Flexural Properties of Structural Lumber Products After Long-Term Exposure to High Temperatures

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Summary

When wood fiber is exposed to significant heat, its strength decreases. It has long been known that prolonged heating at temperatures over 66°C (150°F) can cause a permanent loss in strength. The National Design Specification (NDS) provides factors (C_t) for adjusting allowable properties when structural wood members are exposed to temperatures between 38°C (100°F) and 66°C (150°F) for extended periods of time. The NDS Commentary further states that the use of structural wood members in applications involving prolonged exposure to over 66°C (150°F) should be avoided. Where such exposures do occur, it recommends that adjustments for both immediate and permanent strength reductions should be made.

This study presents results on permanent loss in flexural properties for nominal 2x4 solid-sawn and structural composite lumber heated in air at 66°C (150°F) and 82°C (180°F) at two different equilibrium moisture contents (4% and 12% EMC) for time periods that ranged from a few months to up to six years. The study is still underway. The results confirm that significant loses in bending strength can occur at these temperature and humidity conditions. It is recommended that current design recommendations be updated once this test program has been completed.

1. Introduction

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 is considered 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. The extent of the property loss depends on the stress mode, temperature, duration of exposure, moisture content, heating medium, and species of wood (FPL, 1999).

1.1 Current Design Recommendations

Current design recommendations in the United States assume 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 2005). The National Design Specification for Wood Construction (NDS) provides factors (C_t) for adjusting properties for short-term temperature exposures. Tabulated design values are multiplied by these C_t factors for structural members that will experience sustained exposure to temperatures up to 66°C (150°F) (Table 1). The discussion in the NDS Commentary (AF&PA 2006) 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.

Table 1. NDS Temperature Factor, C_t

Design Value	In Service Moisture Conditions	C_t		
		T≤100 °F	100 °F<T≤ 125 °F	125 °F<T≤ 150 °F
F_t, E	Wet or Dry	1.0	0.9	0.9
F_b, F_v, F_c and F_{cL}	Dry	1.0	0.8	0.7
	Wet	1.0	0.7	0.5

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-inch) specimens, 152.4 mm (6 inches) in length. Four specimens were used for each combination of species, heating medium, and temperature. From these studies, MacLean showed an approximate 10% reduction in bending strength for material exposed for almost one year in water at 66°C (150°F) and that heating in water or steam results in faster weight loss than does heating in an oven. MacLean concluded “if good service life is desired, wood should not be exposed under service conditions where temperatures appreciably higher than 150°F (66°C) will be encountered.” Over the years it has generally been assumed that in normal use, lumber exposed to temperature up to 66°C (150°F) for cumulative periods up to about 1-year did not require a reduction in properties to account for the permanent effect of temperature. If under load at higher temperatures, or for cumulative exposure times of more than a year, it may be necessary to account for both the permanent and reversible effects of temperature on properties (NDS, 2005; Green, et al., 2003).

2. Objectives

The objectives of this paper are to summarize the results of a current study at the USDA Forest Service, Forest Products Laboratory, on the permanent effects of high temperature on the properties of structural lumber products and to discuss the implications of the findings relative to current design recommendations in the United States.

3. Permanent Effects of Temperature on Flexural Properties of Structural Lumber

3.1 Experimental Design and Procedures

Since 1990 an on-going study at the Forest Products Lab has been investigating the permanent reduction due to heating on flexural properties of solid-sawn and composite lumber (nominal 2x4's) (Green, et al, 2003, 2005). The study has evaluated three lumber products (sold-sawn lumber, laminated veneer lumber (LVL), and laminated strand lumber (LSL)), five wood species or species groupings (Spruce-Pine-Fir, Douglas-fir, southern pine, aspen, and yellow-poplar), subjected to four exposure conditions (66°C (150°F) at 25% and 75% relative humidity (RH), and 82°C (180°F) at 30% and 80% RH). Table 1 shows the matrix of product, species and exposure conditions. These conditions are generally assumed to result in approximate equilibrium moisture contents of either 4% or 12% for solid-sawn lumber. Exposure times vary with the severity of the exposure condition and the sensitivity of the product to exposure. At 66°C (150°F) the maximum length of exposure for any group was 68 months at 75% RH and 48 months at 25% RH, and at 82°C (180°F) it was 24 months at 80% RH and 30 months at 30% RH. The total number of solid-sawn and composite lumber specimens that will have been tested by the end of this program is about 3,800 for the main part of the study and 450 for the side studies (Green, et al., 2005). As later noted in this paper, the condition of concurrent high temperature and high humidity is not typical in building environments. Typically, high temperatures are associated with conditions of lower humidity. Thus, the concurrent high temperature, high humidity condition is primarily to study the material response in unusual (extreme) environments, not as an indicator of performance in typical building applications.

Table 2. Experimental Design of Main Study

Species Group	Grade	66°C (150°F)		82°C (180°F)	
		25% RH	75% RH	30% RH	80% RH
Solid-Sawn					
Spruce-Pine-Fir	1650f-1.5E	--	X	--	--
	2100f-1.8E	--	X	--	--
	MSR[2]	X	--	X	X
Douglas-fir	1800f-1.8E	X	X	X	X
	2400f-2.0E	X	X	X	X
	Sel. Str.	--	--	X	--
Southern pine	2250f-1.9E	--	--	X	X
	2700f-2.2E	--	--	X	--
	MSR[3]	X	X	X	X
Yellow-poplar	Ungraded	--	--	--	X
Laminated Veneer Lumber					
Douglas-fir	1.9E & 2.0E[4]	X	X	X	X
Southern pine	1.9E & 2.0E	X	X	--	X
Yellow-poplar	1.9E & 2.0E	X	X	X	X
Laminated Strand Lumber					
Aspen	1.3D & 1.5E[4]	X	X	X	X
Yellow-poplar	1.5E	X	X	X	X

[1] Sample sizes and exposure times vary. Generally there are about 30 pieces per exposure group for sold-sawn lumber and 15 pieces for composite lumber products.

[2] A 50-50 mix of 1650f and 2100f grades SPF 2x4's.

[3] A mixture of three grades from 1.6E to 2.0E

[4] Material obtained at different times. Grades were not mixed at any given set of exposures.

For a given product, grade and species the lumber was equilibrated to about 23°C (73°F) at 65% RH and sorted into the required number of exposure groups using modulus of elasticity (MOE) determined by transverse vibration (Etv), ASTM D 6874. The specimens to be exposed at the lower humidity levels were first equilibrated at room temperature and 25% RH prior to being placed in the heating chambers. Following conditioning, the specimens were placed in chambers at room temperature and a humidity level that corresponded to the anticipated moisture content during exposure (either 4% or 12%) prior to testing.

All MOE's reported in this paper were obtained in transverse vibration with the lumber oriented flatwise and supported at the ends of the piece. Modulus of rupture (MOR) was obtained in edgewise bending using ¼-point loading and a span-to-depth ration of 21:1 (ASTM D198). The rate of loading was approximately 51mm (2 inches) per minute. Following testing, specimens were cut from each specimen near the failure location for determination of oven-dry moisture content (ASTM D4442) and specific gravity (ASTM D 2395).

3.2 Experimental Results and Trends

All MOR and Etv results within each test group were averaged and a residual strength or stiffness value calculated by dividing by the respective control average. Plots of the residual MOR or MOE versus exposure time are shown in Figures 1-8. Lines are shown on the data to aid in visualizing trends. A question mark (?) is shown in some plots to indicate that additional information is still to come.

3.2.1 Modulus of Elasticity (MOE)

Plots of the residual MOE for solid-sawn and composite lumber groups are shown in Figures 1 and 2. As has been observed in the past, there is little change in the Etv of solid-sawn lumber for any of the temperature or humidity conditions used in this study (FPL 1999). There is also little change in the Etv of the LVL or the LSL at low humidity. For the high humidity exposures, the LVL and LSL did show some drop in Etv (15-20%) for the time periods studied.

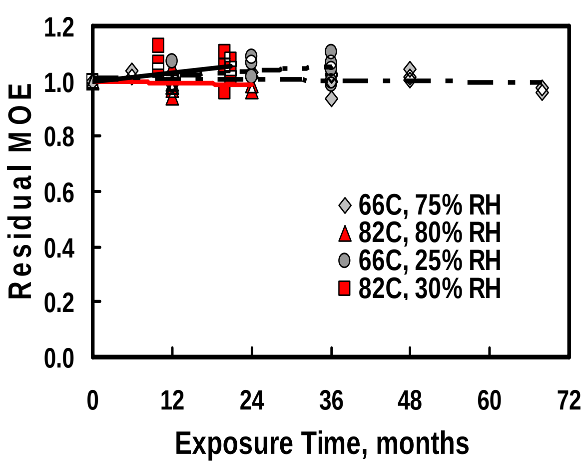

Figure 1. Residual MOE for solid-sawn lumber

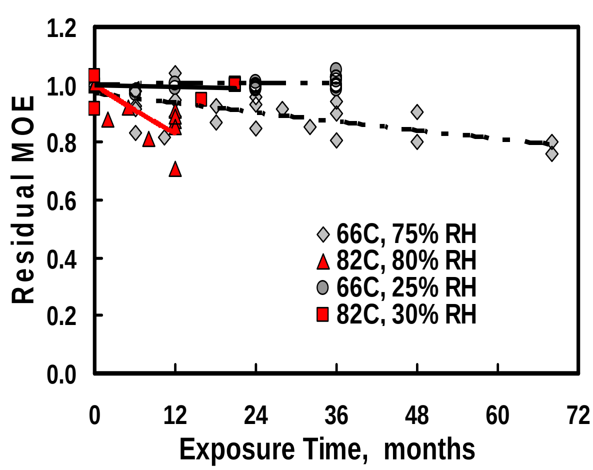

Figure 2. Residual MOE for composite lumber

3.2.2 Bending strength (MOR)

From the plots in Figures 3-8, the permanent loss in MOR implied by the trend lines for a 12 month and 24 month exposure time is shown in Table 3.

Table 3. Permanent loss in MOR (%) implied by trend lines in Figures 3 to 8

Exposure (months)	Product	Percentage Loss in MOR After Continuous Exposure at			
		66°C (150°F) 25% RH	82°C (180°F) 30% RH	66°C (150°F) 75% RH	82°C (180°F) 80% RH
12	Solid-sawn	8	30	14	36
	LVL	10	34	11	54
	LSL	9	32	31	56
24	Solid-sawn	17	~ 40	24	44
	LVL	15	~ 65	22	--
	LSL	14	~ 60	46	--

<u>Solid-sawn Lumber:</u> Figure 3 shows the results to date for the residual strength (MOR) of solid-sawn lumber at low humidity levels that would be expected to produce an equilibrium moisture content of about 4%.

After 12 months of continuous exposure the solid-sawn lumber at 66°C (150°F) has lost 8% of their strength (Table 3). This is consistent with historical assumptions that the permanent loss be 10%, or less, after one-year of exposure. At 82°C (180°F), the loss in MOR after 12 months continuous exposure is 30%. After 24 months of continuous exposure, the solid-sawn lumber at 66°C (150°F) have lost about 17% of their strength and at 82°C (180°F) have lost about 40%. There is not enough data yet to confirm if the trend lines for the lumber at 66°C (150°F) have reached a “plateau”. Data for three additional groups of Douglas-fir and southern pine lumber (“?” on plot) will be available at 48 months exposure for the 66°C (150°F) and 30 months exposure 82°C (180°F) which can be used to make this determination.

Figure 4 shows the residual MOR values for solid-sawn lumber at high humidity that would be expected to produce an equilibrium moisture content of 12%. Such exposures would generally only be found in special applications (such as industrial buildings that use steam as part of a manufacturing process or in food processing buildings where the humidity at the roof is permitted to build up). Under these extreme exposures, solid-sawn lumber at 66°C (150°F) would lose almost 14% of its flexural strength after 12 months of continuous exposure. This is still close to the assumed loss of historical guidelines. At 82°C (180°F) the lumber would lose 36% of its strength. While it is difficult to extrapolate, it would appear that the trend lines for both conditions have reached a plateau that would project to about a 34% loss for 72 months of continuous exposure at 66°C (150°F) and 44% at 82°C (180°F). The studies at these exposures are complete, and thus the projected trends will not change.

Comparison of the two temperature and relative humidity conditions (Table 3) suggests that temperature is the more important factor in the thermal degradation of sold-sawn lumber heated in air.

Laminated Veneer Lumber: Figure 5 shows trends in the experimental data collected to-date for the LVL at low humidity (4% EMC). After 12 months and 24 months exposure the LVL at 66^{o}C (150^{o}F) has lost about 10% and 15% of its strength, respectively. This is about the same as the loss seen for solid-sawn lumber at these conditions (Table 3). The trend line suggests that a "plateau" has been reached. Three more data points (? on plot) will be available for 48 months exposure at 66^{o}C (150^{o}F) to confirm this. After 12 months exposure at 82^{o}C (180^{o}F) the LVL has lost 34% of its strength, again about the same as solid-sawn lumber. After 24 months of exposure the 65% loss is greater than the corresponding loss for solid-sawn lumber. No further data is available at this condition to develop a trend line.

Figure 6 shows trends in the experimental data for the LVL at high humidity (12% EMC). After 12 months of continuous exposure at 66^{o}C (150^{o}F) and a high humidity, LVL has lost about 11% of its bending strength, again similar to that of solid-sawn lumber (Table 3). A comparison trend shown in Figures 4 and 6 indicates that the loss in strength for LVL at this condition is similar to that of solid-sawn lumber for about the first 36 months. With longer exposures the LVL continues to lose strength while the solid-sawn lumber did not. After 72 months of continuous exposure LVL has lost about 67% of its strength while solid-sawn lumber has lost only about 34%. At 82^{o}C (180^{o}F) and a high humidity LVL it has lost 54% of its strength after 12 months compared to 36% for solid-sawn lumber (Table 3). Whether this trend is related solely to temperature or is a more complex interaction of moisture and temperature may not be understood until the results for all exposures are available and analytical models of performance have been formulated. No further data is available at high humidity. As stated earlier, the condition of concurrent high temperature and high humidity is not a typical condition found in normal structural applications.

The results suggest that, when estimating the effects of thermal degradation, both temperature and humidity level are more important for LVL than they are for solid-sawn lumber.

Laminated Strand Lumber: Figure 7 shows trends in the experimental data collected for the LSL at low humidity (4% EMC) and shows that LSL exposed at 66^{o}C (150^{o}F) and low humidity is not very sensitive to change in MOR due to thermal degradation. After 12 and 24 months of continuous exposure, the bending strength is 9% and 14% lower respectively than the controls and is about the same as solid-sawn lumber and LVL at this condition. At 82^{o}C (180^{o}F) and a low humidity, LSL has lost 32% of its strength after 12 months (again comparable to solid-sawn and LVL). However, after 24 months, the loss is approximately 60%. This loss is about the same as LVL, but is higher than solid-sawn lumber (Table 3).

Figure 8 shows trends in the experimental data collected for the LSL at high humidity (12% EMC). At high humidity LSL appears to be more sensitive to thermal degradation due to long term temperature exposure. After 12 months exposure at 66^{o}C (150^{o}F) LSL has lost 31% of its bending strength, compared to about 13% for solid-sawn lumber and LVL (Table 3) and after 24 months it has lost 46% compared to about half that for solid-sawn lumber and LVL. At 82^{o}C (180^{o}F) LSL at high humidity has lost 56 % of its strength, about the same as LVL, but more than solid-sawn lumber. As with LVL, it is difficult to determine whether this trend is related solely to temperature or is a more complex interaction of moisture and temperature. Again, the reader is cautioned not to over-interpret the data presented until the study is complete and to reiterate, the condition of concurrent high temperature and high humidity is not a typical condition found in normal structural applications.

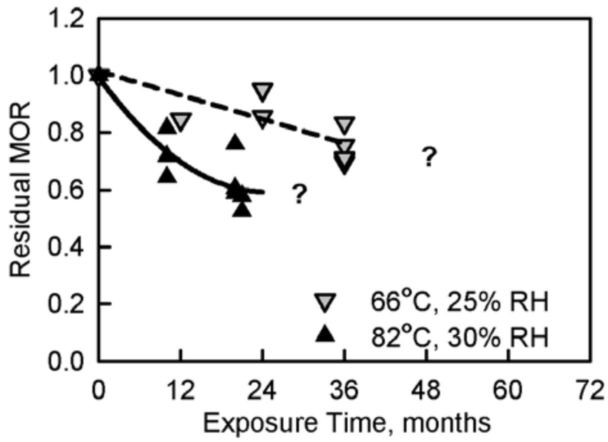

Figure 3. Residual MOR for solid-sawn lumber at low relative humidity

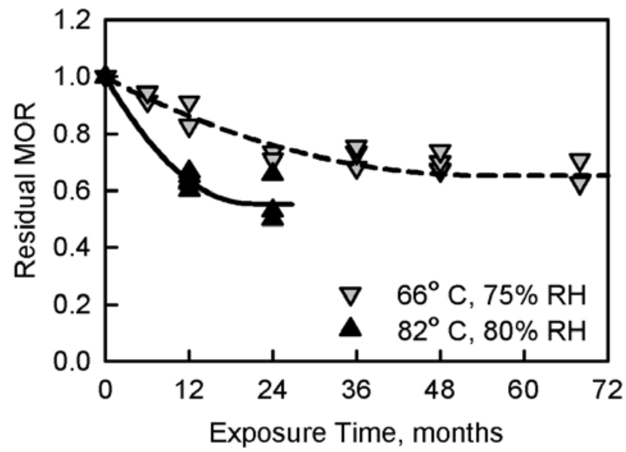

Figure 4. Residual MOR for solid-sawn lumber at high relative humidity

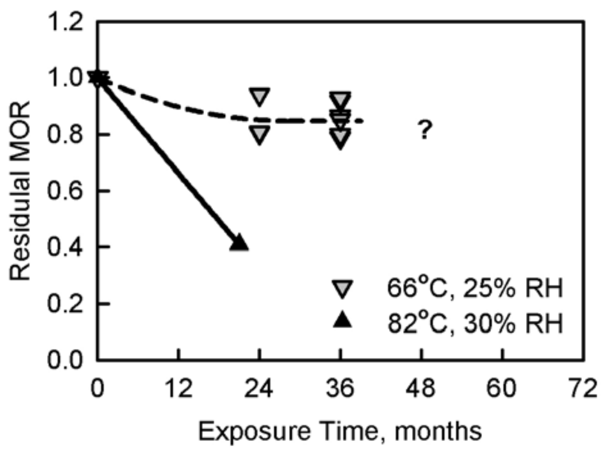

Figure 5. Residual MOR for LVL at low relative humidity

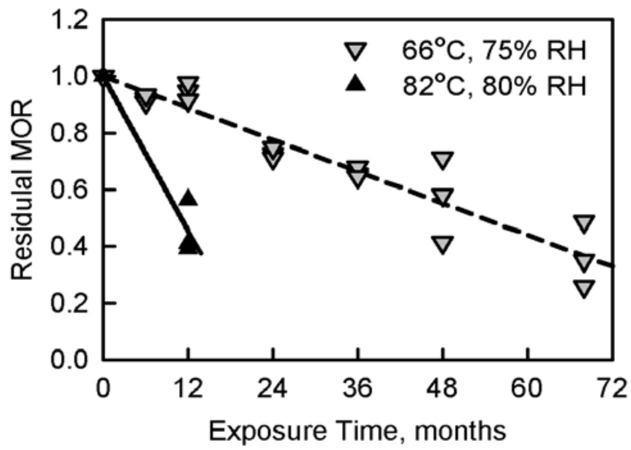

Figure 6. Residual MOR for LVL lumber at high relative humidity

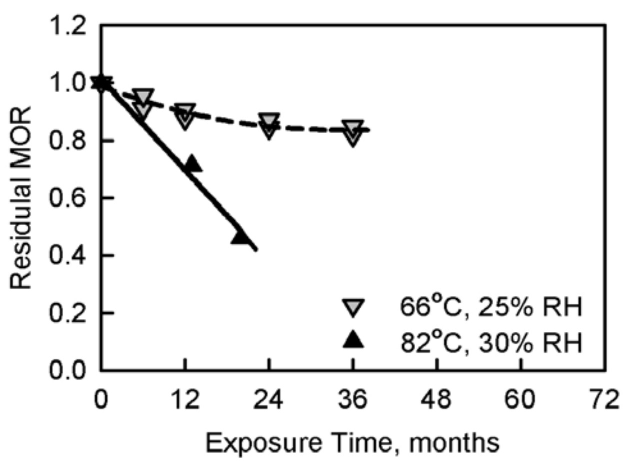

Figure 7. Residual MOR for LSL at low relative humidity

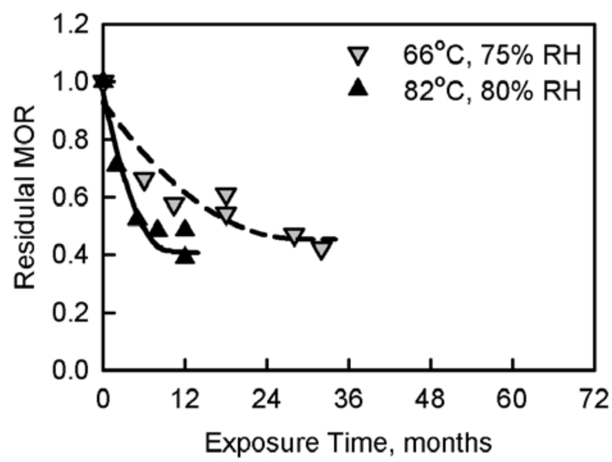

Figure 8. Residual MOR for LSL at high relative humidity

3.3 Study Conclusions

These results confirm the historical assumption that there is minimal loss in bending stiffness and that loss in bending strength at 66°C (150°F) is about 10% for one year of continuous exposure if the humidity level (moisture content of the wood) is low. For solid-sawn lumber and LVL this assumption seems to also be true at 66°C (150°F) and a high humidity. This conclusion is less clear for LSL. The loss in bending strength after one year of exposure is significantly higher at 180°F (82°C) for all lumber products tested. With longer exposures and higher temperatures, especially at higher humidity, the permanent loss in strength can exceed the "standard" temperature reduction factors and the NDS Commentary recommendation to avoid these applications is supported by the data.

However, material performance is only part of the design equation. Just as critical is the thermal load that might be expected in various building applications. This is discussed in the next section.

4. Discussion on Elevated Temperatures in Wooden Buildings

4.1 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 (MS) and Wisconsin (WI) and calculated the average number of hours that the recorded temperature exceeded a given value. Later studies have extended these results for Wisconsin (Winandy, et al., 2004, 2005). Figure 9 shows the summation of the yearly time above exceedence temperatures for the two locations for black roof shingles in a dry location. To get one year (8,760 hours) of continuous exposure at 55°C (131°F) would require 1,369 years for a black roofed house in Wisconsin and 33 years in Mississippi. To get one year of exposure at 66°C (150°F) would require almost 1,500 years in Mississippi. These data indicate that thermal degradation is not likely to be a problem in typical residential construction in the United States.

4.2 Elevated Temperatures in Industrial Buildings

If 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 longer periods in cases where industrial processes within the building involve heat. It is reasonable to assume that 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 specific types of industrial buildings, especially where heat sources are present.

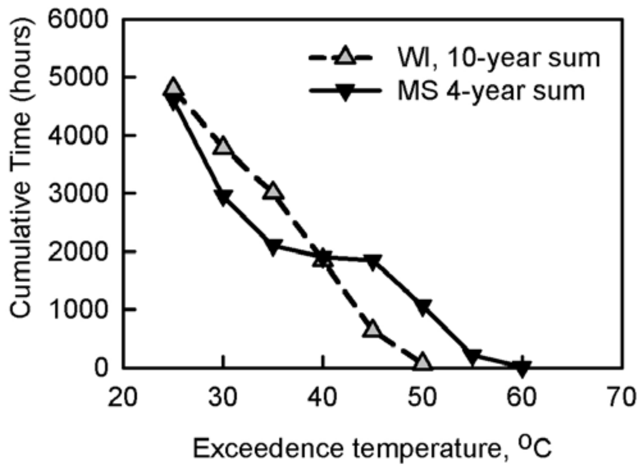

Figure 9. Amount of time that attic rafter temperatures exceeded indicated values

5. Conclusions

While design recommendations caution against the use of structural wood member in applications subject to prolonged heating at temperatures over 66°C (150ºF), historical data has been limited. This study considerably expands the available data, both for solid-sawn and composite lumber and for different humidity levels. The reader is cautioned, however, that over the next year a significant amount of additional data will become available. Until the study is complete, and analytical models relating change in properties to duration of exposure are available, data trends for individual products or species should not be over-interpreted.

The test results confirm that permanent losses occur in wood strength at prolonged exposure to temperature of 66°C (150ºF) and greater. The observed results at 66°C (150ºF) and the low humidity condition (4%EMC) are consistent with the NDS Commentary.

The review of data on elevated temperatures in wooden buildings suggests that long term exposure to temperatures equal to or greater than 66°C (150ºF) is not a concern in residential construction but may be and important consideration for certain industrial buildings where the industrial process creates a high temperature and humidity environment.

Although applications with such concurrent conditions are judged to be rare, it is recommended that the literature referenced in current North American design specifications be updated to reflect this new information.

6. References

AF&PA. 2005. National design specification for wood construction (NDS). American Forest & Paper Association, Washington, D.C.

ASTM. 2005. Annual Book of Standards. Vol. 4.10. American Society for Testing and Materials, West Conshohocken, PA.

FPL. 1999. Wood handbook: Wood as an engineering material. General Technical Report FPL–GTR–113. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr113/fplgtr113.htm

Green, D. W. and J. W. Evans. 2001. Flexural properties of structural lumber products after long-term exposure to 150°F and 75% relative humidity. *In* Proceedings, 35th International Particleboard/Composite Materials Symposium, April 3–5, 2001, Pullman, WA, p. 3–15.

Green, D.W., Evans, J.W., Craig, B.A. 2003. Durability of structural lumber products at high temperatures I: 66°C at 75% RH and 82°C at 30% RH. Wood and Fiber Science, 35(4):499-532.

Green, D.W., J.W. Evans, C.A. Hatfield, and P. J. Byrd. 2005. Durability of structural lumber products after exposure at 82°C and 80% relative humidity. Research Paper. FPL-RP-631 USDA Forest Service, Forest Products Laboratory, Madison, WI. http://www.fpl.fs.fed.us/documnts/fplrp/fpl_rp589.pdf

Heyer, O. C. 1963. Study of temperature in wood parts of houses throughout the United States. Research Note FPL–RN–012. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI.

MacLean, J. D. 1951. Rate of disintegration of wood under different heating conditions. Proceedings of American Wood Preservers' Association 47:155–168.

Meyer, R. W. and R. M. Kellogg (eds). 1982. Structural use of wood in adverse environments. The Society of Wood Science and Technology and Van Nostrand Reinhold Company, NY.

Winandy, J. E., H. M. Barnes, and C. A. Hatfield. 2000. Roof temperature histories in matched attics after four years in Mississippi and eight years in Wisconsin. Research Paper FPL–RP–589. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. http://www.fpl.fs.fed.us/documnts/fplrp/fplrp589.pdf

Winandy, J. E., H. M. Barnes, and R.H. Falk. 2004. Summer temperatures of roof assemblies using western red cedar, wood-thermoplastic composite, and fiberglass shingles. Forest Products Journal, 54(11):27-33.

Winandy, J. E., M. Grambsch, and C. A. Hatfield. 2005. Two-year Wisconsin thermal loads for roof assemblies and wood-plastic composite, and fiberglass shingles. Research Note FPL–RN–0301. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI.

In: Proceedings WTCE 2006 – 9th world conference on timber engineering; 2006 August 6-10; Portland, OR: Oregon State University. Available on CD.