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DENSIFIED WOODEN NAIL FOR ADHESIVE- AND METAL-FREE TIMBER ASSEMBLES

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ABSTRACT: The widespread utilisation of adhesives to assemble engineered wood products may lead to environment and recycle concerns. To improve materials sustainability and recovery at the end-of-life, it is preferable to replace adhesive with mechanical lock-in fasteners such as wood-based connectors. Nowadays, the development of robotic fabrication technologies and wood modification technologies brings the opportunity to rejuvenate traditional wood-joining methods. In this study, thermo-hydro-mechanical densified wooden nail were proposed as an adhesive- and metal-free connector for timber assembles. The densification ratio varied between 40 to 68%. Research has been performed in order to determine the effect of densification on the compression behaviour of wood in the form of nails. The result showed that densification with high compression ratio can successfully increase the density and modulus of rupture of wood, while its influence on modulus of elasticity is not obvious. A set of prototype nails made of densified wood was manufactured. In addition, preliminary insertion tests into wood samples were carried out and served for insertion process understanding. The results obtained reveal a potential for using the densified wooden nail connectors for substitution of adhesive or metal connectors. However, the "success ratio" for proper inserting of wooden nails was not satisfactory. It was observed that the excessive dynamical loading induced buckling failure of the nail during hand-operated insertion.

KEYWORDS: Nail laminated timber; Thermo-hydro-mechanical densification; Compression behaviour

1 INTRODUCTION

Climate change and its dramatic consequences are stimulating a transformation towards sustainable development. The long-term solution of slowing down climate change is to close carbon cycles and reduce greenhouse gas (GHG). In Europe, buildings sectors account for 40% of total energy consumption and 36% of total carbon dioxide emission [1], and it is therefore a key sector for improvements. Compared with other materials used in construction, wood products have much better ecological and environmental performance [2]. In the past decade, the demand to use wood for applications in both residential and non-residential building construction has been increasing. This development has partially result out from the emergence of new engineered wood products (EWPs) and the potential economic benefits of prefabrication and rapid on-site construction [3].

However, EWPs are in majority of cases assembled by adhesives or metal fasteners, which reduce their machinability, sustainability, and limit recyclability. Furthermore, the use of adhesives in EWPs may affect the environment and human health by emitting non-healthy volatile organic compounds (VOC) such as formaldehyde, that increase during use-periods under the high-temperature and varying relative humidity conditions. Therefore, there is a need in the modern timber construction sector for an ecofriendly and recyclable technologies substituting or replacing adhesive and/or metal fasteners [4].

Assembling timber by hardwood connectors like dowels, nails, wedges, and tenon-mortise joints has been invented and applied in furniture making and timber construction from the ancient time [5]. Among these methods, nail connection represent the easiest and fastest method to assemble timber members [6], as metal nails could be successfully inserted into wood and make connection without pre-drilling holes. However, the high thermal conductivity of metal nails affects the overall energetic performance and energy requirements of structures during its service life. The machinability of components joined with metal nails is limited during both, construction and end-of-life transformation. Other problems may occur due to interaction of metal fasteners with tannic acids causing black colored spots on the surface of wooden elements. Therefore, Hasan et al. [7] suggested that wooden nails could be an alternative for renewable fastener used in a robotic fabrication process of nailed laminated timber.

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Hand-operated hammer and pneumatic nailing guns are usually used to drive nails into wood. When inserting by pneumatic nailing guns, the friction between the nail and the surrounding surfaces heats the interface to the glass-transition temperature and softens the cell-wall lignin. The following solidification of the softened lignin when the joint's temperature drops results in additional chemical-physical bonding the wood members [8]. Moreover, wooden nails ensure a firm fixing of the elements as they expand when exposed to moisture, that corresponds to same mechanism as observer in the case of wood dowels [9].

The wooden-nail assembling technology was combined recently with other wood modification technologies such as resin impregnation and/or THM wood densification [10–13]. THM densification involves heating the wood above its glass-transition temperature in the presence of moisture. A compression force can be applied in the transverse direction to make the wood cells collapse without fracturing their cell walls. It leads to the reduction in the lumen volume and in the increase of cell density. It is known that there is a strong relationship between wood density and its mechanical properties. Therefore, THM densification is frequently used to improve the mechanical performance of wood, including advanced use of wood in load-bearing timber construction [14,15].

An important research aspect that has received less attention in the context of wooden nails is the compression behaviour in the longitudinal direction of the elongated beams of densified wood forming the nail. Better understanding of densified wood behaviour under compression stress is extremely important for ensuring appropriate quality of the nailing connection. The nail damage occurring during insertion may disqualify the joint as well as may affect the further behaviour of the connection in the service conditions. A proper use of this knowledge may lead to designing nails with high slenderness ratio useable to assemble thicker panels. It would be a greatly appreciated functionality resulting in expansion of wooden nails usage in construction. The goal of this report if to present a set of preliminary results describing the compression behavior of densified wood in the form of nails made from three different species and various compression ratios.

2 MATERIAL AND METHOD

2.1 MATERIAL

Industrial kiln-dried beech (*Fagus sylvatica* L.), poplar (*Populus tremula* L.), and spruce (*Picea abies* L.) were used to produce the densified wood specimens for compression tests. The boards selected for test were detects-free and conditioned at 20°C and 65% RH to achieve an equilibrium moisture content. Standard metal fasteners (nails) were tested for comparison.

2.2 WOOD DENSIFICATION

The densified wood specimens were manufactured by carrying out the THM densification in the radial direction in an open-system hydraulic hot press. The densification cycle was composed of 10 minutes pre-heating (plasticization), 10 minutes densification, 5 minutes post treatment and 5 minutes cooling (Figure 1). The final cooling of the densified samples was performed out of the press, assuring limitation of the sample flatness changes, by applying clamping. The achieved compression ratio (CR) after densification is calculated as in equation 1:

$$\text{Compression ratio (CR)} = \frac{T_0 - T_d}{T_0} * 100\% \quad [1]$$

Where T_0 is the initial thickness and T_d is the thickness after densification

The densified specimens with different CR were conditioned at 20 °C and 65% RH then sawn to final dimensions of 55 mm (longitudinal) × 3 mm (radial) × 3 mm (tangential) before the compression tests.

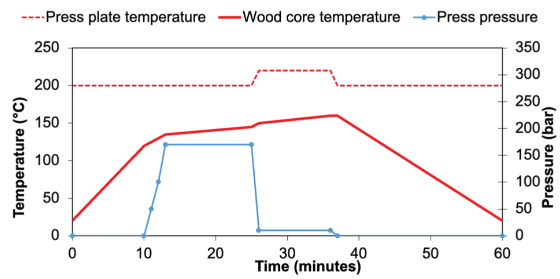

Figure 1: *Schedule of thermo-hydro-mechanical (THM) densification.*

2.3 COMPRESSION TEST

Compression tests were carried out to evaluate the influence of densification on the mechanical behavior of the wooden nails during insertion (Figure 2). Tests were done with the intention to notice the maximum force to be applied during nail insertion, including analysis of the buckling behavior of the nail. For these reasons, the slenderness ratio (which is defined as the ratio of the column length over its diameter) is higher than that recommended for the standard compression tests according to the EN 408 [16]. The ratio of the maximum force to the specimen cross-sectional area was computed here instead of modulus of rapture (MOR) as defined in EN 408. A custom-made mechanical testing machine equipped with a load cell (5 kN) was adopted to conduct the compression load experiments.

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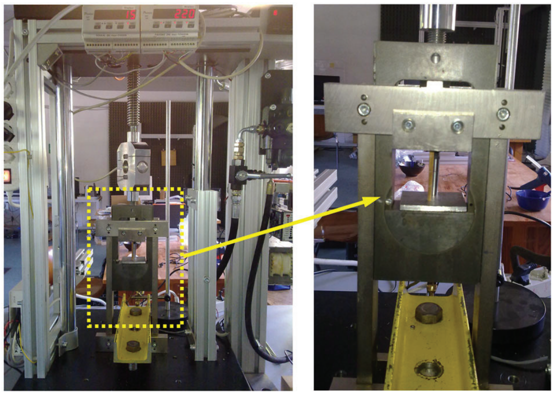


Figure 2: *Compression test setup*

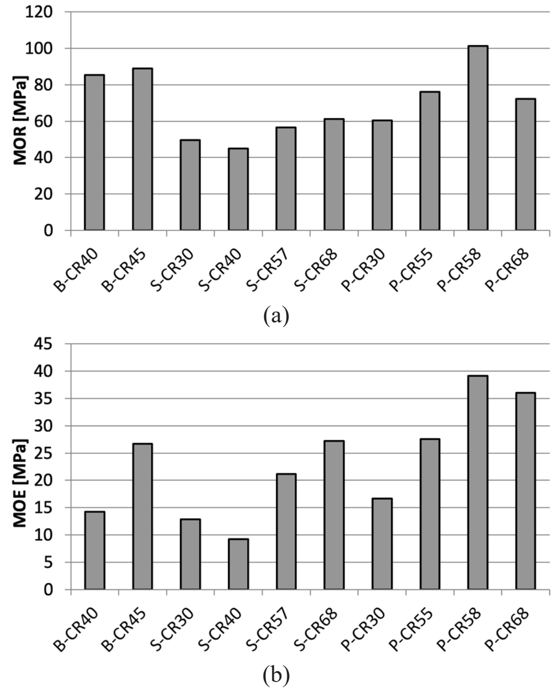


Figure 4: *Mechanical properties of densified specimens measured during compression test (a), modulus of rapture (MOR)(b), modulus of elasticity (MOE)*

3 RESULTS AND DISCUSSION

3.1 PHYSICAL AND COMPRESSION PROPERTIES

Figure 3 and Figure 4 presnts the density and mechanical properties of the wood densified with different CR. It can be noticed that there is a strong positive correlation between CR and densified wood density as well as modulus of rapture (MOR). However, it is also evident that after certain level of CR the MOR is reduced (for example densified poplar wood with 68% CR). It might result from excessive damage of the cellular structure of wood induced by densification. By contrast, there is no clear correlation between the CR and modulus of elastic (MOE). Majority of the samples have been damaged during test by excessive buckling. Only few of compressed samples were damaged by typical collapse of wood cells. The compression tests have been also performed on the standard metal nails with dimension as densified wooden nails. As expected, the performance of the metal nail was superior compared to wooden nail. Both MOR and MOE under compression of metal nails were more than four times higher than the highest value achieved by wooden nails.

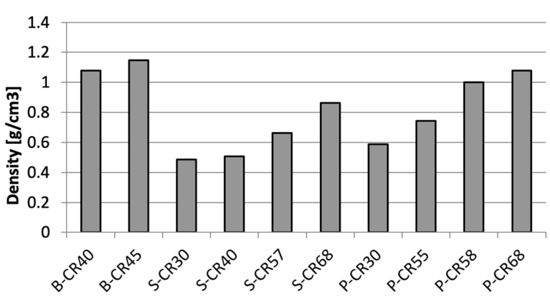


Figure 3: *Density of densified specimens*

3.2 DENSIFIED WOODEN NAIL PROTORTYPE AND PRELIMIARY NAILING TEST

Based on the above observations, it was possible to design a prototype of densified wooden nails. The image of the proposed nail is presented in Figure 5. The slenderness ratio (L/d) depends on the integrity of densified wood. As a rule of thumb, the insertion force is suggested nu exceed the critical buckling load of the nail. The nail's tip geometry depends strongly on the joined material hardness and its anatomical structure. The tip shall never be too sharp. The recommended tip angle (α) is ~30°.

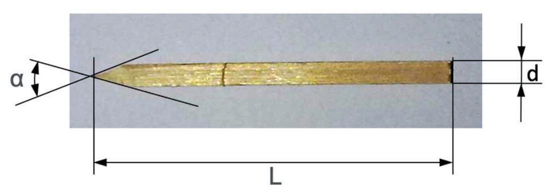


Figure 5: *Image of the developed wooden nail and recommendations for its design.*

The example of the wood pieces joined by densified wooden nails with hand-operated hammer is presented in Figure 6. It should be mentioned here that the ability of the wooden nail to join the other wood pieces is limited by the hardness and anatomical structure of the joined material. Simplifying, the technology developed can be only applied to join wood species of rather low densities. Up to data experiences show acceptable performance if spruce, fir or poplar to be joined together. Any trials to join higher density species or pieces having certain defects (such as knots) have not been successful.

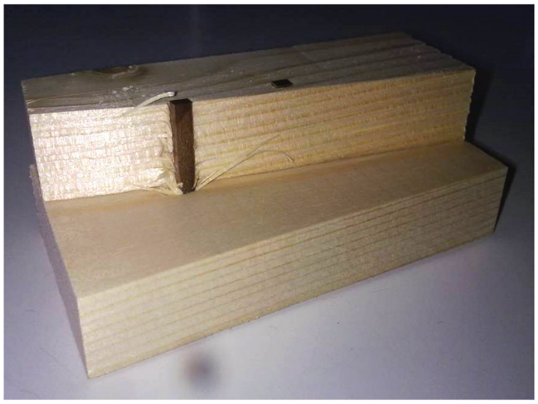
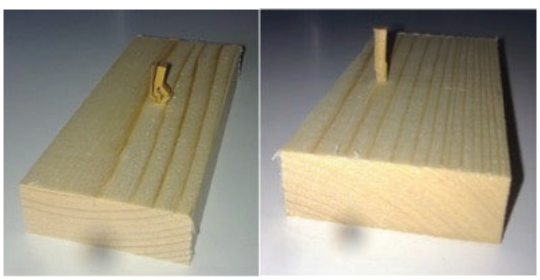


Figure 6. *Wooden nails joining two pieces of spruce wood.*

The "success ratio" of the insertion wooden nails was not exceptionally high. The most typical failures of the nails are presented in Figure 7. Splitting the nail over the surface of joined wood (Figure 7a) occurs if the force direction is not parallel to the nail axis direction. On the other hand, the overload of wood nail (effect in the collapse of wood fibers within the nail structure (Figure 7b). Anyway, the final effect is not satisfactory joint and usually the broken nail protruded over the joined surface.



(a) (b)

Figure 7: *Typical damages to the wooden nail occurring during insertion; (a) splitting of the nail, (b) collapse of the wood fibre due to excessive compression stress.*

4 CONCLUSIONS AND FUTURE WORK

The research was dedicated for development of the novel technology of wood assembling by means of densified wooden nails. The results obtained shows a potential of such joins as an alternative to adhesive and traditional metal nails. However, it should be pointed, in general the "success ratio" for proper inserting of wooden nails was much lower that corresponding to metal joints because of excessive dynamical loading, especially when nailing with hand-operated hammer. The necessary loading to insert a wooden nail result in extensive buckling of the nail column, and this may lead to fracture during nail insertion. Another damaging factor was a compressive stress concentration at the tip of the nail limiting the penetration into the wood components to be joined.

The buckling failure of the nail under compression could be influence by many factors. For example, loading type (either dynamical or static loading), nail tip geometry, slenderness ratio, MOE, tribological properties of the wooden nail etc. Therefore, the future work will be focused on studying how those factors affects the buckling behavior of densified wood. An assist tool will also be designed and test to avoid buckling failure during nailing (Figure 8).

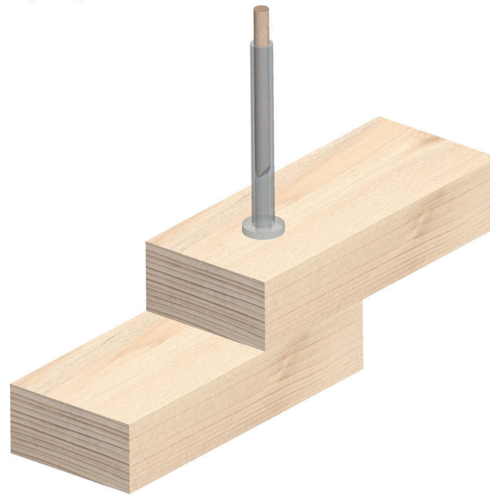


Figure 8. *Concept for the assist tool for avoid buckling during nailing.*

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