

The Effect of Elevated Temperature on Bending Properties of Normal Wood inside Chinese Larch Wood during Fire Events

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Timber is used extensively in construction. Therefore, it is important to characterize the response of wood when exposed to elevated temperatures for a sustained period of time. In fire-resistant designs for timber structures, the main goal is to assess in-fire and post-fire structural integrity. The objectives of this study were to study the immediate effect and the residual effect of temperature on bending properties for Chinese larch (*Larix gmelinii*). A total of 72 specimens were subjected to a static 3-point bending test at various temperatures. The results indicated that both the bending strength (BS) and modulus of elasticity (MOE) decreased nonlinearly as the temperature was increased from 20 to 225 °C for the immediate effect test. For the residual effect test, both the BS and MOE first increased non-linearly and then decreased with increasing temperature. There were significant differences between the immediate effect test and the residual effect test for both BS and MOE. The bending properties in the residual effect test were larger than those in the immediate effect test.

Keywords: Temperature; Fire resistant; Immediate effect; Residual effect; Bending properties; Larch

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INTRODUCTION

Timber is a favored engineered material that has been widely used in construction (Forest Products Laboratory 1999). Undeniably, it is also a combustible construction material. Timber, after exposure to fire, exhibits charring from the surface during the relevant time of fire exposure. As a viscoelastic material, the mechanical properties of wood are affected by temperature (Forest Products Laboratory 1999). The temperature effect of normal wood, including the pyrolysis zone, governs the load-bearing capacity of timber elements in the event of a fire (SP Technical Research Institute of Sweden 2010). For evaluation of the structural condition of timber at any time, or structural fire design to ensure that enough structural integrity is maintained during a fire (Cramer and White 1997), the effect of elevated temperatures on strength and stiffness parameters of timber must be taken into account. Therefore, knowledge of the temperature-dependent reduction behavior of strength and stiffness properties is an important precondition for determination of the resistance of normal wood in a fire (Cramer and White 1997).

The effect of temperature on wood properties has been well studied. MacLean (1945, 1953, 1954) conducted some of the most comprehensive studies of wood subjected to various environmental conditions. Based on these studies, the Wood Handbook (Forest Products Laboratory 1999) presented the reversible and irreversible

effects of temperature on the mechanical properties of wood. Gerhards (1982) summarized the relevant earlier studies reported in the literature on the immediate effects of moisture content and temperature on several mechanical properties of clear wood. These studies focused just on the uni-effect of temperature or moisture content on the mechanical properties of wood and primarily dealt with the reversible effects on clear wood. However, when mass transfer occurs during the exposure of timber to temperature (Eriksson *et al.* 2006), the immediate effects at that condition will include reversible and irreversible portions. Related studies on the permanent effect in wood were the subject of ongoing study. Some researchers have reported the permanent property losses of structural wood induced by different temperature conditions (Glos 1992; Young and Clancy 2001; Green *et al.* 2003; 2005; Jurgen 2005; Green and Evans 2008). There have been some publications dealing with the influence of temperature on mechanical properties of wood during high-temperature drying (Hillis 1984; Zhou and Smith 1991; Sehlstedt Persson 1995; Terziev and Daniel 2002; Thiam *et al.* 2002; Bekhta and Niemz 2003; Muller *et al.* 2003; Poncsak *et al.* 2006; Fruhwald 2007). Literature on heat treatment of wood also has considered the influence of temperature on some mechanical properties (Kubojima *et al.* 2000; Ponscak 2006; Kocaefe 2008a,b; Mburu 2008; Korkut and Budakci 2009; Bekir and Ibrahim 2013). Although it has been observed that the strength of wood decreases as the temperature increases, these test conditions are greatly different from the temperature experience of normal wood below the charring layer of timber in fire. Limited attempts have been made to characterize the effect of elevated temperature on the mechanical properties of wood while simulating fire conditions. Therefore, such knowledge is very important from a practical point of view for building structural response models of wooden elements in a fire.

The objective of the present study was to determine the immediate and residual effects of temperature on the bending properties and the thermo-mechanical behavior of Chinese larch wood beams at elevated temperatures, simulating the different locations of normal wood inside burning elements.

EXPERIMENTAL

Materials

Chinese larch wood was selected as the specimen object in the study because it is traditionally used in ancient buildings and has the potential to be developed for use in modern timber construction. Small, clear specimens were cut from wood logs in the orthotropic direction, with dimensions of 20 mm × 20 mm × 300 mm. All specimens were initially equilibrated at room temperature (20 °C) and 65% relative humidity. The test specimens were sorted by density. To eliminate the effect of specimen itself on the bending properties, all the specimens were selected as close near in density.

Methods

To systematically investigate the changes in bending properties of wood as a result of exposure to elevated temperature, the immediate strength and residual strength after the exposure time for each temperature level were tested. The immediate strength was measured as the following: the specimen was taken immediately out for testing after the exposure time; the immediate strength test was conducted inside a high-temperature controlled chamber, which was preheated to the test condition. To measure residual

strength, the specimen was tested when cooled to room temperature for 24 h after the exposure time. The cooled specimens were not re-equilibrated. Table 1 gives the details of specimen groups for both the immediate strength and residual strength test under various temperatures.

Table 1. Specimen Groups

Temperature (°C)	Specimens	Density (g/cm ³)		Coefficient of variance (%)	
		Immediate	Residual	Immediate	Residual
20	8	0.688		4.70	
75	16	0.675	0.673	4.89	4.32
125	16	0.698	0.701	1.66	4.93
175	16	0.699	0.670	3.87	4.59
225	16	0.695	0.715	2.24	6.28

The test specimens were divided into nine test groups for five temperature levels, *i.e.*, 20, 75, 125, 175, and 225 °C. All specimens were placed into a chamber for conditioning to the various temperature levels. The chamber was pre-heated to the desired temperature, as monitored by internal and external thermocouples. Once the desired temperature was attained, the specimens were inserted in the chamber for the designated heating time. The heating time was obtained when the core temperature measured by a temperature sensor in the core of a control specimen arrived nearest to the target temperature. The process was repeated for all temperatures and all specimens. Exposure time was calculated from the moment when the temperature of the specimen reached the targeted temperature. The exposure time was 2 h.

Static three-point bending tests were conducted to determine the bending properties. The bending tests (Fig. 1) were conducted on an INSTRON 5582 Universal Testing Machine (USA) with a temperature-controlled chamber. The load bases were placed inside the chamber. A constant span-to-depth ratio of 12 was maintained for all the specimens, as recommended by GB/T 1936.1 (2009). The specimens were simply supported and loaded by a concentrated force in the middle span. The specimens were loaded at a constant rate of 7 mm/min, which continued until failure. The bending strength (BS) and modulus of elasticity (MOE) were calculated using the equations in GB/T 1936.1 (2009) and GB/T 1936.2 (2009).



Fig. 1. Test setup for bending strength

Statistical Analysis

The graphical analysis was conducted with the Origin 9 software. The statistical significance analysis between the immediate effect and the residual effect at different temperatures was performed using the SPSS 16.0 software. The multiple comparisons for BS and MOE under different temperatures were calculated by LSD and Tamhane methods with the ANOVA test results using SPSS 19.0, respectively (Yu and He 2006). The significance level was set to 0.05.

RESULTS AND DISCUSSION

The Immediate Effect

Load-displacement curves obtained from the bending test under various temperatures are shown in Fig. 2. Both the bending strength (BS) and modulus of elasticity (MOE) decreased linearly as the temperature increased from 20 to 75 °C. The BS and MOE decreased by 34.9% and 27.0%, respectively. Similar results have been obtained in previous studies on the effect of temperature on the bending performance of wood-based panels (Zhou *et al.* 2012). With temperature increasing from 75 to 175 °C, there was no significant change for either the BS or MOE (Yu and He 2006). However, the findings of Bekhta *et al.* (2003) showed a relationship between BS and temperature that was monotonic, linearly decreasing with increasing temperature from 20 to 140 °C for spruce wood. The BS and MOE were 0.339 and 0.456 times those at 20 °C, respectively. The major reasons for these observations on the bending performance of Chinese larch are the temperature and the moisture content.

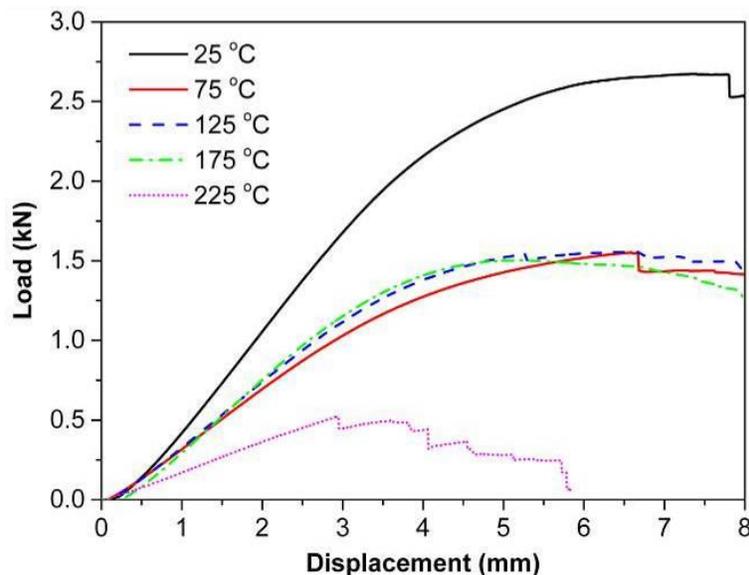


Fig. 2. Typical load-displacement curves under different temperature for the immediate effect

As previously reported (Gerhards 1982; Green *et al.* 2003; 2005), the temperature and the moisture content are important factors affecting the mechanical properties of wood. Increasing temperature causes a decrease in the mechanical properties, while those properties increase with decreasing moisture content. The softening temperature of hemicelluloses and lignin is within the range of 30 to 70 °C with a moisture content of

approximately 10% (Kelley *et al.* 1987). The degradation of some elements of wood results in mass loss and a decrease in the mechanical properties when the temperature is greater than 100 °C. The temperature effects caused by this degradation are irreversible.

Results of the ANOVA and multiple comparison statistics analysis for the temperature effect are shown in Table 2. There were significant differences between 20 and 75 °C, 20 and 125 °C, 20 and 175 °C, 20 and 225 °C, and 75 and 225 °C, 125 and 225 °C, and 175 and 225 °C for both the BS and MOE, with the $p < 0.05$. However, the p -values for both the BS and MOE between 75 and 125 °C, 75 and 175 °C, and 125 and 175 °C were greater than 0.05, which indicated that the effects of temperature for these pairs were not statistically significant. Besides, the findings of Zhou *et al.* (2012) showed that the displacement at the maximum load point significantly increased with the increasing temperature.

Table 2. Statistical Analysis of the Immediate Effect of Temperature on BS and MOE for Chinese Larch

Property	Significance									
	20 °C vs. 75 °C	20 °C vs. 125 °C	20 °C vs. 175 °C	20 °C vs. 225 °C	75 °C vs. 125 °C	75 °C vs. 175 °C	75 °C vs. 225 °C	125 °C vs. 175 °C	125 °C vs. 225 °C	175 °C vs. 225 °C
BS	**	**	**	**	0.574	0.755	**	0.805	**	**
MOE	**	*	*	**	0.440	0.421	**	0.974	**	**

The multiple comparisons for BS and MOE under different temperatures were calculated by LSD and Tamhane methods with the ANOVA test results using SPSS 19.0, respectively. N=8 for each group. The symbols * and ** represent p -values less than 0.01 and 0.001, respectively.

The Residual Effect

Load-displacement curves obtained from the bending test under different temperatures are shown in Fig. 3.

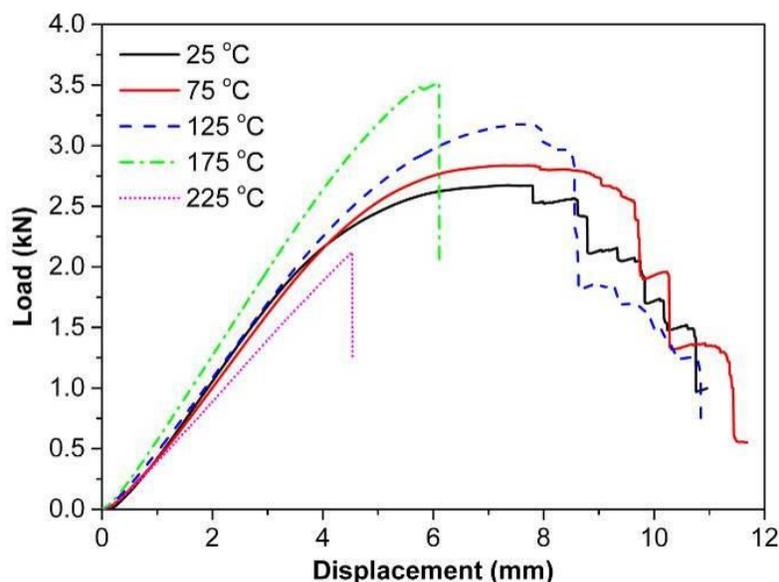


Fig. 3. Typical load-displacement curves under different temperature for the residual effect

Both the BS and MOE first increased non-linearly, and then decreased with increasing temperature. As the temperature was increased from 20 to 75, 125, 175, and 225 °C, the BS was 1.086, 1.295, 1.121, and 0.706 times that at 20 °C, while the MOE was 0.962, 1.162, 1.022, and 0.880 times, respectively.

Results of the ANOVA and multiple comparison statistics analysis for the temperature effect are shown in Table 3. The p-values for both the BS and MOE between 20 °C and 75 °C, 20 °C and 175 °C, 75 °C and 125 °C, 75 °C and 175 °C, and 125 °C and 175 °C were more than 0.05, which indicates that the effects of different temperature for these pairs were not statistically significant. There were significant differences between 125 °C and 225 °C, and 175 °C and 225 °C for both BS and MOE; then, 20 °C and 125 °C, 75 °C and 225 °C only for BS, with the $p < 0.05$.

Table 3. Statistical Analysis of the Residual Effect of Temperature on BS and MOE for Chinese Larch

Property	Significance									
	20 °C vs. 75 °C	20 °C vs. 125 °C	20 °C vs. 175 °C	20 °C vs. 225 °C	75 °C vs. 125 °C	75 °C vs. 175 °C	75 °C vs. 225 °C	125 °C vs. 175 °C	125 °C vs. 225 °C	175 °C vs. 225 °C
BS	0.411	*	0.251	*	0.05	0.742	*	0.100	**	**
MOE	0.646	0.056	0.790	0.153	0.019	0.469	0.328	0.097	*	*

The multiple comparisons for BS and MOE under different temperature were calculated by LSD and Tamhane methods with the ANOVA test results using SPSS 19.0, respectively. N=8 for each group. The symbols * and ** represent p-values less than 0.01 and 0.001, respectively.

The Immediate vs. Residual Effect

Normally, two methods are used to assess the bending properties of wooden beams in a fire. One is the immediate effect test method, and the other is the residual effect test method. Although both the immediate effect and the residual effect have been investigated by many researchers (Glos 1992; Young and Clancy 2001; Green *et al.* 2003; 2005; Jurgen 2005; Eriksson 2006; Green and Evans 2008), there has been no research on the differences between the immediate effect and the residual effect.

Comparisons of both the bending strength and modulus of elasticity between the immediate effect test and the residual effect test are shown in Figs. 4 and 5 (Table 4). There are significant differences between the immediate effect test and the residual effect test for both BS and MOE (Table 5), as determined by the ANOVA test, with $p < 0.05$.

Table 4. The Mean Value and Coefficient of Variances for BS and MOE Under Various Temperatures

Temperature (°C)	BS (MPa)		MOE (GPa)	
	Immediate	Residual	Immediate	Residual
20	108.51 (17.5%)		11.99 (20.2%)	
75	70.66 (9.6%)	117.89 (11.3%)	8.75 (17.7%)	11.53 (19.7%)
125	67.65 (10.0%)	140.53 (11.9%)	9.35 (10.9%)	13.93 (7.1%)
175	68.99 (11.7%)	121.63 (24.9%)	9.37 (14.3%)	12.26 (16.7%)
225	36.74 (25.2%)	76.63 (48.8%)	5.46 (16.4%)	10.55 (26.3%)

Table 5. Significant Differences Analysis Between the Immediate Effect and the Residual Effect Under Various Temperatures

Property	Significance			
	75 °C	125 °C	175 °C	225 °C
BS	**	**	**	**
MOE	**	**	**	**

The multiple comparisons between the immediate effect and the residual effect under different temperature were calculated by LSD and Tamhane methods with the ANOVA test results using SPSS 19.0, respectively. N=8 for each group. The symbols * and ** represent p-values less than 0.01 and 0.001, respectively.

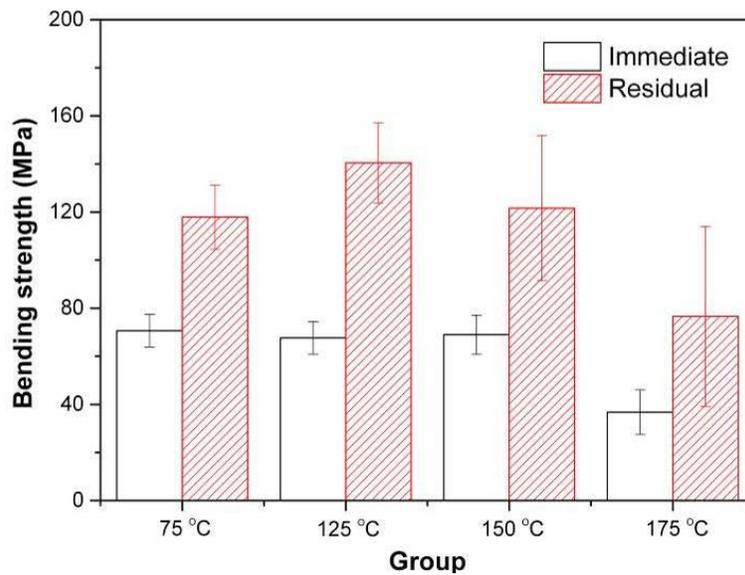


Fig. 4. Comparison of bending strength between the immediate effect and the residual effect under various temperatures. Data presented as the mean ± standard deviation.

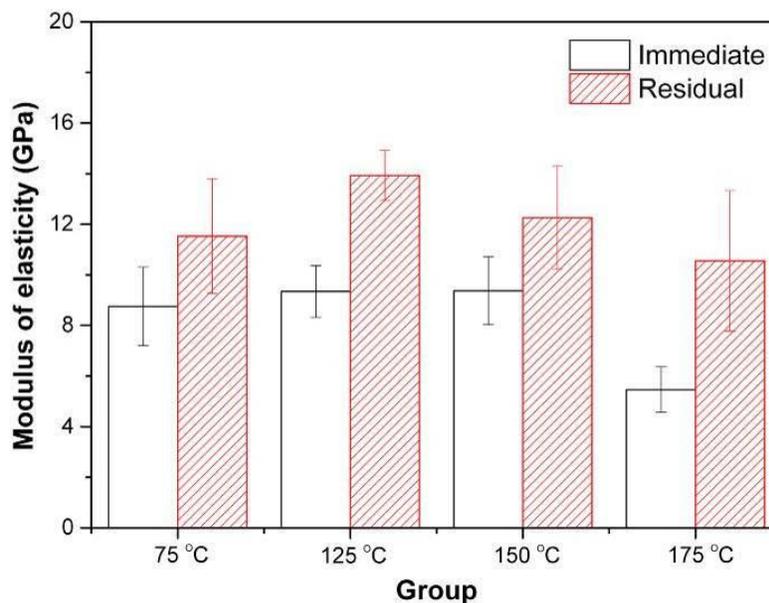


Fig. 5. Comparison of the modulus of elasticity between the immediate effect and the residual effect under various temperatures. Data presented as the mean ± standard deviation.

The bending properties of the residual effect test were larger than those of the immediate effect test. The findings of Eriksson *et al.* (2006) show that the immediate effect includes reversible and irreversible parts. For the residual effect test, the reversible part of the bending properties caused by the high temperature will be the norm. Comparing the immediate effect test, the BS of the residual effect test was 1.668, 2.077, 1.763, and 2.086 times at 20 °C for 75, 125, 175, and 225 °C, while the MOE of the residual effect test was 1.318, 1.490, 1.308, and 1.932 times that at 20 °C for 75, 125, 175, and 225 °C, respectively.

CONCLUSIONS

1. This work determined the immediate and irreversible effects of temperature on the bending properties and the thermo-mechanical behavior of Chinese larch wood beam at elevated temperatures.
2. For the immediate effect test, both the BS and MOE decreased non-linearly as the temperature increased from 20 to 225 °C.
3. Both the BS and MOE first increased non-linearly and then decreased with increasing temperature during the residual effect test.
4. There were significant differences ($p < 0.05$) between the immediate effect test and the residual effect test for both BS and MOE. The bending properties of the residual effect test were larger than those of the immediate effect test.

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