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

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HIGHLIGHTS

- An impregnation process for strengthening the wood in the connector area is proposed.
- The effect of treatment diminish with the increase of the dowel diameter.
- The treatment has no effect in the perpendicular to grain loading direction.
- The treatment helps to distribute the strains around the dowel.

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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.

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],

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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, [15,16,19]. 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 behavior 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 × 89 mm × 38 mm (L × T × R) for the parallel to grain bearing test and at 89 mm × 89 mm × 38 mm (L × T × 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.

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 mmHg 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). Fig. 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.