

# INFLUENCE OF MACHINING PARAMETERS ON THE TENSILE STRENGTH OF FINGER-JOINTED HIGH-DENSITY BLACK SPRUCE LUMBER

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**Abstract.** Finger-jointed softwood lumber is widely used in manufacturing of structural or nonstructural applications such as glued laminated lumber and prefabricated wood I-joists. Black spruce is the most frequently used species for finger-jointed engineered wood products in eastern Canada. However, some key machining parameters must be adjusted according to the properties of the wood to obtain a surface quality suitable for the finger-jointing process. The main objective of this study was to evaluate the effect of cutting speed and chip load on the ultimate tensile strength (UTS) of finger-jointed high-density black spruce. The variables were four cutting speeds and three chip loads. A feather profile was selected with an isocyanate adhesive and an end-pressure of 3.45 MPa. A factorial analysis showed a statistically significant interaction between cutting speed and chip load on UTS and cutting speed was the most significant variable. The influence of chip load on UTS was lower, apparent only at 3260 m/min cutting speed. Suitable finger-jointing could be achieved at 1860-3960 m/min cutting speed with a chip-load of 0.51-1.27 mm. However, the best result was obtained at 3260 m/min cutting speed and 0.89 mm chip load. These results need to be validated in industrial mills to verify tool wear behavior.

**Keywords:** Finger-jointing, wood machining, black spruce, cutting speed, chip load.

## INTRODUCTION

Finger-jointing is a technological process that uses small-dimension, low-quality lumber to obtain high-quality structural wood products. This is possible by removing defects and gluing the remaining pieces into members with a desired length. The final product is stronger, more predictable, and less variable than a solid wood element with equivalent dimensions. The main structural applications of finger-jointed

lumber are glued laminated lumber (glulam), I-joists, and studs.

The economic context in the wood products industry is characterized by a reduction in wood quality, and, at least prior to the subprime crisis in North America, by an increase of the engineered wood product (EWP) demand from both residential and nonresidential building industries. If we add to this the increasing demand for green products (of which the wood is a perfect example being renewable and carbon neutral), we can see that EWPs have a potential to increase their market share against the

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other major structural use materials, concrete and steel.

Glulam can be described as a composite product, the components being wood and adhesive. The quality of the wood–adhesive bonding depends on the properties of these two components and on the finger-jointing process parameters (machining parameters, finger geometry, end-pressure, curing time, wood temperature, etc). The bonding process is therefore influenced among other things by the physical and anatomical properties of wood (density, porosity, etc), surface quality after machining, and the ability of the adhesive to penetrate adequately into the wood and cure properly. In the relationship “wood/jointing parameters/adhesive,” the latter two are easier to control than the first, so it is very important to adjust these values to the characteristics of the wood being used.

Several studies regarding the finger-jointing of softwoods and hardwoods have been conducted in North America. Joint strength is directly related to the effective glue joint area or the total surface of contact (fingertips and shoulders contribute very little to the joint strength) between the adjacent wood members. Raknes (1982) recommended that this surface should be at least 10 times greater than the cross-section of the wood member. His findings confirm the conclusions of Selbo (1963, 1975) who suggested a finger length to pitch ratio greater than 5. Ayarkwa et al (2000a) also concluded that the effective glue joint area influences the modulus of rupture of the finger-jointed member.

Three types of joint geometry are currently used by the manufacturers of finger-jointed wood members: male–female, reversed, and feather. Bustos et al (2003a) found that the feather profile performed better than the others, especially in bending tests. They conclude that the presence of shoulders in male–female and reversed finger profiles generates a concentration of stress and reduces the contact surface in the joint.

Several types of adhesives are used for finger-jointed products, formaldehyde-based and, more recently, isocyanates. Isocyanates have good

gluing capabilities, are easier to use than many other types of adhesives, are less sensitive to variations in moisture content and temperature of the wood, and polymerize at ambient temperature. Therefore, they are a viable alternative to phenol- and resorcinol-based adhesives (Ayarkwa et al 2000b; Chen 2001; Bustos 2003; Vrazel and Sellers 2004; St-Pierre et al 2005).

Adhesive bonding to wood is a chemical process, therefore temperature and moisture content of wood have a significant effect on the end product quality. Dry wood will absorb the adhesive too fast, starving the joint, but too much moisture in the wood makes the glue penetration difficult (Marra 1992). The moisture content difference between the two pieces making up the joint also affects its long-term behavior. High stresses can be generated by a heterogeneous swelling (or shrinkage) action between the two parts of the joint (Knowles 2006). Kennedy (1951) suggests a maximum of 5% difference in moisture content between the parts to limit this effect.

Bustos (2003) studied the influence of temperature (–5, 5, 12, and 20°C) and moisture content (12, 17, and 20% MC) on finger-jointed black spruce mechanical properties using an isocyanate. Joints manufactured at –5°C yielded significantly lower results than the other three temperatures. Moisture content did not seem to influence the strength of the finger-joints, except at 20°C. At this temperature level, the joint strength increased as the moisture content decreased. In a similar study, St-Pierre et al (2005) found that optimal results can be obtained at 12–16% MC and 5–20°C. They also reported that frozen lumber and green wood yield poor results when using isocyanates.

The mechanical properties of finger-jointed members increase with density (Kutscha and Caster 1987). In a comparative study of three species (keruing, southern pine, and Douglas fir), Vrazel and Sellers (2004) reported that the tensile strength of finger-jointed lumber increased with density, keruing showing the highest strength.

An adequate surface finish is an important prerequisite for obtaining a superior quality finger-jointed product. Dulling of cutting knives increases the depth of the crushed cell layer and reduces the penetration of adhesive resulting in poor joint quality (Kutscha and Caster 1987; Reeb et al 1998). The same effect of knife dulling on adhesive performance has been reported by Hernández and de Moura (2002) and Hernández and Rojas (2002) for peripheral planing of hardwoods.

Machining parameters also influence the depth of the crushed cells and subsequently the joint strength. In a study on the influence of machining parameters on the mechanical performance of finger-jointed black spruce products, Bustos et al (2004) reported that cutting speed had a significant effect on tensile strength, recommending cutting speeds of 1676-2932 m/min. Collins and Walford (1998) reported that cutting speed did not affect the quality of finger-jointed *Pinus radiata*, but rather the appearance of the machined surface. At excessively high cutting speeds, the instability and vibration associated with high rotation speeds can generate a poor surface finish (AceCo 2002).

Chip load is the amount of wood removed by the knife in each pass. A small chip load means that the knife will rub rather than cut the wood, increasing the rate of dulling and burning the wood, both effects having a negative influence on surface quality. If the chip load is too high, the pressure on the cutting edge will be increased with negative effects on the knife sharpening cycle, energy consumption, and surface quality (AceCo 2002). Bustos et al (2004) reported that the chip load value has an influence on joint quality, but the influence varies with cutting speed.

The objectives of this study were to evaluate the suitability of high-density black spruce for the finger-jointing process and to define the range of cutting speed and chip load values that will permit manufacturing of high-quality finger-jointed products using this wood. Samples were machined at four cutting speeds, three chip loads,

and glued with an isocyanate adhesive. The ultimate tensile strength of finger joints was determined. Results were compared with previous research and with the finger-jointed product standards.

#### MATERIALS AND METHODS

Experiments were carried out with kiln-dried black spruce (*Picea mariana* [Mill.] B.S.P.) from the Chibougamau region, Quebec, Canada. In accordance with SPS-2 (NLGA 2003a), all pieces were mechanically rated as MSR grade 2400 Fb 2.0E at Chantiers Chibougamau Ltd. The packages contained wood 2.44 m long with a cross-section of 41 × 54 mm. The wood was stored in a conditioning room at 65% RH and 20°C to obtain 12% EMC with top restraint to reduce warping. Defects were visually removed following the requirements of CAN/CSA O122-06 (CSA 2006) and SPS 1 (NLGA 2003b) with respect to knots, splits, slope of grain, wane, etc. Afterward, 1050 wood samples of 0.83-1.34 m length were obtained. After 3 mon in the conditioning room, the best 960 samples were reduced in cross-section to 38 × 51 mm and randomly distributed in 480 pairs.

Finger profiles were obtained using a Conception RP 2000 finger-jointing machine (Conception R.P. Inc, Quebec City, Canada) having a lateral feed system. The cutting head had six sets of knives (bolts) per tool with parameters as shown in Table 1. Four cutting speeds and three chip loads were chosen (Table 2) taking into consideration the results of Bustos et al (2004) and St-Pierre et al (2005). Feed speeds ranged 6.8-36.1 m/min and were calculated according to:

$$A = \frac{c \times n \times N}{1000} \quad (1)$$

where:

A = feed speed (m/min)

c = chip load (mm)

n = number of knives

N = rotation speed (rpm)

Table 1. Parameters used for the finger-jointing process.

Joint geometry	
Type of joint	Horizontal, feather
Board thickness (mm)	38.1
Board width (mm)	50.8
Finger length (mm)	28.27
Finger tip width (mm)	0.76
Pitch (mm)	6.69
Slope	0.091
Gluing	
Adhesive	ISOSET® UX 200/WD3-A300
Spread rate	1.7-2.2 g/joint (104-135 g/m <sup>2</sup> )
Assembly time	Less than 1 min
End pressure	3.45 MPa (Bustos et al 2003b)
Pressure application time	Until 3.45 MPa was reached

Table 2. Feed speeds required (m/min) to produce the four cutting speeds and three chip loads.

Cutting speed <sup>a</sup> (m/min)	Chip load (mm)		
	0.51	0.89	1.27
1860	6.8 (34) <sup>b</sup>	11.9 (35)	16.9 (35)
2560	9.4 (37)	16.3 (36)	23.3 (37)
3260	11.9 (37)	20.8 (36)	29.7 (35)
3960	14.5 (33)	25.3 (34)	36.1 (38)

<sup>a</sup> Determined from the outermost position of the knives (267 mm dia, corresponding to the tip of the knife or the base of the finger).

<sup>b</sup> Values in parentheses are the number of replicates.

Knives and tools were freshly sharpened and kept in good conditions during the finger-jointing process. The machining of the finger profiles was followed by application of adhesive. A manual glue gun was used for mixing and applying the two components, polyurethane prepolymer (UX-200) and emulsion polymer (WD3-A300). Two blocks forming one specimen were placed in a custom-designed crowder and pressure applied. The crowder design prevented lateral and vertical movements, ensuring a high degree of stability. End pressure was measured using a real-time load-level acquisition sensor.

Glued members were then stored on a level surface for 24 h to permit the adhesive to reach handling strength. Tensile tests were performed in accordance with CAN/CSA O122-06 (CSA 2006), SPS 4 (NLGA 2003c), and ASTM D198 (ASTM 2005) (Table 3) standards using a SYSTECH TNS-800 machine (Systech Industrie Inc, Clermont, Canada) 7 da after jointing, ensuring that the adhesive had fully polymerized.

Table 3. Parameters used for the tensile tests on finger-jointed high density black spruce lumber.

Distance between grips (mm)	610
Test duration (s)	70-282
Stress rate (MPa/s)	0.23-0.47
Load cell accuracy	±0.1% for the test range

After each test, small sections were cut from both sides of the joint and density and moisture content measurements were made in accordance with ASTM D 2395 (ASTM 1995). The failure types were evaluated based on the CAN/CSA O122-06 (CSA 2006) and SPS 4 (NLGA 2003c). Samples with failures that occurred away from the joints (failure type 6) as well as samples with defects (missing fingers, misalignments, etc) were excluded from the analysis.

A 3 × 4 two-level factorial design was adopted for this experiment. The statistical treatments were determined a priori. The influence of cutting speed and chip load and their interaction on the tensile strength were determined with an analysis of variance (ANOVA) (SAS, GLM procedure; SAS 2004). A Tukey-Kramer test was applied to determine differences among means (10% probability level). The data normality was verified using the Shapiro-Wilks test and the homogeneity of variances by the Bartlett test. Fifth percentile values were calculated as per ASTM D5457 (ASTM 2004) assuming a two-parameter Weibull distribution.

## RESULTS AND DISCUSSION

The mean basic density of the specimens was 471 kg/m<sup>3</sup>, ranging 389-564 kg/m<sup>3</sup>. Therefore, the specimens covered the higher values of the natural distribution of density of this species, whose mean is 406 kg/m<sup>3</sup> (9.4% coefficient of variation; Jessome 2000). Moisture content of the wood averaged about 13% with a range of 12-15%. Ultimate tensile strength (UTS) was adjusted to 15% MC based on ASTM D1990-00 (ASTM 2000) to facilitate comparison among the joints.

The mean and fifth percentile of UTS as a function of chip load and cutting speed are given

in Tables 4 and 5. All strength results exceeded the UTS (27.9 MPa) required by the SPS 4 standard (NLGA 2003c) for the FS-2.0E grade lumber. In fact, the mean 5th percentiles using different cutting conditions were on average 44% higher than the UTS specified.

As shown in Table 4, the UTS range was 5.2 MPa under the machining conditions. Bustos et al (2004) reported a higher range of variation in UTS (7.0 MPa) using similar machining conditions but with lower density black spruce. This suggests that effect of machining on tensile strength could be more important in lower density woods than in dense woods of the same species. Bustos et al (2004) showed scanning electron micrographs of finger-jointed black spruce transverse sections. Crushed and collapsed

cells were observed near or at the glueline of samples. Extensive damage to wood cells is partially responsible for inferior glue bonding of wood surfaces (Hernández and Naderi 2001; Hernández and de Moura 2002; Hernández and Rojas 2002; Singh et al 2002). Damage in latewood (LW) is less severe than in earlywood owing to the higher density of LW (Bustos et al 2004). Microdensitometry studies show that proportion of LW is less in lower than in higher density black spruce (Koubaa et al 2005). A greater impact of machining is therefore expected in lowest density specimens of a given species.

ANOVA indicated a statistically significant ( $p = 0.07$ ) interaction between cutting speed and chip load on UTS (Table 6). This means that the effect of the cutting speed on UTS depended on the chip load. A more significant interaction effect ( $p = 0.05$ ) was obtained by Bustos et al (2004). Multiple comparisons showed that there are few differences among the four cutting speeds for each chip load condition (Table 4). UTS tended to be lower at the highest cutting speed (3960 m/min). However, these differences were significant only at 0.89-mm chip load, where a cutting speed of 3260 m/min performed better than 3960 m/min. This could occur from the cell damage occurring near or at the glued surface as a result of the high speed at which the knives pass through the wood. However, the reduction in UTS when going from 1860 to 3960 m/min is quite low (2.7 MPa, 5%, chip loads pooled). The effect of cutting speed on UTS could have been more pronounced after accelerated aging of specimens (Jokerst and Stewart 1976; Caster et al 1985; Hernández 1994).

The range of cutting speed (1860-3960 m/min) and chip load (0.51-1.27 mm) appears adequate for finger-jointing high-density black spruce. Data analysis showed slight influences of the

Table 4. Ultimate tensile strength (MPa) of finger-jointed black spruce machined at three chip loads and four cutting speeds.<sup>a,b</sup>

Cutting speed (m/min)	Chip load (mm)		
	0.51	0.89	1.27
1860	53.6 (1.1) <sup>c</sup> AB <sup>d</sup>	54.5 (1.4) AB	52.9 (0.9) AB
2560	51.0 (1.2) B	51.6 (1.2) AB	53.0 (1.0) AB
3260	51.8 (1.2) AB	56.1 (1.2) A	51.0 (0.9) B
3960	51.0 (1.1) B	50.9 (1.3) B	52.4 (1.2) AB

<sup>a</sup> Mean values adjusted to 15% MC.

<sup>b</sup> Sample size 33-38.

<sup>c</sup> Values in parentheses are standard errors of the mean.

<sup>d</sup> Means with the same letter are not significantly different (Tukey-Kramer test,  $p < 0.10$ ).

Table 5. The 5th percentiles<sup>a</sup> of ultimate tensile strength (MPa) of finger-jointed black spruce machined at three chip loads and four cutting speeds.

Cutting speed (m/min)	Chip load (mm)		
	0.51	0.89	1.27
1860	41.0	39.9	43.9
2560	38.5	37.5	41.6
3260	38.9	42.7	41.2
3960	39.3	37.4	38.9

<sup>a</sup> Fifth percentile values based on a two-parameter Weibull distribution.

Table 6. Analysis of variance for ultimate tensile strength—Type III sums of squares.

Source of variation	Sum of squares	df	Mean square	F-ratio	$p$ value
Cutting speed	327.295	3	109.098	2.27	0.0799
Chip load	145.936	2	72.968	1.52	0.2204
Speed $\times$ chip load	560.962	6	93.494	1.94	0.0725
Residual	19951.7	415	48.076		
Total	20983.6	426			

two factors on UTS, therefore the choice of parameters is largely technical. The highest values of UTS occurred over 1860-3260 m/min. The upper value of cutting speed falls within the range given by AceCo (2002) for commercial finger-joint machines (2585-4712 m/min).

Conversely, the analysis showed few statistically significant differences ( $p = 0.10$ ) among the three chip loads (Table 4). These differences occurred only at 3260 m/min cutting speed, where a chip load of 0.89 mm performed better than 1.27 mm. These results are in agreement with those reported by Bustos et al (2004). The chip load values recommended by tool manufacturers such as Wisconsin Knife Works, Inc (2000) and AceCo (2002) vary 0.38-0.53 mm for optimum tool life. Our results suggest that such values could be conservative for machining high-density black spruce. However, higher chip loads can generate greater cutting forces and cause more tool wear during milling.

The impact of knife wear on the adherend surfaces of finger-joint specimens was studied by Reeb et al (1998). As knife wear progressed, the adherent surface became rougher and more irregular. Moreover, if chip load is too low, the cutters will rub rather than cut, which produces friction, heating, and dulls the cutting edge prematurely, which might possibly burn the wood (AceCo 2002). Increased cutting speeds and chip loads will also negatively affect the knife wear but will have a positive influence on the productivity since the feed speed is also increased (Table 3). Experiments on the effect of the machining conditions in the current research on tool wear need to be considered.

UTS values (50.9-56.1 MPa) were significantly higher than those found previously by Bustos et al (2004) (31-38 MPa). As discussed previously, the mean basic density of specimens differed in the two studies ( $471 \text{ kg/m}^3$  in the present work compared with  $437 \text{ kg/m}^3$ ); and it is known that this affects tensile strength (Kutscha and Caster 1987; Knowles 2003). The present study used ISOSET<sup>®</sup> UX 200/WD3-A300 while Bustos et al (2004) used an earlier

version, the ISOSET UX-100/WD3-A322. The pressure application was different as was the cross-section of specimens ( $38.1 \times 51 \text{ mm}$  in the present work compared with  $38 \times 64 \text{ mm}$ ). Furthermore, Bustos et al (2004) prepared between two and three joints per sample compared with only one per sample in the present study. Testing a sample with more than one joint will yield the tensile strength of the weakest, having a diminishing effect on the average.

Data analysis revealed that, within the narrow range of the experiment, variation in moisture content and basic density of the blocks in the joints did not influence the tensile strength. The analysis was performed considering the average, highest, and lowest values of the two blocks making up the finger-jointed stud. The influence of the differential moisture content and density of the two blocks on UTS was also not significant. However, finger-jointed products produced with large differences in density may have differential shrinking and swelling, which may put additional stress on the glueline, causing weakness in the product (Knowles 2006).

The types of failure occurring in finger-jointed specimens are classified into six modes in accordance with SPS 4 (NLGA 2003c). Failure mode number 1, which is associated with a low-quality adhesive bonding, accounted for only 0.6% of the total (Fig 1). Failure mode number 6 (failure away from the joint) occurred in 10.3%. This type of failure is not influenced by the joint and it could reflect the occurrence of internal defects in the material. The quality of the joints is therefore confirmed in that more than 89% of the specimens failed in modes 2, 3, 4, and 5. These modes present a high proportion of failures in wood and are indicative of good adhesive penetration and polymerization, and, consequently, a good glue bond. Figure 2 confirms that such failure modes yielded the high tensile strength.

Failure modes 2 and 3 (wood failure higher than 70%) had the highest UTS means while modes 1 (wood failure less than 70%) and 6 (wood failure far from joint) had the lowest averages. Failure modes number 4 and 5 showed

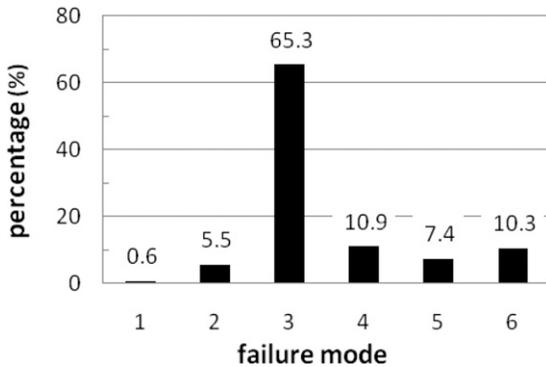


Figure 1. Distribution of modes of failure occurring after tensile strength tests of finger-jointed black spruce (all machining conditions pooled).

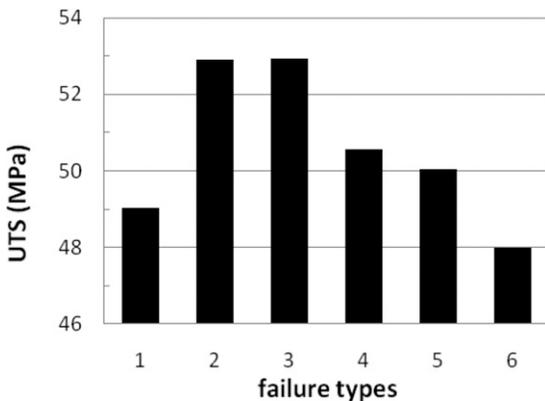


Figure 2. Mean ultimate tensile strength (UTS) values as a function of the failure mode of finger-jointed black spruce (all machining conditions pooled).

lower values than 2 and 3. Failure mode 4 is associated with wood failure occurring at the joint roots or scarf tips and with high overall wood failure. Given that such areas are points of stress concentration, this failure mode could be caused by any wood defect. Mode type 5 is a failure beginning at and progressing away from the finger joint. It can be initiated by a small internal defect, by a missing finger, or uneven adhesive contact between adjacent fingers.

The overall high proportion of wood failure obtained for the different machining treatments confirms that the gluing process was adequate. The adhesive and machining parameters studied can therefore be used for the fabrication of

finger-jointed products based on high-density black spruce.

#### CONCLUSIONS

The results indicate that cutting speed (1860-3960 m/min) and chip load (0.51-1.27 mm) ranges are adequate for the finger-jointing high-density black spruce. The overall mean UTS for all samples was 52.5 MPa with a 5th percentile of 41.2 MPa, both significantly exceeding the UTS requirement of the SPS 4 standard for FS-2.0E grade lumber (NLGA 2003c). All individual samples yielded values significantly greater than the 27.9 MPa UTS value required by the SPS 4 standard. Statistical analysis showed that, within the limits of the studied parameters, the combined action of the cutting speed and chip load had a significant effect on the tensile strength of the finger joints. Comparison with previous results shows that high-density black spruce performs better than lower density material. The high percentage of wood failure and the low proportion of glue-line failure indicate that the ISOSET<sup>®</sup> UX 200/WD3-A300 adhesive can be successfully used for the fabrication of finger-jointed structural products with high-density black spruce. The cutting speed and chip load do not constitute a limiting factor, therefore the maximum chip load (1.27 mm) and cutting speed (3960 m/min) could be used. However, running mill studies are required with these cutting parameters to verify tool wear behavior.

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## REFERENCES

- AceCo (2002) Wood tooling catalog and technical manual. AceCo Precision Manufacturing, Boise, ID. 66 pp.
- ASTM (1995) Standard test methods for specific gravity of wood and wood-base materials. D2395-93. ASTM, West Conshohocken, PA.
- ASTM (2000) D1990. Standard practice for establishing allowable properties for visually-graded dimension lumber from in-grade tests of full-size specimens. American Society for Testing and Materials, West Conshohocken, PA.
- ASTM (2004) D5457. Standard specification for computing the reference resistance of wood-based materials and structural connections for load and resistance factor design. American Society for Testing and Materials, West Conshohocken, PA.
- ASTM (2005) D198. Static tests of timbers in structural sizes. American Society for Testing and Materials, West Conshohocken, PA.
- Ayarkwa J, Hirashima Y, Sasaki Y (2000a) Effect of finger geometry and end pressure on the flexural properties of finger-jointed tropical African hardwoods. *Forest Prod J* 50(11/12):53-63.
- Ayarkwa J, Hirashima Y, Sasaki Y, Ando K (2000b) Effect of glue type on flexural and tensile properties of finger-jointed tropical African hardwoods. *Forest Prod J* 50(10):59-68.
- Bustos C (2003) Optimisation du procédé d'aboutage par entures multiples du bois d'épinette noire. PhD Thesis, Université Laval, Quebec, Canada. 133 pp.
- Bustos C, Beauregard R, Mohammad M, Hernández RE (2003a) Structural performance of finger-jointed black spruce lumber with different joint configurations. *Forest Prod J* 53(9):72-76.
- Bustos C, Mohammad M, Hernández RE, Beauregard R (2003b) Effects of curing time and end-pressure on the tensile strength of finger-jointed black spruce lumber. *Forest Prod J* 53(11/12):85-89.
- Bustos C, Hernández RE, Beauregard R, Mohammad M (2004) Influence of machining parameters on the structural performance of finger-jointed black spruce lumber. *Wood Fiber Sci* 36(3):359-367.
- Caster D, Kutscha N, Leick G (1985) Gluability of sanded lumber. *Forest Prod J* 35(4):45-52.
- Chen G (2001) Two-part polyurethane adhesive for structural finger joints. Industrial applications of isocyanates and polyurethanes. Pages 15-16 in *The wood adhesives 2000 symposium*. Section 2A: Industrial applications of isocyanates and polyurethanes. Forest Products Society, South Lake Tahoe, CA, 22-23 June 2000.
- Collins M, Walford B (1998) Recent research into structural fingerjointing. *New Zealand Engineering. Construction and Construction Materials* 53(6):24-26.
- CSA (2006) CAN/CSA-O122-06. Structural glued-laminated timber. Canadian Standards Association, Mississauga, Ontario, Canada.
- Hernández RE (1994) Effect of two wood surfacing methods on the gluing properties of sugar maple and white spruce. *Forest Prod J* 44(7/8):63-66.
- Hernández RE, de Moura LF (2002) Effects of knife jointing and wear on the planed surface quality of northern red oak wood. *Wood Fiber Sci* 34(4):540-552.
- Hernández RE, Naderi N (2001) Effect of knife jointing on the gluing properties of wood. *Wood Fiber Sci* 33(2):292-301.
- Hernández RE, Rojas G (2002) Effects of knife jointing and wear on the planed surface quality of sugar maple wood. *Wood Fiber Sci* 34(2):293-305.
- Jessome AP (2000) Résistance et propriétés connexes des bois indigènes au Canada. Forintek Canada Corp. *Séries: Publication spéciale SP514F*. Ste-Foy, Quebec, Canada. 37 pp.
- Jokerst RW, Stewart HA (1976) Knife-versus abrasive-planed wood: Quality of adhesive bonds. *Wood Fiber Sci* 8(2):107-113.
- Kennedy DE (1951) Glued, laminated construction (Chapter 11). Pages 281-292 in TA McElhanney and JH Jenkins, eds. *Canadian woods: Their properties and uses*. Canada Department of Resources and Development. Forestry Branch, Forest Products Laboratories Division, King's Printer, Ottawa, Ontario, Canada.
- Knowles CD (2003) Wood properties of finger-jointed southern pine. Master Thesis, Stephen F. Austin State University, Nacogdoches, TX. 157 pp.
- Knowles CD (2006) Characterization of selected wood properties in commercially produced southern pine finger-jointed dimension lumber. *Forest Prod J* 56(9):43-46.
- Koubaa A, Isabel N, Zhang SY, Beaulieu J, Bousquet J (2005) Transition from juvenile to mature wood in black spruce (*Picea mariana* [Mill.] B.S.P.). *Wood Fiber Sci* 37(3):445-455.
- Kutscha NP, Caster RW (1987) Factors affecting the bond quality of hem-fir finger-joints. *Forest Prod J* 37(4):43-48.
- Marra AA (1992) *Technology of wood bonding: principles in practice*. Van Nostrand Reinhold Co, New York, NY. 454 pp.
- NLGA (2003a) NLGA SPS 2. Special products standard for machine graded lumber. National Lumber Grades Authority, Vancouver, BC, Canada. 34 pp.
- NLGA (2003b) SPS 1. Special products standard for fingerjointed structural lumber. National Lumber Grades Authority, Vancouver, BC, Canada. 31 pp.
- NLGA (2003c) SPS 4. Special products standard for fingerjointed flange stock lumber. National Lumber Grades Authority, Vancouver, BC, Canada. 41 pp.
- Raknes E (1982) The influence of production conditions on the strength of fingerjoints. Pages 154-168 in *Proc., Production, Marketing and use of fingerjointed sawnwood*. United Nations Economic Commission for Europe. CFL Prins, ed. Martinus Nijhof/Dr. W. Junk Publishers, The Hague, The Netherlands.

- Reeb JE, Karchesy JJ, Foster JR, Kraemer RL (1998) Finger-joint quality after 4, 6 and 32 hours of knife wear: Preliminary results. *Forest Prod J* 48(7/8):33-36.
- SAS (2004) SAS/STAT users' guide, version 9.1. SAS Institute Inc, Cary, NC.
- Selbo ML (1963) Effect of joint geometry on tensile strength of finger joints. *Forest Prod J* 13(9):390-400.
- Selbo ML (1975) End and corner joint construction. Pages 49-55 in *Adhesive bonding of wood*. Technical Bulletin No. 1512. USDA. Forest Serv., Washington, DC.
- Singh AP, Anderson CR, Warnes JM, Matsumura J (2002) The effect of planing on the microscopic structure of *Pinus radiata* wood cells in relation to penetration of PVA glue. *Holz Roh Werkst* 60(5):333-341.
- St-Pierre B, Beauregard R, Mohammad M, Bustos C (2005) Effect of moisture content and temperature on tension strength of fingerjointed black spruce lumber. *Forest Prod J* 55(12):9-16.
- Vrazel M, Sellers T Jr. (2004) The effects of species, adhesive type, and cure temperature on the strength and durability of a structural finger-joint. *Forest Prod J* 54(3):66-75.
- Wisconsin Knife Works, Inc (2000) Premium Cutting Tools, 07/00 Catalog. Beloit, WI. 112 pp.