INFLUENCE OF MACHINING PARAMETERS ON THE TENSILE STRENGTH OF FINGER-JOINTED SUGAR MAPLE LUMBER

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ABSTRACT

Presently, finger-jointed softwood lumber is used in manufacturing of structural engineered wood products such as glued laminated (glulam) beams and prefabricated wood I-joists. However, the use of high-density hardwoods appears to be an attractive alternative material to achieve a higher performance of these products. Certain machining parameters have to be controlled in order to produce suitable gluing surfaces and to optimize the finger-jointing process. The main objective of this study was to evaluate the effect of machining parameters on the ultimate tensile strength parallel to grain (UTS) of finger-jointed sugar maple dimension lumber. Three different chip-loads and three cutting speeds were used as variables. Based on test results, the cutting speed appeared to influence the UTS the most. The best average UTS (47.1 MPa) of finger-jointed sugar maple specimens was achieved with a chip-load of 0.60 mm and a cutting speed of 2726 m/min (rotation speed of 3250 RPM and feed speed of 11.7 m/min).

Keywords: Finger-jointed lumber, machining, engineered wood products, sugar maple, hardwood.

INTRODUCTION AND BACKGROUND

Finger-jointing allows using low-grade dimension lumber to obtain high-quality structural products with enhanced resistance and visual appearance by removing undesirable defects and producing lumber stock of greater lengths than common sawn timber. Finger-jointed lumber is mainly used in manufacturing of structural engineered wood products (EWP) such as glued laminated (glulam) beams and wood I-joists. The success of the EWP relies on a more intelligent use of wood fiber, which allows reaching higher strength, dimensional stability, and reduced variability of the end product.

The manufacturing process of glulam and I-joists requires a constant feed of high-quality finger-jointed stock. With the increasing demand forecast for EWP over the next 5 years (APA 2006), the declining wood fiber availability on North American landscapes since 1990 (Schuler et al. 2001) and Quebec Chief Forester's decision to reduce harvesting woods of the spruce-pine-fir (SPF) group by 23% beginning in 2008 (Bureau du Forestier en Chef 2006), one can foresee the increasing gap between demand for EWP and the softwood fiber supply. In order to reduce the deficit, some studies have already been conducted looking at the use of hardwood species (Chui and Delahunty 2005; Manbeck et al. 1996; Verreault 2000), structural composite lumber, or fiber-reinforced polymers in EWP (Hernandez et al. 1997; Pelvris and Triantafillou 1992; Spaun 1981).

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Quality and volume of lumber, as well as its machining parameters, are important elements of the manufacturing process in order to achieve the maximum capacity of the engineered product. Numerous studies have been conducted on finger-jointed lumber of softwood species that are commonly approved in North American construction standards, but few are those relating to the machining parameters and finger-jointing of hardwoods. However, the use of high-density hardwoods appears to be an attractive alternative material for the EWP due to their outstanding strength properties. In order to provide a high-performance glued joint, a smooth and undamaged contact surface is required (Sellers Jr. et al. 1988). Poor machining practices damage the wood fibers and generate rough surfaces, which impair full contact, restrain the adhesive flow, and increase the required amount of adhesive for wetting the gluing surface properly. To ensure quality of the finger-jointing process, the gluing surfaces should be machined with well-sharpened tools under prescribed machining parameters, such as chip-load, rotation speed of the cutting heads, feed speed, and cutting speed (Mohammad 2002).

The chip-load is defined as the amount of material removed by each revolution of the spindle, and this parameter should be adequate to prevent the cutting tools from burning and to provide a nice finish to the contact surface. An increase in chip-load creates an increase in the applied pressure by the cutting tools, causing an excessive heat on the wood surface and wood tear-out (Bustos 2003). On the other hand, a too low chip-load implies that the cutting tools will rub the wood and will not produce an adequate cut, because the gluing surfaces are negatively affected by the heat created by the friction (Hernández and Naderi 2001; Hernández and Rojas 2002). Hernández and Naderi (2001) mention that the sugar maple gluing capability decreases with an increase of the cutting tool width. Furthermore, a better shear resistance along the glue lines has been observed when using knives with a smaller rake angle (angle of attack).

There is a significant effect of the knives' wear on the sugar maple gluing capability (Hernández and Rojas 2002). In regards to this effect, Reeb et al. (1998) evaluated the finger-joints quality after 4, 6, and 32 hours of knife wear. Test results on finger-jointed ponderosa pine showed a direct relation between the damaged cells depth and the knife wear. The gluing surface becomes rough and irregular with a prolonged use of knives. It has been concluded that the knife's maintenance is a crucial factor in manufacturing high-quality gluing surfaces.

Bustos et al. (2004) studied the influence of machining parameters on the ultimate tensile strength (UTS) of finger-joints made of black spruce lumber using three chip-loads and three cutting speeds. In most cases, results showed lower UTS for all three chip-loads when using high cutting speeds. It has been concluded that cutting speeds greater than 2932 m/min are not advisable, and a speed in the range of 1676 and 2932 m/min appears to produce satisfactory results for the three studied chip-loads. The best results have been obtained at a cutting speed of 1676 m/min and a chip-load of 0.86 mm. It remains unclear if cutting speeds lower than 1676 m/min would produce better results as it was the lowest speed studied. The adhesive used by Bustos et al. (2004) was a two-component system consisting of an Isoset® UX-100 polyurethane prepolymer mixed with an Isoset® WD3-A322 emulsion polymer, a water-based adhesive of the polyurethane family. Wood is a porous material and it is capable of absorbing a high quantity of water and forming a strong bond. Therefore, water-based adhesives seem to be a logical choice for wood bonding (King and Chen 2001). In this study, an Isoset® UX-200/WD3-A200 adhesive from the same family of polyurethanes was used for finger-jointing, because it is currently used by a number of EWP producers.

The main objective of the present study was to evaluate the effect of machining parameters on the finger-jointing process of sugar maple using an Isoset® UX-200/WD3-A200 adhesive, in an attempt to define an operating envelope where appropriate finger-jointed product performance could be achieved. Specifically, the ultimate tensile strength parallel to grain of finger-jointed sugar maple lumber was studied by varying the chip-load and the cutting speed of the cutting heads and compared with SPS-1 and SPS-4 special products standards requirements (NLGA 2003a, 2003b) for finger-jointed softwood lumber and with results obtained by Bustos et al. (2004) for finger-jointed black spruce with a similar adhesive.

MATERIALS AND METHODS

The raw materials used for this project were 102- × 152-mm (4- × 6-in.) blocks of unseasoned sugar maple heartwood harvested in St-Raymond (Quebec, Canada) and intended for the manufacturing of pallets. A total volume of 22.3 m^3 (4192 pmp) in lengths ranging from 2.4 to 3.6 m (8 to 12 ft) was obtained for this study. The initial moisture content of wood was approximately 50% determined using oven-dry weight method on three random samples. The blocks were sawn to initial dimensions of 45 × 100 mm and were stored in a freezer at a temperature of −8ºC (18ºF) in order to maintain their initial moisture content and dimensions before kiln-drying. Then, the lumber was dried in a conventional kiln-dryer to a nominal equilibrium moisture content of approximately 15%. The drying schedule was based on the drying method for maple lumber of structural uses described by Simpson and Wang (2005). After drying, the lumber was machined to final dimensions nearest to a nominal 2 × 4 in. (38 × 89 mm). Next, based on visual inspection, defects were removed from the dried specimens to generate pieces from 15 to 244 cm (6 to 96 in.) in length meeting the visual grading requirements of SPS-1 (NLGA 2003a) for No.2 lumber grade with respect to knots, wane, slope of grain, warp, splits, etc. A total volume of 7.6 m^3 (1428 pmp) of sound wood meeting the SPS-1 requirements was obtained for finger-jointing, therefore, yielding one third of the initial unseasoned wood volume (34% out of 22.3 m^3) after drying, planing, grading, and defecting.

The pieces were then forwarded to a Canadian Conception RP 2000 finger-jointing machine equipped with a lateral feed system, where the horizontal finger-joint profile (machined across the width) of the feather type was machined at both ends. The geometry and dimensions of the finger profile are shown in Fig. 1. Table 1 shows the machining parameter combinations used to produce the finger joints in this study. Chip-load and cutting speed combinations were chosen with consideration to previous studies by Bustos (2003) and Verreault (2000). Various feed speeds were achieved by varying the chip-load, while keeping the cutting and rotation speed of the cutting heads constant. The feed speed ranged from 9.0 to 19.2 m/min (29 to 63 ft/min). Six sets of knives per tool were used for each chip-load and cutting speed conditions. The cutting speeds were determined from the outermost position (tip) of the knives (267-mm diameter). Knife wear was neglected, assuming that the first four hours of operation would not significantly affect the joint quality (Reeb et al. 1998).

After the machining of finger profiles, the pieces were removed from the production line in

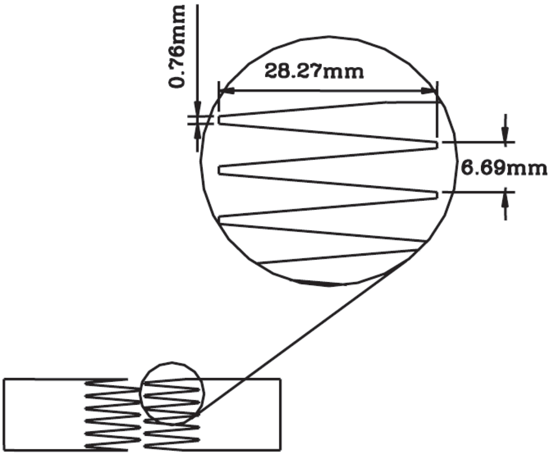

FIG. 1. Feather-type finger-joint profile (Bustos 2003).

TABLE 1. *Machining parameters studies in the experiment.*

Chip-load (mm)	Feed speed (m/min)/cutting speed (m/min) Rotation speed (RPM) 2500	 3250	 4000
0.60	9.00/2097	11.70/2726	14.40/3355
0.70	10.50/2097	13.65/2726	16.80/3355
0.80	12.00/2097	15.60/2726	19.20/3355

order to manually apply the polyurethane adhesive (an Isoset® UX-200/WD3-A200). The gluing system consisted of two tubes containing the polyurethane prepolymer (UX-200) and the emulsion polymer (WD3-A200) which were mixed at a 4:1 ratio in volume. Between 2.5 and 3.5 grams of mixed glue were spread on one end of the joint following the adhesive manufacturer's recommendations. The glued pieces were then returned to the production line to complete the finger-jointing process. The assembled joints were pressed with a constant end pressure of 6.89 MPa (1000 psi) for 20 seconds at 20ºC in accordance with results reported by Verreault (2000). The jointed pieces were then cut to produce 1.8-m (72-in.)-long specimens for tensile tests, which were conducted after 24-h curing in room conditions. The sample size for each test series varied from 23 to 32 replicates.

The tensile tests were performed in accordance with ASTM D-198 (ASTM 2005) and SPS-1 (NLGA 2003a) standards using a Metriguard model 412 machine at Forintek Canada Corp. Eastern Laboratory. Results were evaluated according to SPS-1 (NLGA 2003a) specification for structural finger-jointed lumber. The UTS was calculated based on the actual cross-section area or 38 × 89 mm when the actual cross-section was less than the SPS-1 requirement. Failure modes were examined at joint locations and classified per SPS-4 standard (NLGA 2003b). Data points with failures outside the finger joint were removed from the statistical analysis. Fifth percentile values were determined, with 75% confidence, assuming a 2-parameter Weibull statistic distribution as per ASTM D5457 (ASTM 2004).

RESULTS AND DISCUSSION

Table 2 shows mean values and fifth percentiles of the UTS obtained for each chip-load and cutting speed after adjustment to 15% moisture content per ASTM-D1990 (ASTM 2000). All fifth percentile values were at least twice the tensile strength requirements of SPS-1 (NLGA 2003a) for 2 × 4 No.2 SPF grade. Also, all 9 series obtained higher fifth percentiles than SPS-4 (NLGA 2003b) requirements for FS-1.8E finger-jointed flange stock (requiring 22.8 MPa). Furthermore, all series machined at 2726 m/min passed the FS-2.0E requirement of a fifth percentile UTS of 27.9 MPa.

Table 2. *UTS (MPa) of finger-jointed sugar maple machined with three chip-loads and three cutting speeds.*[a,b,c]

Chip-load (mm)	Cutting speed (m/min)			SPS-1 UTS requirement
	2097	2726	3355	
0.60	35.3 (23.3)	47.1 (32.2)	40.3 (31.0)	10.7
0.70	39.2 (26.9)	42.0 (30.1)	39.1 (27.6)	
0.80	40.4 (23.4)	41.4 (31.0)	45.7 (27.5)	

[a] Number of replicates varied from 13 to 26.
[b] Numbers in parentheses are the 5th percentile values based on a 2-parameter Weibull distribution.
[c] Wood moisture content at the time of test ranged from 9% to 12%. UTS values are adjusted to 15% MC.

Table 3 shows the statistics calculated from the study by Bustos et al., (2004) on finger-jointed black spruce. When comparing the results in Table 2 and Table 3, one can see that only one series from Bustos et al. (2004) showed higher mean UTS value than the lowest mean value obtained in our study. It gives evidence that the use of sugar maple can be an effective alternative to softwood in manufacturing of high-strength structural engineered wood products.

ANOVA statistical tests indicated that the chip-load did not have a strong effect on the UTS ($p = 0.1484$), but cutting speed did have a significant effect ($p = 0.0008$). These tests also indicated a strong interaction between the two variables on the UTS values ($p = 0.0010$).

The multiple comparisons showed significant differences between the three chip-loads for each cutting speed (Fig. 2). The UTS values

Table 3. *UTS (MPa) of finger-jointed black spruce from Bustos et al. (2004).*[a,b,c]

Chip-load (mm)	Cutting speed (m/min)		
	1676	2932	3770
0.64	34.1	36.7	31.1
0.86	37.4	33.6	31.1
1.14	34.4	34.5	30.7

[a] Number of replicates varied from 25 to 34.
[b] Numbers are the mean values of UTS.
[c] Wood moisture content at the time of test ranged from 10% to 12%. UTS values are adjusted to 15% MC.

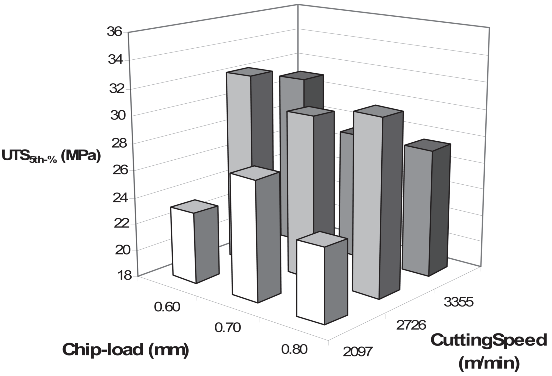

FIG. 2. Influence of chip-load and cutting speed on the UTS (5th percentile) of finger-jointed sugar maple.

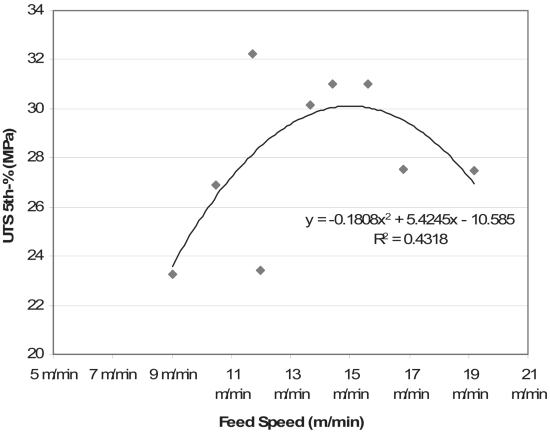

FIG. 3. Influence of feed speed on the UTS (5th percentile) of finger-jointed sugar maple.

showed a tendency to decrease with a lower cutting speed with maximum values when machined with the intermediate cutting speed of 2726 m/min. It is likely that at low cutting speed, the wood surface is damaged due to rubbing. On the other hand, at 2726 m/min, the UTS reach a minimum at the intermediate chip-load, with the opposite effect at the 2097 m/min cutting speed where the highest strength was achieved at a chip-load of 0.70 mm. It can be explained by the damage of the wood surface due to an increased pressure or the heat applied to the wood surface if the chip-load was too high for sugar maple. The maximum UTS value was obtained with a chip-load of 0.60 mm at a cutting speed of 2726 m/min. The 2nd order polynomial trend line from the influence of the feed speed on the UTS predicted an optimum fifth percentile UTS value of 30.1 MPa at a feed speed of 15.0 m/min (Fig. 3).

Test results indicated that satisfactory finger-jointing can be achieved in the range of 2726 to 3355 m/min cutting speeds with a chip-load between 0.60 and 0.70 mm. An ANOVA statistical test (using Bonferroni adjustment for multiple comparisons method) performed on the effect of cutting speed on the UTS showed little differences between the UTS of joints obtained at 2726 and 3355 m/min ($p = 0.6438$). However, the fifth percentile values appeared to be higher for all chip-loads with the cutting speed of 2726 m/min. Therefore, based on the three cutting speeds and chip-loads studied, it can be concluded that 2726 m/min would be the optimum cutting speed to obtain the highest UTS of the finger-joint in sugar maple. In addition, at this speed, less knife wear is expected than at 3355 m/min. Similar statistical tests were performed on the effect of the chip-load. Results indicated that the chip-loads did not produce statistically significant differences (p-values varied between 0.18 and 1.00).

Failures that occur in finger-jointed wood can be classified in 6 classes per SPS-4 standard (NLGA 2003b). Failure modes 1 and 2 are related to glue bond failures indicating a poor bonding and modes 3 to 5 are related to wood failures indicating a good bonding. Failure mode 6 is a 100% wood failure outside the finger-joint; therefore, such specimens are removed from the analysis. Wood failures (modes 3 to 5) were ranging from 41% to 85% for the tested machining conditions (Table 4). Four series out of nine could pass ANSI/AITC A190.1 (ANSI 2002) requirements to have at least 60% of wood failures for adhesives used with dense hard-

TABLE 4. *Wood failure of finger-jointed sugar maple machined with three chip-loads and three rotation speeds.*

Chip-load (mm)	Cutting speed (m/min) 2097	2726	3355	ANSI/AITC A190.1 requirement
0.60	59%	62%	47%	60%
0.70	41%	83%	46%	
0.80	85%	60%	50%	

woods. All series machined at a 2726 m/min cutting speed passed the 60% requirement. The lowest ratio of wood failures was found for a chip-load of 0.70 mm and a cutting speed of 2097 m/min. This result indicates that the machining was not done properly in this case because the glue application was identical for all series.

Finally, the fifth percentile UTS of the finger-jointed series developed 47 to 66% of the fifth percentile UTS value of the control non-jointed specimens. The lowest ratios (47% and 48%) were obtained for the series machined at 2097 m/min and a chip-load of 0.60 mm and 0.80 mm. The highest strength ratio (66%) was obtained for the series machined at 2726 m/min and a chip-load of 0.60 mm.

CONCLUSIONS

Comparison with SPS-1 and SPS-4 special products standards requirements (NLGA 2003a, 2003b) for finger-jointed softwood lumber and with results obtained by Bustos et al. (2004) for finger-jointed black spruce with a similar adhesive shows that finger-jointed sugar maple has a good potential for structural applications in engineered wood products provided that the machining parameters are properly controlled. Among two studied variables, the chip-load and cutting speed, the latter appeared to have the greatest influence on the tensile strength of finger-jointed sugar maple. In this study, all samples manufactured with various chip-loads and cutting speeds met SPS-1 tensile strength requirement for No.2 SPF 2×4 lumber and SPS-4 FS-1.8E flange stock. Four series out of nine passed ANSI/AITC A190.1 requirement for adhesives used with dense hardwoods, which is to have at least 60% of wood failures. Results indicated that satisfactory finger-jointing can be achieved in the range of 2726 and 3355 m/min with a chip-load between 0.60 and 0.70 mm. The highest UTS, and therefore the highest strength ratio (66%) were achieved with a chip-load of 0.60 mm at a cutting speed of 2726 m/min. The lowest strength ratios (47 and 48%) were obtained from two series machined with a chip-load of 0.60 and 0.80 mm and a cutting speed of 2097 m/min. The 2nd order polynomial trend line from the influence of the feed speed on the UTS predicted an optimum fifth percentile UTS value of 30.1 MPa at a feed speed of 15.0 m/min.

REFERENCES

American National Standards Institute (ANSI). 2002. American National Standard for Wood Products—Structural Glued Laminated Timber ANSI/AITC A190.1. American National Standards Institute, sponsored by the American Institute of Timbre Construction, Vancouver, WA.

American Plywood Association (APA). 2006. Market Outlook 2006–2011. Paper presented at the 2006 Annual Meeting, St-Antonio, TX. American Plywood Association, Tacoma, WA.

American Society for Testing and Materials (ASTM). 2000. Standard Practice for Establishing Allowable Properties for Visually-Graded Dimension Lumber from In-Grade Tests of Full-Size Specimens. D1990. American Society for Testing and Materials, West Conshohocken, PA.

———. 2004. Standard Specification for Computing the Reference Resistance of Wood-Based Materials and Structural Connections for Load and Resistance Factor Design. D5457. American Society for Testing and Materials, West Conshohocken, PA.

———. 2005. Static Tests of Timbers in Structural Sizes. D198. American Society for Testing and Materials, West Conshohocken, PA.

Bureau du Forestier en Chef. 2006. *Possibilité forestière 2008–2013—Résultats Provinciaux*, from http://www.forestierenchef.gouv.qc.ca/document/resultats-provinciaux.pdf. (June 11, 2007).

Bustos, C. 2003. Optimisation du procédé d'aboutage par entures multiples du bois d'épinette noire. PhD Thesis, Université Laval, Québec.

———, Hernàndez, R. E., R. Beauregard, and M. Mohammad. 2004. Influence of machining parameters on the structural performance of finger-joined black spruce. Forest Prod. J. 36(3):359–367.

Chui, Y. H., and S. Delahunty. 2005. Glued Engineered Products Made of Red Maple. NRCan Value to Wood project UNB6. University of New Brunswick, Wood Science and Technology Center, Fredericton, N.B.

Hernandez, R., J. F. Davalos, S. S. Sonti, Y. Kim, and R. C. Moody. 1997. Strength and Stiffness of Reinforced Yellow-Poplar Glued-Laminated Beams (Research Paper FPL-RP-554). Forest Prod. Lab., Madison, WI.

Hernàndez, R. E., and N. Naderi. 2001. Effects of knife jointing on the gluing properties of wood. Wood Fiber Sci. 33(2):292–301.

———, AND G. ROJAS. 2002. Effects of knife jointing and wear on the planed surface quality of sugar maple. Wood Fiber Sci. 34(2):293–305.

KING, T. A., AND G.-F. CHEN. 2001. Adhesive and wood. Specialty Wood Journal 4(6):12–18.

MANBECK, H. B., J. J. JANOWIACK., P. R. BLANKENHORN, P. LABOSKY, R. C. MOODY, AND R. HERNANDEZ. 1996. Efficient Hardwood Glued-Laminated Beams. 1–283–290. Paper presented at the International Wood Engineering Conference, Louisiana State University, Baton Rouge, LA.

MOHAMMAD, M. 2002. Finger-joint Process Optimization for Structural Applications (Project No. 2739). Forintek Canada Corp., Sainte-Foy, Québec.

NATIONAL LUMBER GRADES AUTHORITY (NLGA). 2003a. Normes de produits spéciaux pour le bois de charpente jointé SPS 1. National Lumber Grades Authority, New Westminster, BC.

———. 2003b. Normes de produits spéciaux pour la semelle de bois jointé. SPS 4. National Lumber Grades Authority, New Westminster, BC.

PELVRIS, N., AND T. C. TRIANTAFILLOU. 1992. GFRP-reinforced wood as structural material. Materials in Civil Engineering 4(3):300–317.

REEB, J. E., J. J. KARCHESY, J. R. FOSTER, AND R. L. KRAHMER. 1998. Finger-joint quality after 4, 6 and 32 hours of knife wear: Preliminary results. Forest Prod. J. 48(7/8): 33–36.

SCHULER, A., C. ADAIR, AND E. ELIAS. 2001. Engineered lumber products: Taking their place in the global market. Forestry 99(12):28–35.

SELLERS JR., T., J. R. MCSWEEN, AND W. T. NEARN. 1988. Gluing of Eastern Hardwoods: A Review (General Technical Report SO-71). US Department of Agriculture, Forest Service, New Orleans, LA.

SIMPSON, W. T., AND X. WANG. 2005. Drying and Heat Sterilization of Maple Lumber for Structural Uses. Undervalued Hardwoods for Engineered Materials and Components: Pages 51–63. Forest Products Society, Madison, WI.

SPAUN, F. D. 1981. Reinforcement of wood with fiberglass. Forest Prod. J. 31(4):26–33.

VERREAULT, C. 2000. Utilisation des coeurs de bois franc dans des bois d'ingénierie à usage structural (Projet 1949). Forintek Canada Corp., Sainte-Foy, Qc.