

AN EXPERIMENTAL STUDY ON FLEXURAL BEHAVIOR OF GLULAM BEAMS MADE OUT OF THERMALLY TREATED FAST-GROWING POPLAR LAMINAE

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Abstract. In this study, to improve the structural applications of glued laminated timber (glulam) in high RH environment according to its relatively lower MOE, fast-growing poplar laminae with a thickness of 35 mm were thermally treated at 200°C for 3.5 h. The effects of thermal treatment and RH in the surrounding environment on laminae strength class was conducted. Afterward, 12 full-scale same-grade composition glulam beams made out of untreated and thermally treated poplar laminae were prepared. The four-point bending tests were conducted to reveal the effects of laminae thermal treatment and RH in the surrounding environment on flexural properties of glulam beams with a span-depth ratio of 18. The results showed that the strength class of fast-growing poplar laminae was negatively related to RH in the surrounding condition, and thermal treatment can contribute to the increase in strength class. In 90% RH, strength class increased from untreated laminae M_E7 to the heat-treated laminae M_E10 , according to the China standard. The relationship between bending properties of glulam beams and RH in the surrounding environment was negatively correlated, as well as thermal treatment, whereas MOE was improved significantly after thermally pretreated, especially in high RH. In 90% RH, MOE of glulam beams made of thermally pretreated laminae was 29.57% higher than the untreated beams with an MOR reduction of 8.82%. The results of characteristic load–deformation curves, characteristic load–strain curves, average extreme fiber strain, and the failure mode can support each other in this study. Industrial thermal treatment technology to laminae improved the MOE of glulam beams significantly in high RH with a reduction in MOR, and glulam beam made out of thermally treated fast-growing poplar laminae can be used in construction, but need checking in MOR or be used for a limited range of structural elements.

Keywords: Full-scale glulam beam, fast-growing poplar lamina, industrial thermal pretreatment, RH, flexural properties.

INTRODUCTION

Wood has been widely used as building material worldwide according to its mechanical properties and environment-adjusted nature (Yue et al 2017, 2018). However, wood material is severely restricted throughout outdoor conditions on account of its poor decay resistance against decay and insect attack (Yang et al 2012), dimensional stability (Sjödin and Johansson 2007), and the reduction in mechanical properties caused by a high RH in the surrounding environment (Mitchell 1988).

Wood preservatives are widely used to improve the decay resistance. Copper-based preservatives have been extensively used according the relatively low toxicity (Goodell et al 2007; Gaspar et al 2010). The effective ingredient in waterborne preservatives is vulnerable to leaching during service, shows decreased durability with time (Zhang and Kamdem 2000), and leads to pollution. The fixation of active ingredients in treated wood are studied many times, and some measures were proved to be effective (Humar et al 2006; Lin et al 2009). However, the fixation of effective ingredients of preservatives in treated wood is too complicated, not easy to control, and has not been completely resolved.

The RH changes caused moisture gradients in timber, inducing internal stresses that generated uneven shrinkage and swelling. The internal stresses can lead to cracks, which were usual in massive timber structures. It was reported that the capacity of notched beams, curved beams, and prismatic glulam loaded perpendicular to the grain can be negatively affected by the moisture gradients according to the cracks (Aicher et al 1998; Gustafsson et al 1998; Jönsson 2004; Osmannezhad et al 2014; Mirzaei et al 2017). If the position of the timber was fixed, the internal stresses may cause serious damage to the structure as a whole (Sjödin and Johansson 2007). Therefore, there was an urgent requirement for the reduction in internal stress of structural timber element, especially for fast-growing tree species with low density and loose texture under a frequent high–low variation in moisture (Hill 2006). According to Gerhards (1982), 1% increase in the MC results in 1.65% and 4.3% decrease in MOE parallel to the grain and compression strength perpendicular to the grain, respectively, because bound water performs as plasticizer in texture of wood material (Mirzaei et al 2017). More on the effects of MC on the mechanical properties were reported in the studies by Kretschmann (2010)

and Dinwoodie (2000). Therefore, it is generally accepted that mechanical properties of wood strongly depend on its MC, decreasing with increasing MC below the FSP (Gerhards 1982; Pearson et al 2015; Pekka and Mark 2016).

As a chemical-free modification, thermal treatment on wood has been proved efficient in the improvement on decay resistance and dimensional stability. Low oxygen thermal modification at 160-260°C have been widely studied and successfully industrialized (Esteves and Pereira 2009; Cademartori et al 2013; Li et al 2017). Thermal treatment decreases hygroscopicity obviously according to thermal degradation of hemicellulose, as well as cellulose and lignin at higher temperature than 200°C (Hill 2006; Cademartori et al 2013). Heated wood grows dimensionally stabilized when humidity fluctuates (Tjeerdsma et al 1998). Many test results showed that the durability of the treated laminae can be improved significantly, with reduced hygroscopicity, but it decreased mechanical properties in varying degrees (Santos 2000; Kamdem et al 2002; Icel et al 2015). Amounts of the literatures reported mechanical properties decreased with the increase in heating temperature (Morales et al 2004, 2005; Kocaefe et al 2007, 2010; Jiang et al 2014; Zhong et al 2015), especially at 200°C and higher (Poncsák et al 2006). Therefore, the use of heat-treated wood in load-bearing constructions does not seem to be desirable (Jämsä and Viitaniemi 2001).

The importance of the decrease in internal stress in timber has increased in the few years because large cross-section of glulam was required because of the need for load-bearing when used in long-span and medium-rise construction. The cross section of glulam was determined by MOE, not load capacity, especially in high RH. This may be currently hindered by knowledge gaps and perceptions regarding the poor dimensional stability and low MOE of timber buildings.

Thermal modification can attribute to enhanced decay resistance, dimensional stability, and less hygroscopicity with less reduction in mechanical properties using a slightly high temperature (Mitchell

1988; Poncsák et al 2006). Therefore, ideas for using friendly chemical-free thermal treating technology to improve the flexural properties of glulam in high RH may provide an attractive alternative. Fast-growing poplar is one of the most common wood species and intensively used in wood product industry in China (Yue et al 2019). Improving the hygroscopic characteristics of fast-growing poplar by industrial thermal treatment technology would offer the timber product industry many interesting opportunities. To our knowledge, there is little reference about the influence of heat treatment on bending properties of full-scale glulam beam made out of thermally treated fast-growing wood in high humidity. In general, 60% and 90% RH represent the general application and extreme high RH, respectively, and the two RHs were used in this study. Hence, the moisture- and thermal treatment-induced bending properties of the glulam beams are important properties for structural designing that should be calculated in detailed designing of the timber construction (Ranta-Maunus 2003; Mirzaei et al 2017). Therefore, the main objective of the current research work is to investigate the impact of industrial thermal treatment and RH in the surrounding environment on bending properties of full-scale glulam beams made out of the thermally treated poplar wood, including MOE, MOR, the characteristic load–deformation curves, the characteristic load–strain curves, the average extreme fiber strain, and the failure mode.

MATERIALS AND METHODS

Materials

The fast-growing poplar wood (*Populus* spp.) with an air-dried density of 444 kg/m³ (at 12% MC) from Jiangsu province, China, was used in the test. Defect-free flatsawn lumber from the sapwood was selected. The dimensions of the lumbers were 35 × 140 × 3050 mm³ (thickness by width by length), and the MC was controlled to 8-12%. According the nondestructive three-pointed static bending test specified in China standard GB/T 26899 (2011), every piece of lumber was carefully stress graded. The strength class of laminae in the absence of finger joints

was determined by MOE according to China standard GB/T 26899 (2011). The lumbers with a same strength class were used. The lumbers were divided into two groups. One group was conditioned at a temperature of 25°C and an RH of 60% and then was labeled with U_{L60} . The other group was conditioned in 25°C and of 90% RH environment and was labeled with U_{L90} . The conditioning time was both more than 1 mo until the laminae attained constant mass before being tested or preparation of the glulam beams.

Commercial exterior-grade phenol resorcinol formaldehyde (PRF) adhesive from Aike Industrial Co., Ltd. (Nagoya, Japan) was used in the current research work to mount the laminations. The adhesive with a pot life of 35 min at 20°C was dark brown. Phenol resorcinol formaldehyde adhesive consisted of two components: main agent solution and paraformaldehyde powder. Before each test, paraformaldehyde for hardener was added into the PRF main agent and then was homogenized for at least 3 min using a mixer running at a pumping capacity of 200 L/min. The viscosity of the adhesive at 20°C was 7500 MPa. Its solids content and pH value at 20°C were 35.8% and 7.6.

Thermal Treatment

The dimensional lumber was dried to less than 3% MCt, and then thermally treated in a kiln with a capacity 40 m³ by a wood-modified manufacturer (Zhejiang Shiyu Timber Co., Ltd., Nanxun, China). The temperature was set to 200°C according to the literature (Mitchell 1988; Poncsák et al 2006), in which the research works pointed out that the reduction of mechanical properties can be ensured within allowable limits. The thermal treatment was conducted using an industrial treating technology of 3.5 h at 200°C. The superheated vapor was used as both a protection gas and a heat transfer medium. After thermally treated, the lumbers were then divided into two groups. The two groups were conditioned in an RH of 60% and 90% and were labeled with T_{L60} and T_{L90} , respectively. The conditioning was conducted at a temperature of 25°C, and the duration

was more than 2 wk to reach EMC before being tested or preparation of the glulam beams.

Preparation of Glulam

All the glulam beams were made of poplar laminae in the absence of finger joints. The laminae were planned and finished to prepare fresh surfaces before bonding. The PRF adhesive was applied on surfaces of the laminae as 300 g/m² with a brush. The laminae were laid up to assemble glulam beam specimens and then pressed for 6 h at ambient temperature under a pressure of 1.0 MPa. The beam specimens, with a dimension of 75 × 150 × 3000 mm³ (width by depth by length), had a length of 20 times the depth of the cross section. Each glulam beam contained six laminae with a same thickness of 25 mm. The beam specimens labeled with U_{B60} and U_{B90} were fabricated with U_{L60} and U_{L90} poplar laminae, respectively. Those labeled with T_{B60} and T_{B90} were layered up with T_{L60} and T_{L90} poplar laminae, respectively. The preparation of all glulam beam specimens was carried out at ambient temperature and humidity ranging from 55% to 75%. Afterward, the beams labeled with U_{B60} and T_{B60} were conditioned in 60% RH, and U_{B90} and T_{B90} at 90% RH. The conditioning temperature of all glulam beam specimens was 25°C and the duration time was more than 4 mo.

Determination of MC

The MC of laminae was determined in accordance with EN 13183-1 (2002). Defect-free test pieces were the full cross section and were all cut to a dimension of 35 × 140 × 20 mm³ (thickness by width by length) according to BS EN 408 (2012) and EN 13183-1 (2002). The MC ω was determined using the following Eq 1.

$$\omega = (m_1 - m_0) / m_0, \quad (1)$$

where ω is the MC (%), m_1 is the mass of the test piece before drying (g), and m_0 is the mass of the oven dry test piece (g).

Determination of Strength Class of Laminae

The strength classes of laminae in the absence of finger joints were determined by MOE according to China standard GB/T 26899 (2011), and MOE tests were conducted by a nondestructive three-point static bending method in accordance with China standard GB/T 26899 (2011). The flexural testing was carried out using a universal test machine (Hangzhou Meters of Mechanical and Electronic Control Engineering Co., Ltd., China) with a 250 kN load cell. Load was applied continuously at a rate of 5.0 mm/min. Twelve replicates were performed for each condition (U_{L60} , U_{L90} , T_{L60} and T_{L90}).

MOE of the laminae was determined by the following Eq 2.

$$\text{MOE} = \frac{l^3 \Delta F}{4bh^3 \Delta y}, \quad (2)$$

where MOE is the modulus of elasticity (MPa), l is the span in bending (mm), b is the width of cross section in a bending test (mm), h is the depth of cross section in a bending test (mm), ΔF is an increment between upper and lower load limits (N), and Δy is an increment of deformation corresponding to the ΔF (mm).

Flexural Tests

All full-scale glulam beam specimens were tested using the four-point bending method in accordance with BS EN 408 (2012), with the test setup as shown in Fig 1. The flexural behavior of all glulam beam specimens were carried out using a universal test machine (Hangzhou Meters of Mechanical and Electronic Control Engineering Co., Ltd.). Load was applied at a constant of 5.0

mm/min until failure. Lateral roller-type restraint was used to prevent buckling and lateral torsional effects. The glulam beams were symmetrically loaded in bending at two points over a span of 18 times the depth as shown in Fig 1. A combination of YHD-200 linear variable differential transformers (LVDTs) and DH 3816 static strain transformers (LVDTs) and DH 3816 static strain box (Donghua Testing Technology, Co., Ltd., Taizhou, China) was used to record the deformation of glulam beam, and the LVDTs were located at both the midpoint and end supports of glulam beams. The strains were monitored by BX120-50AA paper-based strain gage (Zhejiang Huangyan Testing Apparatus Factory, Taizhou, China) with a sensitivity coefficient $2.08 \pm 1\%$ at the midspan of glulam beams both throughout the depth with a space of 25 mm and on the two face laminae. The four beam groups (U_{B60} , U_{B90} , T_{B60} , and T_{B90}) were three replicates for each.

Bending strength (f_m) and MOE ($E_{m,app}$) of glulam beam were calculated by the following Eqs 3 and 4, respectively.

$$f_m = \frac{aF_u}{2W}, \quad (3)$$

$$E_{m,g} = \frac{l^3 \Delta F}{bh^3 \Delta y} \left[\left(\frac{3a}{4l} \right) - \left(\frac{a}{l} \right)^3 \right], \quad (4)$$

where $E_{m,g}$ is the MOE (MPa), f_m is the bending strength (MPa), F_u is the maximum load (N), W is the section modulus (mm³), a is the distance between loading position and the nearest support (mm), l is the span in bending (mm), b is the width of cross section in a bending test (mm), h is the depth of cross section in a bending test (mm), ΔF is an increment between upper and lower load limits (N), and Δy is an increment of deformation corresponding to the ΔF (mm).

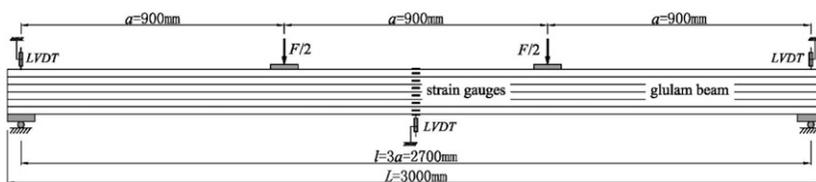


Figure 1. Bending test setup and arrangement.

RESULTS AND DISCUSSION

MC and Strength Classes of Laminae

The data in Table 1 provided how MC and strength classes of laminae in the absence of finger joints were affected by thermal treatment and RH in the surrounding environment.

The results indicated that RH had a significant effect on MC, and MC of untreated laminae in 90% RH was 17.41% and was 83.65% higher than that in 60% RH (see Table 1). After being treated, all the laminae specimens reached a lower MC in 60% and 90% RH (see Table 1). MC of heated lamina specimens in 60% RH was 6.00% and 14.71% in 90% RH. There was an obvious reduction in the MC between untreated and thermally treated laminae specimens in the same RH. The reason for this behavior was probably the thermal modification effect. Thermal treatment was proved to turn wood less hygroscopic because there mainly may be thermal degradation of hemicellulose, as well as cellulose and lignin in a relatively slight degree (Hill 2006; Cademartori et al 2013). Li et al (2013) conducted a similar thermal treatment to that in the present study, in which 25-mm-thick Manchurian ash and 30-mm-thick poplar wood were both heat treated at 200°C for 3 h. The results showed that EMC of heated Manchurian ash ranged from 5.91% to 7.56% at 25°C in 55-70% RH (Li et al 2013), and poplar wood 4.86-6.91% in 50.9-69.0% RH (Li et al 2017). The test results from Li et al (2013, 2017) were generally same as the EMC value of 6.00% in this study.

Table 1 showed that the effects of thermal treatment and RH in the surrounding environment on the strength class were obvious significantly,

and both of them were negatively correlated with the strength class. In accordance with China standard GB/T 26899 (2011), the strength class of untreated laminae (U_{L60}) was M_{E9} because the average MOE of laminae in the absence of finger joints at EMC in 60% RH was 9670 MPa, met the requirement from 9000 MPa to 10,000 MPa, and can be used for the production of TC_{T18} glulam. In 90% RH, the average MOE of laminae in the absence of finger joints at EMC was 7591 MPa, and the strength class was M_{E7} (≥ 7000 MPa and < 8000 MPa) and cannot be used for the preparation of same-grade composition glulam because the strength class of a lamina was not less than M_{E8} according to China standard GB/T 26899 (2011). For the thermally treated laminae, the average MOE was 13,295 MPa after being conditioned in 60% RH. The strength class was M_{E12} ($\geq 12,000$ MPa and $< 14,000$ MPa) and can be used for the production of TC_{T27} glulam according to China standard GB/T 26899 (2011). The average MOE of thermally treated laminae in 90% RH was 11,611 MPa. The strength class was M_{E11} ($\geq 11,000$ MPa and $< 12,000$ MPa) and can be used for the production of TC_{T21} glulam according to China standard GB/T 26899 (2011).

The results of untreated and thermally treated wood in the present study was the same as those of Gerhards (1982), who presented that all mechanical properties of wood increased as the MC decreased below FSP. It has been widely accepted that as the MC goes from green to dry, the strength properties of wood increase. Therefore, the thermally treated laminae with less MC had a higher MOE than the untreated.

Load-Mid-Span Deformation Behavior and Failure Modes

Figures 2 and 3 represented the load–deformation behavior and failure modes of the four series of full-scale glulam beams in 60% and 90% RH, respectively. The results from Figs 2 and 3 indicated that thermal pretreatment and RH in the surrounding environment both caused an obvious change in the failure mode from brittle tension of thermally treated beams in low RH to a ductile

Table 1. MOE and MC of untreated and thermally treated laminae in 60% and 90% RH.

Specimen types	MOE (MPa)		MC (%)
	Mean	SD	
U_{L60}	9670	461	9.48
U_{L90}	7591	1224	17.41
T_{L60}	13,295	1928	6.00
T_{L90}	11,611	1396	14.71

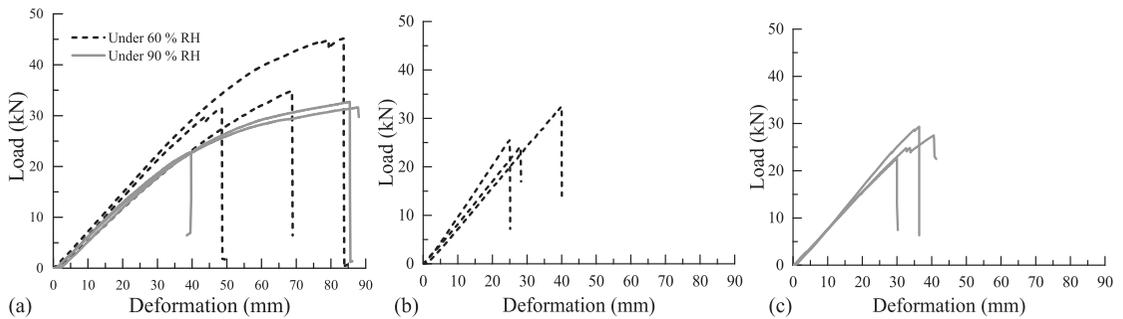


Figure 2. Load–deformation curves for glulam beams made from untreated laminae (a), from thermally treated laminae in 60% (b) and 90% (c) RH.

compression failure or flexure-shear failure of untreated beams in high RH. The flexural performance of glulam beams indicated in Fig 2 was essentially the same as that in Fig 3.

The load–deformation behavior of all the untreated beams in 60% and 90% RH (U_{B60} and U_{B90}) are shown in Fig 2(a). All three of glulam beam specimens (U_{B60}) at EMC in 60% RH exhibited slight nonlinear behavior until the failure at the tension face was due to the presence of either knots or cross grain. No compression yielding occurred in the compression zone of the glulam beams, and the failure was slightly ductile. The fracture surfaces of the untreated beams (U_{B60}) in 60% RH were uneven section, and cracks occurred along the wood fiber direction (see Fig 3(a)). As can be seen from the load–deformation curves of the untreated beams in 90% RH (U_{B90}) shown in Fig 2(a), nonlinear behavior occurred obviously before the maximum load was reached. This meant that the yielding of the wood in the compression zone occurred before the wood of tension face reached the ultimate tensile strain, and the failure was in

the compression mode, which showed obvious wrinkling in the compression zone before tensile fracture (U_{B90}) (see Fig 3(b)). Therefore, the failure was significantly ductile. The curves of load with deformation of thermally treated beams exhibited linear elastic behavior as seen in Fig 2(b) and (c) in spite of the difference of RH between them. The fracture surfaces of the thermally treated beams (T_{B60} and T_{B90}) in 60% and 90% RH were irregular and flat. Thermal treatment caused wood material brittleness. The thermally treated beams (T_{B60}) in 60% RH also failed in the tension mode at the location of natural defects and was similar with that of the untreated beams (U_{B60}) in 60% RH (see Fig 3(c)). The thermally treated beams (T_{B90}) in 90% RH all failed in combined flexure and shear mode (see Fig 3(d)). It should be noted that the plastic deformation of thermally treated beams (T_{B90}) in 90% RH was less than that of the untreated beams in 60% RH. This indicated that the effect of thermal pretreatment was more than that of high RH in the present study. Therefore, the conclusion can be drawn that linear elastic behavior of glulam beam

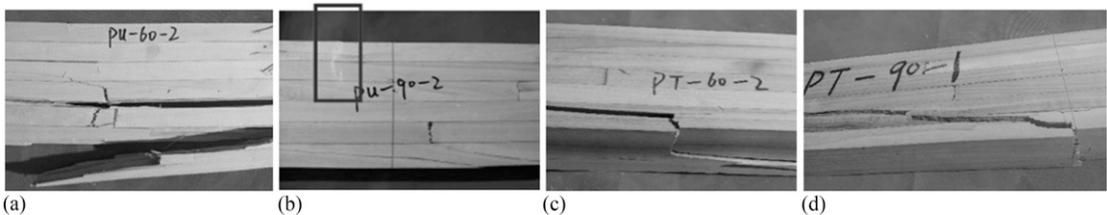


Figure 3. Bending properties of glulam beams at EMC in different RHs.

can be achieved using industrial thermal treatment technology, and it may be attributed to less hygroscopicity of wood caused by heating technology.

The test results about flexural properties are summarized in Fig 4. It can be seen from Fig 4 that the bending strength and MOE were obviously effected by both thermal pretreatment and RH in the surrounding environment. The bending properties of both the untreated and thermally treated glulam beam decreased with the increase in RH since plasticity increased with MC. MOE and MOR of glulam beams both decreased after being thermally treated.

Mechanical Properties of Glulam

The mechanical properties of glulam beams are shown in Fig 2. The results are plotted in Fig 4.

As seen in Fig 4, the average MOR of the untreated beams (U_{B90}) at EMC in 90% RH was 46.5 MPa and was 21.85% less than that in 60% RH. The average MOE of the untreated beams (U_{B60} and U_{B90}) at EMC decreased from 11,438 MPa to 10,257 MPa when RH increased from 60 to 90%. The increment of MOE in different RHs was 10.33%. The relationship between the bending properties of beams and RH in the surrounding environment was negatively correlated according to the MC difference of wood. For the thermally treated beams, MOR and MOE were both negatively correlated, like the untreated beams. It should be noted that the effects of RH on MOR and MOE of heated beams were less than those of the untreated beams. For the thermally treated beams, MOR in 60% RH was 3.42% higher than that in 90% RH, and the difference of MOE between the two RHs was 12.94%. The results showed that the hygroscopicity of beams decreased after being thermally treated, and then the heated beam was not susceptible to moisture when RH increased.

It was still obvious that there was a relatively large decrease for MOR after laminae used in glulam beams were thermally pretreated. MOR of thermally treated beam in 60% RH was 26.22% lower than that of the untreated beams in 60%

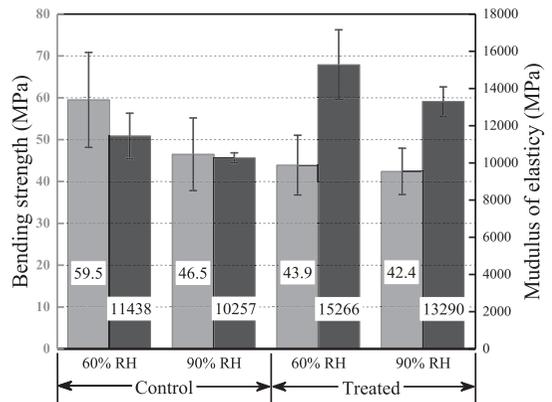


Figure 4. Typical failure modes of full-scale glulam beams: tension failure of the untreated beam in 60% RH (a), compression failure of the untreated beam in 90% RH (b), tension failure of the thermally treated beam in 60% RH (c), and flexure-shear failure of the thermally treated beam in 90% RH (d).

RH. By comparison, MOE of thermally treated beam in 60% and 90% RH was 33.47% and 16.19% higher than that of the untreated beams in 60% RH, respectively. However, compared with the untreated beams in 90% RH, MOR of thermally treated beams in 60% and 90% RH decreased by 5.59% and 8.82%, and MOE of thermally treated beams in 60% and 90% RH increased by 48.83% and 29.57%, respectively. Widmann et al (2014) conducted MOR and stiffness tests of glulam beams made out of the thermally modified beech wood, which was similar to that in this study. The tests also presented that the thermal treatment of wood increased the stiffness of the glulam beams with a reduction in the MOR (Widmann et al 2014), and the conclusion was the same as the results in this study.

Thermal treatment changed the chemical composition of wood materials by degrading cell wall compounds. The hemicellulose, cellulose, and lignin in wood cell wall were all the structural compounds (Esteves and Pereira 2009). The most serious degradation under thermal treatment was hemicellulose, even at low temperatures (Tjeerdsma et al 1998; Sivonen et al 2002; Nuopponen et al 2004). Cellulose was less affected by the thermal treatment because of its crystalline nature (Yildiz et al 2006; Esteves et al 2008). The heat-treated wood had a higher content of lignin than the

untreated wood according to polycondensation reactions and cross-linking with other cell wall components (Tjeerdsma and Militz 2005; Boonstra and Tjeerdsma 2006; Zaman et al 2000; Esteves et al 2008). Therefore, the mechanical properties of thermally treated wood were generally same as that of the untreated.

All the aforementioned showed that MOE of glulam beams made from low-grade fast-growing poplar wood can be greatly improved at the expense of a slight decrease in MOR using industrial heating technology in the extreme high RH in the surrounding environment. A similar conclusion was drawn by Boonstra et al (2007): heat-treated wood can be used in construction because of a slight reduction in the MOR and a great increase in the MOE of heat-treated wood.

Strain Distribution

Typical load–strain curves of glulam beams in bending tests are illustrated in Figs 5 and 6.

It can be seen from Figs 5 and 6 that the load–strain curves for the untreated beams in 60% RH (see Fig 5[a]) and the thermally treated beams in 90% RH (see Fig 6[b]) were slightly nonlinear, and the untreated beams in 90% RH remained dramatically nonlinear according to the high MC of wood (see Fig 5[b]), whereas the thermally treated beams in 60% RH showed linear behavior (see Fig 6[a]).

Thermal pretreatment and low RH both led to the reduction in the MC of wood (see Table 1).

Therefore, it was a good explanation of the greater deformation of the untreated beams in 90% RH than that in 60% RH. The thermally treated beams exhibited obvious linear behavior at different RHs, especially in 60% RH, because the heating technology reduced the hygroscopicity of wood, which was also mentioned by many other authors (Kamdern et al 2002; Esteves et al 2007a, 2007b).

Figures 7 and 8 plotted the typical strain profiles at midspan for typical glulam beams at different load levels until failure.

It has been indicated in Figs 7 and 8 that the mechanical neutral axis position of the untreated beams gradually moved downward as the bending load increased to failure (see Fig 7), and the neutral axis position of thermally treated beams was relatively stable (see Fig 8). The mechanical neutral axis position of untreated beams in 60% RH moved from 3.340 mm to -2.503 mm against the geometric neutral axis (see Fig 7[a]). The position moved from 1.096 mm to -4.191 mm in 90% RH (see Fig 7 [b]). The average extreme fiber strain for both compressive and tensile at failure was significantly affected by thermal pretreatment and RH in the surrounding environment. The average extreme fiber strain of glulam beams was positively related to the RH in the surrounding environment, and the thermal pretreatment had an obvious negative effect on extreme fiber strain. The average extreme fiber strain of wood at failure of untreated beams increased from 0.560% in 60% RH to 0.614% in 90% RH. The average

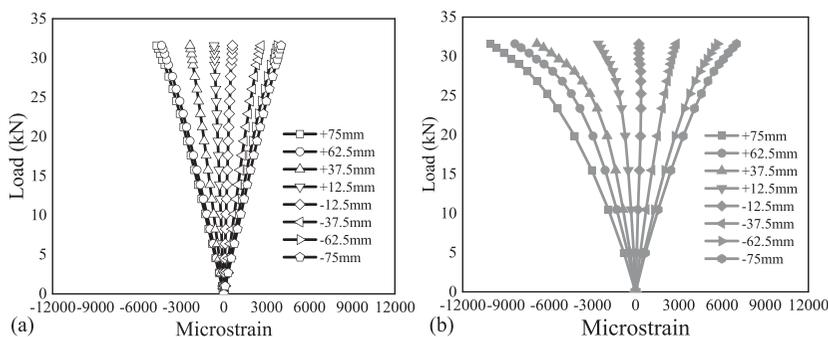


Figure 5. Typical load–strain curves for the untreated glulam beams in 60% (a) and 90% (b) RH.

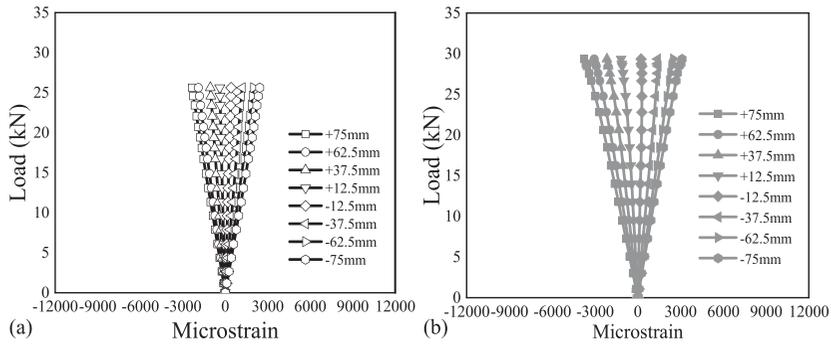


Figure 6. Typical load–strain curves for the thermally treated glulam beams in 60% (a) and 90% (b) RH.

extreme fiber strains of wood at failure of thermally treated beams in 60% and 90% RH were 0.295% and 0.418%, respectively. The reduction in average extreme fiber strains in thermally treated beams were both lower than that of untreated beams in each RH because of the brittleness and high MOE of wood caused by thermal pretreatment.

In comparison with the results of MOE improvement and MOR decrease in the present study, Mirzaei et al (2017) found that MOE and MOR of glulam beams made out of poplar wood both increased slightly after poplar laminae with a thickness of 6 mm was thermally treated at 140°C and 160°C for a duration of 30 min. There are some literatures reporting that mild thermal treatment of wood leads to increase in MOE (Gündüz et al 2009). It is well known that hemicelluloses play key roles in the mechanical properties of wood heated at high temperatures (Hillis 1984). During the mild thermal wood

treatment, less hemicelluloses are extracted from wood cell walls (Tjeerdsma and Militz 2005) and crystalline cellulose is increased because of the thermal treatment (Yildiz and Gümüřkaya 2007). The changes in chemical component within wood were affected by temperature level. Therefore, the mechanical properties of heat-treated wood would change more slightly if being modified using a mild thermal treatment (relatively low temperature and shorter duration), and then there may be a better balance between the improvement on MOE and the reduction in MOR. Enough replications were necessary to evaluate and provide all fundamental mechanical parameters of flexural members at each treatment level for its application in timber structure. It was not possible to conduct a statistical evaluation of the test results in the current research work. However, the present study gave an idea of the possibility of the improvement of load-bearing glulam made out of thermally treated fast-growing wood species in high RH, and

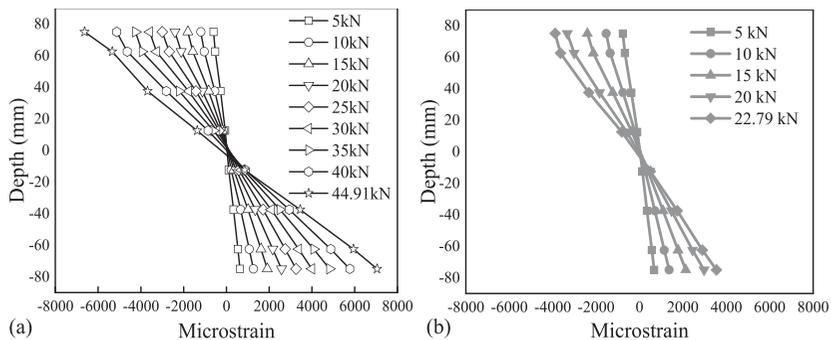


Figure 7. Typical strain profile for the untreated glulam beams in 60% (a) and 90% (b) RH.

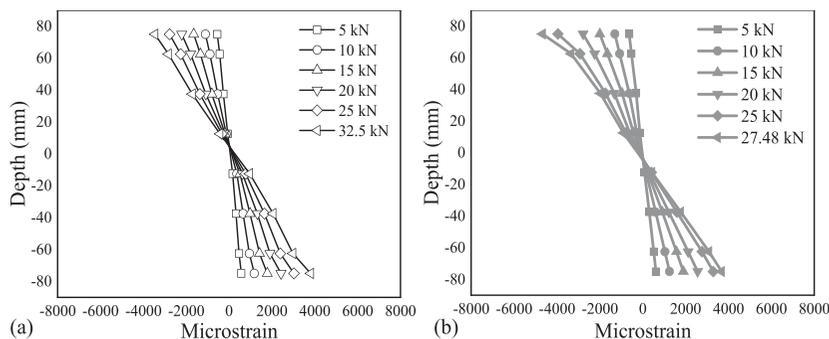


Figure 8. Typical strain profile for the thermally treated glulam beams in 60% (a) and 90% (b) RH.

the heated glulam beams could be used for a limited range of structural elements.

CONCLUSIONS

1. There was a negative relationship between humidity in the surrounding environment and the strength class of laminae in the absence of finger joints, and the thermal treatment can contribute to the increase in the strength class. The strength class of untreated laminae decreased from M_{E9} in 60% RH to M_{E7} in 90% RH. The strength class of thermally treated laminae decreased from M_{E12} in 60% RH to M_{E11} in 90% RH. After thermal treatment, the laminae strength class increased from M_{E9} to M_{E12} in 60% RH and from M_{E7} to M_{E11} in 90% RH.
2. Compared with the untreated beams, MOR of thermally treated beams slightly decreased, and MOE significantly improved. MOE of thermally treated beams in 60% RH was 15,266 MPa and was 33.47% and 48.83% higher than that of untreated beams in 60% and 90% RH, respectively. MOR of heat-treated beams in 60% and 90% RH was 5.59% and 8.81% higher than that of the untreated beams in 90% RH, respectively.
3. The curves of load with deformation, bending failure modes, load-strain curves, and the average extreme fiber strain of glulam beams in each RH showed that the untreated beams exhibited more nonlinearity than the thermally pretreated beams, especially at high RH environment. The observations can be supported among 7 them.

4. The relationship between bending properties of glulam beam and RH in the surrounding environment was negatively correlated, so should be restricted in extreme high RH. Industrial thermal treatment technology improved the MOE significantly in high RH with a slight reduction in MOR. Therefore, thermally pretreated wood materials can be used in construction but need checking of MOR or be used for a limited range of structural elements.

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REFERENCES

- Aicher S, Dill-Langer G, Ranta-Maunus A (1998) Duration of load effect in tension perpendicular to the grain of glulam in different climates. *Holz Roh Werkst* 56:295-305.
- Boonstra M, Acker VJ, Kegel E (2007) The effect of a two-stage heat treatment process on the mechanical properties of full construction timber. *Wood Mater Sci Eng* 2: 138-146.
- Boonstra M, Tjeerdsma B (2006) Chemical analysis of heat-treated softwoods. *Holz Roh Werkst* 64:204-211.
- BS EN 13183-1 (2002) Moisture content of a piece of a sawn timber—Part 1: Determination by oven dry method. European Committee for Standardization, London.
- BS EN 408:2010+A1 (2012) Timber structures—Structural timber and glued laminated timber—Determination of some physical and mechanical properties. European Committee for Standardization, London.

- Cademartori PHG, Santos PSB, Serrano L, Labidi J, Gatto DA (2013) Effect of thermal treatment on physicochemical properties of Gympie messmate wood. *Ind Crops Prod* 45: 360-366.
- CNS (2011) GB/T 26899-2011. Structural glued laminated lumber. Standards Press of China, Beijing, China.
- Dinwoodie JM (2000) Timber: Its nature and behaviour. Van Nostrand Reinhold, New York.
- Esteves B, Domingos I, Pereira H (2007a) Improvement of technological quality of eucalypt wood by heat treatment in air at 170-200°C. *Forest Prod J* 57:47-52.
- Esteves B, Graça J, Pereira H (2008) Extractive composition and summative chemical analysis of thermally treated eucalypt wood. *Holzforchung* 62:344-351.
- Esteves B, Marques A, Domingos I, Pereira H (2007b) Influence of steam heating on the properties of pine (*Pinus pinaster*) and eucalypt (*Eucalyptus globulus*) wood. *Wood Sci Technol* 41:193-207.
- Esteves B, Pereira H (2009) Wood modification by heat treatment: A review. *BioResources* 4:370-404.
- Gaspar F, Cruz H, Gomes A (2010) Production of glued laminated timber with copper azole treated maritime pine. *Holz Roh Werkst* 68:207-218.
- Gerhards CC (1982) Effect of moisture content and temperature on the mechanical properties of wood: An analysis of immediate effects. *Wood Fiber* 14:4-36.
- Goodell B, Jellison J, Loferski J, Quarles SL (2007) Brownrot decay of ACQ and CA-B treated lumber. *Forest Prod J* 57:31-33.
- Gustafsson PJ, Hoffmeyer P, Valentin G (1998) DOL behaviour of end-notched beams. *Holz Roh Werkst* 56: 307-317.
- Gündüz G, Aydemir D, Karakas G (2009) The effect of thermal treatment on the mechanical properties of wild pear (*Pyrus elaeagnifolia*) wood and changes in physical properties. *Mater Des* 30:4391-4395.
- Hill CAS (2006) Wood modification: Chemical, thermal and other processes. Wiley, Chichester, UK.
- Hillis WE (1984) High temperature and chemical effects on wood stability. *Wood Sci Technol* 18:281-293.
- Humar M, Žlindra D, Pohleven F (2006) Effect of fixation time on leaching of copper-ethanolamine based wood preservatives. *Holz Roh Werkst* 65:329-330.
- Icel B, Guler G, Isleyen O, Beram A, Mutlubas M (2015) Effects of industrial heat treatment on the properties of spruce and pine woods. *BioResources* 10:5159-5173.
- Jämsä S, Viitaniemi P (2001) Heat treatment of wood-better durability without chemicals. Pages 9-13 in Review on heat treatments of wood, Proc. Special Seminar COST Action, Antibes, France.
- Jiang J, Lu J, Zhou Y, Zhao Y, Zhao L (2014) Compression strength and modulus of elasticity parallel to the grain of oak wood at ultra-low and high temperatures. *BioResources* 9:3571-3579.
- Jönsson J (2004) Internal stresses in the cross-grain direction in glulam induced by climate variations. *Holzforchung* 58:154-159.
- Kamdern D, Pizzi A, Jermannaud A (2002) Durability of heat-treated wood. *Holz Roh Werkst* 60:1-6.
- Kocaefe D, Chaudhry B, Poncsak S, Bouazara M, Pichette A (2007) Thermogravimetric study of high temperature treatment of aspen: Effect of treatment parameters on weight loss and mechanical properties. *J Mater Sci* 42: 854-866.
- Kocaefe D, Poncsak S, Tang J, Bouazara M (2010) Effect of heat treatment on the mechanical properties of north American jack pine: Thermogravimetric study. *J Mater Sci* 45:681-687.
- Kretschmann DE (2010) Mechanical properties of wood. Pages 5-44 in: RJ Ross, ed. Wood handbook: Wood as an engineering material. USDA Forest Service, Forest Products Laboratory, Madison, WI.
- Li T, Cai JB, Gu LB, Ding T, Zhou DG (2013) Correction factors for a radio frequency-type moisture meter for heat-treated wood. *BioResources* 8:5549-5560.
- Li T, Deng DL, Avramidis S, Wlinder MEP, Zhou DG (2017) Response of hygroscopicity to heat treatment and its relation to durability of thermally modified wood. *Constr Build Mater* 144:671-676.
- Lin LD, Chen YF, Wang SY, Mingjer T (2009) Leachability, metal corrosion, and termite resistance of wood treated with copper-based preservative. *Int Biodeter Biodegr* 63: 533-538.
- Mirzaei G, Mohebbi B, Ebrahimi G (2017) Glulam beam made from hydrothermally treated poplar wood with reduced moisture induced stresses. *Constr Build Mater* 135: 386-393.
- Mitchell PH (1988) Irreversible property changes of small loblolly pine specimens heated in air, nitrogen, or oxygen. *Wood Fiber Sci* 20:320-335.
- Moraes PD, Rogaume Y, Bocquet JF, Triboulot P (2005) Influence of temperature on the embedding strength. *Holz Roh Werkst* 63:297-302.
- Moraes PD, Rogaume Y, Triboulot P (2004) Influence of temperature on the modulus of elasticity (MOE) of *Pinus sylvestris* L. *Holzforchung* 58:143-147.
- Nuopponen M, Vuorinen T, Jamsä S, Viitaniemi P (2004) Thermal modifications in softwood studied by FT-IR and UV resonance Raman spectroscopies. *J Wood Chem Technol* 24:13-26.
- Osmannezhad S, Faezipour M, Ebrahimi G (2014) Effects of GFRP on bending strength of glulam made of poplar (*Populus deltoides*) and beech (*Fagus orientalis*). *Constr Build Mater* 51:34-39.
- Pearson H, Ormarsson S, Gabbitis B (2015) Nonlinear tensile creep behavior of radiata pine at elevated temperatures and different moisture contents. *Holzforchung* 69:915-923.
- Pecka T, Mark H (2016) The effect of temperature and moisture content on the fracture behaviour of spruce and birch. *Holzforchung* 70:369-376.
- Poncsák S, Kocaefe D, Bouazara M, Pichette A (2006) Effect of high temperature treatment on the mechanical properties of birch (*Betula papyrifera*). *Wood Sci Technol* 40:647-663.

- Ranta-Maunus A (2003) Effects of climate and climate variations on strength. Pages 153-167 in S. Thelandersson and HJ Larsen, eds. Timber engineering. E-publishing Inc., Chichester, UK.
- Santos JA (2000) Mechanical behaviour of eucalyptus wood modified by heat. *Wood Sci Technol* 34:39-43.
- Sivonen H, Maunu S, Sundholm F, Jämsä S, Viitaniemi P (2002) Magnetic resonance studies of thermally modified wood. *Holzforschung* 56:648-654.
- Sjödin J, Johansson CJ (2007) Influence of initial moisture induced stresses in multiple steel-to-timber dowel joints. *Holz Roh Werkst* 65:71-77.
- Tjeerdsma B, Boonstra M, Pizzi A, Tekely P, Militz H (1998) Characterisation of thermally modified wood: Molecular reasons for wood performance improvement. *Holz Roh Werkst* 56:149-153.
- Tjeerdsma B, Militz H (2005) Chemical changes in hydrothermal treated wood: FTIR analysis of combined hydrothermal and dry heat-treated wood. *Holz Roh Werkst* 63:102-111.
- Widmann R, Beikircher W, Cabo JL, Steiger R (2014) Bending strength and stiffness of glulam beams made of thermally modified beech timber. Pages 569-576 in S. Aicher and H. Garrecht, eds. Materials and joints in timber structures. E-publishing Inc., The Netherlands.
- Yang TH, Lin CH, Wang SY, Lin FC (2012) Effects of ACQ preservative treatment on the mechanical properties of hardwood glulam. *Holz Roh Werkst* 70:557-564.
- Yildiz S, Gezer D, Yildiz U (2006) Mechanical and chemical behavior of spruce wood modified by heat. *Build Environ* 41:1762-1766.
- Yildiz S, Gümüşkaya E (2007) The effect of thermal modification on crystalline structure of cellulose in soft and hardwood. *Build Environ* 42:62-67.
- Yue K, Cheng XC, Chen ZJ, Tang LJ, Liu WQ (2018) Investigation of decay resistance of poplar wood impregnated with of alkaline copper, urea-formaldehyde and phenol-formaldehyde resin. *Wood Fiber Sci* 50:392-401.
- Yue K, Chen ZJ, Lu WD, Liu WQ, Li MY, Shao YL, Tang LJ, Wan L (2017) Evaluating the mechanical and fire-resistance of modified fast-growing Chinese fir timber with boric-phenol-formaldehyde resin. *Constr Build Mater* 154:956-962
- Yue K, Wang L, Xia J, Zhang YL, Chen ZJ, Liu WQ (2019) Experimental research on mechanical properties of laminated poplar wood veneer/plastic sheet composites. *Wood Fiber Sci* 51:320-331.
- Zaman A, Alén R, Kotilainen R (2000) Thermal behavior of Scots pine (*Pinus sylvestris*) and silver birch (*Betula pendula*) at 200-230 °C. *Wood Fiber Sci* 32:138-143.
- Zhang J, Kamdem DP (2000) FTIR characterization of copper ethanolamine wood interaction for wood preservation. *Holzforschung* 54:119-122.
- Zhong Y, Zhou H, Wen L (2015) The effect of elevated temperature on bending properties of normal wood inside Chinese larch wood during fire events. *BioResources* 10: 2926-2935.