Influence of Specimen Size on Accelerated Weathering of Laminated Veneer Lumber

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Abstract

Moisture intrusion can be significantly higher along specimen edges, particularly at edges where longitudinal grain is exposed, which is referred to as the edge effect. The influence of edge effects on moisture durability are assumed to decrease as the edge area to total-surface-area ratio decreases. Moisture durability assessment of laminated veneer lumber (LVL) is commonly evaluated using accelerated weathering (AW) and outdoor exposure methods, where small specimens are analyzed. The influence of specimen size (i.e., edge effect) on moisture durability evaluation of LVL was investigated in this study. To vary specimen size, three widths with constant length and thickness were evaluated. In addition, three AW methods were used to characterize how the method of inflicting degradation influenced edge effects. No consistent trends in mechanical property loss were found across AW methods, indicating that the influence of specimen size varied with AW method. The greatest influence of specimen size occurred when cyclic vacuum-soak-dry was included, where water absorption decreased significantly with increasing width, and three of four mechanical properties evaluated displayed an influence of specimen size. The smallest influence of specimen size occurred when a single soak-dry procedure was included, where only one of four mechanical properties evaluated displayed an influence of specimen size. Results from this study provide evidence that edge effects may occur during LVL moisture durability assessment but that the severity is dependent on AW conditions.

Laminated veneer lumber (LVL) is an engineered wood composite in the structural composite lumber (SCL) category (APA 2010). LVL is produced by laminating multiple layers of rotary-peeled veneer with a structural adhesive system, where most commonly all veneers are laminated such that grain direction coincides (Nelson 1997). Common uses of LVL include headers, beams, rafters, and flange material for wood I-joists. Most LVL service applications are for protected interior uses, where moisture content (MC) remains below 16 percent. Since LVL is primarily composed of wood, it is inherently hygroscopic. Despite recommendations from most manufacturers to prevent wood-based composite products from moisture exposure, structural building materials, like LVL, can be exposed to the environment during shipping, on site construction, and in use (Chen et al. 1989, Alexopoulos 1992, King et al. 2014, Saad et al. 2016). Therefore, a reasonable level of durability should be expected from LVL and other structural wood composites to ensure structural requirements are met in the event they are exposed to adverse conditions (Alexopoulos 1992, Mirzaei et al. 2015).

Compared with mat-formed composites, in which product performance is highly reliant on the consolidation and compaction of the wood constituents, the use of thicker continuous veneers in LVL results in a composite that depends as much on the wood properties as the wood-adhesive bonding (Kamke and Winandy 2008, Mirzaei et al. 2015). Most LVL uses phenolic adhesives for veneer bonding. While most phenolic adhesives possess excellent moisture durability attributes (Pizzi 2003), the wood-adhesive interphase can be compromised when subjected to shrinking and swelling stresses from changes in MC and

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temperature (Northcott and Colbeck 1960). Failure of the wood-adhesive interphase in the form of delamination can subsequently result in greater swelling along with an entry and/or entrapment point for water (Kamke and Winandy 2008).

Accelerated weathering and long-term outdoor exposure are the primary means for assessing durability of wood-based composites (Alexopoulos 1992, Kojima and Suzuki 2011, Saad et al. 2016, Kojima et al. 2017). Outdoor weathering of unprotected specimens has been considered the most reliable estimate of long-term durability, since it simulates natural weathering conditions that may be encountered during service and incorporates the factor of elapsed time (Alexopoulos 1992, Kojima and Suzuki 2011, Kojima et al. 2017). However, lengthy exposure periods, lack of standardization, and variable climatic conditions limit the applicability of outdoor exposure tests for product development and routine evaluation by the wood-based composites industry (Bodig and Fyie 1986, Alexopoulos 1992, Kojima et al. 2017). Weathering intensity indices incorporated with empirical degradation rate equations have been used to combat the issue of variable climatic conditions and permit comparisons between different weathering conditions (Kojima et al. 2011, 2017). Exposing unprotected specimens to the environment for prolonged periods of time is more severe than reasonably anticipated adverse service conditions, meaning that long-term outdoor weathering is still an accelerated test (Alexopoulos 1992, Saad et al. 2016).

Accelerated weathering (AW) is performed in the laboratory setting. Specimens are exposed to artificial conditions designed to rapidly evaluate durability by maximizing the influences of temperature, moisture, and shrinking and swelling stresses, as opposed to emulating actual adverse service conditions (Baker and Gillespie 1978, Saad et al. 2016). Treatments such as water immersion, boiling, steaming, freezing, and drying are commonly employed (Alexopoulos 1992, Saad et al. 2016, Kojima et al. 2017). Standardization and relatively fast evaluation times allow the wood-based composites industry to use AW for product development, product qualification, and routine quality control. Mechanical property retention after AW treatment is usually evaluated on a pass/fail basis based on specified requirements. AW is also used during new product development as a means of comparing performance between products. Extensive research has been undertaken to attempt to correlate AW and long-term outdoor exposure to allow for estimating long-term service performance in the significantly shorter evaluation periods offered by AW (Alexopoulos 1992, Okkonen and River 1996, Kojima and Suzuki 2011, Saad et al. 2016). Exposure to degradation agents in standardized AW methods is in most cases more severe than exposure from outdoor exposure tests, presenting difficulties in estimating long-term durability of wood-based composites from short-term AW tests (Alexopoulos 1992, Saad et al. 2016).

The size of specimen chosen for durability assessment can potentially influence results (Kojima et al. 2017, Way et al. 2018). Small specimen sizes are usually specified for durability evaluation using standardized AW procedures (APA 2011, ASTM International 2012), which allow for the potential degradation agents to take effect more rapidly and permit increased replication within the confines of laboratory-scale weathering equipment. Moisture intrusion can be heightened along specimen edges, particularly where longitudinal grain is exposed (Kojima et al. 2009, Laleicke 2015). The susceptibility to increased moisture intrusion at the edges is referred to as the edge effect. The edge effect is assumed to be more pronounced as the edge-area to total-surface-area ratio increases.

The ultimate goal in assessing moisture durability of wood-based composites is to accurately depict long-term load-carrying capacity of wood structures subjected to adverse service conditions (Bodig and Fyie 1986). In this case, the best assessment would take place on actual-sized specimens subjected to actual adverse conditions (Mirzaei et al. 2016). Hence, a challenge exists to develop AW treatments capable of reasonably predicting product performance in a range of conditions. As further work progresses to develop AW procedures that provide a better depiction of actual adverse service conditions, while keeping evaluation times within a reasonable time frame, knowledge of how specimen size influences durability evaluations becomes necessary (Kojima et al. 2017, Way et al. 2018). Current standardized AW procedures to assess LVL moisture durability occur on specimens with smaller cross sections and lengths than those typically used in service (ASTM International 2014). Durability assessments of LVL outside of routine quality control have investigated the effects of different layup configurations, including veneer thickness and species, and have used specimen sizes stipulated in product standards (Laufenberg 1982, Hayashi et al. 2002, Paridah et al. 2012). While small specimen cross sections may be advantageous for these purposes, they may not be representative of LVL durability when subjected to adverse service conditions, particularly if edge effects are present.

The influence of specimen size on LVL moisture durability assessment was investigated in this study. AW was used as the means for inflicting moisture degradation in LVL, such that relative durability attributes could be assessed within a reasonable timeframe. Three AW methods were chosen to investigate the influence of specimen size over a range of exposure conditions. Flatwise bending, bending shear, and mechanical connector tests were evaluated as a means of comparing moisture durability performance between different specimen sizes, since past work indicated several mechanical property tests may be necessary to robustly compare durability performance (Alexopoulos 1992). Specimen size was varied by maintaining constant length and thickness over three different widths. While the ultimate goal would be to predict durability of actual-sized specimens in service, specimen length was chosen to coincide with that specified in standardized evaluation procedures for small specimens. Nevertheless, evaluating specimen size based on different cross-section dimensions provides an initial investigation into the influence of LVL specimen size during moisture durability evaluation. Specifically, this study sought to (1) investigate the influence of specimen size on LVL moisture durability assessment within each of the three AW treatments and (2) determine how the means of inflicting moisture degradation (i.e., AW method) influenced moisture degradation between specimen sizes.

Materials and Methods

Materials

Commercially produced LVL was obtained directly from an LVL manufacturer. The LVL, made with Douglas-fir (*Pseudotsuga menziesii*) veneers bonded with phenol formaldehyde adhesive, was obtained at widths of 89, 140, and 286 mm (nominal 4, 6, and 12 in., respectively). All LVL was 38.1 mm (2 in. nominal) thick with 1.7E 2400 APA rating, corresponding to design values of 11.0 GPa (1.7 $\times$ 10^6 psi) for modulus of elasticity and 16.5 MPa (2,400 psi) for modulus of rupture.

Accelerated weathering

Current standardized AW procedures are important for the wood-based composites industry. The goal of this work was to investigate the influence of specimen size on moisture durability assessment to provide guidance to future studies seeking to develop AW procedures more representative of what a product could experience during adverse service conditions, as opposed to suggesting changes to existing AW procedures. Three AW methods were chosen to provide a range of weathering conditions, two of which were based on standardized procedures. Some deviations from the standardized procedures occurred, but since all specimens within a given AW treatment were treated the same, deviations from the standards were considered warranted.

AW1 was a 24-hour continuous water soak based on procedures outlined in section 23 of ASTM D1037 (ASTM International 2012). Water temperature deviated from 20°C stipulated in the standard, but remained between 16°C and 24°C. LVL was oriented edgewise so that the width direction was vertical during soaking with the water level maintained 25 mm above the uppermost surface. Upon completion of soaking, specimens were dried in a forced air convection oven at 60°C until initial mass was reached.

AW2 was a six-cycle vacuum-pressure-soak-dry procedure based on the method described in section 7.17 of US Product Standard 2 (PS2), which consists of (APA 2011):

1. Thirty minutes of submersion in water with applied vacuum pressure of 50.6 kPa.
2. Thirty minutes of submersion in water at atmospheric pressure.
3. Drying for 6 hours at 82°C in an oven with forced air circulation.
4. Repeat steps 1 to 2 and dry for 15 hours under the same conditions as step 3.
5. Repeat steps 1 to 4 two additional times to complete six cycles.

The method stipulates maintaining water temperature of 66°C, which was not achieved in this study, where cold tap water was used instead. Specimens were oriented with the length direction vertical during soaking. Water level was maintained 50 mm above the uppermost surface. If specimens had not reached starting mass upon completion of step 5, then they were dried in the same manner as AW1.

AW3 was a custom procedure consisting of 56 cycles for a total duration of 28 days (Table 1). Each cycle consisted of four steps that subjected LVL to water spray, high humidity, subzero temperatures, and low humidity. AW3 occurred in a large (2.44^3 m^3) computer-controlled weathering unit capable of maintaining temperature at ± 1°C and relative humidity (RH) at ± 1 percent with the ability to change temperature at 1°C per minute and RH at 1 percent per minute. Spray racks with programmable actuated valves were positioned within the chamber to provide water spray. Water was sprayed through six wide-angle nozzles that each applied 2.8 liters per minute based on 206 KPa supply pressure. The intention of water spray application was to continuously wet the LVL surfaces during the period of water spray application, and therefore no specific application amount was targeted. Specimens were oriented edgewise on racks and spaced 25 mm apart. Upon completion of the 56th cycle the chamber was maintained at step 4 (Table 1) conditions until the starting mass was reached.

Table 1.—AW3 schedule and conditions for one cycle.

Step	Temperature set point (°C)	Relative humidity set point (%)	Duration (min)
1	35	Water spray	60
2	40	90	60
3	−20	NA	75
4	40	10	525
Total			720

Mechanical and physical property determination

Three mechanical properties were chosen to investigate the influence of specimen size on LVL, which were flatwise bending, bending shear, and lateral connections. Physical properties of interest were water absorption, thickness swell, and delamination. Except for water absorption, all properties were determined after specimens had equilibrated in an environmental chamber maintained at 20°C and 65 percent RH, resulting in average moisture content (MC) of 10 to 12 percent at time of testing. Mechanical testing was performed with displacement-controlled loading protocols on an INSTRON Series 5582 universal testing machine (UTM). Load and displacement data measured at the UTM crosshead were recorded digitally at 10 Hz for all mechanical test procedures.

Flatwise bending.—Flatwise bending was chosen to investigate the influence of specimen size since all widths had the same thickness and were therefore comparable in this configuration. ASTM D5456 stipulates that flatwise bending tests be conducted in a third-point loading configuration following the methods of ASTM D198 (ASTM International 2013, 2014). The objective of this work was to determine the extent of flexural changes caused by AW. Therefore, a three-point loading configuration was chosen, where changes in LVL structural integrity (i.e., loss of bond quality) would have a higher likelihood of influencing the results due to the shear component induced by three-point loading. Flatwise bending specimens were 774 mm in length providing a span-to-depth ratio of 19:1 with 25 mm of overhang past each reaction. Displacement-controlled loading was applied at constant rate of 5 mm/min, producing failures within 4 to 6 minutes. The properties of interest were maximum moment (bending strength, Eq. 1) and apparent stiffness (EI, Eq. 2), where both properties were normalized for width to merit comparison between specimen widths within a treatment method.

$$M = \frac{P_u \cdot L}{4b} \quad (1)$$

$$EI = \frac{\Delta P}{\Delta x} \cdot \frac{L^3}{48b} \quad (2)$$

where M is maximum moment per unit width (kN-mm/mm), EI is apparent stiffness per unit width (kN mm^2/mm), P_u is ultimate load (kN), L is center-to-center span length (mm), b is specimen width (mm), and $\Delta P/\Delta x$ is slope from the linear region of the load-displacement diagram.

Bending shear strength.—Bending shear strength was assessed following methods outlined in section A4 of ASTM D5456, which is intended to evaluate adhesive durability of SCL after six-cycle vacuum-pressure-soak-dry procedure of PS 2 (ASTM International 2014). Specimens were loaded in a flatwise three-point bending configuration at a span-to-depth ratio of 6:1, specified to promote interlaminar shear. Specimen length was 254 mm as stipulated by ASTM D5456 for 38.1-mm-thick LVL (ASTM International 2014). Displacement-controlled loading occurred at a rate of 5 mm/min, which met the specified target time to failure of 60 seconds (ASTM International 2014). Bending shear strength was taken as the maximum load reached before failure, normalized for width (kN/mm).

Lateral edge nail durability.—Lateral edge nail durability was assessed following section A4 in ASTM D5456, which is intended to evaluate connection durability based on a 24-hour water soak (ASTM International 2014). In this procedure, LVL (305 mm long) acts as the main member and 18.3 mm by 101.6 mm by 305 mm oriented strand board (OSB) act as side members. After taking mass measurements for water absorption (described in the following section), OSB side members are fastened to each edge (tangential face) of LVL, creating a double-shear plane connection, with two 3.4-mm-diameter by 63.5-mm-long bright common nails centered on each edge. The two nails on each edge were spaced 101 mm apart and were offset along the height on each edge by 50 mm. The OSB was offset along the height by 50 mm from the LVL. After attaching OSB, the assembly was dried accordingly for each AW procedure. Displacement-controlled compressive loading (2.5 mm/min) was applied to the main member through a bearing plate housed on a spherical seat, and load was transferred into the UTM base through OSB side members. Loading continued for 1 minute after the load-displacement curve began exhibiting postpeak behavior. Connection strength was determined as the load at 10.2 mm of displacement based on zeroing displacement after applying 100 N preload (ASTM International 2014).

Physical properties.—Water absorption and thickness swell were determined following section 23 of ASTM D1037, measured on the flatwise bending specimens. Initial mass and thickness of each specimen was determined prior to the AW procedures commencing. One thickness measurement was taken with digital calipers ($\pm$0.01 mm) along the center of each edge. The point of measurement was marked with permanent marker. Water absorption was determined by measuring mass at the completion of AW treatment at the following points: AW1, after drip-drying at room temperature for 10 minutes before transferring to oven; AW2, after drip-drying for 10 minutes at room temperature after the last soaking step; and AW3, at the end of step three on cycle 56, in the frozen state. Water absorption was calculated as

$$WA = \frac{M_W - M_0}{M_0} \cdot 100 \quad (3)$$

where WA is weight-based water absorption (%), M_W is mass at moist state (g), and M_0 is initial mass (g).

Final thickness measurements were taken immediately prior to performing flatwise bending tests after specimens had equilibrated at 20°C and 65 percent RH. Nonrecoverable thickness swell was calculated in the same manner as water absorption as the average thickness swell for each edge. Delaminations were measured using a 0.24-mm-thick by 12.4-mm-wide stainless steel probe. Requirements for consideration as a recordable delamination was that the entire width of the probe penetrate 8 mm into a bondline. The probe in this study (0.24 mm vs. 0.3 mm) was thinner than the delamination probe specified in PS2 (APA 2011). PS2 requires that the penetration depth into the bondline must be at least 6.4 mm and that the minimum width be 25 mm (APA 2011). Moisture content (MC) was determined by removing a 125-mm-long piece from the end of five specimens from each treatment combination and calculating dry-basis MC by the ovendrying method (ASTM International 2016).

Experimental design

Data analyses were conducted using a two-factor, factorial design. Factors of interest were specimen width and AW method. In addition to the three AW methods, a set of unweathered control specimens was tested to understand the influence of specimen size for each mechanical property prior to AW treatment. LVL specimens were randomly assigned to each treatment group following sample preparation. The experimental test matrix is shown in Table 2. Two-way analysis of variance (ANOVA) was performed to examine the influence of specimen width within each treatment method. A generalized least squares model format was followed, allowing each treatment combination its own variance in the ANOVA model, as opposed to pooling variance in standard two-way ANOVA (Kuehl 2000a). An ANOVA was performed in R statistical computing software (R Core Team 2015) using the generalized least squares model format available in the nlme library (Pinheiro et al. 2017). Pairwise comparisons were performed using a Tukey honestly significant difference adjustment to correct for the increased likelihood of committing Type I error during multiple comparisons (Kuehl 2000b) using the lsmeans library (Lenth 2016). Statistical significance between differ-

Table 2.—Experimental test matrix.

		No. of specimens		
Width (mm)	Treatment	Flatwise bending	Lateral connections	Bending shear
89, 140, 286	Control	20	10	10
	AW1	20	10	10
	AW2	20	10	10
	AW3	20	10	10

ence of means was determined at the $\alpha = 0.05$ cut-off level. While deemed statistically insignificant, *P* values greater than 0.05 and less than 0.10 were interpreted as suggestive, but inconclusive evidence of a difference in means (Ramsey and Schafer 2012). Mechanical property retention was computed as the ratio of the average value after weathering to the average value for the control group for each width.

Results and Discussion

Water absorption and moisture content

Water absorption differed between AW methods and with specimen size within a given AW method (Fig. 1). The vacuum-soak procedure (AW2) resulted in the highest water absorption, which was attributed to the introduction of vacuum pressure during soaking. Specimen width was influential during AW2, exhibiting decreased water absorption with increasing width, which differed significantly between widths at the 5 percent level (Fig. 1b). All specimen widths reached MC well above fiber saturation point (FSP), commonly assumed to be 30 percent MC (Glass and Zelinka 2010).

The AW3 procedure resulted in the second highest water absorption. Absorption was greatest in 140-mm LVL, but no statistically significant difference was found between 89 and 140 mm at the 5 percent level (Fig. 1c). However, a statistically significant difference was found between 140 and 286 mm. Average MC (39% to 44%) for each width was above FSP at the completion of weathering. Water absorption from the 24-hour water soak (AW1) was small, leading to average MC at the completion of weathering (28% to 31%) near FSP. While no statistically significant difference was found between 89 and 140 mm, both widths achieved significantly higher water absorption than 286 mm at the 5 percent significance level (Fig. 1a). Variability in water absorption decreased with increasing width for AW1 and AW3 and increased with width for AW2.

Thickness swell, or the permanent increase in thickness caused by weathering (River 1994), was less than 3 percent for all specimens, and no statistically significant differences in thickness swell between specimen widths within a given treatment were determined (Fig. 2). Typical compression for plywood is around 5 percent (Kamke and Winandy 2008) and could be anticipated to be similar for LVL. AW2 produced the greatest thickness swell on average (Fig. 2b) at 2.3 percent, indicating that approximately half the compression was lost. Recordable delaminations occurred in less than 2 percent of flexure specimens. Smaller delaminations were observed in many specimens, but were typically less than 5 mm in length. Laufenberg (1982) investigated the bonding performance of LVL to LVL bondlines to determine suitability of LVL for glulam lamstock. Comparisons were made to solid sawn lumber (SSL) to SSL laminations before and after vacuum-pressure-soak-dry treatment using tension perpendicular to the bondline and block shear tests. Under the same bonding parameters, LVL/LVL bondlines exhibited lower amounts of delamination than SSL/SSL bondlines after AW treatment, which was attributed to lower internal stresses development in LVL/LVL from similar grain orientation between veneers along with lathe checks reducing stress development near the bondline (Laufenberg 1982).

Liquid water and water vapor permeability are typically greatest in the longitudinal direction of wood (Siau 1995, Glass and Zelinka 2010). Longitudinal grain only contacts the exterior environment (air and water) on two faces in LVL. The percentage of longitudinal area to total surface area increases with width when length and thickness remain constant (Table 3). Therefore, if liquid water or water vapor transport in the longitudinal direction governed moisture uptake, then an increase in moisture uptake with increasing width would be expected, which was not observed (Fig 1). While longitudinal moisture transport may be important, results from this study (Fig. 1) indicate that moisture transport in the longitudinal direction did not govern the water/water vapor uptake for the AW methods and size of flatwise bending specimens investigated.

The majority of surface area produced from radially peeled veneer that moisture must pass through for entrance into the

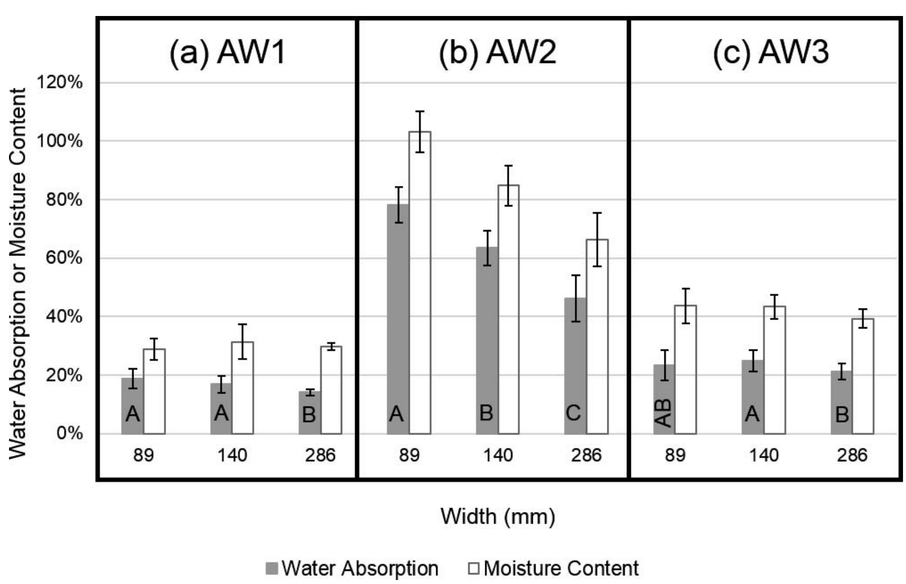

Figure 1.—Water absorption and moisture content results of three laminated veneer lumber specimen widths after the three accelerated weathering (AW) methods. Water absorption bars within the same AW method are significantly different at the 5 percent level if they do not have the same letter. Error bars represent ±1 standard deviation.

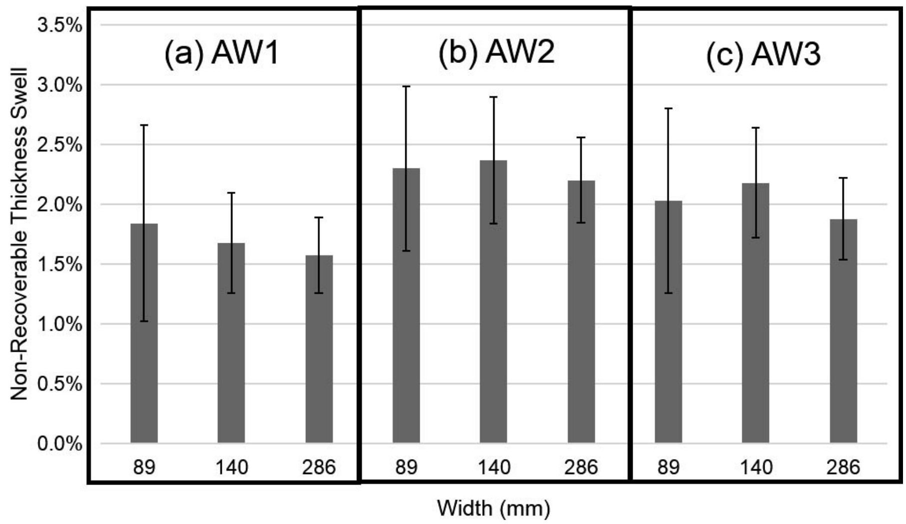

Figure 2.—Nonrecoverable thickness swell of three laminated veneer lumber specimen widths after the three accelerated weathering (AW) methods. Error bars represent ±1 standard deviation.

specimen is in the radial direction. Moisture transport in the radial direction of clear sawn wood tends to be slightly higher than the tangential direction (Olek et al. 2005). The radial direction in LVL occurs through the thickness where lathe checks from veneer peeling also provide lower resistance to moisture intrusion in this direction (Nelson 1997). When LVL was submerged in water (AW1 and AW2), water absorption decreased with increasing radial and longitudinal area (Table 3), which was much more pronounced during AW2 (Fig. 1). The available area in the tangential direction remains fixed for all specimen widths and is the only surface occupying a smaller surface area to total surface area ratio with increasing width (Table 3). This may indicate that moisture intrusion at the tangential surfaces assumes an important role, and although transport in the radial direction should be slightly faster than in the tangential direction, the adhesive bondlines may act as a barrier to moisture transport in the radial direction (Sonderegger et al. 2010). AW3 was the only method in which water absorption did not increase with specimen width, potentially indicating that the relationship between specimen size and water absorption differs between AW methods that use water immersion and those that do not.

Flexural properties

No influence of specimen size was observed for bending strength in the control group. Bending strength increased with width (Fig. 3a), but statistically significant differences between widths were absent, although there was suggestive, but statistically inconclusive, evidence that 286 mm had greater strength than 89 mm ($P = 0.061$). AW1 caused negligible bending strength losses, where the 89-mm-wide group experienced slightly higher mean bending strength than the respective control (retention greater than 100%, Fig. 3b) and no statistically significant differences in bending strength were found between specimen widths, which indicated there was no influence of specimen size. Strength loss after AW2 decreased with increasing width, resulting in 89 mm having significantly lower strength than 140 or 286 mm at the 5 percent significance level (Fig. 3c). These results coincide with those of water absorption, where higher water absorption potentially led to greater losses in bending strength. A statistically significant difference between widths indicates an effect of specimen size with AW2, since behavior differs from the control group. Bending strength loss from AW3 did not vary systematically with specimen width (Fig. 3d). No strength losses were observed for 89 mm, while 140 and 286 mm lost approximately 10 and 6 percent of their initial strength, respectively. Although differences in average strength loss were observed between widths, the differences were not statistically significant for AW3.

Table 3.—Surface area for each face in laminated veneer lumber bending specimens for each width.

	Surface area (cm^2)		
Width (mm)	89	140	286
Longitudinal	68	107	218
Tangential	581	581	581
Radial	1,356	2,134	4,359
Total	2,005	2,821	5,157
Longitudinal:total	0.034	0.038	0.042
Tangential:total	0.290	0.206	0.113
Radial:total	0.677	0.756	0.845

Bending strength reduction was generally small. Average bending strength after AW treatment was not significantly different from the control at the 5 percent level. However, there was suggestive but inconclusive evidence of a statistically significant reduction from the control for 89 mm after AW2 ($P = 0.073$). Tension failure near midspan on the bottom face was the dominant mode of failure, with only a few test specimens failing in shear. Shear failures were dispersed over the four treatment methods, and an insufficient quantity prevented statistical comparison between the two modes of failure observed.

Bending stiffness did not differ significantly between specimen widths at the 5 percent level for the control group, although, like strength, 89 mm was the lowest (Fig. 4a). No loss in stiffness resulted from AW1 for any width (Fig. 4b). Stiffness after AW2 treatment had similar behavior to the

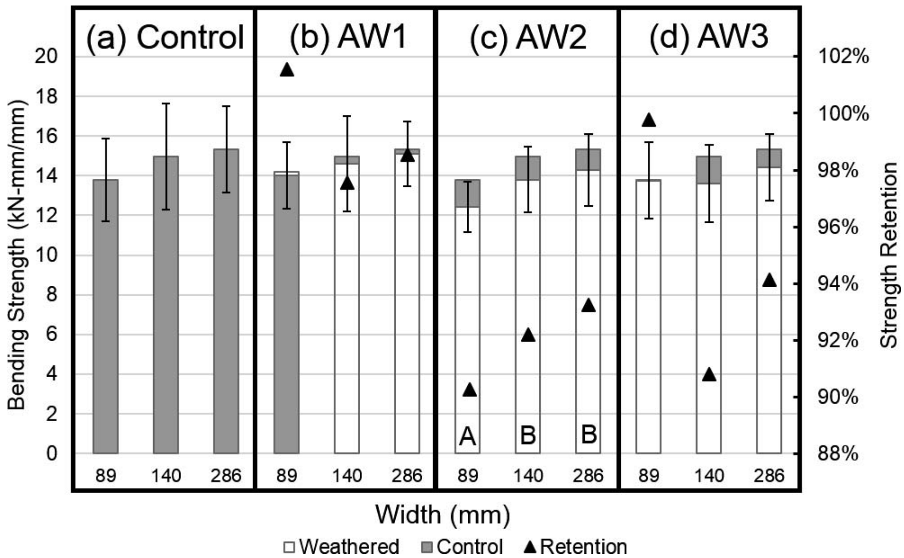

Figure 3.—Bending strength results for all laminated veneer lumber widths after the three accelerated weathering (AW) procedures. Bars with the same letter or no letter within a treatment group indicate no statistically significant difference in bending strength between thicknesses. Error bars represent ±1 standard deviation.

control, where 140 mm had the greatest stiffness and 89 mm the lowest. However, 89 mm had greater stiffness loss than the other widths, resulting in a statistically significant difference in stiffness between 89 and 140 mm (Fig. 4c). The lowest stiffness retention after AW3 was observed for 286 mm, resulting in a statistically significant difference in bending stiffness between 140 and 286 mm (Fig. 4d). Cupping was observed in 286-mm specimens after AW3, a result of differential shrinkage and swelling during cyclic MC changes. The propensity for LVL to cup increases with width (Nelson 1997). Internal stresses that promote cupping could consequently result in formation of microcracks and microdelaminations, reducing LVL's composite action and subsequently decreasing stiffness. Even so, the average retention of 286 mm was only four percentage points less than 89 and 140 mm.

Bending stiffness reduction was generally low. When each width subjected to each AW method was compared with the respective control, average bending stiffness after AW treatment was only significantly different from the control at the 5 percent level for 89 mm after AW2 and 286 mm after AW3, both of which lost approximately 7 percent of their initial stiffness after AW treatment. Suggestive, but inconclusive evidence of a difference in stiffness for 286 mm after AW2 was observed ($P = 0.089$).

Bending shear properties

An influence of specimen size on bending shear strength was observed in the control group. The 286-mm samples had significantly greater bending shear strength than 89 or

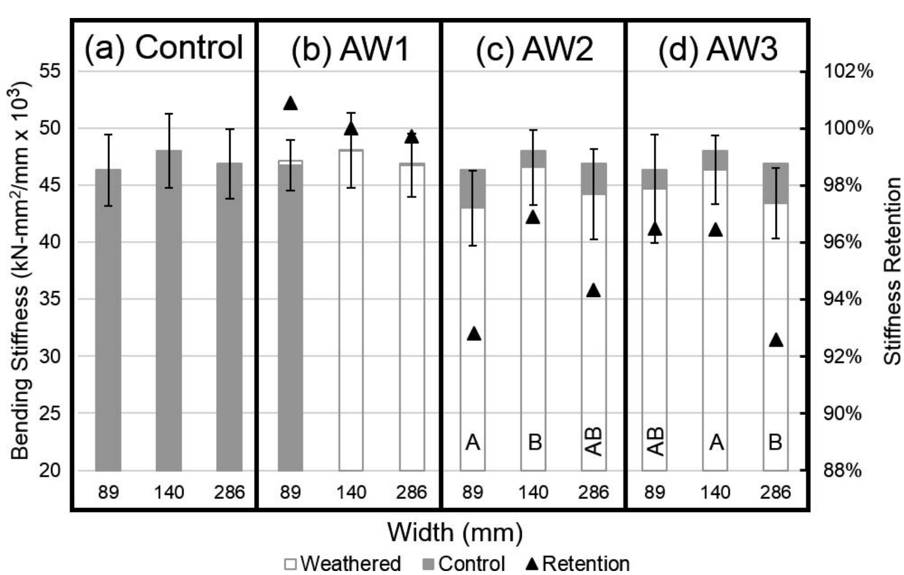

Figure 4.—Bending stiffness results for all laminated veneer lumber widths after the three accelerated weathering (AW) procedures. Bars with the same letter or no letter within a treatment group indicate no statistically significant difference in bending strength between thicknesses. Error bars represent ±1 standard deviation.

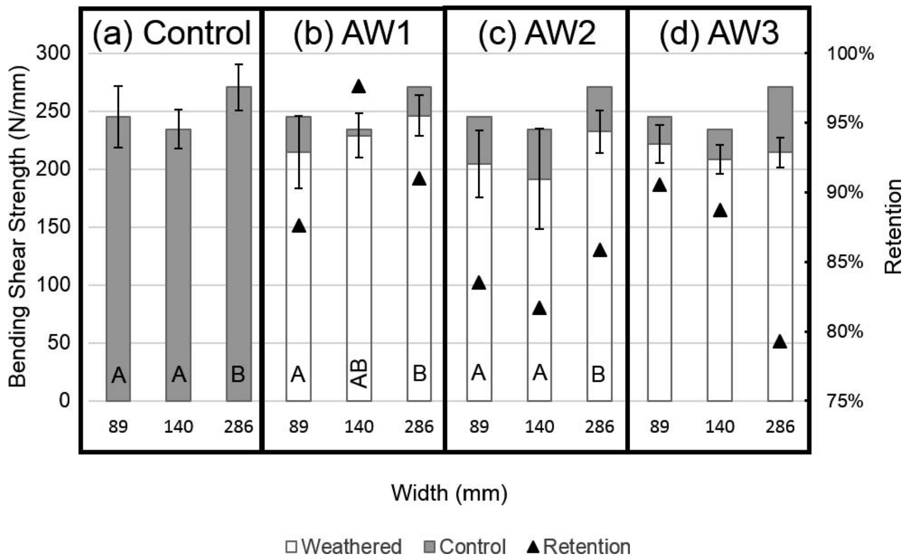

Figure 5.—Bending shear strength results for all laminated veneer lumber widths after the three accelerated weathering (AW) procedures. Bars with the same letter or no letter within a treatment group indicate no statistically significant difference in bending strength between thicknesses. Error bars represent ±1 standard deviation.

140 mm (Fig. 5a). The 140-mm specimens had the greatest bending shear retention after AW1, resulting in no statistically significant difference between 140 and 286 mm (Fig. 5b). Since the control group exhibited a statistically significant difference between 140- and 286-mm specimens, the behavior after AW1 indicates an influence of specimen size on bending shear results. The AW2 treatment method, which with the exception of water temperature was the same method specified in the standard (ASTM International 2014) for assessing bending shear strength after AW treatment, led to the greatest average loss in bending shear strength of any AW procedure (Fig. 5c). Consistent reductions between widths after AW2 resulted in the same behavior of the control group, where 286 mm had significantly greater bending shear strength than the other widths at the 5 percent significance level. Bending shear strength retention after AW3 was similar between 89 and 140 mm, which was approximately 10 percentage points greater than 286 mm (Fig. 5d). Higher losses in shear strength in 286 mm meant statistically significant differences between specimen widths were absent. These relationships varied from the control, illustrating an influence of specimen size. Low retention in the 286-mm group after AW3 is partially attributed to the cupping that occurred in these specimens as a result of cyclic MC changes. The lowest variability for all specimen widths was observed after AW3. Compared with the respective control, 89 and 140 mm experienced statistically significant reductions in bending shear strength after AW2, along with 286 mm for each AW procedure.

ASTM D5456 suggests bending shear tests are useful for evaluating bond quality for product optimization or quality assurance but does not provide a required bending shear strength retention. Instead, target strength retentions are recommended to be based on similar products that have satisfied relevant durability requirements (ASTM International 2014). Hayashi et al. (2002) evaluated 38.1-mm-thick by 89-mm-wide LVL of seven wood species exposed outdoors in Japan for 6 years, randomly selecting a subset of the exposed specimens on an annual basis to track degradation. No correlation was found between bending shear strength and outdoor exposure period within the limits of the experiment (Hayashi et al. 2002). Paridah et al. (2012) investigated bending shear strength of LVL (40-mm thick by 50-mm wide) produced with bintangor (*Callophyllum* sp.) rotary-peeled veneer and phenol formaldehyde adhesive after one, two, five, or ten boil-dry cycles. One boil-dry cycle resulted in average retention of 86.8 percent, two cycles resulted in 76.3 percent retention, and both five and ten cycles resulted in 73.6 percent retention (Paridah et al. 2012). Neglecting differences in species and adhesive bonding, when averaged over width, one boil-dry cycle was more severe than the AW1 and similar in severity to AW3, while retention after AW2 fell between one and two boil-dry cycles. It should be noted that retention after AW2 would likely have been smaller had the higher water temperature specified in the standard (APA 2011) been used.

Lateral connections

Lateral connection strength depends on dowel bearing strength of both the LVL and OSB, fastener diameter, and bending yield strength, and penetration depth of the fastener in both members (Breyer et al. 2015). Parameters were equivalent between specimen widths in the unweathered state, meaning connection strength was not expected to differ between specimen widths. This was verified in the experimental data (Fig. 6a). No specific trend of connection strength with respect to specimen width was observed for AW1, and although 286 mm had an average 7 percent lower retention than 140 mm, statistically significant differences were absent (Fig. 6b). AW2 was the only method to produce statistically significant differences in connection strength between specimen sizes (Fig. 6c). Increased connection strength was observed in 89-mm specimens, while 286 mm was reduced by 8 percent from the control, resulting in a statistically significant difference between the two widths. The 89- and 140-mm groups had similar strength retention after AW3 and were 5 percent greater than 286 mm (Fig.

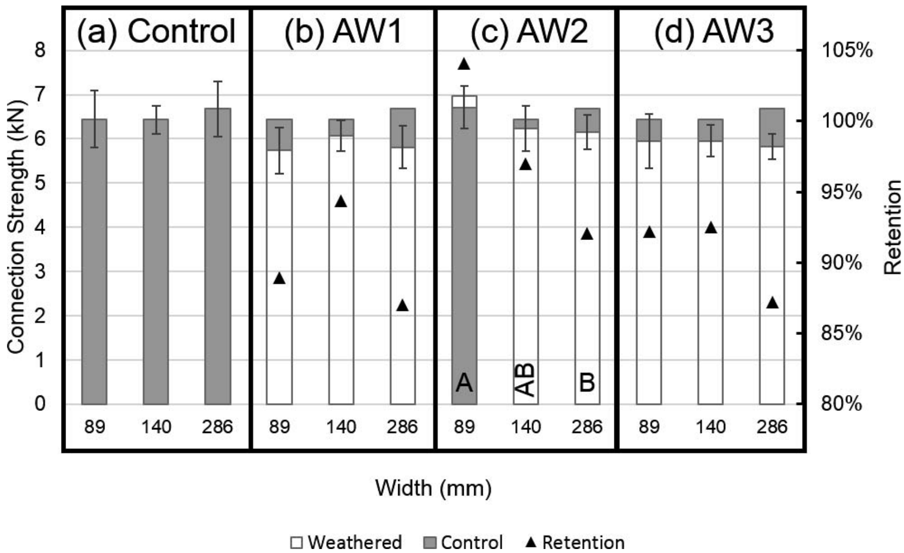

Figure 6.—Connection strength results for all laminated veneer lumber widths after the three accelerated weathering (AW) procedures. Bars with the same letter or no letter within a treatment method indicate no statistically significant difference in bending strength between thicknesses. Error bars represent ±1 standard deviation.

6d). However, no significant differences were detected between specimen widths. ASTM D5456 requires 75 percent average retention after a 24-hour water soak to pass the lateral edge nail durability requirements (ASTM International 2014). All treatment combinations evaluated in this study exceeded the minimum requirement by 10 percentage points or more. Compared with each respective control, no statistically significant difference in connection strength was found after AW2. The AW1 procedure resulted in lower connection strength in 89- and 286-mm specimens compared with the controls, at the 5 percent significance level. The only statistically significant reduction in connection strength from the control for AW3 was for 286 mm.

Sheathing to solid sawn lumber (SSL) connections made with SSL in the green state result in gap formation between the two members, since SSL experiences shrinkage from green to dry (<15% MC) conditions (Mohammad and Smith 1996). Mohammad and Smith (1996) found that lateral connection strength of OSB/SSL connection fabricated with green SSL main members decreased nearly 10 percent after the SSL was brought to 5 percent MC, compared with when tested in the green state. The configuration in this study connected members when LVL was at elevated MC and the OSB was dry. The nail heads remained in their original position on the OSB surface as LVL dried down from FSP, potentially creating a gap between the two members. Gaps between members could result in decreased bearing length in the LVL member along with shifting the bending moment distribution in the nail, effectively reducing connection strength (American Wood Council 2015). The lowest strength retention for each AW group was consistently in 286-mm specimens. If a constant swelling coefficient is assumed for LVL in the tangential direction, then total shrinkage in this direction increases with width for the investigated conditions (above FSP to approximately 10% MC), meaning gap formation between OSB and LVL should be greatest for 286-mm LVL, although gap size was not measured.

Summary and Conclusions

The purpose of this study was to determine the influence of specimen size during durability assessment of LVL. Edge effects, or the susceptibility to moisture intrusion at the edges, were investigated by subjecting LVL of varying widths to three accelerated weathering (AW) procedures while holding thickness and length constant. The three AW methods were chosen to investigate the influence of specimen size over different means of exposure to the degrading mechanisms of moisture, since this information would be useful to future work seeking to more accurately represent durability of actual-size specimens in actual adverse service conditions. In addition, three mechanical properties were evaluated, since past research suggested that multiple tests may be necessary to fully assess durability attributes (Alexopoulos 1992).

In terms of water absorption, the method using vacuum soaking (AW2) led to the highest level of water absorption and illustrated a clear influence of specimen size, where water absorption decreased significantly with increasing specimen width. The relationship between water absorption and specimen size from the AW1 and AW3 procedures differed from AW2 and each other, indicating that the influence of specimen size on water absorption depends on the means in which MC increases were inflicted. Both nonrecoverable thickness swell and the number of recordable delaminations were small and subsequently were not noticeably influenced by specimen size.

No AW method evaluated resulted in statistically significant, or likely practically significant, difference in flatwise bending properties from the unweathered control group for any specimen size. The bending shear test is designed to promote high interlaminar shear stresses and provide an indication of moisture durability of the wood-adhesive bondline. The relationship between specimen size and bending shear strength differed for each AW method. With the exception of one AW method, nailed connection properties did not exhibit an influence of specimen size. However, the widest specimens consistently resulted in the lowest connection strength retention. The AW2 and AW3 procedures both consisted of multiple cycles of wetting and drying; hence, the moisture gradients leading to hygrostresses were introduced in a cyclic manner. Vacuum-pressure soaking in AW2 produced significantly greater levels of water absorption across all specimen widths in six cycles than the water spray/high humidity did in the AW3 method over 56 cycles. In addition, the AW2 procedure used a higher drying temperature to reduce MC. While both the AW2 and AW3 procedures introduced cyclic wet/dry conditions, the influence of specimen size differed between the two methods. When considering average mechanical property retention across specimen widths, retention of flexural properties and bending shear strength were lower after the AW2 method, suggesting that fewer cycles at more severe conditions were more detrimental on mechanical property loss than more cycles at milder conditions (i.e., AW3). One wet/dry cycle was used for the AW1 procedure, which resulted in greater mechanical property retention and lower water absorption on average compared with the AW methods using cyclic conditions.

In general, specimen size influenced moisture durability of LVL differently depending on the physical/mechanical property evaluated and the AW method. Lack of consistent trends between specimen size and AW methods indicates that moisture durability characterization is complex and that future work seeking to predict performance of actual-size specimens under actual adverse service conditions should consider specimen size when assessing durability attributes.

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