

Structural performance of finger-jointed black spruce lumber with different joint configurations

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Abstract

In Eastern Canada, black spruce (*Picea mariana* (Mill.) B.S.P.) is used for producing engineered wood products. However, little information is available on the influence of finger-joint configuration on the structural performance of this species. The purpose of this work was to evaluate the behavior of finger-jointed black spruce for three joint configurations: feather, male-female, and reverse. Isocyanate adhesive was used for all types of joints studied. All of the three joint configurations performed well and strength values were found to meet the Canadian standard requirements. Significant differences were found for bending strength between the three joint profiles. The same trend was observed for tension strength but differences were not statistically significant. The analysis indicated that the feather configuration performs better than male-female and reverse profiles, especially for horizontal structural joints. In tension and bending tests, wood failure was mostly produced along the joint profile but with some failure at the finger roots, indicating an excellent performance of the gluelines.

The engineered wood products industry plays an important role in the Canadian economy. In Quebec, companies dedicated to the manufacture of engineered wood products work mainly with spruce, pine, and balsam fir (SPF) or trembling aspen. Among these, the species of choice is black spruce (*Picea mariana* (Mill.) B.S.P.), which shows high density and mechanical strength for structural applications.

The engineered wood approach aims at developing products from glued-up or assembled elements such as laminated beams, I-joists, open-web joists, laminated veneer lumber, etc. (Lamy 1995). These products require more engineering, design, knowledge, and quality control than conventional products. In Quebec, structural joined wood is

mainly sold as a component of engineered wood products, such as an I-joist, which is made from joined wood in top and bottom flanges with a web of oriented strandboard or plywood. Given that joined wood in structural components must resist high stresses, the mechanical strength is one of the principal performance requirements.

To use wood more efficiently in the development of structural finger-jointed products, specific process parameters must be taken into account. The type of finger-joints, the moisture content, and temperature conditions of joined wood members, as well as the machining process must be controlled and optimized. Many wood-related factors are also

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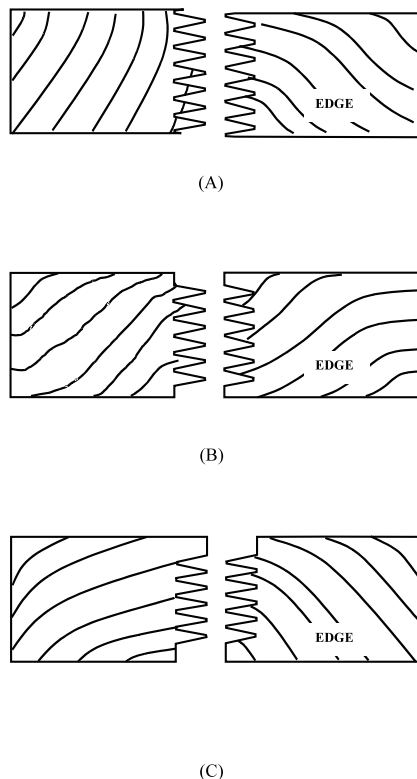


Figure 1. — Side view of the types of structural joints used in Eastern Canadian mills: (A) feather, (B) male-female, and (C) reverse.

known to affect the strength of finger-joints, such as species, density, and natural defects, while others are related to the gluing process.

The type of adhesive, curing time, and the pressure of application have a great influence on the strength behavior of the assemblies. Isocyanate-based adhesives such as polyurethane (PUR) are gaining acceptance in North America for a variety of structural and non-structural applications. Joined wood is an application of interest for PUR adhesives, which is why they are being tested thoroughly. PUR adhesives provide interesting characteristics. They produce a high-strength bond and cure at ambient conditions even though this curing can be accelerated by hot-pressing or RF treatments. The bonds obtained are resistant to creep, to moisture, and to heat exposure treatments (Pagel and Luckman 1984a, 1984b). For these reasons, it is reasonable to think that the PUR adhesives are a viable alternative for wood finger-jointing applications (Verreault 1999, Chen 2001, Lange et al. 2001).

Another important aspect of the finger-jointing process is wood machining, which is usually performed following recommendations given by tool and

machine manufacturers. Poor finger-joints will be obtained when using inadequate machining conditions (ACEco Precision Wood Tooling 2000), where for example, the tear-out is a common defect that can be caused by either worn knives, high feed speeds, or wrong rake angle.

It is known that the finger geometry has an effect on the performance of structural joints. Parameters such as the tip width, pitch width, finger length, and slope are interrelated and can influence positively or negatively the performance of the joint. However, little information is available on the finger-jointing performance of black spruce wood. Jokerst (1980) indicated that the geometry of the joint is the most important aspect for good finger-jointing performance. Considerable work related to the influence of geometrical joint parameters has been done on several species (Madsen and Littleford 1962, Richards 1963, Selbo 1963, Biblis and Carino 1993, Ayarkwa et al. 2000). According to Jokerst (1981) and Selbo (1963), certain geometrical parameters are particularly important for the strength of finger-joints. For example, strength increases with a larger finger length/pitch width ratio and a lesser finger tip width. Selbo (1975)

showed that the tensile strength of various types of end joints depended on the geometry of the assembled parts. Thus, the use of scarf- and finger-joints of sufficiently low slope can yield 85 to 90 percent of the strength of solid wood. As a result, structural finger-joints have relatively longer fingers with thin tips compared to non-structural joints and they are used when joint strength is the primary concern.

Several structural configurations of finger-joints are used to join wood: feather, male-female, and reverse (Fig. 1). The three joint types show basically the same geometry parameters except for the shouldering. Reverse profile presents alternating shoulders on each board side and is the most common joint. The male-female is a less common joint and it is supposed to be used in cases where the finger-joint will be molded or shaped on both sides. The feather joint is used when stock dimension varies significantly (Wisconsin Knife Works 2000). During visits to five finger-jointing plants in Quebec, it was observed that two mills were working with the male-female joint profile, two others with the reverse profile, and one with a feather profile. No agreement existed among these mills on which of these types of geometry produce the best mechanical performance.

Therefore, the purpose of this work was to compare the structural performance of finger-jointed black spruce wood processed with three types of joint configurations. This study is an initial step toward a comprehensive understanding of the black spruce finger-jointing process, which will help the Eastern Canadian wood products industry to optimize its finger-jointing operations.

Materials and methods

Experiments were carried out with 38- by 64-mm (2- by 3-in.) kiln-dried planed black spruce studs coming from the Chibougamau region in the Quebec province. The studs were placed in a conditioning room at 20°C and 65 percent relative humidity to reach a nominal equilibrium moisture content of 11.2 percent. Defects were removed from pieces by crosscutting to produce blocks varying in length between 20 and 91 cm, of No. 2 grade and better quality grades (NLGA 2000a). The test process was based on the Canadian National Grades Lumber Authority NLGA-SPS

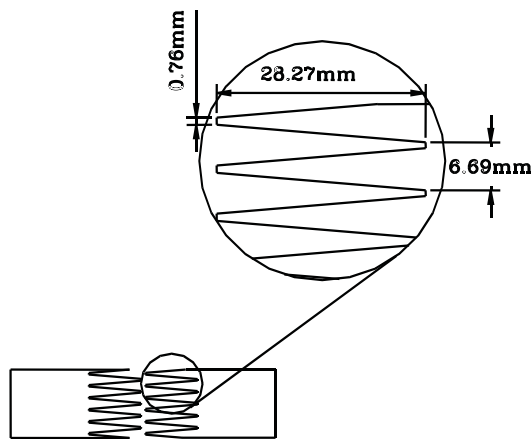


Figure 2. — Dimension of the joint for three profiles of finger-joints used in this study.

Table 1. — MOR determined from edge- and flatwise bending tests for three profiles of finger-joints of black spruce.^a

Statistical parameter	Feather		Male-female		Reverse		SPS 1-2000	
	Edge	Flat	Edge	Flat	Edge	Flat	Edge	Flat
Mean (MPa)	55.3 A	58.7 a	52.9 AB	48.7 b	47.4 B	36.7 c	34.5	34.5
SD ^b (MPa)	8.2	7.4	5.9	8.8	9.4	5.6	--	--
Sample size	12	15	16	15	17	18	--	--

^a Means within a row followed by the same letter are not significantly different at the 5 percent probability level. Uppercase letters are for edgewise bending comparison and lowercase letters are for flatwise bending comparison.

^b SD = standard deviation.

1-2000 specifications for structural jointed wood (NLGA 2000b).

A Conception RP 2000 machine provided with a lateral feed system, common in the North American finger-jointing industry, was used. The ends of blocks were machined across the width in order to obtain horizontal finger-joints. Three types of joint geometry were studied: feather, male-female, and reverse (Fig. 1). A chip load of 0.84 mm (0.033 in.) was obtained by setting the machine at 18.3 m/min. (60 ft/min.) feed speed, and 3500 rpm rotation speed with six knife sets (bolts) per tool. The finger-joint geometry was 28.27 mm (1.113 in.) finger length, 0.76 mm (0.030 in.) tip width, and 6.69 mm (0.263 in.) pitch width (Fig. 2). After finger-jointing, the blocks were glued with an adhesive formulation according to the technical recommendations supplied by the adhesive manufacturer. The adhesive was an ISOSET UX-100/A322 isocyanate combined with a cross-linking agent containing a polymeric isocyanate. A one-face glue line application was used at a spread rate of 110 g/m². The assembled joints were pressed at 20°C under a constant end pressure of 3.79 MPa (550 psi) for 20 seconds.

Thus, given the variable length of the blocks, each of the pieces was composed by a variable number of joints. After the curing period, the pieces were automatically crosscut at 3.05 m or 2.44 m long to obtain the specimens for bending and tension tests, respectively. The specimens were mechanically tested after 24 hours of curing at room temperature conditions.

The mechanical bending properties of the finger-jointed specimens were evaluated according to the SPS 1-2000 standard (NLGA 2000b). Four-point edge- and flatwise bending tests were performed with a Metriguard machine, model 312, over 1270 and 813 mm of total span, respectively. Load rate was set in order to reach the maximum load in about 2 minutes. Testing and data acquisition were controlled with an MTS Systems Corporation's TestWorks™ data logging system (MTS 1999). The modulus of rupture in bending (MOR) was calculated. Failure mode was examined around the joints and near the loading points.

Tension tests were performed according to ASTM D 198 standard (ASTM 1997a) with a Metriguard testing ma-

chine, model 412. Testing and data acquisition were controlled with software developed by Forintek Canada Corp. The ultimate tensile strength (UTS) was calculated. Failure modes were examined around the joints and were classified according to the ASTM D 4688 standard (ASTM 1997b).

After mechanical tests, two samples were cut from each side of the failed joint, and moisture content and density were determined following ASTM D 2395-93 standard (ASTM 1995). The mean basic density of specimens was estimated at 450 kg/m³. Since specimens at the testing time were at 11.2 percent moisture content, their volume at the green state was adjusted considering a total volumetric shrinkage of 11.1 percent and a fiber saturation point of 30 percent.

The experiment in bending test was a factorial design with two factors: mode of bending (edge- and flatwise) and type of profile (feather, male-female, and reverse). A two-way analysis of variance (ANOVA) from SAS (GLM procedure) was performed to evaluate the data (SAS 1998). Furthermore, a one-way ANOVA with this same software was performed to evaluate the tension data (SAS 1998). When a source of variation was significant, multiple comparison tests with Bonferonni corrections were carried out to determine which factor levels differed from the others. These comparisons were done at the comparison-wise error rate of 0.05/c, where c is the total number of comparisons. The normality assumption for both bending and tension tests was verified using the Shapiro-Wilk test, while the homogeneity of variances was analyzed by Levene and Bartlett tests.

Results and discussion

A summary of MOR values in edge- and flatwise bending of finger-jointed black spruce wood is given in Table 1. A comparison between the minimum and mean values of MOR for the three different types of finger-joints is shown in Figure 3.

For edge- and flatwise bending, an ANOVA indicated that a statistically significant difference in MOR existed among the three finger-joint configurations. The MOR edgewise was 7 and 14 percent lower for male-female and reverse profiles, respectively, compared to that obtained by the feather configuration. However, the differences were sta-

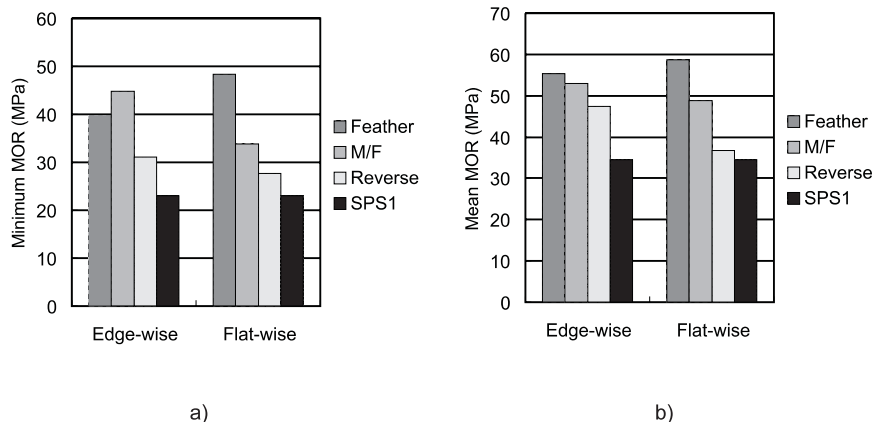


Figure 3. — Comparison among MOR values as determined from edge- and flatwise bending tests for the three profiles of finger-joints of black spruce. a) Minimum MOR; b) Mean MOR.

Table 2. — Ultimate tensile strength (UTS) for the three profiles of finger-joints of black spruce.^a

Statistical parameter	Feather	Male-female	Reverse	SPS1-2000 Proofload tension stress level
Mean (MPa)	33.5 A	31.1 A	29.8 A	6.8
SD ^b (MPa)	4.4	5.2	2.3	--
Sample size	15	15	15	--

^a Means within a row followed by the same letter are not significantly different at the 5 percent probability level.

^b SD = standard deviation.

tistically significant only between reverse and feather profiles (Table 1). In flatwise bending, the MOR was 17 and 37 percent lower for male-female and reverse configurations, respectively, in relation to the feather profile. The factorial experiment confirmed that differences in MOR were more significant for flatwise than for edgewise bending. This can be explained in terms of differences in the glued area and the edge shoulders observed among the joint configurations. The finger-joints machined with edge shoulders (male-female and reverse) ensure that there is a straight line across the surface after final planing. However, this can have a negative impact from a strength or brittle fracture point of view (Bryan et al. 1998). The feather configuration had about 7 and 15 percent more glued area in the joints than the male-female and reverse configurations, respectively. The difference in the glued area comes principally from the shoulder parts of the outside fingers (Fig. 1). Also, in bending, the maximum tensile stress is developed on the convex side of the sample and the bending strength is controlled by the ultimate fiber stress on the tension side. Thus, in flatwise bending, it is the outside finger that receives the most load and initiates the failure.

Therefore, its integrity is very critical to the performance of the joint.

The male-female and reverse configurations have an edge shoulder that in fact is a butt joint, which is a discontinuity that creates a stress concentration area. The feather profile minimizes this discontinuity (Fig. 1). Numerical analyses show that high stress concentrations (stresses along the grain direction) develop in the vicinity of the finger tip/root (Pellicane 1994, Smardzewski 1996). Other studies based on holographic images of deformation patterns in end finger-joints have shown several negative effects of the finger connection on the strength (Sandoz et al. 1994, Hernández 1998). Thus, the presence of local stress concentration leads to the initiation of failure at the finger base and, as a consequence, a lower strength is obtained. Since in flatwise bending the shoulders are resisting the tensile stress developed at the bottom fibers, higher tensile strength can be achieved with feather joints compared to male-female or reverse joints.

In edgewise bending, differences in MOR among the three configurations were less evident given that each finger works in an identical way and stresses

are, hence, equally distributed across all fingers. However, the lower glued area in reverse configuration affected negatively the mechanical strength in edge-wise bending.

The minimum MOR values obtained for the three types of joints were found to be higher than those required by NLGA-SPS 1-2000 (NLGA 2000b) for No. 2 and better grade of the SPF group (Fig. 3).

The mean ultimate tensile strength (UTS) values for the three types of finger-joints are given in Table 2. A similar trend to that observed in bending strength for the different configurations of joints can be seen. The feather joint has the highest mean UTS value compared to either male-female or reverse profiles (34 MPa compared to 31 and 30 MPa, respectively). However, the ANOVA showed that these differences were not statistically different, even though the probability level was close to 0.05 ($p = 0.056$). The results suggest that the number of repetitions was probably not sufficient to detect any significant differences. Yet all joint profiles tested exhibited higher minimum tensile strength compared to the SPS-1 standard (NLGA 2000b) specified value (Fig. 4). In fact, the minimum strength of the three types of joints tested is more than 3.6 times the proofload tension stress level specified by the SPS1-2000 (NLGA 2000b) (mean value of 24.8 MPa, all joints pooled, compared to 6.8 MPa).

The quality of the glueline was evaluated by the percent wood failure in the finger-joint. The ASTM D 4688 (ASTM 1997b) used to classify the wood failure in the finger-joint is based only on the tension test. However, observations on joint failures in the bending tests were also recorded. Most specimens in the three groups (male-female, reverse, and feather) failed mainly in simple tension characterized by a combination of brash tension failure and splitting of wood fibers. Failure was mostly initiated in the middle of the specimen, that is, at the finger-joint location. This failure was more obvious for specimens tested in edgewise than flatwise bending. The second most dominant failure mode was in splintering tension. It was observed, however, that even though failure initiated at the location of the finger-joint (midspan), it was predominately in wood and not in

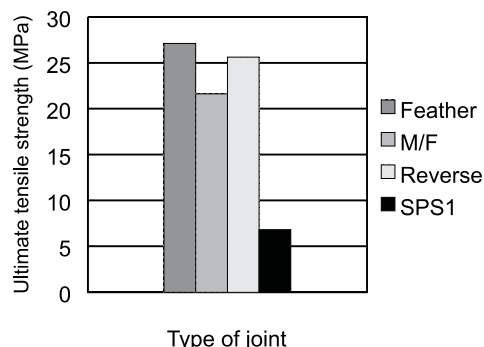


Figure 4. — Comparison among minimum UTS values for the three profiles of finger-joints of black spruce and those specified in SPS-1 2000 (NLGA 2000b).

the glueline. These results indicate a good quality of bonding.

Failure modes for tension tests were evaluated according to ASTM D 4688 (ASTM 1997b). Generally, wood failure was high for all types of finger-joints tested. More than 74 percent of specimens failed in modes number 3 and 4. Failure mode number 3 is mostly along the joint profile but with some failure at the finger roots, while mode 4 is associated with tensile wood failure occurring at the joint roots and with high overall wood failure. Such failures are the most common in structural finger-jointed material. Almost no gluebond failure was observed, which confirms that the gluing process was appropriate.

Differences in failure modes among the three types of finger-joints studied were most pronounced in bending rather than in tension. When loading perpendicular to the finger length, a bending test tends to open the fingers, unlike a tension test that tends to shear through the glueline along the wood grain.

Conclusion

The profile of structural finger-joints had a significant influence on MOR in edge- and flatwise bending but not on the ultimate tensile stress (UTS) of black spruce wood. However, the authors are inclined to think that a greater number of repetitions could possibly produce significant differences in UTS. In all cases, the feather profile exhibited the highest mean strength in both bending and tension strengths. Differences were found to be due to the higher bonded area and non-existent shouldering for this profile when compared to the two others. This type of finger-joint profile is therefore the most efficient among the three profiles tested. However, all types of profiles largely met strength specifications outlined in the

Canadian NLGA standard SPS 1-2000 for structural lumber. The results have also shown that finger-joints of high flexural and tensile performance can be produced using the type of isocyanate adhesive studied.

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