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Thermal degradation of bending properties of structural wood and wood-based composites

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Abstract

Wood and wood-based composites are being used extensively in single-family residential dwellings. Therefore, it is important to categorize their response when exposed to elevated temperatures for a sustained period of time. In fire-resistant design for wood structures, the main goal is to ensure that enough structural integrity is maintained, during and after a fire, to prevent collapse and to maintain means of egress. Another goal is an ability to assess post-fire structural integrity and residual strength of an existing structure. The objectives of this study are: (a) to study the effect of temperature and exposure time on bending strength (MOR) and stiffness (MOE) of solid sawn lumber (SSL), laminated veneer lumber (LVL), oriented strand board (OSB) and plywood; and (b) to develop predictive relations between different temperatures and times of exposure and the thermal degradation of strength. A total of 1080 samples were tested in static bending under various heat treatments. The results indicated that exposure to elevated temperature caused significant degradation of bending strength and stiffness. A statistical regression-based model and a kinetics-based model were developed and evaluated for predicting the strength loss of wood and wood-based composites as a function of thermal exposure temperature and exposure time. The kinetics-based model fit the data better and predictions consistently matched the observed values, making the model preferred over the regression approach.

Keywords: bending strength; thermal degradation of strength; wood and wood-based composites.

Introduction

Single-family residential dwellings in the United States are typically timber-frame structures. In a timber-frame structure walls and partitions are framed with solid sawn lumber (SSL). Wood composites such as plywood or oriented strand board (OSB) are used as sheathing and are nailed to the framing. Owing to an increasing demand for quality and more uniform structural lumber, many engineered wood composites developed in recent years, such as laminated veneer lumber (LVL), are also used for framing.

Because the amount of wood-based composites in building construction is increasing, it is important to categorize their response when exposed to elevated temperatures (Grundahl 1992; White and Winandy 2006). The main objective of fire-resistant structural design is to ensure that enough structural integrity is maintained during a fire (Cramer and White 1997). Another objective of fire-resistant design deals with rehabilitation of a partially burnt structure. When encountering a fire-damaged building, engineers are faced with the challenge to evaluate and design a rehabilitation plan. Knowledge of residual strength of the damaged material is required to decide between reuse and replacement. Understanding and predicting material behavior after exposure to elevated temperatures is important in developing rehabilitation plans.

Fire-design is moving towards performance-based fire safety regulations and away from prescriptive codes, which are predominantly used in the United States. These codes empower the designer with the possibility of a wide array of solution strategies for providing fire safety (Bukowski and Babrauskas 1994) based on performance. However, the only way to predict performance is by simulation of the building behavior, using integrated data models. This requires a database of structural testing on various components of buildings which will be used in developing and validating fire endurance models and numerical models for simulation of post-fire building performance. Knowledge of the thermal degradation of materials represents one of the most crucial gaps in the development of fire endurance models (Cramer and White 1997).

Solid wood performs well during fire and maintains a substantial part of its load-bearing capacity and stability after exposure to fire owing to its low conductivity and formation of a char layer that prevents further burning. Several studies have modeled (White 1988; White and Nordheim 1992; AFPA 2003) and experimentally verified (White and Tran 1996; White 2006) the residual strength of solid wood based on the reduced cross-sectional area. The effect of temperature on various mechanical properties of lumber such as modulus of elasticity (MOE), modulus of rupture (MOR) and compressive strength (Young and Clancy 2001) has been well-studied and compiled by Green et al. (1999). The authors observed that strength of lumber decreases with increasing temperature. The variation of mechanical properties with temperature is linear to 150°C. Buchanan (2002) validated the findings of Green et al. (1999) and further developed a stress-strain relation at various temperatures by using com-

puter modeling of bending tests. Green and Evans (2008a) reported a 40% loss of MOR for Douglas-fir wood after exposure to 82°C for 30 months. Green and Evans (2008b) also characterized the immediate effect of temperature on the MOE of wood. However, no attempt was made to characterize the permanent change in MOE with exposure to temperature. Several studies (Bekhta and Niemz 2003; Kocaefe et al. 2008) have investigated the effect of heat treatment on mechanical properties of solid lumber. Many studies focused on the degradation of strength of lumber following treatment by fire retardants (MacLean 1953; Winandy and Lebow 1996). Winandy and Lebow (1996) studied degradation in strength using a kinetics-based approach and calculated an activation energy of 93 kJ mol^{-1} required for thermal degradation of wood below 200°C. Stamm (1956) observed the activation energy for thermal degradation of various softwoods to be between 104 and 121 kJ mol^{-1}. These studies report significant degradation in MOR of solid lumber as temperature increases, whereas MOE does not show significant degradation. All these studies either investigated the immediate change in MOR and MOE at the elevated temperature or the effect of heat treatment; limited attempts were made to characterize the irreversible changes in properties of lumber following exposure to elevated temperature.

The performance of wood composites, such as OSB and plywood, at elevated temperature is less studied. Their bending properties at ambient temperature are well studied and reviewed (Younquist 2000), but few studies at elevated temperature are found (Bekhta and Niemz 2003; Paul et al. 2006). A 15% reduction in the MOR of OSB was observed by Bekhta and Niemz (2003) at 100°C, whereas a 30% loss in strength was observed at 140°C, each after exposure of 1 h at that temperature followed by testing at that same temperature. There is a lack of literature on ambient properties of OSB and plywood after exposure to elevated temperature which quantifies the irreversible changes.

Winandy et al. (1988, 1991) investigated various failures of roofs constructed using fire retardant-treated (FRT) plywood. The authors identified thermal degradation of FRT plywood at service temperatures, which can go up to 80°C (APA 1989). In these tests, both FRT plywood and untreated controls were exposed to temperatures ranging from 0°C to 80°C. At 77°C, the MOR degrades, but degradation beyond 21 days of exposure is not significant. By contrast, the FRT plywood loses approximately half its bending strength when exposed to 77°C for 63 days. The rate of strength degradation depends on exposure temperature and generally decays at a constant rate for fixed exposure conditions (Winandy et al. 1991). The highest temperatures in these studies were 88°C; hence, more data are needed to study exposure at higher temperatures.

Sinha et al. (2010) studied the MOR degradation of OSB and plywood at nine different temperatures ranging from 50°C to 200°C for various exposure times and observed the increase in the strength degradation rates as the temperature increased. A kinetics-based analysis along with time-temperature superposition was used to develop a master curve which predicted degradation of strength with time on exposure at a reference temperature. The master curves showed that in terms of strength degradation after exposure to elevated temperature, OSB performed better than plywood although plywood had higher initial strength. Measurement and evaluation of mechanical properties of individual materials of a structural assembly, such as SSL, LVL, OSB and plywood are crucial. This study characterized the thermal degradation of strength and stiffness of these structural materials. In addition to OSB and plywood, which was studied in great detail in Sinha et al. (2010), this work studied the strength loss of solid lumber, LVL and two different thicknesses of OSB and plywood.

In summary, the post-fire residual strength of wood and wood-based composites should be studied. Specific objectives of this work were to: (a) investigate the changes in bending properties of wood and various wood-based composites as a result of exposure to elevated temperature for different exposure times; (b) develop prediction models using either multiple linear regressions or a kinetics-based approach; and (c) compare the prediction capabilities of the two models. Characterization of mechanical properties of these materials after exposure to elevated temperatures will probably lead to more informed decision-making between rehabilitation or retrofit for fire-damaged structures.

Materials and methods

Static third-point bending tests were conducted at 25°C on the wood and wood-based composites listed in Table 1 after exposure to elevated temperature. The specimen dimensions for various materials, along with their species, specific gravity and symbols are also listed

Table 1 List of materials, their respective symbols, species, specific gravity (SG), (coefficient of variation, COV for n=36) and specimen sizes to determine MOE and MOR.

Material	Symbols	Species	SG (COV%)	Specimen size (mm×mm)	Depth (mm)	Span-to-depth ratio (l/d)
Solid sawn lumber	SSL	Douglas-fir	0.487 (14.3)	25.4×25.4	25.4	12
Laminated veneer lumber	LVL	Douglas-fir	0.512 (3.1)	1016×89	38	24
Oriented strand board (half inch)	OSBH	Aspen	0.592 (4.0)	406×76	11.9	24
Oriented strand board (one inch)	OSBO	Aspen	0.563 (3.2)	762×76	22	24
Plywood (half inch)	PWH	Douglas-fir	0.553 (6.4)	406×76	11.2	24
Plywood (one inch)	PWO	Douglas-fir	0.468 (3.4)	762×76	24	24

in Table 1. The plywood and LVL were bonded with phenol formaldehyde (PF) resin, whereas the OSB panels were bonded with PMDI in the core and PF on face. The bending specimens were cut along the major axis (parallel to the fiber direction) of each panel according to ASTM D 3043-00 (ASTM 2006) and cut into the desired specimen size. Third-point bending tests (Figure 1) were conducted on an INSTRON 5582 universal testing machine. A constant span-to-depth ratio of 24 was maintained for all the materials as recommended by ASTM D3043, except SSL where the span to depth ratio was 14. The specimens were simply supported and loaded on the wide face by two equal, concentrated forces spaced equidistant between the supports. The specimens were loaded at a rate of 8 mm min^{-1} (0.315 in. min^{-1}) and continued until failure. The MOR and MOE were calculated by the equations in ASTM D198 (ASTM 2009). For each of the six different materials (SSL, LVL, OSBH, OSBO, PWH and PWO), 180 specimens were prepared. These specimens were randomly divided into five exposure time-temperature groups consisting of 36 specimens each. Hence, for the six different material types a total of 1080 bending tests were conducted.

The ambient residual bending MOR and MOE of the specimens were studied after exposure to elevated temperatures (100°C and 200°C) in comparison to controls (25°C). The elevated temperatures were chosen to correspond to pre-charring temperatures that might occur in a protected timber-frame structure. Moreover, the structural design code for timber construction (AFPA 2007) requires a structure to meet either 1 h or 2 h fire ratings. This implies that the structure will neither collapse nor allow the flame or higher temperature to pass through for the rating period of time. Hence, five different treatments were considered, namely, control (CTRL), 100°C-1 h, 100°C-2 h, 200°C-1 h and 200°C-2 h of exposure. The test program did not include characterization of the mechanical properties at elevated temperatures and did not include conditions that caused charring.

The samples were heat treated in a conventional oven. A separate oven run was scheduled for each treatment. The oven was pre-heated to the desired temperature, as monitored by internal as well as external thermocouples. Once the desired temperature was attained, the samples were inserted in the oven for the designated exposure time. The process was repeated for all the temperatures and all the materials. Once the specimens were taken out of the oven, they were allowed to cool to room temperature before testing. All specimens were conditioned to equilibrium moisture content (EMC) in a standard room maintained at 20°C and 65% relative humidity (RH), before exposure to temperature. The measured average EMCs were 6.7% for plywood, 4.9% for OSB, 12% for SSL and 5.3% for LVL. After exposure to elevated temperature, the specimens were cooled to room temperature for 24 h, but were not re-equilibrated with moisture. As a result, our strength changes could represent the combined effects of strength changes owing to moisture change and as a result of high temperatures. Slight reductions in moisture tend to increase strength (Gerhards 1982) of wood. Therefore, any observed degradation in strength was probably caused by elevated temperature exposure and not by moisture effects.

Comparison of bending properties between the treatments was conducted by means of analysis of variance (ANOVA). A regression model was constructed to characterize the effect of time and temperature on the measured responses (MOR and MOE). Assumptions of ANOVA and regression such as normality and homogeneity of variance were evaluated with Shapiro-Wilk test and Levene's test, respectively. The α level for test of significance in this study was set to 0.05. A goodness-of-fit χ^2 test was conducted to assess how well the datasets fit the proposed models.

Results and discussion

Static bending test

Table 2 summarizes the bending tests data for all materials and all treatments. The values of MOE and MOR and their respective standard deviations (Table 2) are comparable with those reported in the literature (MacLean 1953; Winandy et al. 1988; Winandy and Lebow 1996; Wang and Rao 1999; Biblis 2001; Green and Evans 2008a,b; Kocaefe et al. 2008). Statistical analysis (ANOVA) on the dataset for one material at a time indicates that there were highly significant differences in MOR for all the materials between treatments. Various studies have reported loss of MOR for SSL and wood-based composites after exposure to heat from 5% to 70% (MacLean 1953; Winandy and Lebow 1996; Paul et al. 2006; Green and Evans 2008a; Sinha et al. 2010) depending on the exposure time, temperature and material. In these results, exposure to 200°C for 2 h caused an 18% drop in bending strength for SSL compared with control samples. For all the materials, the drop in MOR ranged from 18% to

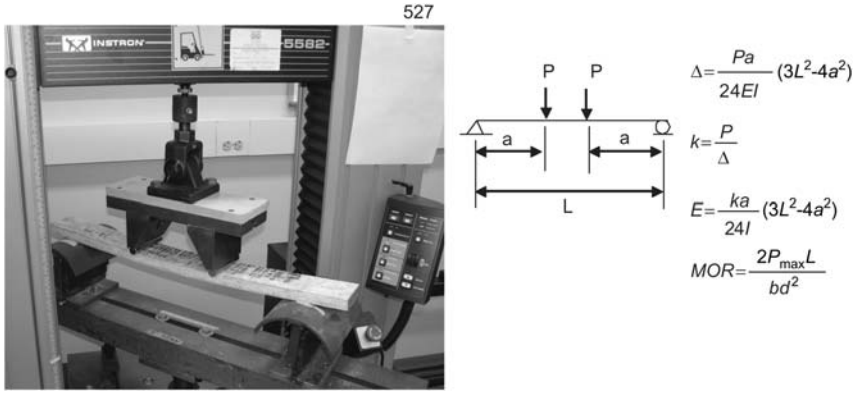

Figure 1 Static third-point bending test set-up. All specimens were tested in third-point bending ($a=L/3$). Modulus (E or MOE) and strength (σ or MOR) were calculated from the above equations where Δ, deflection at L/2; k, slope of the load-deflection curve in the linear region; P, applied load; P_{max}, maximum load; I, bending moment of inertia.

Table 2 Summary of average MOR and MOE along with their respective standard deviations (SD) of various materials after subjection to treatments at different elevated temperatures and exposure times. P-values are the probability calculated from the ANOVA F-test to determine whether means of MOR and MOE were different for different heat treatments within a material. For abbreviations see also Table 1.

	SSL				LVL				PWH				PWO				OSBH				OSBO			
Treatment	MOR (MPa)	SD	MOE (GPa)	SD	MOR (MPa)	SD	MOE (GPa)	SD	MOR (MPa)	SD	MOE (GPa)	SD	MOR (MPa)	SD	MOE (GPa)	SD	MOR (MPa)	SD	MOE (GPa)	SD	MOR (MPa)	SD	MOE (GPa)	SD
CTRL	96.86	16.30	12.47	1.97	63.38	9.93	12.85	1.26	46.30	12.50	10.01	2.08	35.84	7.26	6.98	1.04	32.37	6.79	6.86	1.27	31.47	4.66	8.19	1.39
100°C-1 h	98.83	17.14	12.64	2.08	52.22	8.35	11.32	0.81	44.87	12.22	9.41	3.12	28.90	6.75	6.71	1.03	29.24	7.95	6.44	1.38	31.33	3.44	8.44	0.61
100°C-2 h	101.61	17.77	12.74	1.71	57.11	9.20	13.59	0.93	41.13	11.93	9.75	2.00	31.30	7.76	6.72	1.10	33.08	5.82	6.88	1.31	31.86	5.00	8.27	0.79
200°C-1-1 h	83.93	21.07	12.32	2.14	50.55	8.65	13.18	1.10	31.40	10.07	9.18	2.32	20.86	5.56	6.25	1.06	26.48	6.28	6.87	1.40	27.13	4.48	7.77	0.88
200°C-2-2 h	78.93	20.57	12.21	2.19	42.03	6.84	12.33	0.71	18.26	6.17	6.34	2.11	18.21	4.77	6.12	0.94	21.31	6.27	6.30	1.73	23.08	9.40	7.26	2.26
P-value	<0.001		0.79		<0.001		<0.001		<0.001		<0.001		<0.001		0.002		<0.001		0.25		<0.001		0.002	

61% after exposure to 200°C for 2 h. The maximum drop in MOR was observed for plywood (PWH) which was approximately 61%. The minimum drop was observed for SSL (18% after exposure to 200°C for 2 h). The drop in MOR for OSBH, observed in this study, was 34% after 2 h of exposure at 200°C which is consistent with the findings of Sinha et al. (2010). Paul et al. (2006) heat treated strands before manufacturing OSB panels for 30 min at 220°C and observed a 50% drop in MOR. The difference to the quoted literature is partly a result of the difference in materials investigated and also of a difference in exposure temperature. Paul et al. (2006) heat treated the strands before manufacturing OSB at 220°C for 30 min, whereas in this study the OSB panels were heated at 200°C for a maximum of 2 h.

The MOE showed highly significant ($P < 0.05$, F-test ANOVA) differences between treatments for all the materials except for SSL and OSBH. This is consistent with the findings of MacLean (1953), Green and Evans (1994), Bekhta and Niemz (2003) and Kocaefe et al. (2008). The quoted authors observed no significant change in MOE after heat treatments for SSL. MacLean (1953) reported that MOE is the least affected mechanical property by heat treatment for solid lumber. Some wood composites in this study did show significant degradation in MOE after exposure to elevated temperatures. Paul et al. (2006) reported 10% loss in MOE of OSB (strands exposed to 220°C for 30 min), whereas in this study the drop in MOE was 8% (OSBH exposed to 200°C for 2 h). The MOE of plywood (11.2 mm thickness) dropped 37% after exposure to 200°C for 2 h. Winandy et al. (1988) reported a slight but non-significant drop in MOE after several days of exposure at 77°C. At a similar, but higher temperature of 100°C after 2 h of exposure, a drop of 3% in MOE was observed in the present study.

Analytical models

Two models, one based on statistical regression and the other based on kinetics analysis, were constructed to investigate the effect of elevated temperature and exposure time on bending properties of wood and wood-based composites. In this study the variables for regression analysis were time (t) and temperature of exposure (T). The multiple linear regression approach was applied:

$$MOR \text{ or } MOE = \beta_0 + \beta_1 t + \beta_2 T + \beta_3 Tt \quad (1)$$

where β_i are the regression coefficients associated with various terms, temperature (T in °C) and time of exposure (t in h). The effect of temperature on bending properties of wood is time dependent (Winandy and Lebow 1996). Hence, it becomes important to include an interaction between time and temperature in our model, which is present in the β_3 term.

Various kinetics-based models for thermal degradation of strength have been proposed (Millet and Gerhards 1972; Woo 1981; Winandy et al. 1991; Winandy and Lebow 1996; Branca and Di Blasi 2003; Sinha et al. 2010). Generally, models based on degradation kinetics are developed for MOR, because it is more susceptible to temperature changes

in wood-based materials than is MOE (MacLean 1953). The assumption in these models is that degradation kinetics follows an Arrhenius activation energy model. This assumption is twofold. First, at a constant temperature (T) the rate of change of bending properties is dependent on the time of exposure (t). Therefore, at a constant T:

$$d\sigma \propto t \text{ or } \frac{d\sigma}{dt} = -k(T). \quad (2)$$

This part is similar to linear regression, where at constant temperature (T) the bending property degrades linearly with time of exposure (t). Second, at a given time, the change in property follows an activation energy theory, which can be represented as:

$$k(T) = Ae^{-\frac{E_a}{RT}} \text{ or } \frac{d\sigma}{dt} = -Ae^{-\frac{E_a}{RT}}. \quad (3)$$

This equation is more commonly expressed in logarithmic form as:

$$\ln k(T) = \ln A - \frac{E_a}{RT}. \quad (4)$$

Here, E_a is activation energy, R is the gas constant, T is the absolute temperature (K) and A is a constant. This nonlinear dependence of rate with temperature is what distinguishes the kinetics-based model from the linear regression model. MOR is found by integrating over any applied thermal history, $T(t)$. In summary, first, the degradation is modeled to vary linearly with time at a constant temperature (T). The rate of degradation at a constant temperature is $k(T)$. Then, various rates of degradation for different temperatures are fitted with Eq. (3) based on Arrhenius activation theory. Sinha et al. (2010) applied Arrhenius activation energy theory to their strength degradation model and then used the principles of time-temperature superposition to construct master curves for the thermal degradation of strength for OSB and plywood at a given reference temperature. The methodology of kinetics modeling is explained in great detail in Winandy and Lebow (1996) and Sinha et al. (2010) where the reader is directed for more background.

Regression model The linear regression models relating MOR and MOE with temperature and time of exposure for all materials are presented in Table 3. A total of 36 samples were tested for each heat treatment for each material. The regression was based on 30 tests after each heat treatment and the remaining were used to validate the regression models. The results indicated that bending parameters such as MOR and MOE decreased as the exposure time increased at a given temperature. Increasing the exposure temperature also caused a decrease in MOR and MOE. Their relations could be represented by a linear regression formula (Table 3). The F statistic expresses how well the model represents the data. An F-value of 2.66 or greater (Ramsey and Schafer 2002) is a good fit for the dataset because it provides a corresponding P-value of 0.05 or less. By contrast, an F-value less than 2.66 implies that the model poorly represents the data. All the relations studied were significant ($F > 2.66$; $P < 0.05$) except for MOE for SSL (marked with *). As explained in the previous section, a change in temperature did not have much effect on MOE of SSL. This was also evident from the non-significance of the regression equation.

The R^2 for the linear regression relations were generally weak particularly for MOE. The low R^2 values could be owing to many reasons ($R^2 = 1$ is ideal for linear fits). Wood as an engineering material has highly variable properties within a species and within a tree also. This inherently induces variation in the tested parameters such as MOR and MOE and poses a challenge for any regression model. The presence of knots, e.g., can cause variations. Similarly, for composites such as plywood and OSB, manufacturing processes could cause variability in the material properties. Wang and Rao (1999) analyzed MOE and MOR of FRT plywood by a regression model to establish a relation between strength loss

Table 3 Regression models for various materials depicting MOR and MOE as a function of time of exposure (t), temperature of exposure (T) and their interaction. R^2- and F-values of respective models are presented (*non-significant). For abbreviations see Table 1.

Material	Analytical model for calculation of MOR (MPa) and MOE (GPa)	R^2	F-values
SSL	MOR=79+0.07T+22.2t-0.1489Tt	0.170	12.24
	MOE=11.89+0.0034T+0.69t-0.0043Tt	0.007	0.46*
LVL	MOR=53.79+0.10T+9.21t-0.08Tt	0.374	35.09
	MOE=9.45+0.02T+2.70t-0.02Tt	0.159	11.06
PWH	MOR=36.75+0.05T+13.63t-0.14Tt	0.474	52.96
	MOE=6.91+0.0249T+3.12t-0.0295Tt	0.226	16.06
PWO	MOR=31.16-0.0.98T+6.6136t-0.0456Tt	0.510	61.15
	MOE=6.875-0.0024T+0.224t-0.0018Tt	0.089	5.77
OSBH	MOR=22.26+0.0494T+10.68t-0.0805Tt	0.280	40.35
	MOE=6.29+0.0096T+1.2811t-0.0112Tt	0.060	7.42
OSBO	MOR=24.88+0.0364T+7.8765t-0.062Tt	0.255	19.95
	MOE=7.56+0.0096T+0.915t-0.012Tt	0.080	5.11

and time of exposure at one temperature. The R^2 values of Wang and Rao (1999) were higher than those of this study. This difference can be attributed to the fact that the model proposed here also takes into account both exposure temperature and time, whereas the one proposed by Wang and Rao (1999) only regressed time of exposure at one temperature. With a wide array of exposure times at one temperature the data can explain the variability better at that temperature. The R^2 values are comparable with other regression models proposed in the literature for MOR of wood (Winandy and Lebow 1996; Brancheriau and Baillères 2003; Ikonen et al. 2008) and other parameters related to wood, such as knot diameter (Vestol and Hoibo 2001).

Kinetics-based model Degradation of composites after exposure to elevated temperature follows a two-phase regime (Sinha et al. 2010). The first phase is below 100°C and the second phase being degradation after exposure to 100°C and above. In general, wood does not degrade in strength after exposure to 100°C (Green et al. 1999). However, there is ample research (Winandy et al. 1988, 1991; Wang and Rao 1999) that suggests that wood composites, such as plywood and OSB, do degrade in this temperature region, however, very slowly. This could be owing to complex interactions between wood and resin in a composite, where resin degradation entails strength losses. Moreover, as the material is exposed to 100°C, the moisture from the material is driven out, which might increase the strength. Therefore, the combined effects of resin degradation and moisture change are active. At longer exposure times the former exceeds the latter, resulting in strength loss. Winandy et al. (1988, 1991) did observe strength loss in plywood exposed to temperatures below 100°C, only after an exposure time of a few months. The second regime of degradation of bending strength is at exposure above 100°C. After exposure to temperature higher than 100°C, both wood and wood composites lose strength (Green et al. 1999; Buchanan 2002; Sinha et al. 2010).

Wood (SSL) does not suffer strength loss after exposure to 100°C (Table 4). At 100°C, the rate of degradation (k) was positive for both varieties of plywood (PWH and PWO) and LVL (Table 4). However, for OSBH and OSBO along with SSL, the rate of degradation was negative or the MOR increased. We observed positive degradation rates below 100°C (Table 4) for plywood (PWH and PWO) and LVL. By contrast, all the materials showed positive rates of degradation in strength when exposed to 200°C. The temperature of 200°C is high enough to counter all the moisture effects and moreover causes both wood and resin to degrade. As a result, all the materials exhibited strength losses (Table 4).

The rate of degradation $k(T)$ was obtained from the change in strength per unit time $k(T) = \frac{\Delta\sigma}{\Delta t}$, and is presented in Table 4. From these calculated $k(T)$ values, the Arrhenius parameter E_a/R was calculated by plotting ln $k(T)$ versus $1/T$ (K^{-1}). In Figure 2, ln $k(t)$ is plotted versus $1/T$ (K^{-1}) for all materials. All experimental results with positive degradation rates in the study (black symbols) are plotted, which are materials treated at 200°C and LVL, PWH and PWO at 100°C. Data from Sinha et al. (2010) for OSBH and PWH and data from Winandy and Lebow (1996) for SSL (other softwood species, Southern yellow pine) are overlaid on the graph at various temperatures for comparison (open symbols). For materials with a positive rate of degradation, the Arrhenius parameter is the slope of the fits to the Arrhenius equation [Eq. (4)]. For materials with negative rate of MOR degradation (SSL, OSBH and OSBO) the Arrhenius parameter (E_a/R) was calculated based on data available in the literature. Data from Winandy and Lebow (1996) and Sinha et al. (2010) were used to calculate the rate of degradation as well as the Arrhenius parameter for SSL and OSBH, respectively, according to the Arrhenius activation energy model. No study involving thermal degradation of OSB with a thickness in the range of 20–24 mm was found; hence, the second stage of the kinetics model for OSBO was not calculated. Table 4 summarizes the kinetics-based modeling results, i.e., $k(T)$ and E_a/R, along with their standard errors. The rate of degradation for OSBH and PWH at 200°C is consistent with the rate of degradation observed by Sinha et al. (2010). Exposure times for the current study were 1 h or 2 h at each temperature, whereas it ranged from 1 to 8 h for Sinha et al. (2010). This can be the reason for slight variations in the degradation rates. Winandy and Lebow (1996) proposed kinetics-based degradation models for solid lumber. Their exposure times ranged from 200 to 600 days, which was long enough to detect some degradation in strength after exposure to low temperatures of 65°C or 82°C.

Table 4 Kinetics-based model for degradation of MOR with temperature and exposure time for all the materials (abbreviations explained in Table 1). The intercept and the strength degradation rate $k(T)$ along with their standard errors (SE) is presented. The Arrhenius parameter (E_a/R) is the slope of ln $k(T)$ versus $1/T$ plot (Figure 2).

Material	T (Kelvin)	Intercept	SE	$k(T)$	SE	E_a/R
SSL	373	96.73	2.59	–		*728.61*
	473	95.54	2.95	8.97	2.29	
LVL	373	60.71	1.51	3.13	1.16	2163.30
	473	62.66	1.31	10.68	1.01	
PWH	373	46.69	1.59	2.59	1.43	2981.70
	473	46.09	1.50	14.02	1.66	
PWO	373	34.28	1.15	2.27	0.89	2393.30
	473	33.79	1.01	8.82	0.78	
OSBH	373	31.21	1.08	–		*7892.90*
	473	32.25	0.98	5.53	0.76	
OSBO	373	31.36	0.67	–		–
	473	31.42	0.99	4.20	0.77	

–, refers to negative rate of strength degradation.
The italicized numbers means that the second step of the kinetics modeling is conducted using data available in the literature.

Validation and comparisons of models A total of 36 tests per material per heat treatment were conducted. Thirty of these tests were used to build the models, i.e., to obtain the parameters β_i (Table 3) for the regression-based model and $k(t)$ (Table 4) for the kinetics-based model. The remain-

ing six tests for elevated temperature (100°C and 200°C) were used to validate the models, hence, a total of 24 data points were available to validate the models. A goodness-of-fit chi-square (χ^2) statistic as the sum of squares of difference between the observed and expected results normalized over expected results was calculated for each model and are presented in Table 5. The formula for χ^2 for n data points is as follows:

$$\chi^2 = \sum_{i=1}^{n} (E_i\text{-}O_i)^2/E_i. \quad (5)$$

The relations between MOR degradation, temperature and time of exposure for PWH and OSBH were also validated based on data from Sinha et al. (2010) and χ^2 was calculated (Table 5). For direct comparison, the degrees of freedom were kept constant by selecting the same number of data points (24) from Sinha et al. (2010). The critical χ^2-value for a probability level of 0.05 and 24 data points was 35 (Ramsey and Schafer 2002). A χ^2-value of 35 or less indicated a good fit. Moreover, the lower the χ^2-value, the better the fit.

It was evident from the χ^2-values (Table 5) that both the proposed models, i.e., regression-based and kinetics-based models provided good fits to the independent datasets used for validation, except for the regression-based model for LVL ($\chi^2 = 97.9$). Comparing the χ^2 values for kinetics and regression models, all the values were lower for the kinetics model than for the regression models, except for plywood. The regression-based model consistently predicted the MOE and MOR values for exposure temperature of 100°C, but it tended to under-predict the MOE and MOR values for plywood after exposure to 200°C. However, the predictions were consistent with observed values for OSB at 200°C temperature exposure. For example, the regression models predicted the MOR for plywood (11.2 mm thickness) to be 25% lower than actual value, whereas for OSB the predictions were 5% lower than the observed values. The predictions with the kinetics-based model were more consistent with the observed values. The predictions were within 0.1–12% of the observed values. The lower χ^2-values suggest that the kinetics-based model should be preferred over the regression models.

Table 5 Goodness-of-fit chi-square statistic for regression and kinetics-based models for strength degradation.

Material	Model type	
	Regression	Kinetics
SSL	32.2	26.1
LVL	97.9	32.5
PWH	24.7	26.8
Sinha et al. (2010)	33.1	33.8
PWO	10.9	14.4
OSBH	20.7	18.8
Sinha et al. (2010)	21.9	14.2
OSBO	17.7	16.8

Conclusions

After exposure to elevated temperature, the ambient MOR of wood and wood-based composites, such as plywood, OSB and LVL were lower than that of the control specimens. Exposure to elevated temperature caused degradation in strength for all tested materials. The MOE was also affected by exposure to elevated temperature for the wood-based composites, but no degradation in MOE was observed for SSL after exposure to these elevated temperatures.

A statistical regression-based model incorporating the effects of temperature, time of exposure, and interaction between the two was developed. A model based on the

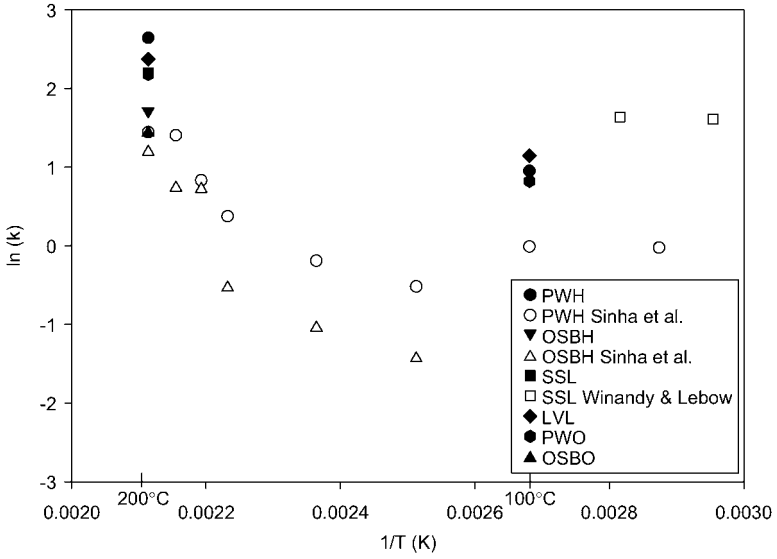

Figure 2 ln (k) versus inverse of absolute temperature plot for all the materials. Data from Winandy and Lebow (1996) and Sinha et al. (2010) are overlaid with the current data.

assumption that strength degradation follows first-order kinetics was also developed and this model relies on the same data. These two models were evaluated for predicting the strength loss of wood and wood-based composites as a function of thermal exposure temperature and time. The kinetics-based model was better than the regression-based approach. The kinetics-based models fit the data better and the prediction consistently matched the observed values. The predictive models can serve as a tool to provide engineers with more comprehensive information on thermal degradation of structural wood and composites, and will help guide the rehabilitation and retrofit of fire-damaged structures. The measured $k(T)$ and the Arrhenius parameters here can be used to predict the degradation in strength of these structural wood composites at various temperatures and further used to calibrate new models.

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