ISSN impresa 0717-3644
ISSN online 0718-221X

Maderas. Ciencia y tecnología 13(3): 319-328, 2011
DOI 10.4067/S0718-221X2011000300007

EFFECTS OF END-PRESSURE ON THE FINGER-JOINT QUALITY OF BLACK SPRUCE LUMBER: A MICROSCOPIC ANALYSIS

***Cecilia Bustos*[1] *, Roger E. Hernández*[2]*, Robert Beauregard*[2]*, Mohammad Mohammad*[3]**

ABSTRACT

Efficiency of finger-joints in the Engineered Wood Products is key to the performance of these products. The aim of this research work was to evaluate, by scanning microscopic analysis, the effect of end pressure on the performance of horizontal finger-joint of black spruce (*Picea mariana* (Mill.) B.S.P) specimens. A feather joint configuration glued with an isocyanate type of adhesive cured at room-temperature was used. The finger-joints were machined at a feed rate of 18.3 m/min, rotational speed of 3500 rpm, and at a feed per knife (chip-load) of 0.86 mm. A single-face glueline application was used at a spread rate of 110 g/m^2. The curing time was kept at 24 hours. Six end-pressure levels ranging from 1.38 MPa to 4.82 MPa applied for 20 seconds were investigated. Results showed that cell depth damage increased as end-pressure increased. Joints also showed formation of some air bubbles within the glueline which lead to a reduction in their tensile strength.

Keywords: Finger-joint, end-pressure, microscopic analysis, structural adhesives, Engineered Wood Products.

INTRODUCTION

Finger-jointed products are manufactured by taking short pieces of defect free kiln-dried lumber, machining a finger profile in each end of the pieces, applying an appropriate structural adhesive, and joint the pieces together under end pressure to form long length soft lumber. Finger-jointing is used in several Engineered Wood Products such as glulam and it is also commonly used for flange material in wood I-beams. Such structural applications require the wood and the glued joint to be strong enough to resist specified service loads in bending and tension. In principle, the finger-jointing process allows the removal of strength reducing defects, the increase of the surface area of the glue joint, which will produce a product with high engineering properties. The strength of the joints is controlled by specific process parameters such as moisture content and temperature of lumber, machining process parameters, several wood-related factors such as species, density, natural defects, as well as others that are related to the gluing process (Bustos *et al.* 2003a, 2004, Karastergiou and Ntalos 2005, St-Pierre *et al.* 2005, Dagenais and Salenikovich 2008, Vassiliou *et al.* 2009). Little information is available on the influence of end-pressure when using an isocyanate type of structural adhesive for finger-jointing black spruce. The effects of end-pressure and curing time on the performance of finger-jointed black spruce were investigated earlier by Bustos *et al.* (2003b) in order to determine the optimum conditions for the production of finger-joints for structural applications. Both curing time and end-pressure were found to have a statistically significant influence on the finger-jointing quality using isocyanate type of adhesives. After 5 hours of curing time, finger-joints made with isocyanate achieved more than 90% of the reference ultimate tensile strength based on a 24 hours curing time. Analysis also indicated that finger-jointed black spruce achieved its best performance at an end-pressure of 3.43 MPa. Lower or higher end-pressure can result in a lower tensile strength.

---

[1] Associate Professor, Departamento de Ingeniería en Maderas, Universidad del Bío-Bío, Concepción, Chile, 4081112
[2] Professor and Dean respectively of the Dept. of Wood and Forest Sciences, Laval University, Quebec, QC, Canada, G1V 0A6.
[3] Group Leader and Research Scientist, FPInnovations-Wood Products Division, Otawa, ON, Canada K1S 5R1.
Corresponding author: cbustos@ubiobio.cl
Received: 02.06.2011 Accepted: 04.08.2011

The main purpose of end pressure is to bring the adjoining surfaces together so that the glue forms a thin and continuous film between these surfaces. This pressure also allows a uniform distribution of the adhesive and creates an optimum glueline thickness. Several authors have investigated the effect of the glueline thickness on strength of finger-joints (Groom and Leitchi 1994, River 1994, Sandoz 1984, Ebewele *et al.* 1979). Findings from these studies have indicated that the glueline thickness needs to be controlled in order to produce strong joints. Generally, thin glue lines lead to starved joints while thicker gluelines (i.e., beyond optimum thicknesses) may lead to stress concentration in the adhesive layer due to cure-shrinkage. Pressure must also be applied to force fingers together to form an interlocking connection, giving a certain immediate handling strength (Raknes 1980). While the increase of the end-pressure up to a certain level gives a better contact of the fingers to obtain strong joints, cell damage or splitting of the finger root could be induced due to excessive pressure (Kutscha and Caster 1987, Marra 1984, Jokerst 1981).

Several opinions exist regarding the optimum pressure needed to produce high-strength finger-joints. The German standard DIN 68-140 (Deutsches Institut fuer Normung 1971) specifies minimum acceptable values for the different lengths of fingers. For example, 11.77 MPa for 10 mm fingers and 1.96 MPa for 60 mm fingers. The German standard also establishes that a minimum pressure of 0.98 MPa must be applied (Deutsches Institut fuer Normung 1971). Strickler (1980) stated that an end-pressure of about 2.76 MPa is near optimum for most of softwood species. Typically, with an increase in end-pressure, a better contact between the sides of the finger is obtained and the gap between the fingertip and root is reduced. Thus, as a higher end-pressure is applied, more locking efficiency and performance can be obtained up to the point where damage to the tips of fingers or splitting of the wood at the root occurs (Dawe 1965). Madsen and Littleford (1962) used end-pressures between 0 and 4.14 MPa with casein and phenol-resorcinol adhesives. Their results showed that 2.76 MPa end-pressure was adequate to facilitate curing and to develop optimum tensile strength. Juvonen (1980) also studied the effects of the end-pressure on joint strength but considering the geometry and size of the fingers. The end-pressure had a relatively small effect on joints with long fingers and, adequate joints could be obtained with a relatively low end-pressure. However, with short fingers, the effect of end pressure in the low pressure range was greater. As a result, a certain minimum pressure is recommended depending on the size of fingers. Ayarkwa *et al.* (2000) tested three end-pressures on finger-jointed African hardwoods. Results showed no significance of this parameter on Modulus of Rupture (MOR) and Modulus of Elasticity (MOE) in bending. On the other hand, Sandoz (1984) noted that a “back pressure” can be obtained during the phase of release of the pressure, which can cause separations and lead to adhesive-free gaps at the end of the finger. The key objective of this additional analysis is to complement the study carried out by Bustos *et al.* (2003b) on the effect of end-pressure on finger-joint quality in black spruce wood by providing a better understanding on how end pressure affects the finger-joint quality and be able to quantify that effect.

MATERIALS AND METHODS

Experiments were carried-out with 38 mm by 64 mm, kiln dried planed black spruce studs coming from the Chibougamau region in the province of Quebec. The studs were placed in a conditioning room at 20°C and 65 percent relative humidity to reach equilibrium moisture content (EMC) of 11.8%. Defects were removed from pieces by cross-cutting to produce blocks varying in length between 20 and 91 cm of N° 2 and better grades (National Lumber Grading Authority 2000a). The defecting and sampling process was based on the Canadian National Lumber Grades Authority NLGA-SPS 1-2000 specifications for finger-jointed structural lumber (National Lumber Grading Authority 2000b).

A Conception RP 2000 finger-jointing machine with a lateral feed system, commonly used in the North American finger-jointing industry was used. The ends of the blocks were machined across their width in order to obtain horizontal finger-joints. A feather profile was selected due to its good mechanical performance (Bustos *et al.* 2003b). A chip-load of 0.84 mm was obtained by setting the machine at 18.3 m/min feed speed, and 3500 rpm rotational speed, with 6 knife sets (bolts) per tool. The finger-joint geometry was 28.27 mm length, 0.76 mm tip width, and 6.69 mm pitch. Following finger-jointing, the blocks were glued with a structural adhesive formulation according to the technical recommendations supplied by the adhesive manufacturer. The structural adhesive was a two-component system consisting of an ISOSET UX-100 polyurethane prepolymer mixed with an ISOSET WD3-A322 emulsion polymer. These two components are mixed immediately prior to use. A single-face glueline application was used at a spread rate of 110 g/m^2. The assembled joints were pressed at 20°C. The end-pressure ranged from 1.38 MPa to 4.90 MPa and was applied for 20 seconds. The finger-jointed lumber was cross-cut to produce test specimens of 2.44 m long. Their average basic density was estimated at 448 kg/m^3. The specimens were mechanically tested after twenty-four hours of curing at room temperature. Tension tests were performed according to ASTM D 198-99 (American Society and Materials 1997) and SPS-1 2000 (National Lumber Grading Authority 2000b) requirements using an MTS Metriguard testing machine, model 412. Testing and data acquisition were controlled with software developed by FPInnovations (MTS Systems Corporation 1999). The ultimate tensile strength (UTS) was determined.

Scanning electron microscopy (SEM) evaluations were performed to quantify the effect of the end-pressure on the finger-jointing of black spruce wood. One of the 2.4 m length finger-jointed lumber containing at least 5 joints was randomly selected in order to obtain the joint samples for SEM analysis. Twelve blocks of about 1 cm^2 of transverse face that includes the gluelines, were removed from the joints zone of the specimen. Seven blocks of 1 cm^2 of longitudinal face that includes gluelines were cut from specimens manufactured with low, medium and high end pressure (Figure 1).

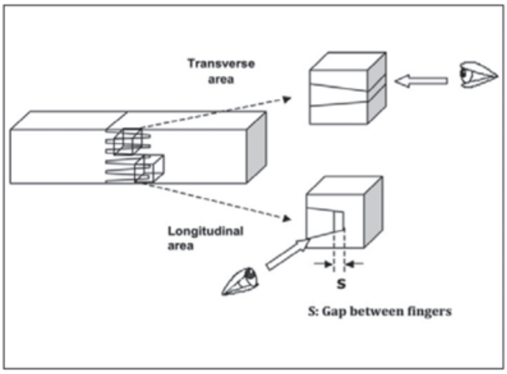


Figure 1. Samples for SEM analysis taken from transverse and longitudinal surfaces

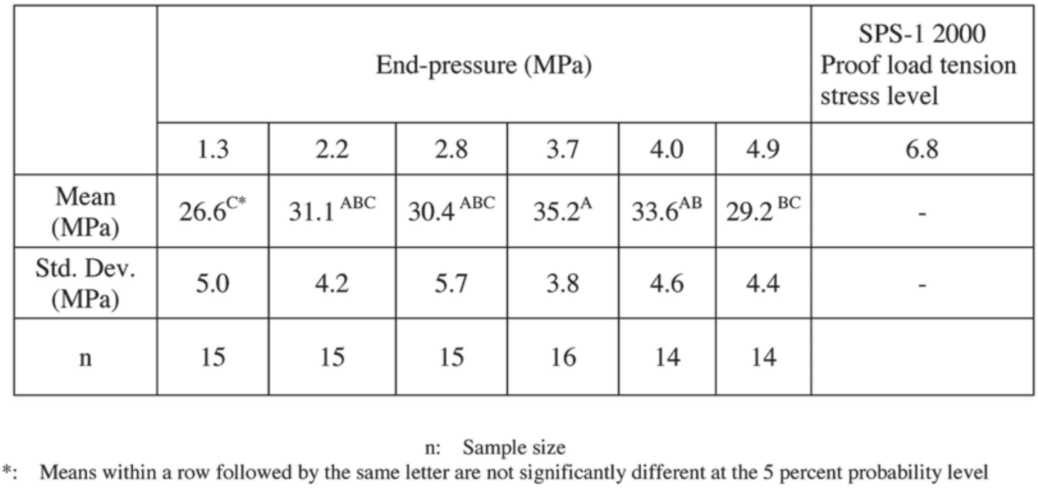
The blocks were prepared with a razor blade by carefully cutting either the end-grain surface or the longitudinal surface for SEM analysis. The blocks were then desiccated with phosphorus pentoxide over two weeks, mounted on a standard aluminum stub with silver paint, redesiccated and coated with gold palladium in a sputter-coater. Electron micrographs of representative sub-surfaces were taken for each of the end-pressure applied. The depth of damage and glueline thickness were evaluated at five systematically chosen points from each SEM micrograph. The gap at the tip of the finger (S) was also measured in each micrography taken in the longitudinal side of the surface.

RESULTS AND DISCUSSION

Mechanical properties of finger-joints at different end-pressures

A summary of results reported by Bustos *et al.* (2003a) on the influence of end-pressure on the ultimate tensile strength (UTS) is given in table 1. These results were associated with the amount of end pressure applied during the manufacturing process. UTS increased slightly with the increase of pressure until it reached a maximum value at 3.43 MPa end pressure. After that, the UTS decreased as the end-pressure increased. Pressure in excess of 3.43 MPa will likely cause a reduction of the UTS, triggering splitting due to compression load at the finger root, even without the tips of fingers reaching the roots of the opposite fingers. On the other hand, an end-pressure of 1.35 MPa (196 psi) was enough for the joined wood to be handled even though it represented the lowest performance on the structural properties. Nevertheless, the mean UTS values in all tension tests were higher than those specified in SPS-1 2000 (National Lumber Grading Authority 2000b) for S-P-F group, grade No. 2 and better for finger-jointed structural lumber (Table 1). Detailed results are given in Bustos *et al.* (2003a).

Table 1. Summary of UTS values of finger-jointed black spruce lumber as determined from tension tests with different end-pressure levels, Bustos *et al.* (2003a).



	End-pressure (MPa)						SPS-1 2000 Proof load tension stress level
	1.3	2.2	2.8	3.7	4.0	4.9	6.8
Mean (MPa)	26.6^{C*}	31.1 ^{ABC}	30.4 ^{ABC}	35.2^{A}	33.6^{AB}	29.2 ^{BC}	-
Std. Dev. (MPa)	5.0	4.2	5.7	3.8	4.6	4.4	-
n	15	15	15	16	14	14	

n: Sample size

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

SEM analysis of transverse glueline faces

SEM analysis on transverse sections of specimens showed signs of damaged cells close to the gluelines. Crushed and collapsed cells were observed near or at the glueline. In general, the depth of damaged cells (D) was more pronounced as the end-pressure increased from 1.3 MPa to 4.9 MPa (Fig. 2 and Fig. 3). Variability in the depth of damage observed could be affected by the presence, or not, of latewood or earlywood in the glueline. The random growth ring orientation observed in the different joints could have also contributed to this variability. Tracheids near at the glueline were highly compressed at higher end-pressures. Rays were also compressed and deformed. As expected, the damage in latewood (LW) was less severe than in earlywood (EW), which is owing to the higher density of LW. The maximum depth of cell damage (53 µm) was reached at 4.9 MPa of end-pressure. This represents 90% more cell damage than that observed at a low end-pressure of 1.3 MPa (28 µm). On the other hand, at low end-pressures (1.3 MPa), air bubbles inside the glueline were observed, which can also explain the lower quality of the finger-joints. Pellicane (1994) observed a similar effect on the mechanical strength of finger-joints, which lead to a considerable reduction in the tensile strength. The mechanical fracture of a joint can be initiated by a discontinuity of the adhesive due to stress concentrations in the joints. According to River (1994), an air bubble in the glueline is an example of geometrical discontinuity inside the joint.

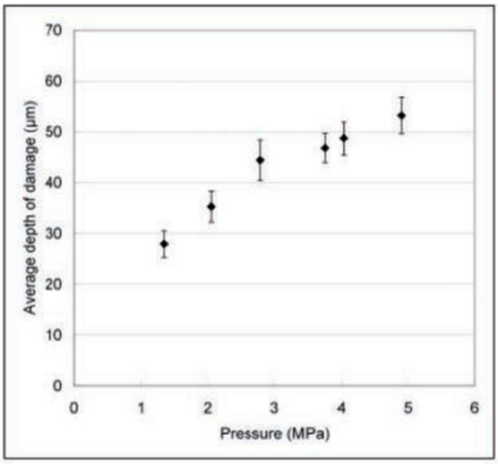


Figure 2. Effect of end-pressure on depth of cell damage of finger-jointed black spruce lumber. Values are mean and standard error of the mean.

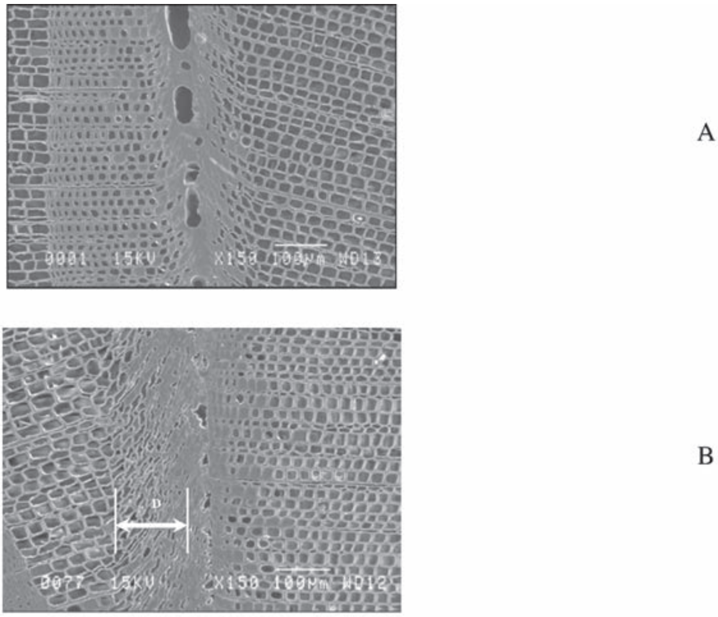


Figure 3. SEM micrograph of cell depth damage of finger-jointed black spruce wood at end-pressure of A) 1.3 MPa and B) 4.9 MPa.

SEM analysis of longitudinal glueline faces

The SEM analysis of longitudinal surfaces of black spruce finger-joints showed mainly the effect of the end-pressure on the gap at the tip of the fingers (S). The results are shown in figures 4 and 5. As can be seen, the gap size did not exceed the maximum value required (1600 µm) by the SPS 1-2000 standard. Results confirm that the gaps at the tip of fingers decrease as the end-pressure increases. This behaviour is more important at lower pressures (i.e. from 1.3 MPa to 3.7 MPa). At higher end-pressures, this effect decreases slightly until reaching a gap size at the tip of the fingers of 53 µm at 4.9 MPa. This can be explained in terms of a greater incompressibility of the adhesive within the reduced gaps. The formation of air bubbles appeared clearly for the low end-pressures due to excess of gap because this is part of a discontinuity within the bonded joint. Cracks were also observed at the ends of the joints when the end-pressure was increased (Figure 5F). Tension stress perpendicular to the grain due to excessive axial compression loading exerted by the end-pressure could cause cracks in wood. River (1994) studied the fracture of adhesive-bonded wood joints and established that the fracture of wood and bonded joints and materials begins at a geometric or material discontinuity, where displacement of the adherents (due to external or internal stress) creates the greatest stress concentration and where either the adherent or the adhesive is the weakest. Also, the finger-joints have a flat portion of each finger tip that represents a small butt joint and geometric as well as material discontinuity. This makes this type of joint less efficient in terms of their mechanical performance. Some examples of the geometric discontinuities in adhesive-bonded wood joints are the square-cut ends of overlapped adherents, voids at the tips of fingers in finger-joints, voids, etc.

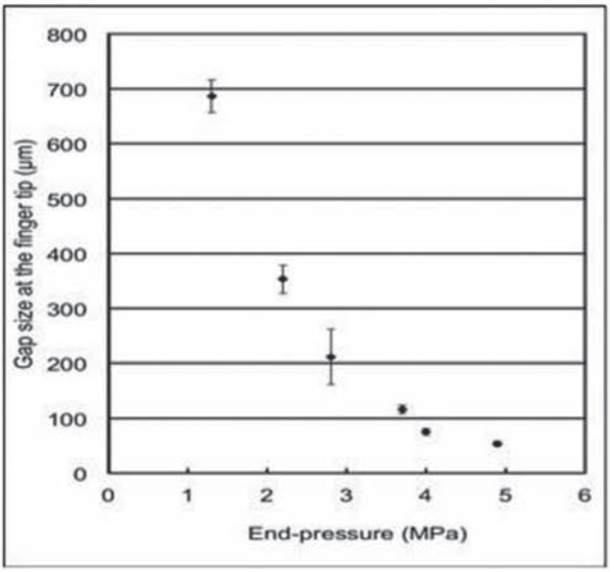


Figure 4. Gap size at the finger tip in black spruce finger-joint according to the end-pressure applied. Values are mean and standard error of the mean

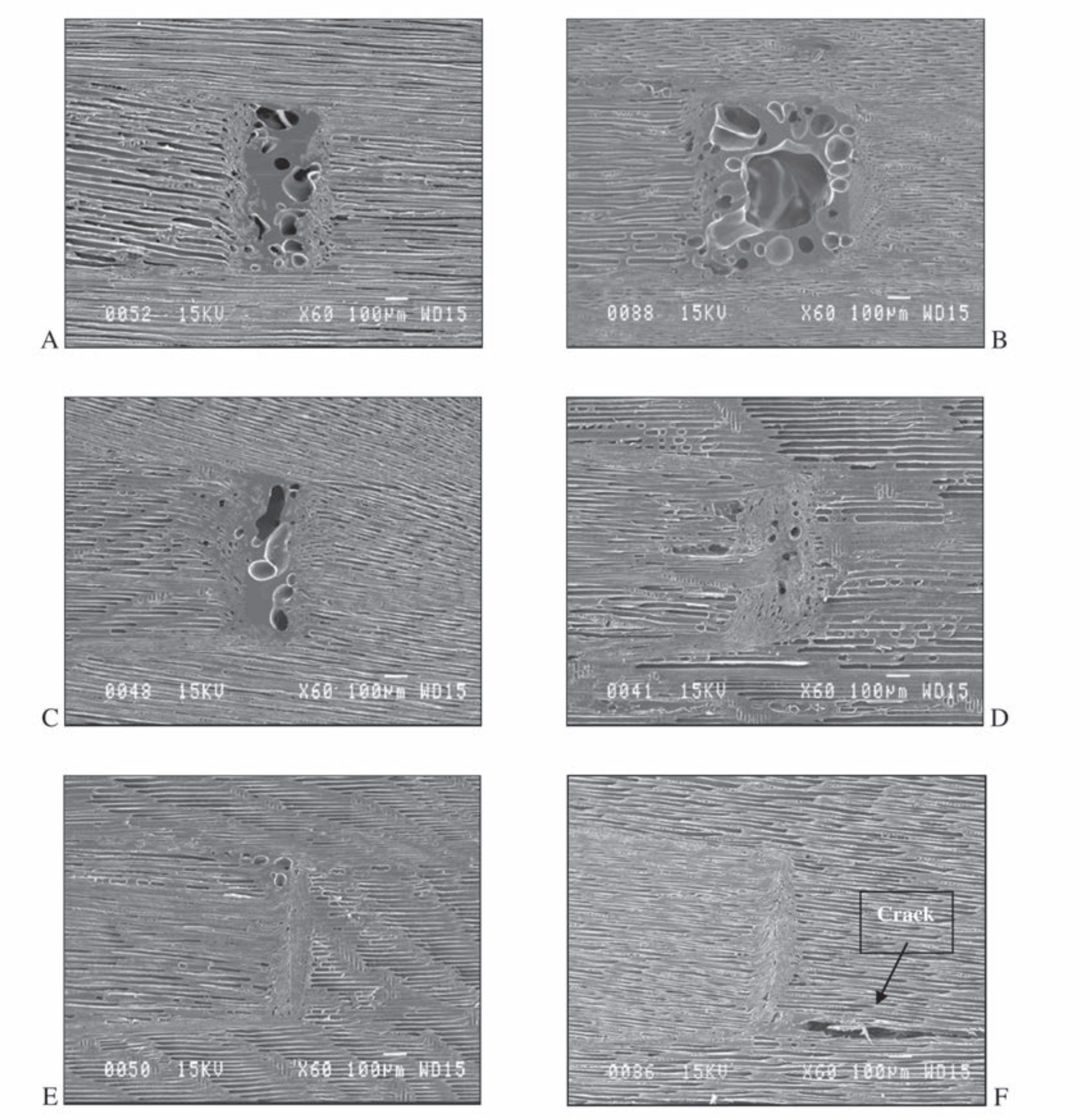


Figure 5. Gap between fingers at end-pressures of
A) 1,3 MPa, B) 2,2 MPa, C) 2,8 MPa, D) 3,7 MPa, E) 4,0 MPa and F) 4,9 MPa

In the feather joint configuration, the rigid fingers are inserted into a pre-cut finger-joint piece. The fingers are pushed into the precut piece due to the end-pressure applied, and can cause splitting along the plane of the precut piece. When the finger-tip is pushed further into the precut specimen, the crack propagates. Figure 5F shows a crack occurred at 4.9 MPa of end-pressure applied. Cracking was initiated at the finger corner and propagated along the grain. As the joint was loaded by the end-pressure, some energy was probably stored within the interface of the adhesive and wood. Thus, micro cracking in the wood surrounding the crack tip could have occurred. Once cracking began, the crack front then advanced and dissipated the stored energy until this energy drops at a lower level. A rapid propagation of the crack can occurs when the stored energy reaches the critical level (strain concentration around the finger-tips) and the wood grain is parallel to the end-pressure applied. The fracture appears to follow the grain. According to Smith *et al.* (2003), three types of failure can be distinguished microscopically in wood, inter-cell failure (IC) that occurs at the middle lamella and represents the separation of cells, intra-wall failure (IW) that refers to failure within the secondary wall, and trans-wall failure (TW) when fracture travels across the wall. River (1994) also established that this kind of failure advances by continuous transwall cracking of thin-walled cells, and intrawall or diagonal transwall cracking of thick-walled cells. The authors think that the inter-cell failure has occurred in the case of the crack at 4.9MPa.

CONCLUSION

End-pressure applied during the manufacturing process in structural finger-jointed lumber has a significant influence on ultimate tensile strength of the product. Black spruce has a good potential in finger-jointing with isocyanate adhesive for structural applications. The tensile strength of all finger-joints fabricated using various end-pressures treatments met the minimum specified tensile strength requirements as outlined in the Canadian National Lumber Grades Authority (NLGA) SPS 1-2000 (National Lumber Grading Authority 2000b) for structural finger-jointed lumber. The depth of damage in cells increased as end-pressure increased. At lower end-pressures, air bubbles can be developed inside the glueline, which could trigger a significant reduction of the tensile strength of finger-joints. The microscopic analysis showed how the gap at the fingers-tip decreases as the end-pressure increases.

ACKNOWLEDGES

The authors wish to thank technicians from the Dept. of Wood and Forest Sciences at Laval University as well as those from the Value Added Program and Building Systems Departments at FPInnovations for their technical support.

REFERENCES

ASTM, American Society for Testing and Materials. 1997. Standard test methods of static tests of lumber in structural sizes. ASTM D 198-99. Philadelphia, PA. : 57-75.

Ayarkwa, J.; Hirashima, Y.; Sasaki, Y. 2000. 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.

Bustos, C.; Mohammad, M.; Hernández, R.E.; Beauregard, R. 2003a. Effects of curing time and end-pressure on the tensile strength of finger-joined black spruce lumber. *Forest Prod. J.* 53 (11-12): 85-89.

Bustos, C.; Beauregard, R.; Mohammad, M.; Hernández, R.E. 2003b. Structural performance of finger-joined black spruce lumber with different joint configurations. *Forest Prod. J.* 53(9): 72-76.

Bustos, C.; Hernández, R.E.; 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.

Dagenais, C.; Salenikovich, A. 2008. Influence of machining parameters on the tensile strength of finger-jointed sugar maple lumber. *Wood Fiber Sci.* 41(1):55-61.

Dawe, P.S. 1965. Strength of finger-joints. Paper presented at the International Symposium on joints in timber structures. 30 March-1April. Edited by Timber Research and Development Association. London, England. 9 pp.

DIN, Deutsches Institutfuer Normung. 1971. Wood joints: Dovetail joints as longitudinal joints. DIN 68 140. German National Standard, Berlin, Germany.

Ebewele, R.; River, B.; Koutsky, J. 1979. Tapered double cantilever beam fracture tests of phenolic-wood adhesive joints. Part I. Development of specimen geometry; effects of bondline thickness, wood anisotropy and cure time on fracture energy. *Wood Fiber* 11(3):197-213.

Groom, L.H.; Leitchi, R.J. 1994. Effect of adhesive stiffness and thickness on stress distributions in structural finger joints. *J. Adhesion* 44 (1-2):69-83.

Jokerst, R.W. 1981. Finger-jointed wood products. Res. Pap. FLP 382.USDA Forest Serv., Prod. Lab. Madison, WI. USA 23 pp.

Juvonen, R. 1980. End pressure for finger-jointing. Proceedings of Production, Marketing and use of Finger-jointed Sawnwood. C.F.L. Prins, ed. Timber Committee of the United Nations Economic Commission for Europe. Martinus Nijhof/Dr. W. Junk Publishers. The Hague, Boston, London. pp.181-189.

Karastergiou, S.; Ntalos, G. 2005. Bending strength properties of scarf jointed European spruce wood (*Picea excelsa*). Proceedings of International Scientific Conference Engineering Design "Interior and furniture design".Oct. 15-17, Sofia, Bulgaria.

Kutscha, P.; Caster, R.W. 1987. Factors affecting the bond quality of hem-fir finger-joints. *Forest Prod. J.* 37(4):43-48.

Madsen, B.; Littleford, T.W. 1962. Finger joints for structural usage. *Forest Prod. J.* 12(2):68-73.

Marra, G. 1984. The role of adhesion and adhesives in the wood products industry. In: Adhesives for wood. Research applications, and needs. Edited by Robert H. Gillespie. USDA. *Forest Serv., Prod. Lab. Madison, WI.* pp. 2-9.

MTS Systems Corporation. 1999. Test Works R4, Version 4.03, Eden Prairie, MN. Minnesota. USA.

NLGA, National Lumber Grading Authority. 2000a. Standard grading rules for Canadian lumber. National Lumber Grading Authority. Vancouver, BC, Canada. 238 pp.

NLGA, National Lumber Grading Authority. 2000b. Special products standard for finger joined structural lumber. NLGA-SPS 1. Vancouver, BC, Canada. 25 pp.

Pellicane, P.J. 1994. Finite element analysis of finger-joints in lumber with dissimilar laminate stiffnesses. *Forest Prod. J.* 44(3):17-22.

Raknes, E. 1980. The influence of production conditions on the strength of finger-joints. Proceedings of Production, Marketing and use of Finger-jointed Sawn wood. C.F.L. Prins, ed. Timber Committee of the United Nations Economic Commission for Europe. Martinus Nijhof/Dr. W. Junk Publishers. The Hague, Boston, London. pp.154-168.

River, B. 1994. Fracture of adhesive-bonded wood joints In: *Handbook of adhesive technology.* Edited by Pizzi and Mitall. pp. 151-177. NewYork: MarcelDekker, ForestProductsLaboratory, USDA-ForestService, Madison, Wisconsin.

Sandoz, J. 1984. Study of stress dispersion in finger-jointed wood. Work placement research conducted at the Federal Polytechnical School of Lausanne (EPFL). Wood construction chair, IBIOS.75 pp. (in French). Lausanne, Switzerland.

Smith, I.; Landis, E.; Gong, M. 2003. *Fracture and fatigue in wood.* John Wiley & Sons Ltd. ISBN 0-471-48708-2. 233pp. Chichester, England.

St-Pierre, B.; Beauregard, R.; Mohammad, M.; Bustos, C. 2005. Effect of moisture content and temperature on the tension strength of finger jointed black spruce lumber. *Forest Prod. J.* 55(12): 9-16.

Strickler, M.D. 1980. Finger-jointed dimension lumber - past, present, and future. *Forest Prod. J.* 30(9): 51-56.

Vassiliou, V.; Barboutis, I.; Ajdinaj, D.; Thoma, H. 2009. PVAc Bonding of finger jointed Beech wood originated from Albania and Greece. Proceedings of International Conference “Wood Science and Engineering in the third millennium”, ICWSE.715:721 p. Transilvania. University of Brasov, Romania.