	15.8
	68	18	8.7	0.49	1.654	11.40	6.6	2.760	19.03	19.4
					LSL					
Aspen 1.3E	0	15	8.9	0.61	1.609	11.09	5.3	6.808	46.94	6.0
	6	13	10.2	0.58	1.493	10.29	5.9	4.512	31.11	10.2
	18	13	10.4	0.59	1.490	10.27	7.1	3.701	25.52	14.7
	28	15	9.9	0.57	1.474	10.16	7.0	3.204	22.09	11.3
YP 1.5E	0	14	9.0	0.69	1.675	11.55	6.3	7.510	51.78	13.6
	10.4	14	11.8	0.65	1.371	9.45	10.9	4.331	29.86	10.5
	18	12	11.0	0.64	1.457	10.05	5.2	4.586	31.62	9.6
	32	13	9.5	0.62	1.430	9.86	9.0	3.174	21.88	11.3

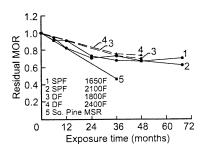[a] DF is Douglas-fir; SP, Southern pine; and YP, yellow-poplar.

FIG. 1. Average residual MOR for solid-sawn 2 × 4 lumber exposed for various times at 66°C (150°F), 75% RH and tested at 23°C (73°F), 67% RH.

that for LVL, there was no general indication of delamination. Of the heated specimens, only three or four pieces showed delamination prior to testing. These appeared to be random occurrences that showed no pattern by species or length of exposure. These delaminated pieces were not tested and thus are not included in the results shown in Table 8. No delamination was evident in LSL specimens.

The solid-sawn SPF lumber showed a progressive decrease in MOR that was approximately linear for the first 2 years and then began to flatten after 4 years' exposure (Fig. 1). The magnitude of the decrease appears to be

independent of grade; the ratio of MOR of heated specimens to MOR of unheated (control) specimens averaged about 0.67 after 68 months of continuous exposure. The change in MOR of Douglas-fir also appears to be independent of grade. After 4 years of continuous exposure, the residual value for Douglas-fir was about 0.72, compared to about 0.67 for SPF. Thus, the permanent reduction in MOR for Douglas-fir is apparently of the same order of magnitude as that of the SPF. The residual curve for Douglas-fir appears higher than that of SPF for the first 2 years of exposure. However, there are no test data for Douglas-fir during this period, and thus only a straight line can be drawn between zero time and 3 years. The similarity of results between Douglas-fir and SPF at years 3 and 4 leads us to believe that the results would have been similar at earlier periods as well. After 3 years of continuous exposure, the residual MOR of southern pine was 0.47, compared to about 0.71 for SPF and 0.73 for Douglas-fir. These results confirm the observations noted earlier from the clear wood studies of MacLean and of Millet and Gerhards that southern pine is more sensitive to thermal degradation than are other softwood species. After 3 years' exposure, the residual MOR is less than the value of 0.60 found by Winandy (2001) for untreated small clear southern pine specimens at the same temperature and humidity conditions (Table 5).

For LVL, the change in MOR was similar to that for solid-sawn Douglas-fir and SPF lumber for the first 2 to 3 years of exposure; thereafter, MOR of LVL decreased at a faster rate. These results are shown in Fig. 2; the results for solid-sawn SPF are given for comparison. After 68 months of continuous exposure, southern pine LVL retained 0.49 of its original MOR value, Douglas-fir 0.35, and yellow-poplar 0.26. The LSL specimens appear to be more sensitive to thermal degradation than either solid-sawn SPF lumber or LVL. After 28 months' exposure, aspen LSL retained 0.47 of its initial MOR value; after 32 months, yellow-poplar LSL retained 0.42. As
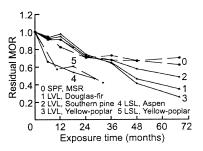

FIG. 2. Average residual MOR for composite 2×4 lumber exposed for various times at 66°C (150°F), 75% RH and tested at 23°C (73°F), 67% RH.

can be seen in Fig. 2, both species of LSL appear to have reacted in a similar manner to thermal degradation.

Exposure at 82°C (180°F), 30% RH

Table 9 summarizes the properties of both solid-sawn and composite lumber products at 82°C (180°F) and 30% RH. Unfortunately, a large portion of LVL and some solid-sawn SPF were lost due to smoldering caulking material that came loose from the duct work and burned its way through the stacked lumber. The LSL, which was in a different stack within the chamber, was not affected. However, we thought that the remaining material nevertheless provided useful results and so it was retained in the study. As was generally true for the lumber exposed at 66°C (150°F) and 75% RH, the moisture content of the lumber after exposure at 82°C (180°F) and 30% RH was slightly lower than that of unexposed specimens. In addition, as was true for the previously discussed conditions, temperature exerted little effect on the E_{TV} of solid-sawn lumber. With the possible exception of aspen LSL, which was heated longer than was yellow-poplar LSL, temperature also exerted little effect on E_{TV} of composite lumber.

For solid-sawn Douglas-fir and SPF, the retention in MOR after 21 months' exposure at 82°C (180°F) and 30% RH was approximately 0.55 (Table 9). MOR retention is plotted in Fig. 3, along with the results for solid-sawn SPF at 66°C (150°F) and 75% RH. Again, the results for Douglas-fir suggest little effect of

TABLE 9. *Properties of solid-sawn and composite 2 × 4 lumber tested at 23℃ (73°F) and 65% RH after exposure at 82℃ (180°F) and 30% RH for indicated periods.*

	Exposure (months)	n	Moisture content (%)	Specific gravity	E_{TV} Mean (10^6 lb/in^2)	(GPa)	COV (%)	MOR Mean (10^3 lb/in^2)	(MPa)	COV (%)
					Solid-sawn					
SPF MSR	0	30	4.4	0.44	1.617	11.15	9.7	7.350	50.68	26.5
	21	18	3.0	0.45	1.739	11.99	11.1	4.240	29.23	33.0
DF	0	30	4.1	0.47	1.957	13.49	13.0	6.953	47.94	35.2
1800f-1.8E	21	25	3.1	0.51	1.977	13.63	13.6	3.646	25.14	41.3
2400f-2.0E	0	29	4.0	0.54	2.466	17.00	10.5	10.232	70.55	28.4
	21	30	3.1	0.68	2.567	17.70	12.5	5.913	40.77	39.4
SP, MSR	0	52	4.2	0.65	2.510	17.31	21.6	11.471	78.72	35.4
	21	52	3.4	0.75	2.378	16.40	20.7	5.672	39.11	33.2
					LVL					
DF	0	15	4.1	0.54	2.332	16.08	5.7	9.125	62.92	10.5
2.0E	21	5	3.3	0.69	2.208	15.22	3.3	3.729	25.71	7.6
YP	0	16	3.4	0.52	2.134	14.71	5.4	11.038	76.11	9.3
2.0E	21	7	2.7	0.56	2.141	14.76	6.9	4.526	31.21	17.2
					LSL					
Aspen, 1.3E	0	15	3.3	0.59	1.803	12.43	6.6	6.594	45.47	9.9
	20	15	2.6	0.60	1.651	11.38	7.8	3.033	20.91	14.2
YP	0	14	3.5	0.69	1.782	12.29	8.1	7.334	50.57	12.1
1.5E	13	14	2.8	0.68	1.834	12.65	7.4	5.232	36.07	10.2

[a] SPF is Spruce–Pine–Fir; DF, Douglas-fir; SP, southern pine; and YP, yellow-poplar.

grade on the retained value. Retention in MOR for southern pine MSR was only slightly lower (0.50) than that for the other two species.

For the composite lumber products, the retention in MOR for LVL was about 0.40 after 21 months' exposure for both Douglas-fir and yellow-poplar (Fig. 3). Aspen LSL, which was exposed for 20 months, had a MOR retention of 0.46. This is slightly higher than the retention for LVL (Fig. 3). At 13 months' exposure, the MOR retention of yellow-poplar LSL was 0.71, slightly higher than that of aspen LSL at a similar exposure interval. As Fig. 3 indicates, at 82℃ (180°F), MOR retentions of the various products were not as distinctly separated as those at 66℃ (150°F). Thus, we hypothesize that moisture content exerts a greater effect on the thermal degradation of composite products compared with solid-sawn products. Lack of sufficient moisture to utilize the available acetyl groups and more restrictive movement of acids as a result of compaction due to shrinkage could have contributed to fewer differences between groups. The confirmation of this hypothesis awaits the completion of other phases of this study.

DISCUSSION

Changes in wood chemistry

The tables in Appendix B present changes in chemical composition of lumber with duration of exposure. Over time, the pH of all products decreased as the material became more acidic. Also for all products, arabinose showed the largest, and most consistent, decrease with time of exposure (Figs. 4 and 5). As was true for MOR, the retention of arabinose at 82℃ (180°F) and 21 months' exposure was lower than it was at 66℃ (150°F) and 75% RH. For all products, there was no consistent loss of mannose with exposure time.

After 68 months' exposure at 66℃ (150°F), retention of galactose and xylose of solid-sawn SPF was about 80% of original values (Table 10). At 48 months' exposure, galactose
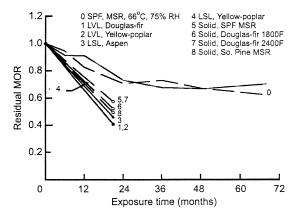
FIG. 3. Average residual MOR for solid-sawn and composite 2 × 4 lumber exposed for various times at 82°C (180°F), 30% RH and tested at 23°C (73°F), 67% RH.

FIG. 4. Average amount of arabinose remaining in solid-sawn 2 × 4 lumber exposed for various times at 66°C (150°F), 75% RH.

retention of solid-sawn Douglas-fir was only about 68% of original value, while that of xylose remained about 86% (similar to retention of SPF after the same exposure). A difference in the retention of galactose and xylose also occurred for southern pine MSR after 3 years' exposure; galactose retention was about 55% of its original content and xylose about 82%. At 82°C (180°F) and 21 months' exposure, galactose was more sensitive to thermal degradation than was xylose for solid-sawn Douglas-fir, but not for SPF and southern pine. Thus, temperature sensitivity trends are generally inconsistent between the two temperature/humidity levels.

For Douglas-fir and southern pine LVL at 66°C (150°F), galactose retention was about 90% and xylose retention about 84% after 68 months' exposure (Table 10). For yellow-poplar LVL, the retention of both types of hemicellulose was about 88%. For aspen LSL, only 40% galactose remained after 28 months' exposure, whereas 97% xylose remained. For yellow-poplar LSL, 77% galactose and 95% xylose remained after 32 months' exposure. At 82°C (180°F), galactose was more sensitive than xylose for aspen and yellow-poplar LSL, but not necessarily more sensitive for the other composite products.

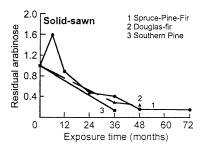Overall, of the hemicelluloses only arabinose apparently shows a large and consistent

reduction with time of exposure. For the other hemicelluloses, there is considerable variability in the amount retained. Although both galactose and xylose may exhibit significantly lower retention by the end of the treating period, there is no consistency as to which is more sensitive to thermal degradation. Despite a 30% loss in strength for solid-sawn SPF and up to 75% loss in MOR for LVL over 6 years of exposure, no noticeable loss was found in cellulose or lignin content. These latter results support the conclusions of LeVan et al. (1990) and Winandy (1995) that when wood is heated over long periods, significant strength loss is possible without a reduction in the amount of cellulose or lignin.

Changes in bond properties

As noted previously, there was no general indication of LVL delamination with time of exposure. Likewise, there was no indication of internal delamination or surface spalling of
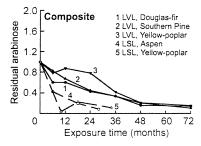

FIG. 5. Average amount of arabinose remaining in composite 2 × 4 lumber exposed for various times at 66°C (150°F), 75% RH.

TABLE 10. *Retention of selected hemicelluloses at maximum exposures used in study.*[a]

Product	Species	Duration (months)	Retention of hemicellulose		
			Arabinose	Galactose	Xylose
66°C (150°F), 75% RH					
Solid-sawn	Spruce–Pine–Fir	68	0.15	0.81	0.79
	Douglas-fir	68	0.23	0.68	0.86
	Southern pine	68	0.14	0.55	0.82
LVL	Douglas-fir	68	0.14	0.90	0.84
	Southern pine	68	0.10	0.90	0.84
	Yellow-poplar	68	0.15	0.88	0.88
LSL	Aspen	28	0.09	0.40	0.97
	Yellow-poplar	34	0.11	0.77	0.95
82°C (180°F), 30% RH					
Solid-sawn	Spruce–Pine–Fir	21	0.23	0.96	0.87
	Douglas-fir	21	0.38	0.70	1.06
	Southern pine	21	0.22	1.05	0.90
LVL	Douglas-fir	21	0.19	0.61	0.71
	Yellow-poplar	21	0.36	0.80	0.77
LSL	Aspen	20	0.31	0.83	0.97
	Yellow-poplar	13	0.54	0.90	0.97

[a] See appendix B.

wood strands with LSL. Because the specimens were tested in edgewise bending, most failure surfaces were quite short. Examination of these failure surfaces seemed to indicate failure at the glue–wood interface, rather than failure within the glue line. Recently, Umemura and Kawai (2002) and Umemura et al. (2002) investigated the durability of two types of isocyanate resin adhesives under dry heat and under constant steam heating for a range of temperatures up to 180°C (356°F). Degradation of bond strength was observed, and the durability under steam heating was markedly inferior to that under dry heating. Tensile shear bond strength was determined using two-ply parallel veneer-laminated specimens of lauan (*Shorea* spp.) that was exposed in a steam injection press to temperatures of 120°C, 140°C, 160°C, and 180°C (248°F, 284°F, 320°F, and 356°F). Examination of failure surfaces indicated a high percentage of wood failure for steaming periods up to 6 h. They concluded that more degradation took place in the wood compared to that of the adhesive under steam heating. These observations coincide with our observations of a lack of adhesive failure with LSL.

Comparison with analytical models

Although the development of analytical models to predict the effect of thermal degradation on strength is an objective of this study, data are insufficient for the development of adequate models at present. However, some models are available in the literature, and it would be of interest to see how well these models predict the results observed in this study. As noted in the Background, as part of their accelerated aging research Millet and Gerhards (1972) developed Arrhenius models to predict the relationship between thermal degradation and bending strength. The equations developed by Millet and Gerhards are given in Table 11, along with predicted times to reach various residual MOR values at the two temperatures presented in our study. Of the specimens in our study, solid-sawn lumber exposed at 82°C (180°F) and 30% moisture content come closest to matching the conditions of the Millet and Gerhards study. Their equations predict that about 1.5 years is required to reach 5% loss in MOR (residual value of 0.95) at 82°C (180° F). As Fig. 3 shows, solid-sawn lumber had a residual value of 0.50

TABLE 11. *Estimated times to residual MOR values by Arrehenius relationships of Millett and Gerhards (1972).*[a]

Residual MOR	Log t = a + b/T	Time (years) to residual MOR at	
		82°C (355.4 K)	66°C (338.7 K)
0.95	−13.940 + 5925/T	1.5	9.8
0.90	−13.806 + 6000/T	3.3	22.2
0.85	−13.768 + 6063/T	5.4	37.2
0.80	−13.755 + 6125/T	8.3	58.3
0.75	−13.702 + 6136/T	10.1	71.0
0.70	−13.552 + 6150/T	15.5	110.4
0.65	−13.481 + 6162/T	19.8	141.0
0.60	−13.451 + 6202/T	27.5	198.3
0.55	−13.420 + 6237/T	37.0	270.2
0.50	−13.391 + 6267/T	48.1	354.2

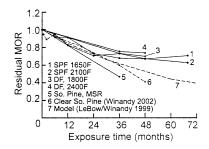[a] T is time, in days; K, exposure temperature, Kelvin units.

FIG. 6. Residual MOR values for small clear southern pine (LeVan et al. 1990; Winandy 2001) and analytical model of Winandy and LeBow (2001) compared with study results for solid-sawn 2 × 4 lumber at 66°C (150°F), 75% RH.

to 0.60 in 1.5 years. Millet and Gerhards would predict 48 to 27 years to achieve reductions of 50% to 40%, respectively (Table 11). At 67°C (153°F), we observed residual values of 0.75 to 0.50 after 3 years exposure. Similar MOR residuals in Table 11 are predicted to require 71 to 354 years to achieve. Thus, the equations of Table 11 predict much longer exposure times to reach the residual values observed in our study.

Two factors must be considered in regard to the Millet and Gerhards study. First, we are using the equations to predict residuals much below the minimum temperature of 115°C (239°F) employed by Millet and Gerhards. Second, and of more importance, the Millet and Gerhards study was conducted to characterize accelerated aging with respect to treating processes, not to evaluate the durability of lumber in structural situations. The specimens in the Millet and Gerhards experiments were exposed in a closed chamber with no outside air intake (Millet et al. 1967). While perhaps appropriate for lumber that would be chemically treated in a retort, this exposure restricted the amount of oxygen available in the chamber and led to much slower rates of degradation than would be experienced with wood heated with adequate air replacement (Stamm 1964).

LeBow and Winandy (1999) developed kinetics-based models for predicting thermal degradation of fire-retardant treatments under long-term exposure on the bending strength of clear southern pine. Coefficients were also developed for untreated southern pine. In the development of this model, it was assumed that the primary cause of degradation was temperature and that moisture content was not a significant factor. At 82°C (180°F), the model predicts a retention in MOR of 0.49 at 21 months' exposure. This is very close to the value of 0.50 observed in our study for southern pine exposed at 30% RH (Fig. 3), but slightly lower than the values of 0.52 to 0.58 observed for Douglas-fir and SPF. However, the values predicted by the model at 67°C (150°F) are higher than the results we observed with southern pine 2 × 4s at 75% RH and lower than the values we found for Douglas-fir and SPF lumber (Fig. 6). Furthermore, the kinetics-based model does not show the leveling of MOR retention at about 0.70 observed with the latter two species at ≥4 years exposure. Thus, we believe that the applicability of this model to untreated wood is still in question for southern pine, as well as for Douglas-fir and SPF 2 × 4s. Additional information should be available after about a year of exposure at 82°C (180°F) and 80% RH and later for exposure at 67°C (150°F) and 25% RH.

Immediate Temperature Effect Factors (C$_t$)

The reversible effect of temperature on bending strength was determined by placing
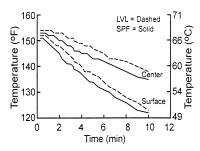
FIG. 7. Effect of cooling representative pieces of solid-sawn SPF and Douglas-fir LVL at 21°C (70°F).

solid-sawn SPF lumber and LVL in the 66°C (150°F)–75% RH chamber for approximately 48 h. The lumber was then removed from the chamber one piece at a time and quickly tested to failure. The temperature in the room outside the conditioning chamber was approximately 21°C (70°F). The total time from removal of the specimen until failure averaged 3 min, with no specimen requiring more than 5 min to failure. In this period, the surface of the specimen cooled only about 5.5°C (10°F), and a thermocouple inserted in the middle of the piece indicated the center cooled only about 2.5°C (5°F) (Fig. 7). This cooling was negligible compared to the initial temperature and is ignored in the following discussion. Data for the lumber tested after a short duration of exposure (48 h assumed to be zero time) are given in Appendix A. Data on the MOE of yellow-poplar LSL were also available from a previous study (Green et al. 1999).

The ratio of the property tested at 66°C (150°F) relative to that tested at approximately 21°C (70°F) is given in Table 12. For MOR, these ratios range from 0.82 to 0.88 for both solid-sawn and LVL specimens. In the NDS, the C_t factor for Fb at 52°C to 66°C (125°F to 150°F) is 0.7 (Table 1). Thus, the C_t factor seems overly conservative for bending strength. However, it is noted that the C_t factor is for a group of four properties, only one of which is Fb. For E_{TV}, the experimentally determined ratio ranges from 0.86 to 0.91 for solid-sawn lumber and LVL. The C_t factor for MOE is 0.90 in the NDS. Thus, the NDS recommendations seem appropriate. The experimental ratio at 66°C (150°F) versus 21°C (70°F) is 0.84 for yellow-poplar LSL. A C_t factor of 0.80 would seem more appropriate for LSL; however, there is only one data set for this product on which to make a judgment. Further information on the reversible effect of temperature on MOE of LSL is needed before definitive judgments are possible.

Estimation of total strength loss

If wood were tested hot, after long exposure to high temperatures, it has been recommended that the total loss in strength be estimated as the sum of the reversible and permanent effects (Forest Products Laboratory 1999). However, apparently no data are available to check the validity of this recommendation. This assumption was investigated by testing some lumber hot after exposure to high temperature for a short period (reversible effect) and also by testing some lumber hot after exposure to high temperatures for a long period

TABLE 12. *Reversible effect of heating to 66°C (150°F) on flexural properties of lumber products.*

Product	Species	Grade	Moisture content	Factor[a]	
				MOR	E_{TV}
Solid-sawn	Spruce–Pine–Fir	1650f-1.5E	dry	0.87	0.89
		2100f-1.8E	dry	0.83	0.89
	Southern pine	MSR	dry	—	0.92
LVL	Douglas-fir	2.0E	dry	0.88	0.90
	Southern pine	2.0E	dry	0.88	0.86
	Yellow-poplar	2.0E	dry	0.82	0.91
LSL[b]	Yellow-poplar	1.5E	dry	—	0.84

[a] MOE determined by transverse vibration in flatwise orientation and MOR by static bending in edgewise orientation. SS is Select Structural.
[b] Data from Green et al. 1999.

TABLE 13. *Estimated total loss in MOR for material tested at 66°C (150°F) and 75% relative humidity after 3 years continuous exposure.*

Product and grade	Estimated loss (%)			Actual total loss (%)
	Reversible	Permanent	Total	
Spruce–Pine–Fir solid-sawn				
1650F-1.5E	13	33	46	44
2100F-1.8E	17	27	44	38
LVL, 2.0E				
Douglas-fir	12	35	47	43
Southern pine	12	32	44	45
Yellow-poplar	18	35	53	55

(total effect). By combining these data with data obtained by exposing lumber to high temperature for long periods and then reconditioning it to room temperature prior to testing (permanent effect), it is possible to verify the assumption.

Appendix A also gives the properties of lumber tested hot at 66°C (150°F) after a continuous exposure of 3 years. The results are the total effect of temperature on MOR. Adding the loss (defined as 1 − retention) due to permanent effects (Tables 7 and 8) to the loss due to the reversible effects (Table 12) gives an estimate of the total loss. As Table 13 indicates, the estimated total loss in strength is a good estimate of the measured total loss in MOR. As can be seen from Appendix A, there is virtually no difference in the MOE of solid-sawn lumber tested hot after zero and 3 years of exposure. This is consistent with the results from Table 7 that show no consistent loss in MOE over the 3-year period when the lumber was subsequently tested at room temperature. For LVL, there does appear to be some difference in MOE when the lumber was tested hot at the two exposure periods (Appendix A). However, the generally higher moisture content levels after 36 months' exposure confuse the interpretation of the results, and comparison between the results from Appendix A and those of Table 8 fail to clear up the confusion. Additional information on the reversible effect of temperature for a wide range of temperatures and moisture contents is given in Green et al. (1999).

Elevated temperatures in commercial and industrial buildings

If commercial and industrial buildings are adequately ventilated, and if internal heat sources are not present, building temperatures may remain near ambient readings. However, there is a potential for exposure to higher temperatures over long periods in cases where industrial processes within the building involve heat. Most temperature exposures in commercial and industrial buildings would be at 66°C (150°F) or less. However, exposures of up to 149°C (300°F) have been reported (Green and Evans 2001). Higher temperatures in industrial buildings will generally result in very low relative humidity levels. However, in a discussion comment in Meyer and Kellogg (1982), Powell notes that in an industrial plant that uses wet processing involving steam, the moisture content of structural wood probably varies from 12% to 20%. In addition, the temperature in the wood will be in the range of 17°C to 65°C (80°F to 150°F). Mujumdar (1982) reports that wood used in cooling tower environments may be exposed to temperatures up to 55°C (130°F) at 100% relative humidity. These examples illustrate that thermal degradation could be a concern in industrial and commercial buildings, especially where heat sources are present. Additional information on wood in adverse environments may be found in Meyer and Kellogg (1982), Nelson and Petterson (1985), Green et al. (1999), and Green and Evans (2003).

Elevated temperatures in residential construction

Temperatures higher than ambient can be reached in residential roof systems as a result of solar radiation. However, it is unlikely that the maximum temperature reached would be as high as 66°C (150°F) and even less likely that a significant accumulation of time at that temperature would occur. For example, in measuring temperatures in six houses and one office building in various locations throughout the United States, Heyer (1963) found that although maximum temperatures in the attic space where joists were located ranged from 49°C to 54°C (120°F to 130°F), the cumulative time at those temperatures was 1 day or less over the course of a year. The highest temperature was 69°C (157°F) in a building in Tucson, Arizona; however the cumulative time when the temperature exceeded 66°C (150°F) appears to have been short.

Recently, Winandy et al. (2000) measured room temperatures in matched attics in Mississippi and Wisconsin and calculated the average number of hours that the recorded temperature exceeded a given value. Thermocouples were placed in various locations in the structures, including the insertion of some thermocouples in the center of 38- by 140-mm (nominal 2- by 6-in., standard 1.5- by 5.5-in.) rafters and one attached to the bottom ply of the sheathing. For the purposes of judging rafter exposure, the latter thermocouple provided an idea of the temperature that might be experienced by the top edge of the rafter. For a black-shingled attic in Mississippi, the 4-year average of the exceedance temperatures measured in the roof rafters was 11 h at 55°C (122°F) and the temperature never exceeded 60°C (140°F) (Fig. 8). In the hottest of the four summers (1999), temperatures exceeded 55°C (122°F) for a total of 30 h, but did not exceed 60°C (140°F). At the bottom of the roof sheathing (top of rafters), the average maximum exceedance temperature was 60°C (140°C) for a total of 13 h. During the summer of 1999, the rafters were exposed to the max-
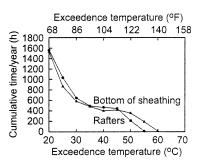

FIG. 8. Exposure times above given temperature for black-shingled roof in Mississippi (Winandy et al. 2000).

imum exceedance temperature of 60°C (140°C) for 28 h. If the average temperatures over the four summer period are assumed to be typical, the rafters would require 796 years to accumulate a year of exposure, even at 55°C (122°F). Even if all the years had temperatures like those recorded in 1999, it would require 292 years for the mid-depth of the rafters to accumulate a year of exposure at 55°C (122°F). For the latter scenario, it would require 312 years for the top of the rafters to accumulate a year of exposure at 60°C (140°F). These data imply that thermal degradation is not likely to be a problem in typical residential construction.

CONCLUSIONS

Continuous exposure at 66°C (150°F) and 75% RH[2]

- Solid-sawn Spruce–Pine–Fir (SPF) and Douglas-fir machine stress rated (MSR) lumber and laminated veneer lumber (LVL) degraded at about the same rate for the first 2 to 3 years. After 1 year of exposure, both types of lumber retained about 90% of their original bending strength and after 3 years, about 72%. Solid-sawn southern pine MSR lumber retained about 50% of its strength after 3 years' exposure.
- After 3 years of continuous exposure, LVL degraded faster than did solid-sawn SPF and Douglas-fir lumber. After almost 6 years of

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[2] EMC of about 12%, if wood is unheated.

continuous exposure, solid-sawn SPF lumber retained about 67% of its original bending strength and LVL from 26% to 49%.
- Bending strength of laminated strand lumber (LSL) is more sensitive to thermal degradation than is bending strength of solid-sawn SPF lumber or LVL. After 28 months of continuous exposure, LSL retained 47% of its original strength.
- For solid-sawn lumber, there appears to be little, if any, difference in thermal degradation attributable to MSR grade.
- Modulus of elasticity (MOE) was less sensitive to thermal degradation than was modulus of rupture (MOR). None of the solid-sawn species experienced a significant loss in MOE over the various exposure periods. After almost 6 years of exposure at 66°C (150°F), LVL retained 75% to 80% of its original MOE.
- Tests of solid-sawn SPF and LVL material conducted ''hot'' after 3 years of continuous exposure confirmed that estimates of the total effect of temperature on MOR should be based on the sum of the reversible and permanent effects.
- Data on MOE of solid-sawn lumber and laminated LVL confirm the C_t factors for adjusting properties for the reversible effect of temperature given in the NDS for dry lumber at 66°C (150°F). The C_t factor of 0.70 that is applied to allowable bending (F_b), shear (F_v), compression parallel to grain (F_c), and compression perpendicular to grain ($F_{c\perp}$) strength seems overly conservative for dry MOR when applied to solid-sawn and LVL lumber.

Exposure at 82°C (180°F) and 30% RH[3]

- Solid-sawn SPF and Douglas-fir MSR lumber retained about 55% of their original MOR after 21 months of continuous exposure, solid-sawn southern pine about 50%, and LVL about 41%; retentions for LSL were similar to those for solid-sawn lumber.

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[2] EMC of about 4% if wood is unheated.

- MOE of all products was less sensitive to thermal degradation than was MOR; the greatest effect occurred for aspen LSL (retention of 0.92 after 20 months of continuous exposure).

Overall conclusions

- The results suggest that there may be less difference in strength loss due to thermal degradation between species and product types at very low moisture content levels than at higher levels. Future results at other exposure conditions should clarify this speculation.
- The accelerated aging models of Millet and Gerhards (1972) predict much longer exposure periods to reach the same retention levels for MOR than were observed in the current study for solid-sawn 2 × 4 lumber. This difference is likely a result of oxygen deficiency in the treating chamber used by Millet and Gerhards.
- The analytical models of Winandy and LeBow (2001) for untreated southern pine clear wood yielded a good prediction of the MOR of southern pine 2 × 4 lumber tested in this study at 82°C (180°F) and 30% RH after 21 months' exposure. However, the model predicted a lower retention for MOR of Douglas-fir and SPF than was observed. The model for untreated wood did not adequately predict strength loss at 66°C (150°F) and 75% RH for any of the solid-sawn species tested.
- The primary chemical mechanism of thermal degradation is acid hydrolysis of the hemicelluloses. Of the hemicelluloses, arabinose is by far the most sensitive to thermal degradation. No change was observed in the amount of cellulose or lignin.
- LVL and LSL showed no sign of progressive delamination over the duration of exposure.
- Information in the literature, coupled with years of practical experience, suggests that in most applications, wood in residential construction is unlikely to experience any

significant accumulation of exposure at temperatures at or above 150°F (66°C) over the life of the structure. Thermal degradation may be possible in commercial and industrial applications involving significant heat sources.

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APPENDIX A—*Properties of lumber tested at 66°C (150°F)*

Species[a]	Grade	Exposure (months)	Sample size	Moisture content (%)	Specific gravity (OD/OD)	MOE			MOR		
						Mean		COV (%)	Mean		COV (%)
						(10^6 lb/in^2)	(GPa)		(10^3 lb/in^2)	(MPa)	
Solid-sawn lumber											
SPF	1650f	0	31	11.5	0.42	1.40	9.7	13.0	6.06	41.8	23.4
		36	31	12.8	0.39	1.39	9.6	14.9	3.96	27.3	38.3
	2100f	0	30	11.8	0.45	1.67	11.5	8.2	7.44	51.3	16.3
		36	30	12.7	0.44	1.66	11.4	9.5	5.60	38.6	20.0
Laminated veneer lumber											
DF	2.0E	0	15	9.7	0.52	2.13	14.7	5.4	7.91	54.5	12.7
		36	14	13.4	0.49	2.00	13.8	7.3	5.14	35.4	10.1
SP	2.0E	0	16	10.1	0.61	2.53	17.4	5.4	10.06	69.4	8.8
		36	15	13.1	0.59	2.04	14.1	5.7	6.23	43.0	10.4
YP	2.0E	0	16	9.6	0.49	1.97	13.6	6.5	8.79	60.6	6.9
		36	16	13.1	0.46	1.65	11.4	5.4	4.82	33.2	6.8

[a] SPF is Spruce–Pine–Fir; DF, Douglas-fir; SP, Southern pine; and YP, yellow-poplar.

APPENDIX B—*CHANGES IN CHEMICAL COMPOSITION OF LUMBER*

Table B–1. *Chemical composition[a] of solid-sawn 2 by 4 lumber exposed to 66℃ and 75% RH.*

Exposure (months)	Spruce–Pine–Fir	Southern pine	Douglas-fir	Exposure (months)	Spruce–Pine–Fir	Southern pine	Douglas-fir
	pH				Xylose		
0	4.5	4.1	4.0	0	6.80	6.00	3.70
6	4.4	—	—	6	6.77	—	—
12	4.2	—	—	12	6.49	—	—
24	3.9	—	—	24	6.50	—	—
36	4.0	3.8	3.6	36	6.43	4.90	3.52
48	4.0	—	3.4	48	5.10	—	3.19
68	3.8	—	—	68	5.37	—	—
	Arabinose				Mannose		
0	0.95	0.94	0.91	0	12.74	11.22	12.90
6	1.52	—	—	6	11.12	—	—
12	0.85	—	—	12	10.73	—	—
24	0.46	—	—	24	11.00	—	—
36	0.39	0.13	0.26	36	11.74	12.82	12.30
48	0.15	—	0.21	48	11.42	—	13.34
68	0.14	—	—	68	11.27	—	—
	Galactose				Glucose		
0	2.43	2.23	2.76	0	45.60	42.48	45.09
6	3.70	—	—	6	42.90	—	—
12	2.22	—	—	12	44.40	—	—
24	3.43	—	—	24	43.10	—	—
36	4.71	1.22	2.42	36	43.50	46.00	44.80
48	3.89	—	1.88	48	42.90	—	46.10
68	1.96	—	—	68	45.50	—	—

[a] Percentage of dry weight.

TABLE B–2.   *Chemical composition of composite 2 by 4 lumber exposed at 66℃ and 75% RH.*

Exposure (months)	Laminated veneer lumber			Laminated strand lumber	
	Douglas-fir	Southern pine	Yellow-poplar	Aspen	Yellow-poplar
			pH		
0	6.2	6.1	6.4	4.8	4.8
6	6.1	5.5	5.8	4.1	—
10	—	—	—	—	4.0
12	5.6	5.4	5.7	—	—
18	—	—	—	4.1	4.1
24	5.3	5.0	5.1	—	—
28	—	—	—	3.9	—
32	—	—	—	—	3.9
36	5.0	5.1	4.9	—	—
48	4.5	4.7	3.8	—	—
68	4.6	4.6	4.1	—	—
			Arabinose		
0	0.95	1.06	0.33	0.35	0.35
6	0.58	0.88	0.26	0.15	—
10	—	—	—	—	0.15
12	0.58	0.72	0.29	—	—
18	—	—	—	0.07	0.08
24	0.41	0.48	0.26	—	—
28	—	—	—	0.03	—
32	—	—	—	—	0.04
36	0.32	0.36	0.14	—	—
48	0.15	0.21	0.07	—	—
68	0.13	0.11	0.05	—	—
			Galactose		
0	3.13	2.10	0.40	0.53	0.48
6	3.26	1.99	0.37	0.49	—
10	—	—	—	—	0.43
12	2.75	1.89	0.38	—	—
18	—	—	—	0.48	0.42
24	2.65	2.10	0.38	—	—
28	—	—	—	0.21	—
32	—	—	—	—	0.37
36	3.18	1.55	0.33	—	—
48	2.31	2.27	0.29	—	—
68	2.81	1.90	0.35	—	—
			Xylose		
0	3.99	6.35	14.6	15.6	15.1
6	3.46	5.83	14.4	15.9	—
10	—	—	—	—	15.0
12	3.44	5.54	14.2	—	—
18	—	—	—	15.7	14.6
24	3.53	5.55	14.3	—	—
28	—	—	—	15.2	—
32	—	—	—	—	14.4
36	3.68	5.09	13.9	—	—
48	3.36	5.46	14.2	—	—
68	3.36	5.33	12.8	—	—

TABLE B–2. *Continued.*

Exposure (months)	Laminated veneer lumber			Laminated strand lumber	
	Douglas-fir	Southern pine	Yellow-poplar	Aspen	Yellow-poplar
			Mannose		
0	11.6	11.0	2.48	1.75	2.59
6	12.6	11.1	2.82	1.74	—
10	—	—	—	—	2.73
12	11.8	10.3	2.55	—	—
18	—	—	—	1.73	2.55
24	11.9	11.1	2.76	—	—
28	—	—	—	1.71	—
32	—	—	—	—	2.52
36	11.1	11.5	2.47	—	—
48	11.5	10.0	3.05	—	—
68	11.0	10.7	2.52	—	—
			Glucose		
0	41.0	42.9	43.6	43.6	41.0
6	43.6	43.1	42.8	44.6	—
10	—	—	—	—	42.2
12	42.4	41.8	43.6	—	—
18	—	—	—	45.8	41.8
24	42.6	42.7	43.1	—	—
28	—	—	—	45.3	—
32	—	—	—	—	143.5
36	41.4	43.7	44.6	—	—
48	42.2	41.9	44.7	—	—
68	41.7	43.2	44.0	—	—

TABLE B–3. *Chemical composition of solid-sawn and laminated veneer lumber exposed at 88°C and 30% RH.*

Exposure (months)	Solid-sawn lumber			LVL	
	Spruce–Pine–Fir	Southern pine	Douglas-fir	Douglas-fir	Yellow-poplar
			pH		
0	4.5	4.1	4.0	6.2	6.4
21	3.8	3.7	3.5	5.4	5.2
			Arabinose		
0	0.95	0.95	0.91	0.95	0.33
21	0.22	0.21	0.35	0.18	0.12
			Galactose		
0	2.43	2.23	2.76	0.40	0.53
21	2.33	2.35	1.92	0.32	0.44
			Xylose		
0	6.80	6.00	3.70	3.99	14.6
21	5.89	5.40	3.94	2.82	11.2
			Mannose		
0	12.74	11.22	12.90	11.58	2.48
21	10.52	10.97	12.90	8.96	1.78
			Glucose		
0	45.60	42.48	45.09	41.0	43.6
21	44.00	42.68	46.47	42.5	44.8

TABLE B–4. *Chemical composition of laminated strand lumber exposed at 88°C and 30% RH.*

Exposure (months)	Aspen	Yellow-poplar
	pH	
0	4.8	4.8
13	—	4.2
20	4.1	—
	Arabinose	
0	0.35	0.35
13	—	0.19
20	0.11	—
	Galactose	
0	0.53	0.48
13	—	0.43
20	0.44	—
	Xylose	
0	15.57	15.05
13	—	14.61
20	15.11	—
	Mannose	
0	1.75	2.59
13	—	2.45
20	1.66	—
	Glucose	
0	43.63	40.97
13	—	41.40
20	44.20	—

APPENDIX C—*PERTINENT SPECIES AND SPECIES GROUPS.*.

Species or group	Official common name	Botanical name
Spruce–Pine–Fir	Subalpine fir[a]	*Abies lasiocarpa*
	Engelmann spruce[a]	*Picea engelmannii*
	Lodgepole pine[a]	*Pinus contorta*
	White spruce[a]	*Picea glauca*
	Black spruce[a]	*Picea mariana*
	Red spruce	*Picea rubens*
	Balsam fir	*Abies balsamea*
	Jack pine	*Pinus banksiana*
Southern pine	Loblolly pine	*Pinus palustris*
	Longleaf pine	*Pinus taeda*
	Shortleaf pine	*Pinus echinata*
	Slash pine	*Pinus elliottii*
Douglas fir	Douglas-fir	*Pseudotsuga menziesii*
Yellow poplar	Yellow-poplar	*Liriodendron tulipifera*
Aspen	Aspen	*Populus* spp.

[a] Species most likely to be found in Spruce–Pine–Fir from Vancouver, BC, area.