

ORIGINAL ARTICLE

Tensile strength of thermally modified laminated strand lumber and laminated veneer lumber

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ABSTRACT

Laminated strand lumber (LSL) and laminated veneer lumber (LVL) were thermally modified as a post-treatment at 140°C, 150°C, 160°C, 170°C, and 180°C. The tension modulus of elasticity (MOE) of LSL was not significantly impacted by the treatments, with the 180°C treatment group exhibiting the highest tension MOE (11.8 GPa). The LVL also experienced minimal impacts, with the 150°C treatment group having the highest tension MOE (19.4 GPa) and the 160°C treatment group exhibiting the lowest (17.1 GPa). The maximum tensile strength (MTS) of the LSL and LVL significantly decreased with increasing temperatures, with the control and 180°C treatment groups experiencing the highest and lowest MTS, respectively. The lowest MTS for LSL was 10.8 MPa (180°C treatment), which was 70% lower than the controls. The lowest MTS of the LVL was 24.4 MPa (also at the 180°C treatment), which was a 49% decrease compared to the controls. These results suggest that thermal-modification post-treatments minimally impact tension MOE, but can significantly reduce MTS at higher treatment temperatures. Combined with previous work improving the moisture properties and equilibrium moisture content of thermally modified LSL and LVL, it may be possible to optimize the treatment technique(s) to yield products with desirable properties.

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Introduction

Thermally modified wood is currently used primarily for solid wood flooring, external cladding, and decking products. Thermal modification can impart advantageous properties in wood, including attractive darker color, reduced equilibrium moisture content (EMC), reduction of mass, degradation of water-binding hemicelluloses (Sinoven *et al.* 2002, Hakkou *et al.* 2005, Repellin and Guyonnet 2005, Kocaefe *et al.* 2008), and elimination of many volatile organic compounds compared to air-dried wood (Manninen *et al.* 2002). The result is a high-value, high-performing solid wood product with increased moisture resistance, decreased swelling and shrinkage due to weathering and atmospheric moisture changes, and increased resistance to biological degradation (Syrjanen and Kangas 2000, Rapp and Sailer 2001, Tjeerdsma *et al.* 2002, Weiland and Guyonnet 2003, Esteves *et al.* 2006, Spelter *et al.* 2009). However, most mechanical properties decrease with increasing treatment intensity (Santos 2000, Unsal and Ayrimis 2005, Poncsak *et al.* 2006). It has been shown that modulus of rupture (MOR) typically decreases at higher treatment temperatures (Kocaefe *et al.* 2008), while modulus of elasticity (MOE) can decrease or even increase slightly, depending on treatment intensity (Donahue *et al.* 2011).

While there is an increasing amount of scientific understanding and performance data for thermally modified solid wood components, there is very limited information on the impacts of thermal-modification processing, especially using the closed, pressurized process, on the performance of

engineered wood products. Donahue (2011) discovered that the bending MOE of aspen plywood thermally modified at 190°C increased 28%. Slight increases in bending MOE were also found for aspen waferboard panels subjected to a short 240°C thermal post-treatment (Hsu *et al.* 1989). Similar results were found by Bonigut *et al.* (2012) when post-treating oriented strand board (OSB) panels at temperatures between 160°C and 180°C. Others reported that OSB panels heat-treated for 12–20 minutes at either 190°C or 220°C in a single opening hot-press experienced no significant reduction in bending MOE (Del Menezzi *et al.* 2009). In addition, Aro *et al.* (2014a, 2014b) reported that the bending MOE of exterior-rated plywood thermally modified as a post-treatment at 180°C decreased 2.4%, while the bending MOE of OSB treated at the same condition experienced very little change.

Chotchuay *et al.* (2008) examined oriented strand lumber from Parawood strands thermally modified at 190°C and found compression (39 MPa) and tensile strength (36 MPa) parallel to the grain, and flatwise (59 MPa) and edgewise bending strength (61 MPa), were significantly higher than those of untreated controls. Poncsak *et al.* (2007) prepared laminated veneer lumber (LVL) from thermally modified yellow poplar, Scots pine, jack pine, and aspen lamellas bonded together. Shear strength of most samples was reduced 30–50%, but Scots and jack pine had only moderate decreases of 5% and 11%, respectively. The interfacial bonding for jack and Scots pine was much stronger than yellow poplar and aspen. A similar study (Sernek *et al.* 2007)

examined thermally modified spruce lamellas and found no significant decrease in shear strength. Also, shear strength did not vary significantly with treatment temperature. In contrast, spruce laminated timbers thermally modified at 21 °C for three hours had reduced shear strength and delamination rates of 26.5% and 32%, respectively. Shear strengths were higher when the timbers were thermally modified after bonding versus thermally modifying the lamellas before bonding (Henriksson *et al.* 2009). Nazerian *et al.* (2011) studied LVL prepared from beech, poplar, and maple veneers thermally modified at 120°C and 180°C for four hours at atmospheric pressure. After bonding the veneers into three-layer, 20 mm-thick LVL, water absorption, and thickness, tangential, and longitudinal swelling decreased with increasing temperature. In particular, the thickness swell of the beech LVL manufactured from juvenile wood decreased an average of 28.4% and 41.2% at the 120°C and 180°C treatment temperatures, respectively. Longitudinal swelling of the juvenile beech LVL decreased 13.1% and 38.0% at the 120°C and 180°C treatment temperatures, respectively. Water absorption of the same material decreased 29.3% when treated at 180°C. Similar moisture properties were reported for juvenile maple and poplar LVL. The improvement of moisture properties, as noted above, is likely due to the reduced number of hydroxyl groups caused by degradation of hemicelluloses (Nazerian *et al.* 2011).

The flatwise MOR of juvenile beech, maple, and poplar LVL decreased 45.5%, 45.7%, and 41.7%, respectively, and MOE decreased 41–53%. Similar results were found in laminates made from tali, iroko, and pine (Kohl *et al.* 2009, Sahin Kol *et al.* 2009). In addition, the effects of heat treatment on the compression strength parallel to the grain, bending strength, and bending MOE of laminated window profiles manufactured from Kosipo wood using either polyurethane- or polyvinyl acetate-based adhesives were examined (Korkut *et al.* 2008). It was reported that heat treatment generally reduced all mechanical properties, with compression strength being significantly influenced by temperature and time. Widmann *et al.* (2007) also reported that finger-jointed boards manufactured from heat-treated beech had lower tension strength than those from untreated beech. Also, the heat-treated samples failed predominantly in the wood, as opposed to the joint.

It is likely that the degradation of hemicelluloses in the wood cell wall, which leads to a weaker wood structure, causes most of the aforementioned reductions in mechanical properties of thermally modified engineered wood products. As noted, thermal-modification processing can slightly increase the MOE of engineered wood products. This may be partially due to the elimination of natural resins and hemicelluloses from the wood as well as increased cellulose crystallinity, which may make the wood more rigid and brittle (Aro *et al.* 2014a).

While bending properties of thermally modified engineered wood have been examined by others, there is very little performance data on the tension properties. This paper reports on the tension MOE and maximum tensile strength (MTS) of laminated strand lumber (LSL) and LVL specimens

that were thermally modified as a post-treatment at 140°C, 150°C, 160°C, 170°C, and 180°C in a closed, pressurized kiln. Other work on thermally modified LSL and LVL is underway by the authors. The goal of our overall study is to develop baseline data that may help expand thermal-modification technology toward growing engineered wood product markets and applications where tension properties are important, such as truss chords and webs of engineered wood trusses. This scientific information is required for industry practitioners and their customers to fully understand the potential for thermally modified engineered wood.

Materials and methods

Materials

Commercially available 45 mm thick by 241 mm wide LSL and LVL lumber were obtained for this study. The LSL was manufactured from a proprietary hardwood species mix bonded with polymeric diphenylmethane diisocyanate (pMDI) adhesive, while the LVL was manufactured from a proprietary softwood species mix bonded with phenol formaldehyde (PF) adhesive. All specimens were 1270 mm long. We selected specimens that were free from any major visual defects.

Thermal-modification procedures

The LSL and LVL specimens were thermally modified as a post-treatment at 140°C, 150°C, 160°C, 170°C, and 180°C in the University of Minnesota Duluth Natural Resources Research Institute's (UMD NRRI) thermal-modification kiln (Model no. AT-700/2600, Industrial OLMAR, SA, Gijon, Spain). All specimens were first stored in the pilot plant area (23°C ± 2°C and 35% ± 5% relative humidity (RH)) to be equilibrated to constant weight prior to modification. The conditioning space had an EMC of approximately 7.0%, which is similar to the moisture equilibrium occurring in a home. Upon reaching the constant weights, representative sections from the LSL and LVL were trimmed and placed in a forced-convection oven maintained at 103°C ± 2°C for 24 hours, at which point no appreciable change in mass was noted when readings were made at approximately four-hour intervals. The moisture content of the LSL and LVL was then calculated according to ASTM D4442 (ASTM International 2007). The LSL and LVL had average moisture contents of 4.80% and 5.85%, respectively. (The effect of the starting EMC on the tensile properties was not investigated.) The average density of the LSL and LVL was 735 and 503 kg/m³, respectively.

The LSL and LVL specimens were then each divided into six groups, with 16–20 specimens per group. Group 1 was used as a control, while Groups 2–6 underwent thermal modification at 140°C, 150°C, 160°C, 170°C, and 180°C, respectively. In each treatment run, specimens were separated with wood stickers to allow for more effective heat transfer and air flow inside the kiln. Figure 1 illustrates a charge of LSL specimens entering the kiln. Cover sheets were placed on top of the specimen stacks to protect the panels from excess water spray during the cooling cycles.

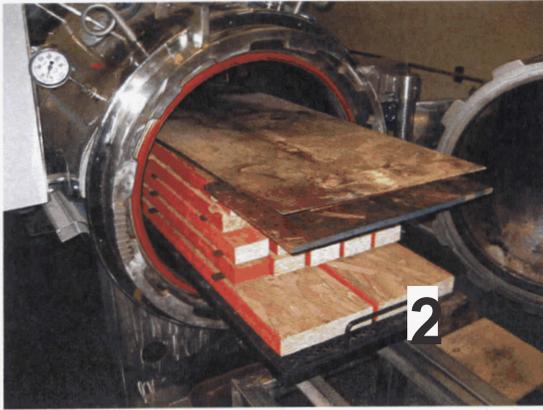


Figure 1. LSL entering the hydrothermal-modification kiln.

During each thermal-modification cycle, the temperature and pressure inside the kiln were monitored and recorded. While the engineered wood was subjected to heat, moisture was evaporated from the wood as steam and was kept contained in the sealed kiln; gasified wood substances produced from thermal decomposition of the wood were also retained in the kiln. This created an acid hydrolysis mechanism which further supported modification of the specimens. After the specimens remained at the top temperature for 135 minutes, the temperature was reduced using an automated fine water spray inside the kiln. The cycle ended when the final temperature of 105°C was maintained for 60 minutes. The average mass loss for the thermally modified LSL was 3.8%, 4.2%, 7.6%, 10.1%, and 16.4% when thermally modified at 140°C, 150°C, 160°C, 170°C, and 180°C, respectively. The average mass loss for the LVL was 3.0%, 4.9%, 7.6%, 10.5%, and 15.5% when thermally modified at 140°C, 150°C, 160°C, 170°C, and 180°C, respectively.

All specimens were then placed in a conditioning room (24°C and 65%RH) until EMC was reached. The average moisture contents of the specimens at the time of tension testing are shown in Table 1

Table 1. Average moisture content of LSL and LVL specimens at time of tension testing.

	Treatment temperature					
	Control	140°C	150°C	160°C	170°C	180°C
LSL	6.8%	6.7%	6.1%	5.5%	5.8%	4.3%
LVL	7.8%	7.4%	7.0%	6.4%	5.5%	

Tension specimen preparation and testing

Upon equilibrating, each specimen was first cut to 178 mm wide by stripping off 31.5 mm edges from each side. Specimens were then cut into a dog-bone shape 330 mm long with a 45 mm-wide neck (Figure 2). The configuration of the specimens was designed based on the practical limitations on the loading and grip capacities of the tension apparatus and the requirements set forth in ASTM D4761 (ASTM International 2013). For each specimen, four shear plate seats were cut on each end and on both faces with a 67 mm groove cutter to fit 67 mm by 19 mm shear plates. Shear plate seat dimensions are also shown in Figure 2. Figure 3 shows the cut-to-configuration specimens ready for tension testing.

Figure 4(a) illustrates the tension test setup. A load cell of 489 kN was installed between the actuator and the grip plates (which connect to the shear plates). The specimens were placed between the grips and connected with the grip plates through eight 19 mm by 127 mm grade-5 bolts. Two linear variable differential transformer (LVDT) sensors (Model no. 0241-0000, Trans-Tek, Inc., Ellington, CT) were installed on the specimens over a gauge length of 381 mm, one on each side (Figure 4(b)). Tension tests were conducted according to ASTM D4761 (ASTM International 2013) with a loading rate of 25.4 mm/min. Following tension testing, a 34 mm-long sample was cut from the neck section of the tension specimen (away from the failure zone) for determination of the moisture content and density. Density was determined based on the weight and dimension measured on the small samples immediately following cutting. Moisture content was determined using the oven-dry method according to ASTM D4442 (ASTM International 2007).

Results

The majority of the test specimens failed in the neck section as shown in Figure 5. Analysis revealed that the tension MOE of the six specimens that failed in grip were still valid; however, the MTS values were not. (In a very limited number of load-extension curves, one of the LVDT sensors may have malfunctioned. After careful analysis of the curves of these six specimens, it was determined that the maximum loads were still valid and they were therefore included in the results.) The tension MOE was calculated based on the linear range of the load-extension curves. The parameters measured on each specimen included:

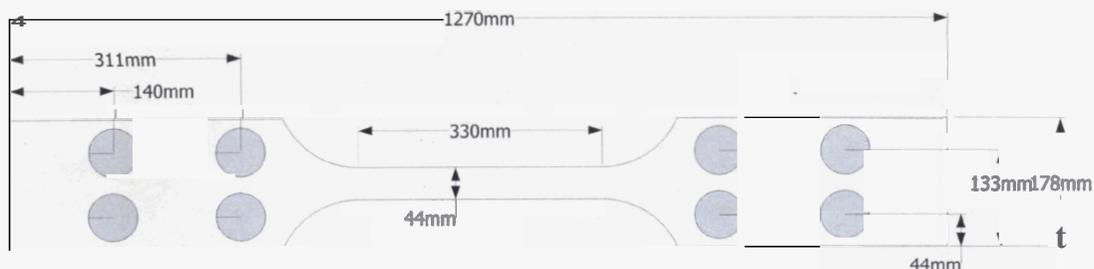


Figure 2. Specimen configuration and shear plate seat dimensions.



Figure 3. Cut-to-configuration specimens prior to tension testing.

- Maximum load (PMax) (N),
- Extension at the maximum load (ExtPmax) (mm),
- Tension MOE (GPa), and
- MTS (MPa).

The average tension MOE and MTS are shown in Table II.

The average tension MOE for the LVL control specimens falls within the range (15.6–20.3 GPa) reported by Jung (1982), while the average MTS falls within the range (20.8–49.1 MPa) reported by Kretschmann et al. (1993). The average tension MOE for the LSL control specimens is near the published value of 10.6 GPa, while the average MTS is higher than the value published (22.5 MPa) for a commercially available LSL product (CSTB 2013). Care must be taken when comparing the results of this study's control specimens to published values because, as previously noted, configuration of the specimens was designed, in part, based on the practical limitations on the loading and grip capacities of the tension apparatus.

Results were analyzed using a one-way ANOVA followed by post hoc t-tests using a Bonferroni correction at the 95% significance level. The average tension MOE for the LSL showed little variation as treatment temperature increased, with the lowest tension MOE (10.9 GPa) at the 150°C treatment. The 180°C treatment exhibited a tension MOE of 11.8 GPa, which was 6.2% higher than the control specimens. There was no statistically significant difference between any of the LSL treatment groups. The average tension MOE of the LVL also showed little variation, with no statistically significant difference between any of the treatment groups. The 160°C treatment resulted in the lowest tension MOE (17.1 GPa), which was 10.3% lower than the control group. The highest tension MOE (19.4 GPa) was at the 150°C treatment.

The average MTS for both LSL and LVL decreased with increasing treatment temperature. Compared to the control group, the LSL experienced statistically significant reductions at all temperatures, except for the 140°C treatment ($p < .05$). The lowest MTS (10.8 MPa) was found at the 180°C treatment temperature. The LVL experienced 14.0% and 42.2% reductions in MTS at the 140°C and 160°C treatment temperatures, respectively. The lowest MTS (24.4 MPa) was found at the 180°C treatment temperature. These results conflict with Chotchuy et al. (2008) who found that the tensile strength parallel to the grain of oriented strand lumber manufactured from Parawood strands increased when thermally modified at 190°C. Our results, however, are similar to others that discovered the tension strength of finger-jointed beech boards heat-treated at temperatures from 160°C to 250°C for 2–16 hours was reduced by an average of 59% (Widmann et al. 2007). (The exact temperatures and heating durations used in this study were not reported.)

In addition, the reductions in MTS at temperatures exceeding 160°C were more pronounced in the LSL than the LVL. The MTS of the LVL treated at 170°C was 27.5 MPa, which was only

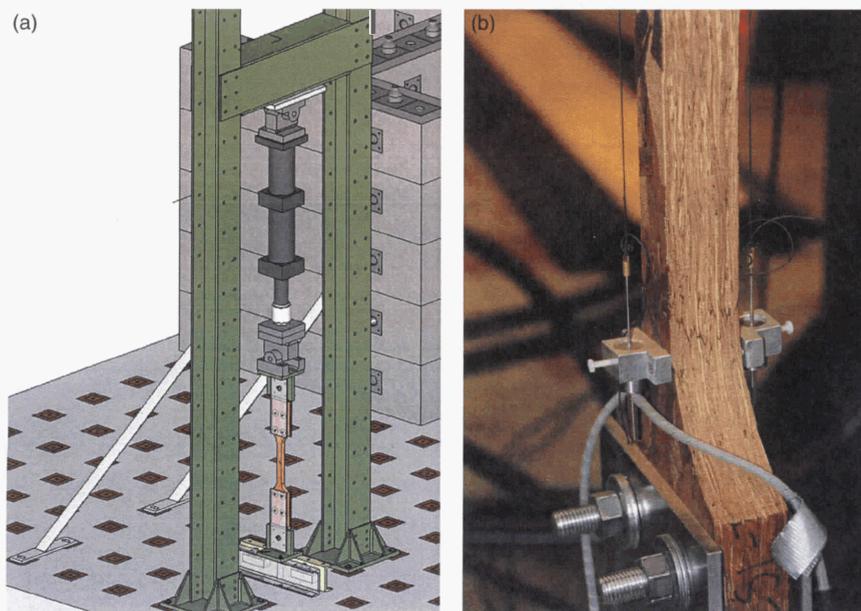


Figure 4. (a) Tension test setup. (b) Two LVDTs installed on a tension specimen.



Figure 5. LSL specimen failed at neck section during tension testing.

0.5% lower than the 160°C treatment group. The MTS of the LVL treated at 180°C was 24.4 MPa, which was 11.1% lower than the 170°C treatment group (this reduction was statistically significant ($p < .05$)). In contrast, the MTS of the LSL treated at 170°C was 20.0% lower than the 160°C treatment group, while the MTS of the 180°C treatment group was 26.6% lower than the 170°C treatment group.

Compared to the control specimens, the density of the thermally modified LSL decreased 2.3%, 8.4%, 11.7%, 11.6%, and 13.2% at the 140°C, 150°C, 160°C, 170°C, and 180°C treatment temperatures, respectively. The density of the LVL specimens decreased 1.4%, 3.3%, 6.3%, 3.5%, and 7.0% at the 140°C, 150°C, 160°C, 170°C, and 180°C treatment temperatures, respectively. Density of the control specimens versus tension MOE of the LSL and LVL control specimens revealed very little correlation, and density of the treated specimens as tested versus tension MOE of the treated LSL and LVL revealed very little correlation. Density versus MTS of the LVL also revealed little correlation. Density versus MTS of LSL thermally

modified at all treatment temperatures is plotted in Figure 6. Regression analyses yielded a coefficient of determination (R^2) of 0.58, suggesting a moderate relationship between density and MTS.

Discussion

Relationships between the degree of polymerization (DP) of α -cellulose and the tensile strength and strain of wood have been studied, with higher DP corresponding to higher strength and strain. It is also believed that lignin contributes to the compression strength of the wood cell wall by restraining the lateral buckling of microfibrils. Hemicellulose, which readily absorbs moisture, has a strong indirect influence on mechanical properties. Because it is present in substantially lower quantities and is of lower molecular weight than α -cellulose, its contribution to the mechanical behavior of composites can be expected to be somewhat less significant than that of other principle chemical components (Bodig and Jayne 1982). When wood is thermally modified, hemicelluloses degrade first, typically at 160–220°C (Pavlo and Niemz 2003); this leads to an increase in crystallinity of cellulose in the cell wall (Fengel and Wegener 1984). Crystalline cellulose typically does not degrade until temperatures in excess of approximately 300°C (Kim *et al.* 2001) are attained. Lignin is the most thermally stable component of the wood cell wall with only significant degradation occurring at temperatures exceeding 280°C. However, the loss of hemicellulose leads to an increase in the relative proportion of lignin in the cell wall (Hill 2006).

Although there is very little literature on the tension MOE of thermally modified engineered wood, it is known that the bending MOE of plywood and OSB post-treated with a closed, pressurized thermal-modification method can increase with moderate treatment temperatures (Aro *et al.* 2014a, 2014b). It is also known that the bending MOE of thermally modified solid wood products can decrease or increase slightly, depending on treatment intensity. Donahue *et al.* (2011) showed a slight MOE increase for yellow poplar and basswood treated at 200°C and 210°C. The minimal change in tension MOE for both the LSL and LVL analyzed in the current study suggests thermally modified engineered wood products may behave similarly (i.e. minimal change) when subjected to tension and bending loads. This result may partially be due to the elimination of hemicelluloses and natural

Table II. Average tension MOE and MTS of LSL and LVL thermally modified at several treatment temperatures (standard deviation in parentheses).

	Treatment temperature					
	Control	140°C	150°C	160°C	170°C	180°C
<i>LSL</i>						
Tension MOE (GPa)	11.1 ^a (1.19)	11.4 ^a (0.75)	10.9 ^a (0.81)	11.1 ^a (2.74)	11.3 ^a (1.36)	11.8 ^a (1.39)
MTS (MPa)	35.8 ^a (5.47)	32.5 ^a (2.94)	25.3 ^b (2.83)	18.3 ^c (1.99)	14.7 ^d (1.90)	10.8 ^e (2.19)
<i>LVL</i>						
Tension MOE (GPa)	19.0 ^a (1.12)	18.2 ^a (1.65)	19.4 ^a (7.15)	17.1 ^a (1.71)	19.1 ^a (2.05)	18.2 ^a (4.52)
MTS (MPa)	47.8 ^a (4.56)	41.1 ^b (5.25)	33.8 ^c (4.86)	27.6 ^d (3.45)	27.5 ^{de} (3.44)	24.4 ^e (2.87)

Note: Unique letters in each row indicate values that are statistically significantly different from each other at the 95% significance level.

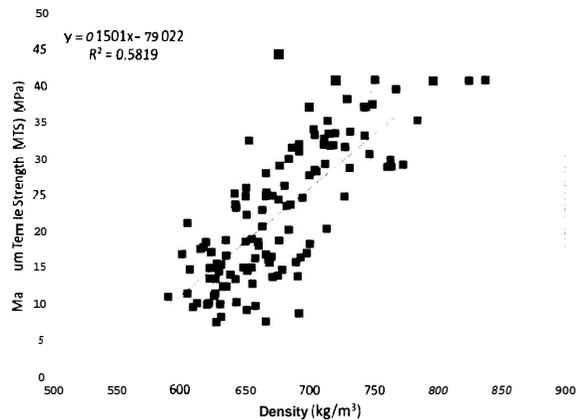


Figure 6. Density versus MTS for all hygrothermally modified LSL specimens (all treatment temperatures).

resins from the wood; increases in cellulose crystallinity may also contribute. These changes, collectively, render the wood more rigid and brittle.

The decrease in MTS at temperatures above 160°C is likely largely explained by the weakening of the wood cell wall via hemicellulose degradation and overall weakening of the wood structure. Representative specimens analyzed utilizing scanning electron microscopy support this claim, as previously described by Aro *et al.* (2015). The statistically significant decrease in MTS for the LSL and LVL at the 140°C and 150°C treatment temperatures was unexpected because hemicellulose degradation does not generally occur until the wood reaches approximately 160°C (minor degradation can occur at lower temperatures (Hill 2006). However, previous research has shown that lignin can display major structural alterations at temperatures as low as 110°C in oak (Assor *et al.* 2009), and significant thermal degradation can occur in water-soaked wood as low as approximately 100°C (Funaoka *et al.* 1990). It is unknown whether lignin structural alterations have occurred or not in the LSL and LVL analysed in the current study. If present, they would have caused significant reductions in MTS. Also, it is possible that humidity levels reached in the kiln during the current study could promote wood thermal degradation at the lowest treatment temperatures used, which could partially explain the MTS reductions, even at the lowest treatment temperatures. Our results differ from Chotchuay *et al.* (2008) who found that tensile strength parallel to the grain of Parawood-oriented strand lumber increased 79% to 36 MPa (compared to untreated controls) when the strands were heat-treated at 190°C. The heat treatment used in their study, however, differed from our study because it used a two-stage heat treatment consisting of boiling the wood strands in water for 30 minutes followed by heat treatment in an electric oven at 190°C for 30 minutes.

Generally, there is a linear relationship between wood density and MOE for solid wood materials. But the strength of the correlation is actually not very high, and wood density is generally considered a poor indicator of wood stiffness. Thus, it was not surprising that we found no correlation between density and tension MOE for the thermally modified LSL and LVL specimens. One possible factor could be that LSL and LVL, as engineered materials, exhibit higher degrees of

non-homogeneity compared to solid wood. Another contributing factor could be related to bonding quality, which may not substantially affect density, but may significantly influence the stiffness. Poor bonding among the wood elements (laminae or strands) could result in a weak composite effect, thus reducing mechanical properties. Because there was no correlation between density and tension MOE for the thermally modified LSL and LVL, we expected there to also be no correlation with MTS because strength is more controlled by local properties. Thus, we cannot explain why there was a moderate correlation between density and MTS for the LSL but not the LVL. This may be an area for future study.

The effect of heat and pressure on the integrity of the resins used in this study must also be discussed. While it may be reasonable to suggest that the temperatures used in this study had a deleterious effect on the structure of the PF and pMDI resins used to manufacture the LVL and LSL, respectively, previous work revealed that phenolic resin-bonded aspen waferboard panels successfully withstood heat post-treatments up to 240°C (Hsu *et al.* 1989). Cured PF is known to have very good thermal stability, greater than that of cured pMDI resin. Umemura *et al.* (1998) reported that the chemical structure of cured MDI resin was rather stable at temperatures up to about 200°C, well above the temperatures used in this study. As previously noted, the current study utilized a closed, pressurized thermal-modification process that retained the hot, pressurized acid gases in the sealed reactor. Keeping these reactive volatiles available for repolymerization reactions has been shown to quicken the thermal-modification process while allowing for effective modification at lower temperatures (compared to non-pressurized thermal-modification systems) via the formation of organic acids (primarily acetic acid) that catalyze the hydrolysis of hemicellulose (Hill 2006, Willems 2009, Willems *et al.* 2014). It is possible that the presence of these pressurized acid gases could have had a deleterious effect on the structure of the PF and pMDI resins, which could ultimately reduce MTS. However, more study is needed to confirm this. In addition, care must be taken when comparing thermally modified LSL and LVL to thermally modified solid wood because of the relatively unknown effects of heat and pressure on the adhesives used to manufacture the LSL and LVL.

These results suggest that thermal-modification processing has relatively minor effect on the tension MOE of LSL and LVL. Without further research, however, the significant reductions in MTS with increasing treatment temperatures for both LSL and LVL may limit their application in traditional construction applications, such as for engineered wood truss components. With the expected improvement in moisture properties, however, it may be possible to identify and develop high-value, non-traditional applications, especially in areas with high humidity and precipitation.

Conclusions

This study examined the tension MOE and MTS of LSL and LVL that were thermally modified in a closed, pressurized

treatment vessel as a post-treatment at 140°C, 150°C, 160°C, 170°C, and 180°C. The results revealed that:

- Average tension MOE for the LSL and LVL showed little variation as treatment temperature increased, with no statistically significant changes found at any treatment temperature when compared to the control specimens.
- Average MTS for both the LSL and LVL decreased with increasing treatment temperatures, with the highest MTS found for the control specimens and the lowest found for the 180°C treatment groups.
- The reduction in MTS at temperatures exceeding 160°C was more pronounced in the LSL than the LVL.
- There was little correlation between density and tension MOE of the LSL and LVL, while there was a moderate correlation between density and MTS of the LSL.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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