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The Effect of Heat Treatment on the Withdrawal Capacity of Screws in Spruce Wood

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The withdrawal capacity of screws in heat-treated spruce wood (*Picea abies* Karst.) was measured in the radial and tangential directions. Wood was heat-treated at temperatures of 150, 170, 190, 210, and 230 °C. Screw withdrawal capacity decreased as the degree of thermal modification was increased. Also, image analysis was used to measure the size of the deformed wood area around the screw, which increased with higher thermal modification temperatures. This leads to the practical recommendation that connections in heat-treated wood should be constructed with screws with larger diameters and deeper penetration. Moreover, larger spacing between screws is needed to ensure sufficient withdrawal capacity compared to non-treated wood.

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INTRODUCTION

The importance of wood as a building material is increasing due to greater ecological awareness, as well as wood's ability to store carbon, which trees absorb as carbon dioxide from the atmosphere through photosynthesis. New processes for improving the properties of this natural and renewable material have been developed, which increase the scope of its use and the variety of possible applications. The mild pyrolysis which occurs during the heat treatment of wood at elevated temperatures ranging from 160 to 260 °C improves wood's dimensional stability and increases its biological durability (Jämsä and Viitaniemi 2001; Militz 2002; Hill 2006). This process avoids the use of wood preservatives, represents an attractive "non-biocidal" alternative to traditional preservation treatments (Chaouch *et al*. 2010), and broadens the use of less durable species.

During such thermal treatment of wood, chemical modifications of hemicelluloses, cellulose, and lignin occur (Militz 2002; Mayes and Oksanen 2003; Hill 2006), which can lead to less favourable mechanical properties such as lower bending and tension strengths, reduced toughness, and increased brittleness of the wood (Boonstra *et al*. 1998; Tjeerdsma *et al*. 1998; Jämsä and Viitaniemi 2001; Esteves and Pereira 2009).

Strength loss is strongly influenced by the type of heat treatment employed, *i.e.* the used temperature and duration (Stamm 1956; Tuong and Li 2010). The changes that occur in wood during heat treatment cause lower equilibrium moisture content. This effect could result in an increase in the modulus of elasticity (MOE) and strength (MOR) (Dinwoodie 2000), but thermal degradation decreases this positive effect.

The strength and stability of any structure depend on the material of the elements used, but also heavily on the connections that hold the elements together. In most wood

structures, connections are some of the most important components. Connections may consist entirely of wood members, but frequently they involve connections of wood to steel or other members, where a wide variety of fastenings can be used: nails, spikes, screws, bolts, lag screws, drift pins, staples, and metal connectors of various types. In order to achieve the greatest rigidity and strength and longest serviceability, each type of fastening requires joint designs, which are adapted to the strength properties of the wood along and across the grain (Taj *et al*. 2009; Aytekin 2008; Rammer 2010). Connections are equally important in furniture construction as in wooden structures, because they are the critical links between the elements of a structure, maintaining load path continuity and providing structural rigidity. It is important for the connections to be designed properly, so that they can carry loads safely under service conditions without excessive deformation or failure (Taj *et al.* 2009).

Screws and nails are widely used as joint components of wood construction, and because each wood species has its own properties, the corresponding screw and nail withdrawal resistances vary. It is therefore important that both producers and consumers are aware of the screw and nail withdrawal resistance for the various wood species (Aytekin 2008).

The resistance of wood screws to withdrawal from the side grain of wood varies directly with the square of the specific gravity of the wood, the depth of penetration of the threaded portion, and the diameter of the screw (Rammer 2010). In addition, the shear strength of the wood (Eckelman 1975), the wood species, the angle between screw and fibre direction, the wood moisture content, the temperature (Pirnbacher and Schickhofer 2009), and the type of screws used (Aytekin 2008) all affect screw withdrawal resistance.

Heat treatment changes the mechanical properties of wood, which can affect the withdrawal capacity of screws. Heat treatment at temperatures higher than 160 °C, and especially above 210 °C, causes thermal degradation of wood, which reduces resistance to screw withdrawal (Poncsak *et al*. 2006; Kocaefe *et al*. 2010). On the other side, treatment time does not appear to have a significant effect on screw withdrawal strength (Kocaefe *et al*. 2010). Lower withdrawal strengths can be explained by the lower shear strength of the modified wood. A reduction in shear strength after thermal treatment can be explained by the partial conversion of polyoses, which make up to 20% of the middle lamella of the cell wall. On the other hand, increased cross-linking within the lignin polymer network could have a positive effect on shear strength (Stamm 1964).

In the case of heat-treated spruce, lower equilibrium moisture content can improve mechanical properties, but thermal degradation usually reduces this effect. The withdrawal capacity of screws is related to the shear strength of wood (Eckelman 1975), which is strongly related to moisture content and density. The shear modulus of wood and screw withdrawal resistance below the fibre saturation point decreases with increasing moisture content (Keunecke *at al*. 2007; Hübner *et al*. 2010).

Because of the modified properties of heat-treated wood, some recommendations for the usage of screws and nails have been made. Mayes and Oksanen (2003) recommend pre-drilling (for screws close to ends, in order to prevent crack-splitting) and countersinking for ThermoWood®. For better holding strength they recommend coarse-thread screws and self-drilling screws, so as to avoid pre-drilling. Stainless steel screws with countersunk heads are the most suitable for use outdoors and in humid environments. It is recommended that fasteners should be placed at least 70 mm from the product ends, and at least 10 mm from the sides in order to prevent splitting.

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The aim of the present study was to determine the effect of the degree of heat-treatment on the withdrawal capacity of screws in spruce wood. Only one type of screw (self-drilling Spax 4CUT) and one heat treatment process was used because the emphasis of the study was on the effect of wood treatment temperature on the screw withdrawal.

EXPERIMENTAL

Materials
Heat-treated wood

Spruce (*Picea abies* Karst.) wood lamellas were heat-treated (HT) using the process of heat treatment in a vacuum, developed by Rep and co-workers (Rep *et al*. 2004). The lamellas were heat-treated at five different temperatures: 150, 170, 190, 210, and 230 °C, and oven dried to the dry state before and after heat treatment in order to determine mass loss during modification. The heat-treated lamellas were then conditioned in standard climate at a temperature of 20 ± 2 °C, and a relative humidity of $65 \pm 5\%$ (20/65) so that a equilibrium moisture content (MC) was achieved before cutting the lamellas into specimens for the determination of the withdrawal capacity of screws.

Methods
Determination of the withdrawal capacity of screws by testing

The withdrawal capacity of screws was determined according to standard EN 1382 Timber structures-test methods-withdrawal capacity of timber fasteners.

The specimens were conditioned in a standard climate prior to testing. SPAX 4CUT 3.5 x 50 mm screws were used without predrilling (Fig. 1). The withdrawal capacity was determined for a load acting perpendicularly to the grain in the radial and tangential directions. The specimens were tested by means of a Zwick Z100 universal testing machine, with a constant loading rate, which was determined in such a way that F_{max} was reached in 90 ± 30 s. The test was stopped when the withdrawal resistance fell to 20% of the maximum load achieved.

The withdrawal parameter of the screw was calculated according to the following expression,

$$f = \frac{F_{max}}{d \times l_p} \tag{1}$$

where f is the withdrawal parameter of the screw (N/mm^2), F_{max} is the maximum withdrawal load (N), d is the diameter of the screw (mm), and l_p is the depth of the penetration of the screw including the point (mm)-complete length of screw in wood (threaded part and tip of the screw). Duncan's multiple range test was used for statistical analysis of results and indicated significant differences between the control group and heat-treated groups.
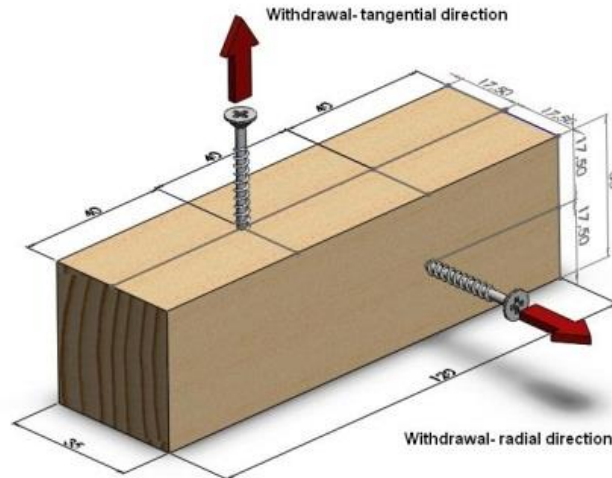
Fig. 1. Samples used in tests to determine the withdrawal capacity of screws in the radial and tangential directions

Image analysis of deformed area

The screws were removed from the samples after testing, and samples were cut out with a table saw through the middle of the screw hole. The main fractures were seen only in the radial cut, so that only images of this section were analysed. The images of the fractured area around the pulled-out screws were obtained using an Olympus SZX12 microscope and an Olympus E-M5 digital camera. The images were analysed using suitable image analysis software (Image-Pro). Points on the edges of the fractured area were selected, and the area limited by these points was calculated (Fig. 2). Five images were made and analysed for each degree of thermal modification of the wood and average values were calculated for comparison.

Fig. 2. Measuring method for the fractured area using a polygon-shaped area

RESULTS AND DISCUSSION

Mass loss of wood is one of the main indicators of the degree of thermal modification. The higher the mass loss is, the more the properties of the wood are changed (Militz 2002; Hill 2006). Mass loss increased with increasing modification temperatures (Table 1). At a temperature of 150 °C, the mass loss was 0.5%. It then rose exponentially to 9.1% in the case of treatment at 230 °C. Similar results have been obtained in previous research (Kariz and Sernek 2010). The control specimens were not

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modified, but were oven dried at 100 °C in order to determine the wood moisture content (MC). The average MC of the wood conditioned in a standard climate (20/65) decreased after modification from 11% (in the case of the Control samples) to 5% (in the case of the HT-230 samples).

Table 1. Heat Treatment Temperature, Mass Loss, MC, and Average Density of the Tested Wood Specimens

Group of specimens	Temperature of modification (°C)	Mass loss (%)	MC of wood in standard climate (20/65) (%)	Average density (kg/m^3)
Control	100	0.00	10.9	443
HT-150	150	0.51	8.8	441
HT-170	170	0.73	7.7	427
HT-190	190	1.90	7.3	432
HT-210	210	3.43	6.0	431
HT-230	230	9.17	4.8	392

The average withdrawal capacity of the screws decreased with the temperature of the heat treatment (Table 2). A similar trend was observed in the case of withdrawal capacity in both the radial and tangential directions. Statistical analysis for withdrawal in the radial direction showed significant differences between the control wood and all the modified groups, except HT-190. All the heat-treated groups (except HT-150) showed lower average values than the control wood.

Statistical analysis in the case of withdrawal in the tangential direction showed significant differences between the control wood and HT-210/HT-230. All the heat-treated groups (except HT-190) showed lower average values than the control wood.

Table 2. Average Withdrawal Capacity of the Screws in the Radial and Tangential Directions

Group of specimens	Radial direction			Tangential direction			Wood shear strength (Kariz 2011) (N/mm^2)
	Number of specimens	Withdrawal capacity of screws (N/mm^2)	St. deviation	Number of specimens	Withdrawal capacity of screws (N/mm^2)	St. deviation	
Control	21	20.0	1.01	16	20.7	2.01	8.67
HT-150	15	22.8	3.33	12	20.1	4.97	8.15
HT-170	19	18.4	1.95	13	19.2	2.80	8.74
HT-190	15	19.6	1.02	12	21.0	2.09	8.66
HT-210	15	16.5	0.85	10	17.3	1.51	7.60
HT-230	11	13.1	1.29	11	12.7	1.09	7.21

Screw holding strength is related to wood density. The basic formula for the calculation of screw holding strength is, according to Rammer (2010):

$$p = 108.25 \times G^2 \times d \times L \tag{1}$$

where p is the maximum withdrawal load (N), G is the specific gravity based on oven dry weight and volume at a 12% moisture content, d is the diameter of the screw (mm), and L

is the length of penetration of the threaded part of the screw (mm). In the case of the tests described in this paper, the diameter and depth of screw penetration were constant, but density varied due to the heterogeneity of the wood and also mass loss during heat treatment. Mass loss and consequently lower wood density is one of the reasons for lower screw withdrawal capacity from modified wood.

Screw withdrawal strength also depends on wood moisture content (Pirnbacher and Schickhofer 2009). Heat treatment reduces the equilibrium moisture content, so that it decreases with the increasing temperature of the heat treatment. Moisture content has a positive effect on the shear strength of wood, and therefore also on screw holding strength. The withdrawal capacity from heat-treated wood should be higher because of the reduced moisture content, but this effect was not observed in the case of the performed measurements because the other changed properties (due to thermal degradation) diminished this effect.
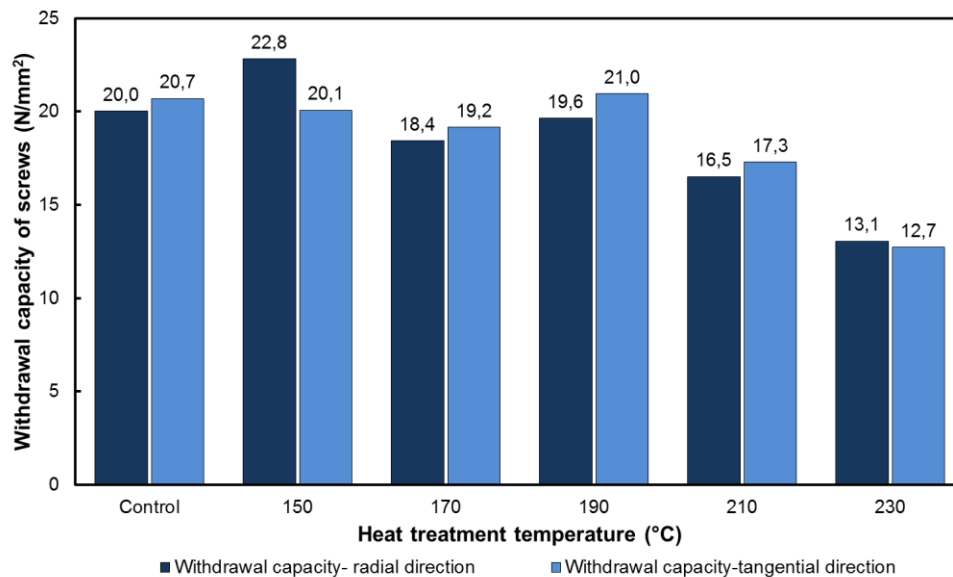

Fig. 3. Withdrawal capacity of screws in the radial and tangential direction for wood that was heat-treated at different temperatures.

Not only did the screw holding strength decrease with increasing modification temperature, but the deformed area around the screw hole increased in size with the increasing heat treatment temperature of the wood (Figs. 4 and 5). This indicates greater brittleness and lower strength of the modified wood. The shear strength of the heat-treated wood (Table 2) decreased from a value of 8.67 N/mm^2 (control) to 7.60 N/mm^2 (HT-210) and 7.21 N/mm^2 (HT-230) (Kariz 2011).
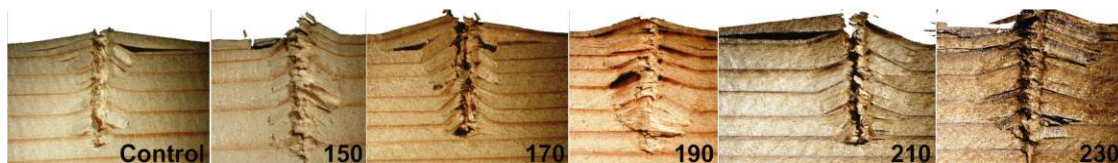

Fig. 4. Increasing average deformed area around the screw after withdrawal from wood modified at different temperatures (Control, 150, 170, 190, 210, 230 °C).

The results of the statistical analysis showed significant differences between the control wood and the heat-treated groups of specimens. The average value of the size of the deformed area was greater in the case of all the groups of specimens compared to the control wood.
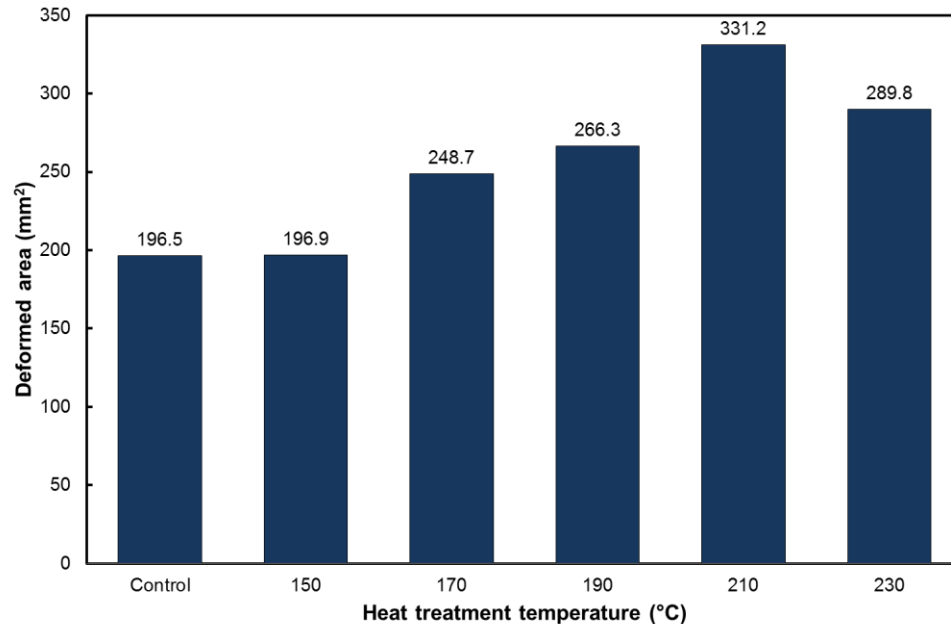

Fig. 5. The influence of the temperature of the heat treatment of wood on the average deformed area around the screw after withdrawal.

Because of the lower screw withdrawal strength of modified wood, screws with larger diameters or deeper penetrations should be used to provide sufficient holding force. Also, greater spacing distances between the screws should be used because of the larger deformation area around the screws.

CONCLUSIONS

1. Heat treatment reduces the withdrawal capacity of screws. The withdrawal capacity of screws from spruce wood that was heat-treated at temperatures of 210 °C and 230 °C decreased significantly compared to the control wood.

2. The deformation area around the screw increased with the heat treatment of the wood.

Obtained results of this research are vaild for the used type of wood, process of modification, and the type of screw (thread, diameter, and material). Different types of screws inserted in differently modified wood could have different performances.

ACKNOWLEDGMENTS

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