Title

Impact of a reinforcement treatment with acrylate impregnation on the mechanical behavior of black spruce as connector member.

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Abstract

As a previous study has shown, it is possible to increase by 50% the dowel bearing strength of black spruce with an acrylate formulation applied by impregnation. Three diameters of bolts and two orientations of loading were included in this study. The effect of treatment on the dowel-bearing strength appeared to increase while the diameter of bolt decreased. The orientation of loading was significant as the treatment had a major impact in the parallel to grain direction and no impact in the perpendicular direction. With the digital image correlation analysis, an expanded strain field perpendicular to the load direction was observed. The superior embedding capacity would help to reduce the dimensions of the timbers as well as the number of connections required in the building design. With an increase of ductility, wood connections show a safer yielding behavior.

Key words

Polymer-matrix composites (PMCs); Strength; Stress concentrations; Structural composites; Wood

Main text

1.Introduction

It is not without reason that architects try to expand the use of wood in tall buildings. This renewable material makes stunning structures with a warm and bright look. It also answers to an increasing demand of environmentally friendly construction materials. Wood buildings can offer lower greenhouse gas emissions, less air pollution and lower volumes of solid waste [1] . The choice of products in buildings correlates to its environmental impact, and wood can help to reduce it [2]. In the life cycle assessment (LCA) study of a building, wood shows significant advantages. Compared to functionally-equivalent products made from other materials, Werner and Richter [3] reported that wood products are particularly good to limit the consumption of non-renewable energy and cumulated energy demand. The trees in a forest can absorb and store quantities of CO_2. Approximately 0.9 metric tons of CO_2 equivalent is stored in every cubic meter of wood. Furthermore, wood can help to reduce the carbon footprint by 1.1 t of CO_2 per cubic meter of wood in substitution of steel or concrete structure, resulting in a total of 2 t of CO_2 per cubic meter of wood [4]. Replacing concrete by timber in tall buildings is a current trend for architects [5]. As the size of the buildings grows, the fastener design is the significant limiting criterion of the structural design. Consequently, the constructive system tends to lead to an over-size timber structure, bringing limitations in the architectural design. New strategies need to be developed with the aim to reinforce the critical point of a structure. Creating new types of connectors and improving current ones, are often covered topics in timber construction research, such as in Gattesco [6], Loferski and Platt [7], Mungwa, *et al.* [8], Pantelides, *et al.* [9], Pizzi, *et al.* [10], Yeh, *et al.* [11]. Not only the fastener could be enhanced, but the timber material could be too. Improvement of wood properties by increasing its water repellent capacity, dimensional stability, or flame retardancy was done by Mathias, *et al.* [12], Hazarika, *et al.* [13], Wang, *et al.* [14], Cai, *et al.* [15], Islam, *et al.* [16], Bailing, *et al.* [17], Devi, *et al.* [18]. Furthermore, it is well known that adding nanoparticles leads to better results, such as increase of hardness or dynamic Young's modulus, [15] [19] [16]. With the aim to improve the mechanical properties of wood, Bergman, *et al.* [20] used impregnation and coating. Most of the time, high chemical retentions are wanted to distribute the solution equally and fully in the wood. Hence, previous studies [21] showed that impregnation of low permeable species, like black spruce, resulted in a noticeable increase in mechanical resistance without high chemical retention. Therefore, surface treatments with limited penetration, such as brushing and pulverisation, were tested in preliminary work. It was concluded that these treatments were efficient in increasing the mechanical resistance in wood dowel bearing strength by 20%. However, with the impregnation process, the gain reached 50%. As it showed the highest potential, this last method was retained for further experiments. The impact of the impregnation treatment with and without nanoparticles on the dowel bearing strength of black spruce was presented in the work of Lafond, Blanchet, Landry, Galimard and Ménard [21]. A better understanding of the strain behavior of wood after treatment was needed to explain the 50% strength increase. For the past decades, dial gages, electrical strain gages and linear variable differential transformers (LVDTs) have been the popular method to measure point-source displacement in wood [22]. Yet, these devices are not suitable for full-surface strain measurements. Digital image correlation (DIC) has been included in different fields of science and engineering since the 1980s. The aim was to measure very small strains by measuring homogeneous surface displacements with subpixel accuracy [23]. The conventional DIC technique calculates surface displacement between a gray scale pattern in an undeformed image and the corresponding grey scale pattern from a deformed image. A first-order shape function is applied to approximate the variation in displacement field and calculate the strain [24]. With the DIC, many properties of wood can be evaluated. Stelmokas, Zink and Loferski [22] used this technique to measure the strain field beneath the bolts in multiple-bolted wood connections. Elastic modulus and Poisson ratios were determined for earlywood and latewood by Jeong, *et al*. [25] while Kwon and Hanna [26] suggested an improved DIC for analyzing the wood drying behavior. Therefore, in the current study, DIC was chosen to observe the strain field in a dowel bearing strength test, based on the theory of timber connections by Johansen [27] and the work of Jorissen [28] on the behaviour of double shear connections. Comparison between acrylate impregnated wood and untreated wood was achieved. Moreover, as previous studies suggested, the depth penetration of the formulation could not be enough in the perpendicular direction to obtain an important increase in the mechanical properties of treated wood. Thus, the dowel-bearing strength test was carried out in the perpendicular and parallel to grain directions. Besides, the load carrying capacity of joints with laterally loaded dowel type fasteners is dependent of the wood thickness on the dowel diameter ratio as detailed in the Eurocode 5 [29]. Since the importance of the slenderness parameter on the ductile behavior of connection, the bolt diameter needed to be evaluated as a factor in the impact of the treatment on the mechanical properties of wood. Same diameter was kept from previous studies with the addition of one smaller and one larger diameter.

2.Materials and method

2.1 Materials and Impregnation Process

2.1.1 Wood specimens

Black spruce (*Picea Mariana* (Mill.) BSP) was obtained from Chantiers Chibougamau in Chibougamau, Québec, Canada. This species account for 12% of Canada's total softwood inventory and is well wanted for its straight grain, light weight, fiber density and dimensional stability [30]. Wood block samples were cut at dimensions of 140 mm x 89 mm x 38 mm (L x T x R) for the parallel to grain bearing test and at 89 mm x 89 mm x 38 mm (L x T x R) for the perpendicular to grain one (Fig. 1). Then, both dimension groups of samples were conditioned at 20°C and 65% RH until constant mass was reached. Samples were from defect-free wood and more precisely, without the strong presence of small knots that are frequent in black spruce. If a knot was apparent on a sample, it should not be located under the connection hole. A 11 mm, 14 mm, or 17 mm diameter hole was drilled in the radial direction, on the longitudinal-tangential plane for each specimen. Sixty samples were attributed in each group of diameter hole for the parallel to grain test. Another sixty samples were cut with the 14 mm diameter hole only for the perpendicular testing.

The letter C is for the control group, D1 is for the 9,5 mm bolt diameter group, D2 for 12,7 mm bolt diameter group and D3 for 15,9 mm bolt diameter group. Number 90 was attributed to the perpendicular to grain groups.

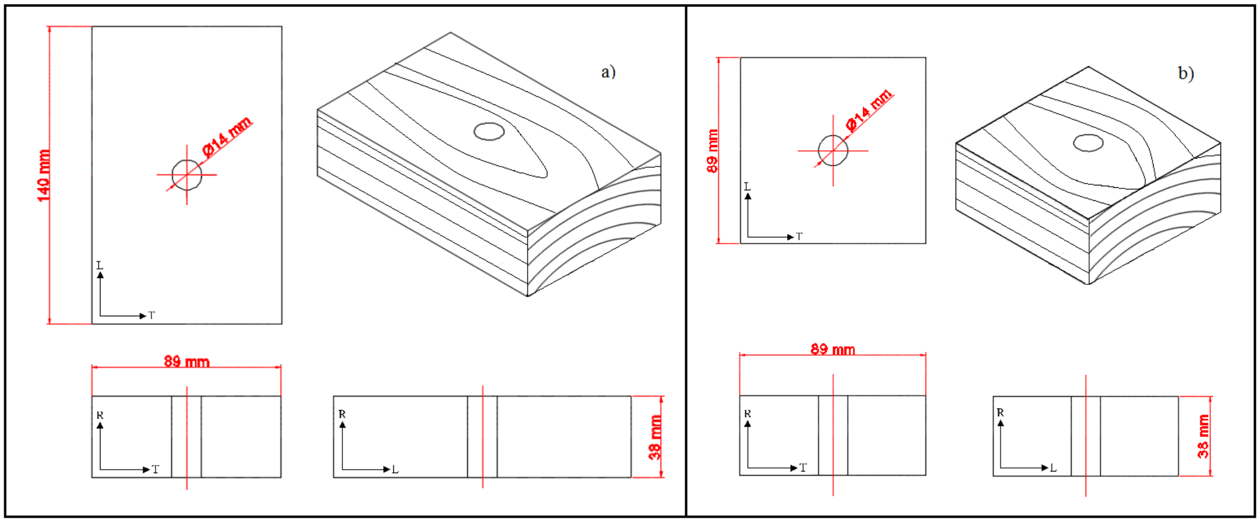


Fig. 1. Wood sample dimensions for sample tested in the parallel to grain direction with a 12,7 mm diameter bolt. a) Parallel to grain tested sample b) Perpendicular to grain tested sample.

2.1.2 Chemicals and formulations

Chemicals 1,6 hexanediol diacrylate (HDDA), trimethylpropane triacrylate (TMPTA) and a polyester acrylate oligomer (CN2262) were obtained from Sartomer Americas. The thermal polymerization initiator, Vazo 67 (2,2′-azobis(2-methylbutyronitrile)) was supplied from DuPont Canada. The acrylate monomer HDDA was chosen because of its low viscosity while TMPTA brings three functional sites for a three dimensional polymeric network. The aim to include an oligomer was to obtain a less brittle polymer. Ratio of HDDA, TMPTA and CN2262 were adjusted to obtain a 16 cP viscosity formulation.

2.1.3 Impregnation process

The mass of samples was measured before and after treatment in order to monitor the chemical retention. Then, samples were set in a plastic container, no contact allowed and immobilized with a heavy load on top to prevent floating. Chemicals were poured on them until entirely covered and the recipient was placed in the impregnation cylinder. A vacuum of 27 mm Hg was created and maintained for 15 min to remove the air from the wood pores. Then a pressure of 520 kPa was applied for 15 min. Samples were wiped off and placed in the oven at 85°C for 24 h to achieve resin polymerization. After polymerization, all blocks were conditioned at 20°C and 65% RH until the equilibrium state was reached. The impregnation process was defined as traditional program [31] to ensure a maximal retention, but the process parameters could be optimized.

2.2 Test method

2.2.1 Dowel-bearing strength

According to ASTM D5764 standard [32], dowel-bearing strength (embedment) parallel to grain was measured. The dowel-bearing behavior is the load-deformation behavior of wood under lateral loading by an assumed non-bending fastener. The dowel-bearing strength (σ_{max}) is defined as the max load (P_{max}) obtained from the load-deformation curve divided by the dowel diameter (d) and specimen thickness (e) (seen in Eq. 1).

$$\sigma_{max} = \frac{P_{max}}{(d * e)} \tag{1}$$

The stiffness (k) is mathematically defined in Eq. 2. Figure 2 represents the load-displacement curve of a dowel-bearing test parallel to grain for the group D3. The stiffness is calculated as the slope between the point at 25% ($P_{25\%}$) of the maximal load and 50% ($P_{50\%}$) of the maximal load.

$$k = \frac{\Delta P}{\Delta u} = \frac{P_{50\%} - P_{25\%}}{u_{50\%} - u_{25\%}} \tag{2}$$

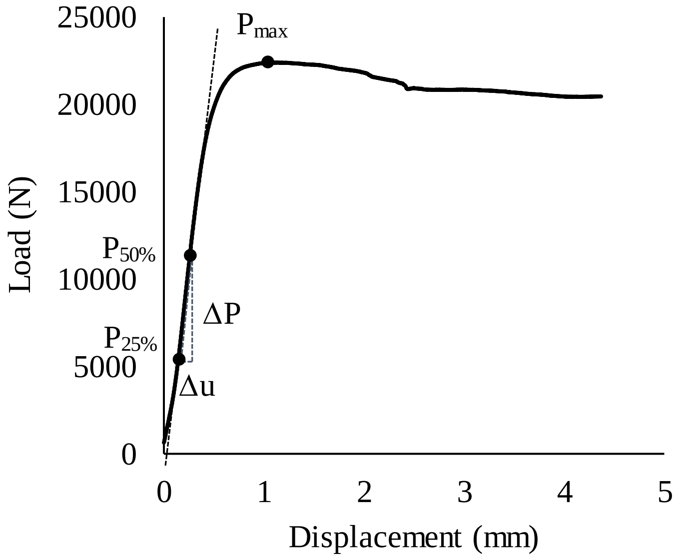


Fig. 2. A typical load-displacement curve for the dowel-bearing test parallel to grain.

A dowel of 9.5 mm, 12.7 mm or 15.9 mm diameter was inserted in the predrilled hole. A MTS Alliance RT/50 testing machine (MTS Systems Corporation, USA) with a 100 kN load cell was used. Rate of motion of the movable crosshead was 1 mm/min during the test with a maximal displacement of 5 mm. A testing device (Fig. 3) was manufactured and assembled on the cross-head in order to carry out the test. Samples were prevented to slip by a surrounding basement fixed on the testing machine. The dowel displacement was measured with two linear variable differential transformers (LVDT) placed each side of the sample. The ultimate load and the load-displacement curve were recorded by TextWorks software (MTS Systems Corporation, USA). Mean displacement of the two LVDT was used in the load-displacement curve. The ultimate loads and the load-displacement curves were monitored at 1 N accuracy. The qualitative analysis of the ductility was achieved by interpreting the occurrence or not of the splitting of wood instead of crushing.

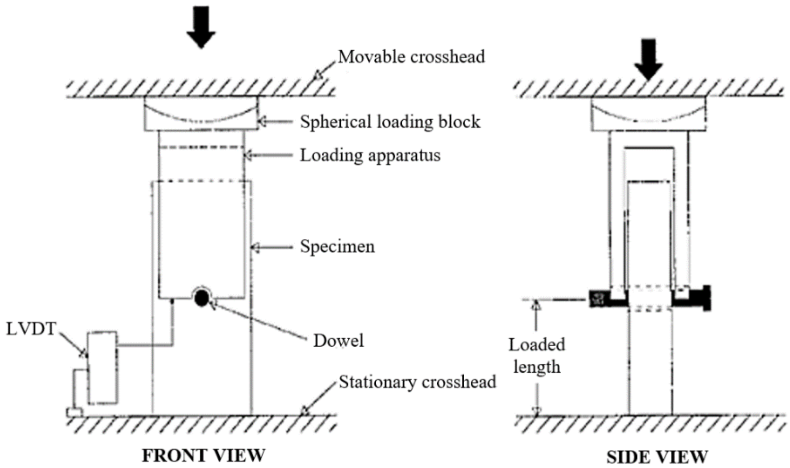


Fig. 3. Testing device to determine dowel-bearing strength (from ASTM D5764).

2.2.2 Moisture content and oven-dry density

After test, samples were cut and weighted to determine mass when conditioned at 20°C and 65% HR. Then, they were placed in the oven at 103 ± 2°C until constant mass to determine oven-dry weight. Moisture content during dowel-bearing test is defined as the difference between the sample mass conditioned at 20°C and 65% HR and the oven-dry mass divided by the oven-dry mass. The oven-dry dimensions of cut samples were also measured to determine the oven-dry density accordingly to ASTM D2395 [33].

2.2.3 Digital image correlation

DIC was performed to analyze the impact of the treatment, the bolt diameter and the load direction on the stress field. Two AVT Pike F421B 4 Megapixel (Allied Vision Technologies GmbH, Germany) with high-quality CCD sensors cameras running at 15 fps (full resolution) were used to capture 2048 x 2048 pixels images. The format of the 8-bits grayscale images was the Tagged Image File Format (.tif). To perform a 2D analyze, cameras were mounted on tripod aligned in parallel with the specimen on both sides of loading machine. Two white spot lights with aluminum shield were placed on each side of the cameras to illuminate properly the specimen. Attention was paid to eliminate any source of shadow, especially the bolt shadow on the wood. Focus was manually adjusted until a well contrasted and clear image was obtained before the camera position was fixed. A first image was then taken with a ruler placed in front of the sample to calibrate the scale of the image. When loading, the speed of crosshead movement was set at 1mm/min while images were taken at interval of 1 second. The VIC 2D software (Correlated Solutions, United States) was used for the mathematical cross-correlation. A sum of squared differences (SSD) of the pixel values was applied as the correlated function to track the displacement between the reference subset and the deformed subset. The digital image correlation was applied on three specimens in each group sample.

2.2.4 Experimental design and data analysis

Table 1 shows the two factorial designs used in this experiment. Factors were the presence of treatment into the wood (t0/t1), the bolt diameter (D1/D2/D3) and the loading direction (0°/90°). First design measured the effect of the treatment and the bolt diameter as the interaction between them while the second measured the effect of the treatment and the loading direction as the interaction between them. Each combination included 30 repetitions. Analysis of variance (ANOVA) using SAS Software version 9.4 TS (SAS Institute Inc., USA) was conducted on dowel bearing strength and on the stiffness results. The influence of each factor and their interaction were analyzed.

Table 1. Factorial experimental design used in this study.

Sample	Treatment	Orientation	Diameter
Design 1			

CD1	No	0°	D1
D1	Yes	0°	D1
CD2	No	0°	D2
D2	Yes	0°	D2
CD3	No	0°	D3
D3	Yes	0°	D3
Design 2			
CD2-90	No	90°	D2
D2-90	Yes	90°	D2

3.Results and discussion

3.1 Dowel-bearing strength

The dowel-bearing strength and stiffness, as determined according to ASTM D5764, are shown in Table 2 for all wood samples of designs 1 and 2. These data are the mean values of each 30 specimen groups. Characteristic values, defined as the 95% lower confidence bound on the 5th-percentile value, are included for the bearing strength and the stiffness results. All groups of treated samples showed a better performance than the equivalent untreated one for the bearing strength and stiffness. The highest bearing strength value was associated to the smallest diameter (D1) group sample with 44.9 MPa, a 67% of increase compared to the untreated group CD1 (26.9 MPa). For the intermediate diameter (D2), the bearing strength increased from 25.3 to 38.5 MPa, a 52% increase, while for the largest size (D3), the bearing strength increased from 26.0 to 36.6 MPa, a 40% improvement. Impact of the treatment is obviously rising while the diameter of the connector was decreasing. Besides, when observing the characteristics values (5^{th}-percentile) of the stiffness, it appears that the percentage of change after treatment is higher than for the maximal value, and this, for all the groups samples. The same trend is present for the characteristic value of the bearing strength, while the more important improvement is for the smaller dowel diameter (D1) with 79% of change, and the least one is for the larger diameter (D3) with 48% of change.

Table 2. Bearing Strength and Stiffness for Groups of Samples from design 1 and 2 (Mean value and characteristic value of 30 samples).

Wood sample	Bearing strength (COV) (MPa)	Change (%)	Bearing strength f5% (MPa)	Change f5% (%)	Stiffness (k_e) (COV) (kN/mm)	Change (%)	Stiffness (k_{e5}) f5% (kN/mm)	Change f5% (%)
CD1	26.9 (11%)		22.1		9.3 (22%)		5.9	
D1	44.9 (7%)	67%	39.5	79%	12.1 (20%)	29%	8.2	39%
CD2	25.3 (11%)		20.7		18.9 (19%)		13.1	
D2	38.5 (7%)	52%	34.1	65%	23.8 (17%)	26%	17.0	30%
CD3	26.0 (9%)		22.2		31.7 (27%)		17.5	
D3	36.6 (6%)	41%	32.9	48%	42.6 (22%)	35%	27.0	54%
CD2-90	21.0 (18%)		14.73		12.4 (33%)		5.8	
D2-90	21.7 (17%)	4%	15.70	7%	15.9 (14%)	28%	12.3	114%

The analysis of variance was used to evaluate if the means between groups sample are significantly different. The F value is the quotient between the effect variance (between-group) and the error variance (within-group). The interaction between treatment and bolt diameter was statistically significant at 0.01 probability level as seen in Table 3. With respect of the weight of the F values of the individual factor treatment (F = 1152.07), it is reasonable to figure that the treatment alone had a significant impact on the bearing strength values. After polymerization of the formulation, the treated wood connector area is denser than the untreated wood. We can hence infer a positive correlation between the density of the modified wood and mechanical properties.

Table 3. Effect of dependent variables on the dowel-bearing strength and stiffness of black spruce for design 1 and 2.

Source	Degree of freedom	F value	Pr > F
ANOVA for the dowel-bearing strength			
Design 1			
Repetition	29	1.47	0.0726
Bolt diameter	2	51.82	<.0001**
Treatment	1	1152.07	<.0001**
Bolt diameter x treatment	2	26.63	<.0001**
Design 2			
Repetition	29	0.88	0.6398
Orientation	1	277.74	<.0001**
Treatment	1	121.24	<.0001**
Orientation x treatment	1	97.04	<.0001**

ANOVA for the stiffnesss

	Design 1		
Repetition	29	1.43	0.0894
Bolt diameter	2	318.03	<.0001**
Treatment	1	48.10	<.0001**
Bolt diameter x treatment	2	7.80	0.0006**
	Design 2		
Repetition	29	1.84	0.0158
Orientation	1	166.88	<.0001**
Treatment	1	50.66	<.0001**
Orientation x treatment	1	0.25	0.6171

Fig. 4 shows the impact of treatment decreasing as the diameter bolt increases while for the untreated samples, the diameter bolt had no significant impact. Bearing strength results for the diameter of 12.7 correspond to results found in Lafond, Blanchet, Landry, Galimard and Ménard [21]. A percentage of change near 50% was obtained. Bearing strength results for CD1, CD2 and CD3 (all untreated and loaded parallel to grain) were similar, confirming a good reproducibility of the test, even with a natural heterogeneous material such as wood. Accordingly to previous studies, the coefficient of variation (COV) decreased for the treated group samples compared to the untreated ones. For building application, in agreement with standard bases, this could be an advantage, as the variance of mechanical performances of materials need to be as low as possible. Furthermore, the enhancement of the characteristic values is an important asset for the potential application of the treatment.

Indeed, the building design is based upon the characteristic value of the construction material.

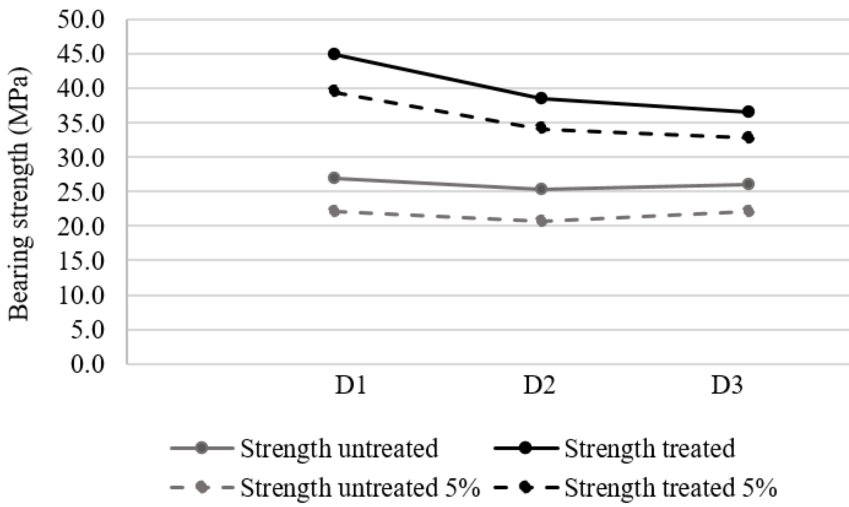


Fig. 4. Interaction between the bolt diameter and the treatment on the bearing strength of black spruce for mean of the value and the 5% characteristic value (design 1).

The stiffness values were less influenced by the treatment than the bearing strength ones. The higher impact of treatment was shown for the D3 group, increasing from 31.7 to 42.6 kN/mm, a 35% increase. The samples tested with the D2 bolt diameter presented an increase of stiffness of 18.9-23.9 kN/mm or 26%. For the smaller diameter, D1, the stiffness values increased from 9.3 to 12.1 kN/mm, a gain of 29%. Again, for the characteristic values of the stiffness results, the same trend is repeated.

The COV is higher in stiffness data than in strength. As seen in Table 3, the interaction between the bolt diameter and the treatment was statistically significant. However, here, the F value for the individual factor bolt diameter (F = 318.03) is much more important than for the treatment (F = 48.10). This could be explained by the relation between the diameter of the dowel and the ductile behavior. Stiffness values are higher for samples tested with large dowel diameter while the small diameter brings ductility to the assembly. In Fig. 5, the slopes of lines for the stiffness are increasing with the enlargement of the diameter, due to the smaller bolt slenderness associated to brittle failure and higher stiffness. The lesser influence of treatment on stiffness than on bearing strength is due to the low penetration of formulation into the wood as seen in Lafond, Blanchet, Landry, Galimard and Ménard [21].

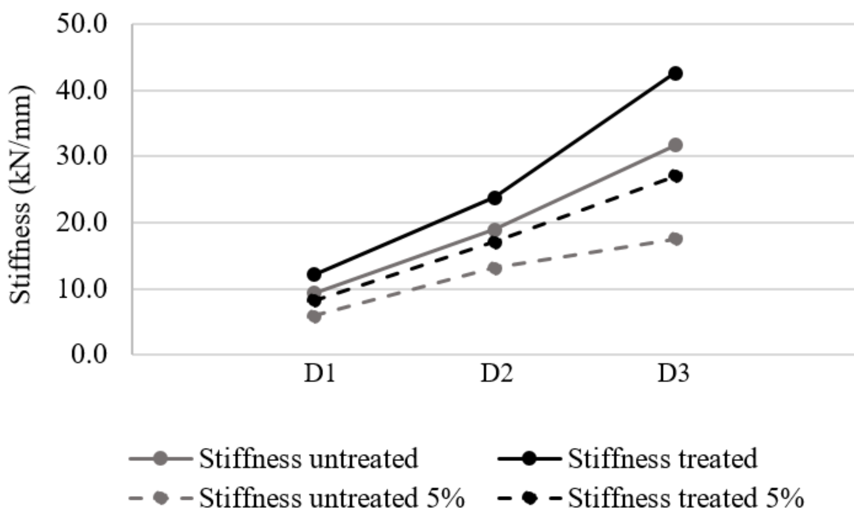


Fig. 5. Interaction between the bolt diameter and the treatment on the stiffness of black spruce for mean of the value and the 5% characteristic value (design 1).

Because of the orthotropy of wood and potential application in timber joints, the impact of treatment on the bearing strength and stiffness needed to be analyzed in the perpendicular to grain direction. The design 2 presents the parallel to grain and perpendicular to grain bearing test results. The data of group sample from design 1 with the mean diameter (CD2 and D2) were used to compare with the perpendicular orientation (CD2-90 and D2-90). The bearing strength value for the treated group in the perpendicular direction has risen from 21.0 to 21.7 MPa, a light 4% increase. The increase is slightly superior for the characteristic value, with 7% of change. The impact is far less important than for the parallel to grain direction where an increase of 65% was observed. However, for the stiffness values, the gain reached 28% with an increase from 12.4 to 15.9 kN/mm, while the gain was 114% for the characteristic value. However, the distribution of data is large, with a high coefficient of variation for the untreated samples (CD2-90), limiting the weight of this observation. For the bearing strength and stiffness results in the perpendicular direction, coefficients of variation are superior than for the parallel to grain direction. Due to annual rings of wood, a perpendicular compression tends to create splits at the failure. The mechanical behavior of wood differs completely in the two directions studied. Moreover, to explain the inferior impact of the treatment in the perpendicular to grain bearing strength, the anatomy of wood is also a key. Indeed, the depth of penetration of the formulation into the wood is limited in this direction. There is no presence of tracheids to conduct the solution. Hence, the layer of polymer is very thin on the hole of the bolt border. As Table 3 shows, there was a significant interaction between the orientation and the treatment for the bearing strength. Both individual factors are significant too. Looking at the F values, (F = 277.74 for the orientation and F= 121.24 for the treatment), the orientation plays a bigger role on the bearing strength results than the treatment. Also, the different range of data between the bearing strength results for the parallel to grain test (25 MPa up to 38 MPa) and the perpendicular to grain one (around 21 MPa) is convincing.

Besides, in the Fig. 6, it is possible to see how important is the impact of the treatment in the parallel direction, while it is barely non-existent for the perpendicular to grain one. Therefore, the interaction is significant due to the absence of impact of the treatment in the perpendicular direction to grain. For the stiffness, the interaction between treatment and orientation was not statistically significant, as seen in Table 3. Individual factors are both strongly significant, but the F value for the orientation (F = 166.88) is more meaningful than for the treatment factor (F = 50.66). As seen previously, the grain orientation is a crucial factor in mainly all wood properties. In the Fig. 7, the line for the mean values of untreated and treated are almost parallel showing the absence of interaction between the orientation and the treatment for the stiffness. However, for the characteristic value, the treatment seems to better improve the stiffness while loading in the perpendicular to grain direction than for the parallel to grain one.

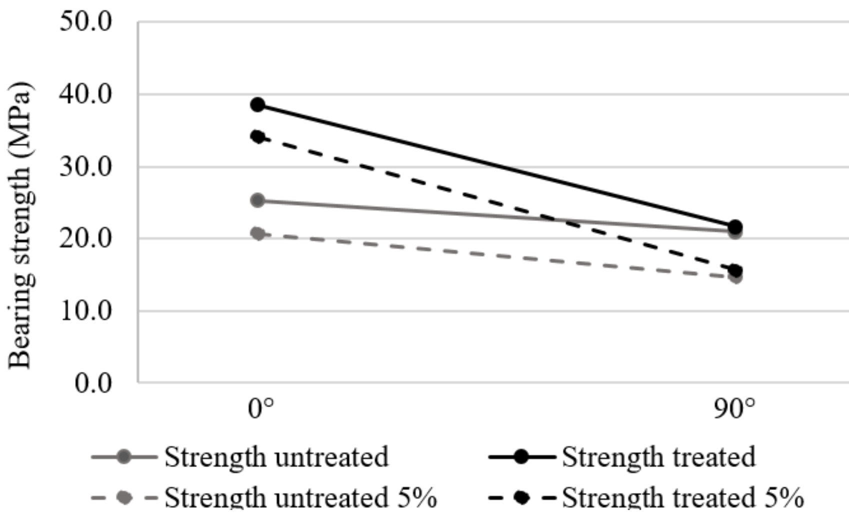


Fig. 6. Interaction between the orientation (0° and 90°) and the treatment on the bearing strength of black spruce for the mean value and the 5% characteristic value (design 2).

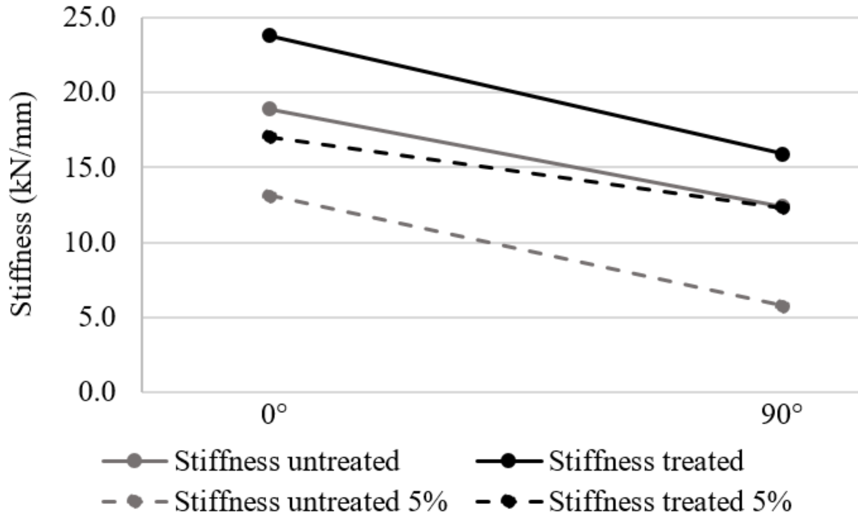


Fig. 7. Interaction between the orientation (0° and 90°) and the treatment on the stiffness of black spruce for the mean value and the 5% characteristic value (design 2).

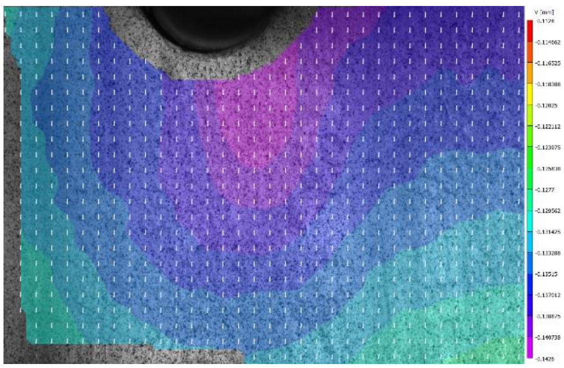
3.2 Digital image correlation

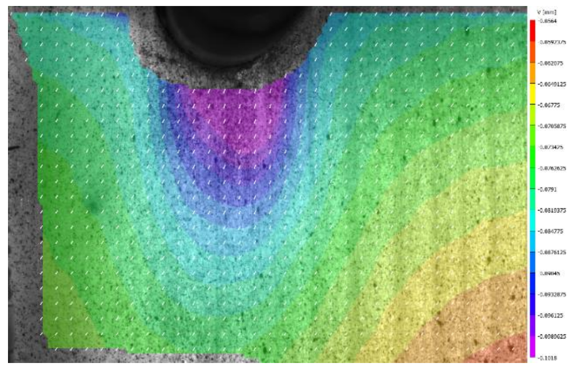
The mechanical behavior of wood after treatment has been analyzed trough the digital image correlation. Because of the amplitude of the bearing strength variation between the D1 and CD1 wood samples, these were chosen to analyze the strain propagation according to the stress. Stress increment of 10 MPa until reaching the ultimate stress was used to illustrate the strain field as shown in Fig. 8 for untreated sample and treated sample. Vector is shown for each 3 subset of pixels and is enlarged by 350%. The color scale of strains is relative in those pictures. Strain levels are starting at 15 MPa due to the poor strain field before getting to this amount of stress. At 15 MPa, both untreated and treated wood had strain field concentrated under the bolt. Displacements appeared to be more oriented vertically for the untreated group sample. At 25 MPa, strain field elongated under the bolt for the untreated while the strain field expanded around the bolt for the treated. This phenomenon was even more visible at 32 MPa, the ultimate stress for the untreated sample.

At 46.4 MPa, the maximal stress before failure of the treated sample, strain was distributed largely around the bolt as the strain vectors showed displacement in the horizontal axis too. DIC suggests that treatment resulted in a more efficient distribution of the strain around the bolt, limiting splits to occur.

Untreated -15 MPa

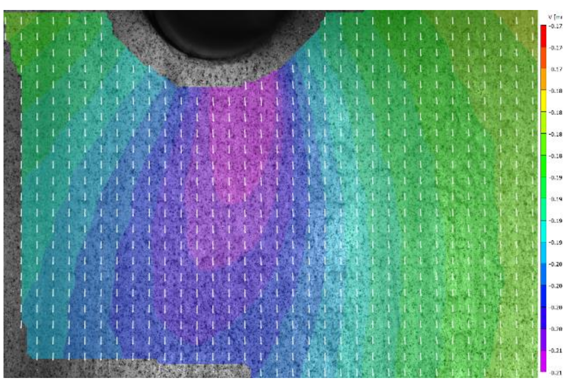
Treated -15 MPa

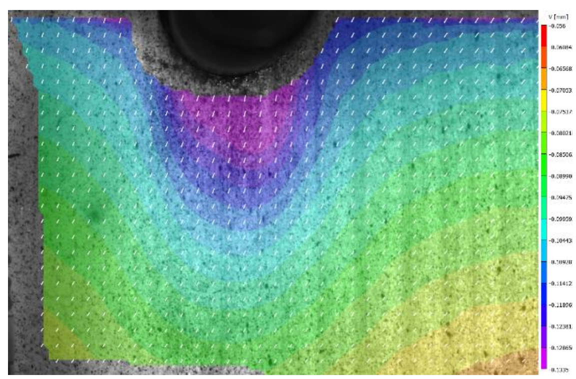




Untreated -25 MPa

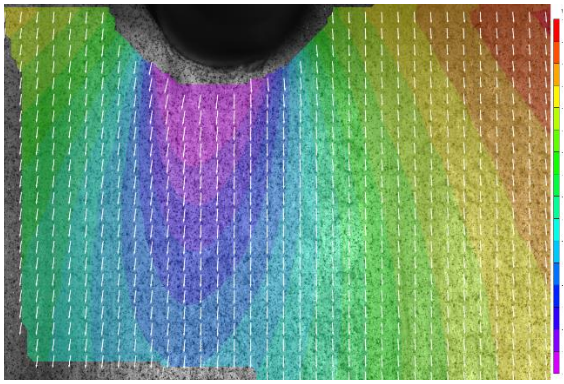
Treated -25 MPa

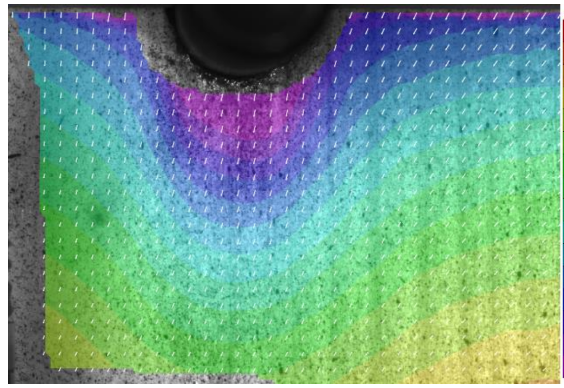




Untreated -32 MPa

Treated -35 MPa





Treated -46 MPa

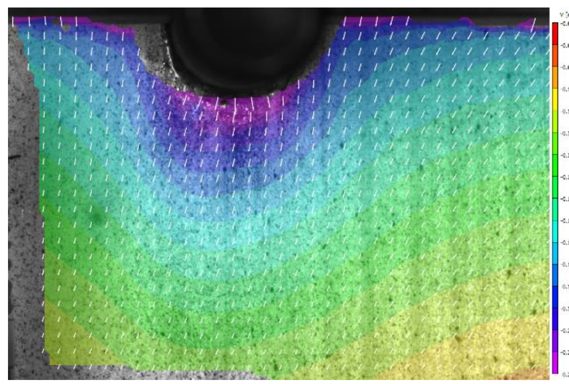
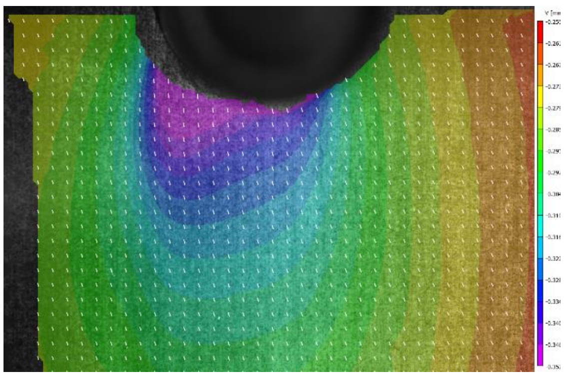


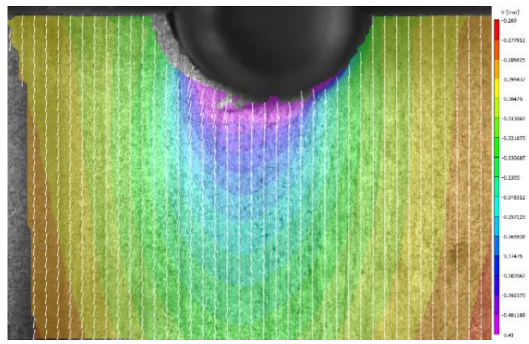
Fig. 8. Strain field in the y direction (parallel to grain) and strain vector field measured by 2D-DIC of untreated and treated black spruce during the dowel-bearing test

The impact of different bolt diameters on the reaction to treatment is shown in Fig. 9. For each wood sample, a specimen was chosen to represent the group. Analysis of sample tested with diameter of bolt D1 corresponds to images found in Fig. 8 at 32 MPa for untreated and 46 MPa for treated sample. Images of the strain field analysis are shown as the ultimate stress was reached. Same observations are made on D2 and D3 as with D1, while the concentration of strain under the bolt is reduced after treatment and the strain tends to move on each side of the bolt. Among the different bolt diameters, D1 was the sample group to show the greater difference in the strain distribution on the wood surface after treatment, when in D2 and D3 the strain field is less visible on perpendicular to load sides of the bolt. With the expansion of strain horizontally, wood is crushed and splits are limited. This observation confirms the theory of the gain of ductility while using a smaller diameter of connector.

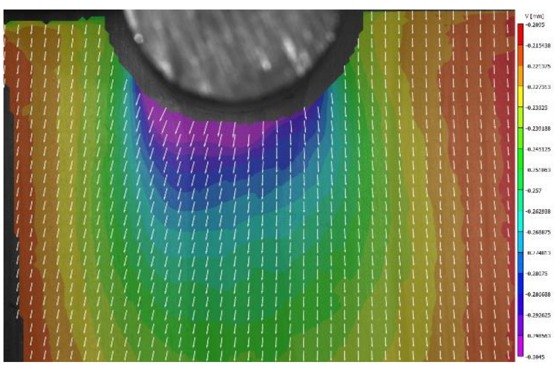
D2 untreated (25.3 MPa)



D2 treated (38.8 MPa)



D3 untreated (32.2 MPa)



D3 treated (45.4 MPa)

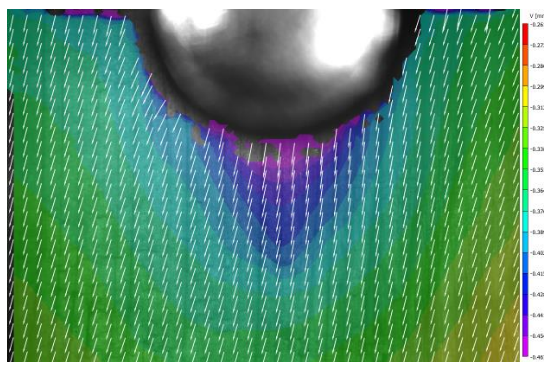


Fig. 9. Strain field in the y direction measured by 2D-DIC during the dowel-bearing test of black spruce for diameter of bolt D2 and D3

4.Conclusion

As timber jointing is often a limiting factor in wood structure design, impregnation treatment was chosen to reinforce the local mechanical properties of wood. It has been applied to black spruce to create an innovative structural product. Because of the orthotropy of wood, penetration of formulation during impregnation is not equal in the different orientations of wood. Hence, perpendicular to grain and parallel to grain bearing tests were realized in this experiment. As the embedment strength depends on the dowel diameter according to standards, three sizes of bolt were used for the dowel bearing test in the parallel to grain direction.

Results for the dowel bearing strength have shown a higher impact of treatment as the diameter of connector decreased. The characteristic values for treated wood with D1 (9.525 mm) were increased by 79%, while for D2 (12.700) and D3 (15.875) the improvement was 65% and 48%.

The stiffness results have shown a lesser impact of treatment. The most important increase of characteristic values after treatment was found for the larger diameter, D3 with 54%. Better mechanical performances after treatment are associated to the increase of density provided by the polymerization of formulation at the border of the bolt hole.

According to the statistical analysis, the interaction between the treatment and the bolt diameter was significant for the bearing strength and the stiffness. With a superior F value, the treatment was the determinant factor in the interaction since the bolt diameter did not had an impact on untreated wood and had one on the treated wood. For the stiffness, the bolt diameter influenced largely the ductility behavior of wood. This factor was dominant on the treatment. Change in dowel bearing strength was almost nonexistent for the perpendicular to grain orientation. Regarding the stiffness, 114% of gain was achieved. However, the coefficient of variation was high for the untreated wood tested in the perpendicular to grain direction, leading to an ambiguous analysis. The interaction between the orientation and the treatment was largely significant as the impact of treatment was clearly shown for the parallel to grain direction and was not for the perpendicular one.

In order to analyse the impact of the treatment on the mechanical behavior of wood, digital image correlation was used. It appeared that the strains were distributed more evenly around the bolt, particularly in the perpendicular to loading axis (x). This phenomenon tended to create less brittle failure due to spliting. In structural design, the gain of ductility as well as a decrease in variability are desired to assure a secure behavior. To include the treatment in an industrial process, further investigation to speed up the polymerization need to be done. The possibility of using a CNC tool to achieve all steps of the treatment procedure in the connection hole should be considered.

5.Aknowledgment

The authors are grateful to Natural Sciences and Engineering Research Council of Canada for the financial support through its ICP and CRD programs (IRCPJ 461745-12 and RDCPJ 445200-12) as well as the industrial partners of the NSERC industrial chair on eco-responsible wood construction (CIRCERB). The authors also thank the French National Research Agency (ANR) for supporting the study here presented, through the Xyloplate platform, Equipex project XYLOFOREST (ANR-10-EQPX-16).

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