Effect of Knots and Related Grain Deviation on the Rolling Shear in Dimension Lumber Used in Cross-Laminated Timber Transverse Core Layers

Thibault Grandvuinet
Lech Muszyński

Abstract

Cross-laminated timber (CLT) technology has the potential for utilization of lower grades and underused species of lumber, because the core layers perpendicular to the principal loading direction transfer loads through shear, which is not correlated to the grade of lumber. Currently the product standard specifies the minimum grade requirements for all lumber to be used as CLT laminations. In this study, the effect of the presence of knots in the transverse core layer of CLT billets was examined in matched CLT samples where the heavy presence of knots and the related grain disturbance in the transverse core layer were the only variables compared with knot-free reference. All samples were tested as short beams in three-point bending and all failed in rolling shear in the transverse core layer. The presence of knots had no measurable effect on the shear capacity or stiffness of the tested CLT beam samples.

Cross-laminated timber (CLT) is an engineered structural composite panel usually consisting of three to nine layers of dimensioned lumber arranged perpendicular to each other. It is not merely a new structural material but a new building technology in which CLT panels are used as prefabricated load-bearing walls, floors, and roofing elements. This technology is being proposed as a new solution for tall wood building construction to compete with traditional concrete and steel building construction.

The cross-lamination of layers provides for dimensional stability of CLT elements. In this arrangement, however, the layers oriented perpendicular to the main loading direction contribute little to compression capacity of walls. In floor elements, the core layers perpendicular to the major strength axis transfer shear stress between the layers, but because of the discontinuity of the laminations, do not transfer normal bending stress (Fellmoser and Bla 2004, Mohammad et al. 2012, Ross et al. 2012, Zhou et al. 2014). Shear in the radial–tangential plane is often referred to as rolling shear. A diagram illustrating the effect of the rolling shear in CLT layups is shown in Figure 1.

In certain applications, with supports at short spans, design of the CLT floor assemblies may be actually controlled by the rolling shear strength of the cross-layer (e.g., Fellmoser and Bla 2004, Mohammad et al. 2012, Hochreiner et al. 2014) in combination with tension perpendicular to the grain (Nie 2015). Both properties are among the lowest strength characteristics of small, clear, straight-grained wood (3% to 5% of ultimate tensile stress in direction along the grain). Interest in rolling shear strength in dimension lumber was marginal until the emergence of CLT. Rolling shear is not the easiest property to measure, and it received only limited coverage in the literature (Muthe and Ethington 1968, Norlin et al. 1999, Aicher and Dill-Langer 2000, Fellmoser and Bla 2004, Zhou et al. 2014, Nie 2015). What has been documented was that the rolling shear strength and stiffness of the cross-layer in CLT floor panels is related to the species, density, growth ring orientation, and manufacturing parameters (e.g., presence of

The authors are, respectively, Graduate Student, École Nationale Supérieure des Technol. et Industries du Bois (ENSTIB), Épinal, France (t.grandvuinet@gmail.com); and Professor, Dept. of Wood Sci. and Engineering, Oregon State Univ., Corvallis (Lech.Muszynski@oregonstate.edu [corresponding author]). Thibault Grandvuinet is currently Wood Engineer, Atelier Volet SA, Lausanne, Switzerland. This paper was received for publication in August 2016. Article no. 16-00042.

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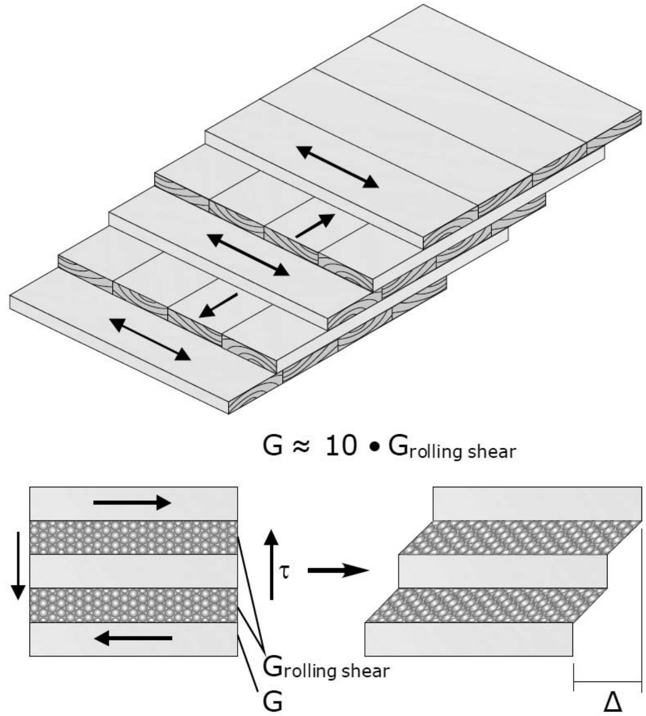

Figure 1.—Diagram illustrating rolling shear in the transverse core layers of cross-laminated timber panels (Ross et al. 2012).

edge bonding, clamping pressure, size, and geometry of the laminate's cross-section), but there is no evidence for a meaningful correlation with the grade of lumber, whether established by visual or machine grading. On the contrary, Hochreiner et al. (2014) have demonstrated that capacity and failure modes of square 1.2 by 1.2-m CLT panels loaded with a center force were dominated by rolling shear in the core layer triggered at the same load level regardless of the grade used for the laminations. This is consistent with earlier reports on the insignificant effect of knots on shear along the grain (Gupta et al. 2004).

Thus the CLT technology, with substantial volume of the core material transferring loads through rolling shear, is perceived as a potential for utilization of lumber of lower grades and underused species.

The North American product standard for CLT (ANSI/APA PRG 320) prescribes lumber grades for all layers in the layup (ANSI/APA 2012) even though there is no evidence that the rolling shear strength is in any way related to the grade as determined primarily by the number, size, and position of knots in the laminations.

The aim of this study was to determine the effect of knots present in the core layer lamellas of three-layer CLT panels on their flexural stiffness and ultimate capacity. The approach was to measure the effect of knots on flexural properties of CLT layups following the standard short-span bending tests ASTM D198-13 (ASTM International 2015) used to determine panel grade and design purposes (per ANSI/APA PRG 320). For expediency of a proof-of-concept study, boundary test conditions were investigated.

Materials and Methods

The center-point bending tests were performed following sections 4 through 11 in the ASTM D198-13 (ASTM International 2015) on short beams (span-to-depth ratio of 5.95) extracted from 570 by 610-mm three-layer Douglas-fir CLT billets produced in the lab, with the exception that the bearing blocks were rectangular instead of rounded, with a radius two to four times the specimen depth. This arrangement was deemed sufficient for short-span beams where shear failure in core layers was expected. The test setup is shown in Figure 2.

Nominal 51 by 102-mm (2 by 4-in) Douglas-fir (*Pseudotsuga menziesii*) lumber kiln-dried to 12 percent moisture content (MC) was obtained from a local sawmill. All laminations were conditioned at 20°C and 65 percent relative humidity for at least 48 hours before manufacturing of the CLT billets to ensure full moisture equilibration within 3 percent of the target 12 percent MC. At the target MC, laminations were planed to 28.5 ± 0.2 mm within a few hours of layup and pressing. Annual ring orientation of the core laminations was random, roughly reflecting the distribution determined for the delivered pack (Table 1).

The billets were face-bonded with phenol resorcinol formaldehyde adhesive (resin [CASCOPHEN LT-75C] and a hardening agent [CASCOSET FM-282C] mixed at a resin-to-hardener ratio of 100/15–17) donated by Hexion, with a spread rate of 270 to 490 g/m^2. The narrow edges were not bonded. The billets were pressed at 0.69 MPa in a small-scale pneumatic press.

The laminations designed for the transverse core layer were carefully selected from longer pieces to obtain one-half of the length substantially charged with knots and the other half almost clear (Fig. 3). These laminations were arranged in a way that each of these 570 by 610-mm billets could be sawn into two short beams of width of 305 mm (12 in) and span-to-depth ratio falling between 5 and 6, as required by the short-beam bending test method in ASTM D4761-13 (ASTM International 2013). One set of these beams included a core layer heavily charged with knots and the other almost clear, whereas in all other aspects the core

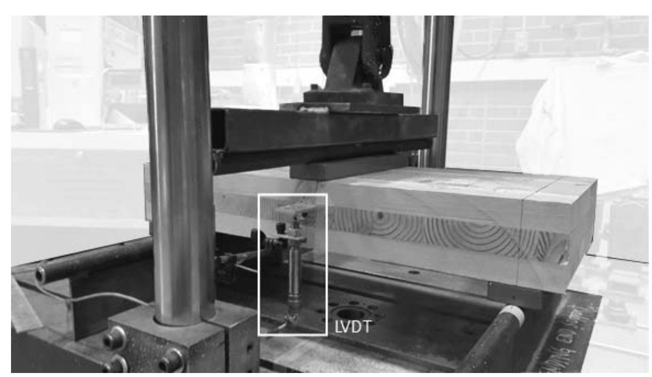

Figure 2.—Schematic diagram of the short-span bending tests setup following ASTM D198-15 (ASTM International 2015). LVDT = linear variable differential transformer.

Table 1.—Growth ring orientation in the lumber used for laminations.

	No. (%)
Flat sawn	40 (53)
Rift sawn	33 (43)
Quarter sawn	3 (4)
Total	76 (100)

pieces in both beams would be perfectly matched. There were 12 beams in each set.

Although neither situation represents a realistic distribution of knots in the core layer made of No. 2 or No. 3 lumber, they were consciously selected as providing opposite extremes, the boundary of possibilities one could practically consider, useful for a test aimed at providing a proof of the concept.

Center-point bending tests were performed at a cross-head movement of 0.250 mm/min until failure. The mid-span deflection of the neutral axis (d) was measured using a 10-mm linear variable differential transformer (LVDT). The setup is shown in Figure 2.

As the test progressed beyond the linear elastic region, the loading procedure was paused and the LVDT disengaged to protect it from damage during the specimen failure. After disengaging the LVDT, the loading was resumed until failure. From this point the cross-head position was used as a proxy for deflection. Consequently, although the actual load-displacement curves were used to calculate the stiffness (approximated here as the load-deflection curve slope $\Delta P/\Delta d$), load-position curves were produced to illustrate the responses of individual specimens to the loading regime from the beginning to the ultimate fracture. Since the rolling shear stiffness of the knotty sections was not known, meaningful comparison of the composite modules and ultimate bending stresses could not be conducted. Instead, in the analysis the ultimate loads (P_{max}) and the load-deflection curve slopes ($\Delta P/\Delta d$) are compared.

The failure mode of each specimen was observed and recorded.

Results

All specimens tested in this study broke by rolling shear failure in the core layer at various positions of the shear span (Figs. 4 and 5).

Typical load-deflection curves for CLT beams with clear and knotty core layers are shown in Figure 6. In these graphs the position of the cross-head was used instead of the actual deflection to provide full visual record of the specimen response to load up to the fracture point. The short set of straight lines to the left of the curves represents actual deflections of the neutral axis of the beams as recorded with the LVDT and used for calculation of the load-deflection curve slope ($\Delta P/\Delta d$). The LVDT, however, was removed before the final stage of loading that led to failure.

Load and deflection data for specimen A6 (clear core) have not been registered because of equipment failure.

Load-deflection curves for all specimens are presented in Figure 7.

The ultimate loads (P_{max}) and the load-deflection curve slopes ($\Delta P/\Delta d$) for individual specimens are presented in Table 2.

Summary results: mean ultimate load and mean load-deflection slope values and the related coefficients of variation are summarized in Table 3.

Comparing the distributions of P_{max} values, it is clear that there is virtually no difference between the shear capacity of beams including core layers composed of clear and knotty

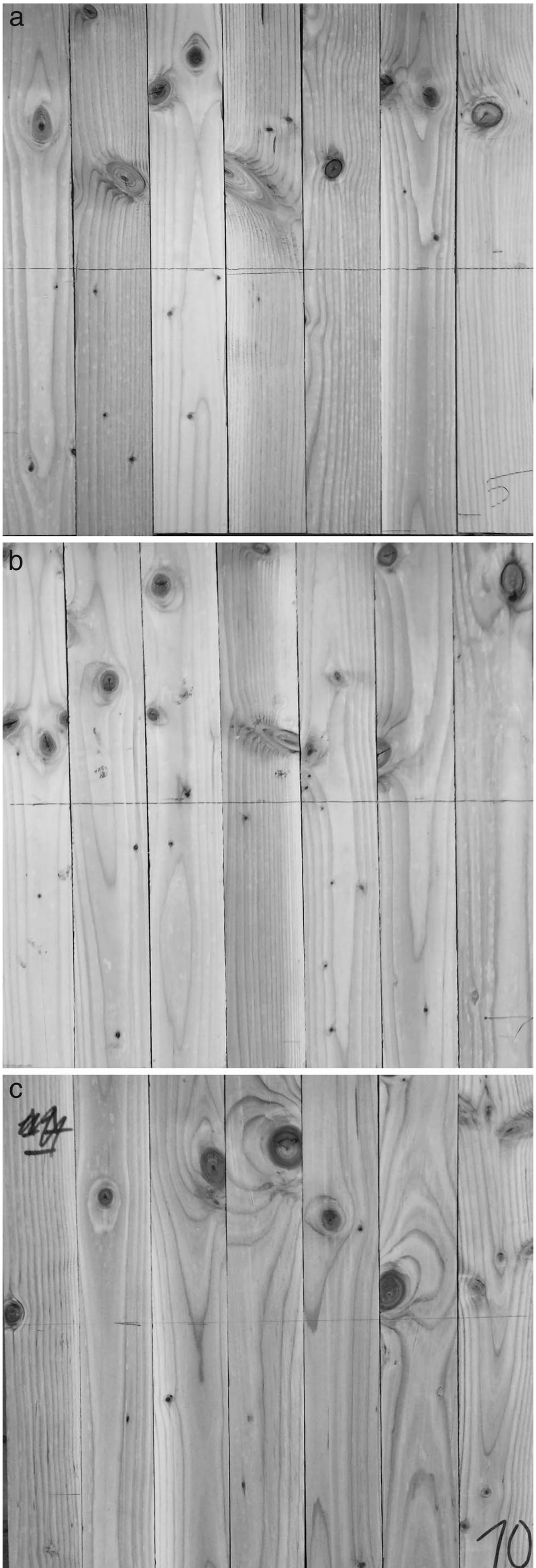

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Figure 3.—Examples of the arrangement of knots in the core layer of test billets.

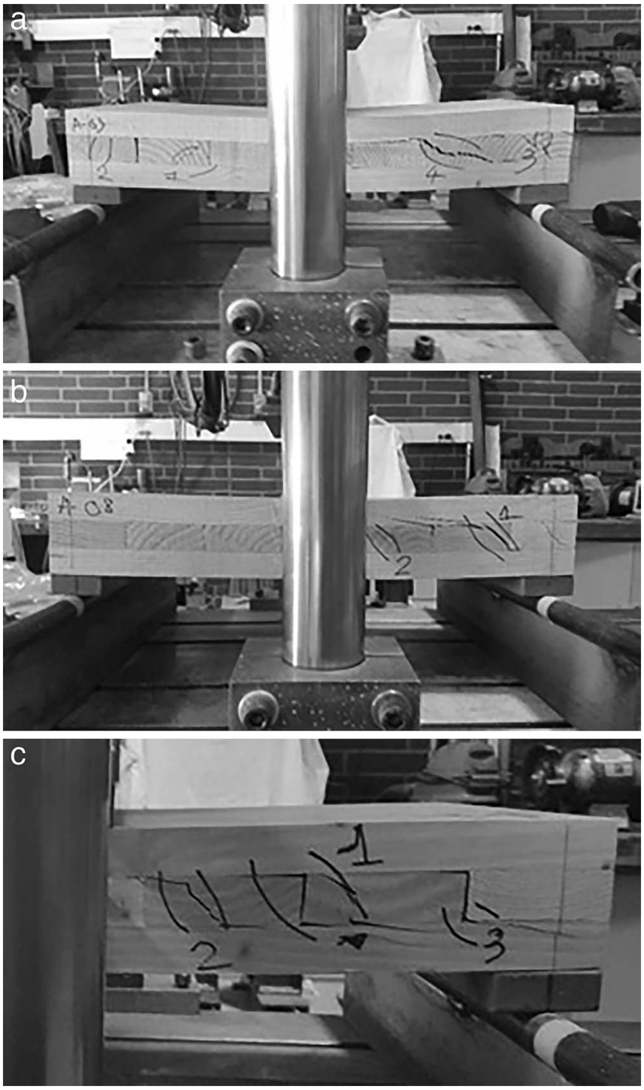

Figure 4.—Typical rolling shear failure modes in the short beams with clear cores.

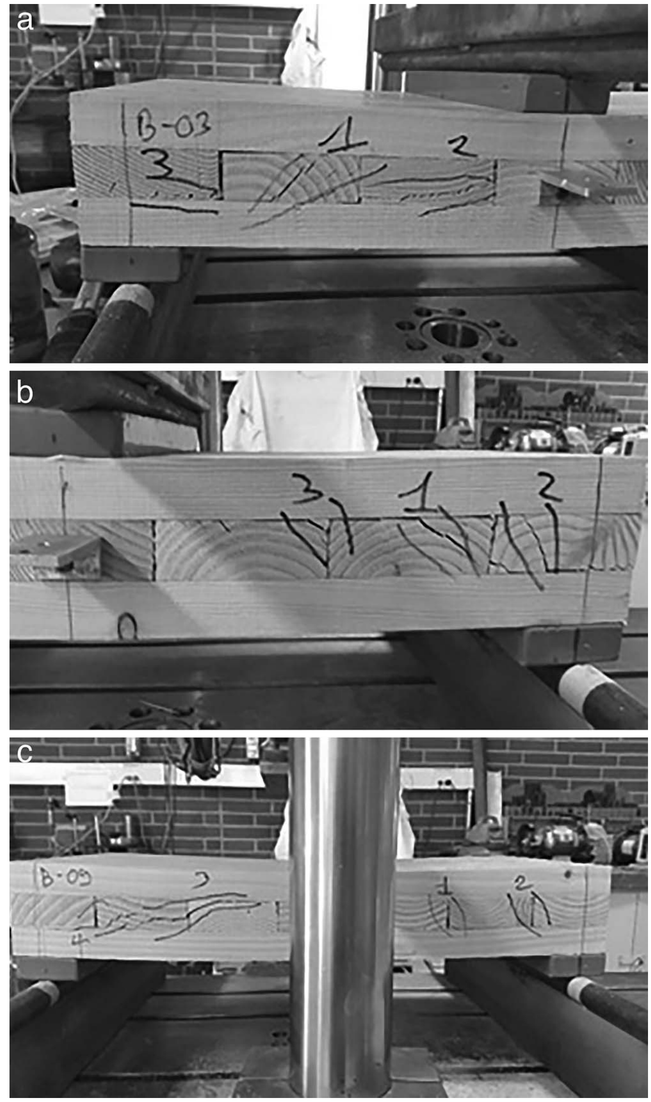

Figure 5.—Typical rolling shear failure modes in the short beams with knotty cores.

laminations. If anything, the beams with knotty cores appear slightly stiffer than these with clear cores, although the $\Delta P/\Delta d$ values show higher variability than P_{max} values.

Paired sample t tests for the P_{max} and $\Delta P/\Delta d$ values determined on specimens with clear and knotty cores, respectively, showed no statistically significant differences between the paired specimens at 0.95 significance level (specimen 6 has been excluded from the analysis).

Table 2.—Test results for individual specimens.

	Clear core (A specimens)		Knotty core (B specimens)	
	P_{max} [kN]	$\Delta P/\Delta d$ [kN/mm]	P_{max} [kN]	$\Delta P/\Delta d$ [kN/mm]
1	88.3	20.3	90.4	25.1
2	97.3	23.3	112.5	28.4
3	95.4	22.6	90.6	25.2
4	87.0	24.7	82.0	24.3
5	83.7	26.5	93.5	29.7
6	—	—	82.6	27.4
7	88.1	22.5	92.0	27.3
8	95.7	26.3	88.7	28.7
9	91.3	25.2	105.5	22.7
10	83.7	17.2	90.0	19.5
11	73.0	16.3	86.1	25.4
12	73.5	14.9	79.6	19.6

Discussion

One of the possible explanations of this outcome is that the rolling shear is failure mode ''preferring'' clear straight-grained wood, where failure can easily propagate through regularly arranged rows of tracheids or along the earlywood/

Table 3.—Summary test results.

Specimen	P_{max} mean [kN]	P_{max} CV[a] (%)	$\Delta P/\Delta d$ mean [kN/mm]	$\Delta P/\Delta d$ CV (%)	Sample size
Clear core (A specimens)	87.0	9	21.8	19	11
Knotty core (B specimens)	91.1	10	25.3	13	12
t values (paired samples)[b]	0.0334*		0.0025*		

[a] CV = coefficient of variation.
[b] * = $P < 0.05$.

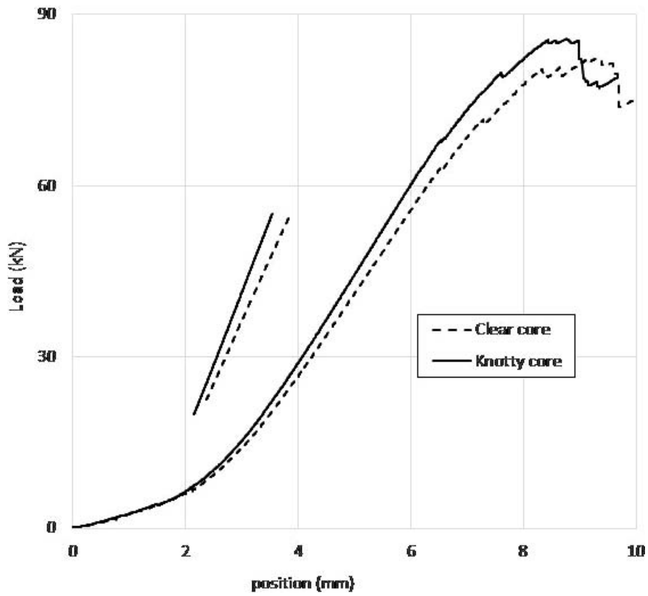

Figure 6.—Typical load position curves for cross-laminated timber beams with clear core layers (A specimens) and knotty core layers (B specimens).

latewood boundaries, which present easy shear fracture paths. The presence of knots and related grain angle deviations disturb this regular cell structure arrangement and are likely to make the propagation of shear fraction through the material more difficult.

The presence of large knots on the flat surfaces may compromise the quality of the adhesive bonds between lamellas in adjacent layers, increasing the local presence of cross-grains and extractives on the surface. Apparently, these two opposing effects offset each other and the net effect on the rolling shear capacity of the short panels

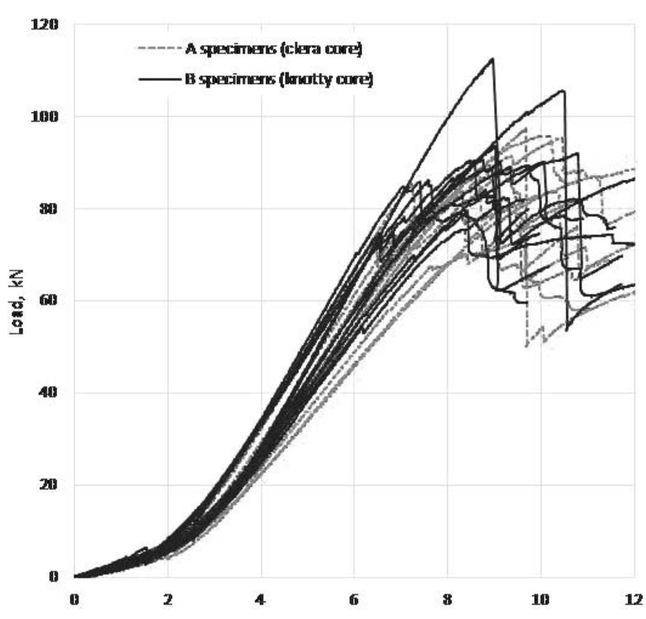

Figure 7.—Load position curves for cross-laminated timber beams with clear (A specimens) and knotty core layers (B specimens).

loaded in three-point bending is negligible. This negligible effect of the heavy presence of knots in the transverse core layer on the stiffness of the assemblies is more complicated and no easy explanation can be offered without additional analysis.

Limitations

It is important to note several substantial limitations to this study. The most important is the fact that the presence of knots and the related disturbed grain is just one of many criteria used to grade structural lumber. Other characteristics evaluated include slope of grain away from the knot vicinity, presence of wane, shape distortions (particularly crooked pieces), and cutting marks. Most of these characteristics would be unacceptable in the core layers of CLT.

It follows that although this study proves that the heavy presence of knots and the related grain deviations in core laminations perpendicular to the main loading direction do not affect the engineering characteristics of CLT panels subjected to short-span bending conditions, it does not prove that lower grades of lumber, as they are presently defined, are suitable for the core layers without further limitations. Further, although the presence of knots is related to substantial local grain angle deviation, the effect of grain angle alone has not been isolated in this study. This may and should be a subject of a separate study.

Finally, this study was limited to three-layer CLT specimens with one core layer in the middle plane. Although a valid hypothesis can be made that a similar effect would be expected with knotty transverse core layers in five-, seven-, and nine-layer layups, such a hypothesis should be confirmed with an experimental study.

Opportunity

Should the effect described in this study be confirmed for CLT layups including a larger number of layers and constructed with a larger variety of commercially important species, it would be possible to specify unique grading criteria for the transverse core layers of CLT. The glulam industry may serve as an example, or a precedent, for defining special lumber-grading criteria for a specific product. Special grade rules for transverse core layers in CLT allowing certain carefully defined features not acceptable in other structural grades would help promote and add value to lumber currently considered unacceptable for any structural applications.

Conclusion

The outcome of this study is not only in agreement with earlier observations that the rolling shear response of wood does not depend on its grade, but demonstrates that even a heavy presence of knots in core laminations perpendicular to the main loading direction does not affect the engineering characteristics of CLT panels subjected to unfavorable short-span bending conditions.

This finding is of major importance for the perspective of utilization of low-quality lumber downgraded because of the presence of knots and related grain deviations in the core layers of structural CLT panels. Presence of substantial shape distortions and cutting marks would still be unacceptable.

If future work leads to determination of the effects of the slope of grain and the presence of wane, it may be possible to specify unique grading criteria for the transverse core layers of CLT that would promote added value to lumber currently considered unacceptable for structural applications.

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