Impact of Thermal Modification of Spruce Wood on Screw Direct Withdrawal Load Resistance

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This paper reports on the dependence of screw direct withdrawal load resistance on thermal modification of spruce wood. Screw direct withdrawal load resistance was measured in native and thermally modified spruce wood. The thermal modification was performed at three different temperatures: 140, 180, and 220 °C. Tests were carried out using two types of screws in three anatomical directions. The effect of the thermal modification was unambiguous: the screw direct withdrawal load resistance decreased with increasing modification temperatures. The largest decline 44.2% was found in the axial direction and at a temperature of 200 °C, while the lowest decrease 4.1% was found in radial direction and at temperature 140 °C for conventional screws without pre-drilling. The highest values were identified in the radial direction, and the lowest in the axial direction. While conventional screws without pre-drilled holes may be regarded as the most suitable, the self-drilling screws achieved the lowest values.

Keywords: Screw; Direct withdrawal load resistance; Spruce wood; Thermal modification; Temperature; Anatomical direction

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INTRODUCTION

Spruce is one of the most commonly used wood species in both construction and furniture manufacturing. Spruce wood has a good solidity yet it is light, making it easier to handle while working and jointing various components. On the other hand, spruce wood is relatively soft and less resistant to biotic influences, which are mostly faced when used in exteriors.

The ThermoWood process, invented in Finland, fundamentally changes properties of wood. This method produces a virtually new material with altered properties and resistances to various influences without adding any chemical or other substance. The wood biological resistance can thus be increased to the level of hardwoods. The first sign of the modification is a darkening in coloration. In addition to a change in color, there are also changes in the primary physical and mechanical properties of the wood (Požgaj *et al.* 1993; Vernois 2001; Yildiz *et al*. 2006; Phuong *et al*. 2007; Esteves and Pereira 2009; Gaff and Matlák 2014; Fekiač *et al.* 2015). The most significant effects registered have been in wood density, dimensional stability, and moisture absorption. The advantage is a reduced absorption of moisture as well as wood shrinkage (Mayes and Oksanen 2003), which increases the dimensional stability of wood in exteriors. Another excellent ability is the resistance to biotic influences, which is the main reason for the application. The high temperature alters the structure so much that the resistance to fungi, mold, and rot is increased substantially (Reinprecht and Vidholdová 2008). Among mechanical properties, practically all the strengths are reduced, based partially on the density change and also on chemical changes. In general, thermally modified wood has lower compressive, tensile, and bending strength due to the change in the structure, and the extent of such changes depends on the temperature and the time of its application. Thermally modified wood is applied in products that are not load-bearing structural elements *i.e*., are not loaded mechanically. On the other hand, it is more than suitable for exterior use, typically for paneling, terraces, stairs, and decorative elements (Viitaniemi 2000).

Screws, along with nails, are the most commonly used type of jointing components for wood (Wills *et al*. 1996) in construction, joinery, and furniture production. Screws come in different designs in terms of length, thread angle, and diameter. The basic categorization is into conventional screws with full-shank thread and self-drilling screws, which have a thread only on 2/3 of the shank length. The thread (shank) length and diameter are the basic parameters of screws and also influence their ability and strength of fixation in wood (Fig. 1). This ability is expressed as the screw direct withdrawal load resistance, the resistance of the wood that has to be overcome, which is why it can be compared when using various lengths of screws or nails. Since this ability also depends on the wood structure, it is reduced by thermal modification.

Akyildiz and Malkocoglu (2001) identified the screw direct withdrawal load resistance in five different wood types: beech, alder, chestnut, spruce, and pine. They found that the effect of wood moisture is negative, *i.e*., that the value of screw direct withdrawal load resistance was lower at 28% moisture content than at 12%. Their research confirmed the fact that the higher the wood moisture, the lower the screw direct withdrawal load resistance. This dependence is also confirmed by Keunecke *et al*. (2007) and Hübner *et al.* (2010) who have identified the highest screw direct withdrawal load resistance in the radial plane (tangential direction) of wood. On the other hand, Ferah (1991) identified higher values of screw direct withdrawal load resistance in the radial direction in seven different wood types. This fact is generally confirmed by the structure of the wood and the arrangement of elements in the wood.

Broker and Krause (1991) identified screw direct withdrawal load resistance in static and dynamic experiments on three-layered particleboard, spruce, and beech wood with nine different types of screws. They found out that screw direct withdrawal load resistance is directly proportionally dependent on the length and diameter of the screws.

Fig. 1. Fixation of screw in wood

This study includes the comparison of screw direct withdrawal load resistance for native and thermally modified spruce wood. The screw direct withdrawal load resistance values were obtained from the radial, tangential, and longitudinal directions of wood samples. The data represent the testing of screw direct withdrawal load resistance of two types of screws in the following combinations: conventional screws with pre-drilling, conventional screws without pre-drilling, and self-drilling screws.

EXPERIMENTAL

Materials

The experimental European spruce trees (*Picea abies* L.) were 70 years old and grew in the central region of Czech Republic at an altitude of 391 m, near Kostelec nad Černými lesy, east of Prague. The parts chosen for sample preparation were in the middle distance between the pith and bark. Suitable zones were cut from the trunk at a height of 2 m from the stump. These zones were cut into boards. Spruce samples with annual rings 2.5 mm wide and with dimensions of 55 × 400 × 660 mm were used for thermal modification.

Methods

Thermal modification

Thermal modification was carried out in collaboration with a company known as KATRES Ltd. (Jihlava, Czech Republic). Spruce samples were modified in a thermal furnace S250/03 (LAC; Czech Republic) (Fig. 2). Thermal modification consisted of three basic phases (Fig. 3). The first phase was characterized by an initially sharp increase of temperature up to 100 °C while drying occurred. There was then a gradual increase up to 130 °C. In the second phase, the temperature increased from 130 °C up to the required final temperature of 140, 180, or 220 °C. This final temperature was kept for a further 3 h. The last phase served for gradual cooling of the wood, which was completed at 40 °C, after which the thermal chamber was opened. Then, samples were acclimated for 3 h in the surrounding environment (Table 1). The thermal modification procedure took into account previous researches by Barcík *et al*. (2014) and Holeček (2014).

Fig. 2. Laboratory thermal furnace S250/03

Table 1. Procedures for Thermal Modification

Required final temperature (°C)	Thermal modification			
	I. phase (h)	II. phase (h)	III. phase (h)	Total time (h)
140	30	6	10	46
180	30	8	11	49
220	30	13	10	53

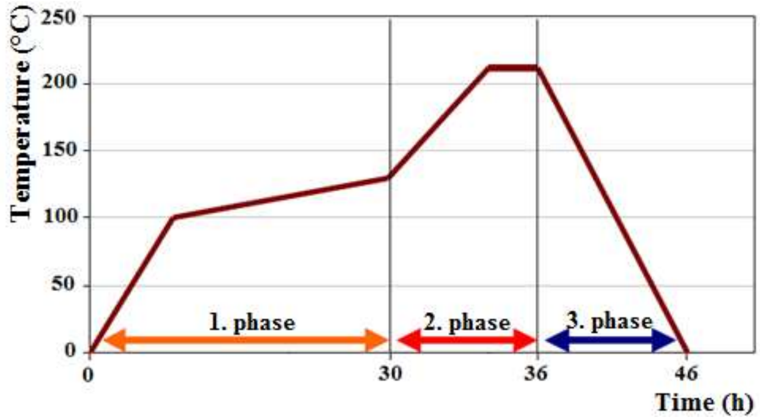

Fig. 3. Phases of thermal modification for final temperature 140 °C

All native and thermally modified wood samples were cut to the final dimensions of 50 × 50 × 150 mm determined for screw direct withdrawal load resistance testing according to ISO 9087 (1998). Clear native and thermally modified samples were conditioned in the conditioning room (ϕ = 65 ± 3% and t = 20 ± 2 °C) for more than four months to achieve an equilibrium moisture content (EMC).

For each combination (screw type × final temperature of modification), 20 samples were used so that the whole investigation contained 240 samples.

Native spruce and thermally modified wood samples were prepared in compliance with standards ISO 13061-1 (2014) and ISO 13061-2 (2014) to determine their density and moisture content. These samples were cut from screw direct withdrawal load resistance samples after testing.

Withdrawal resistance determination

Withdrawal testing was carried out according to ISO 9087 (1998) and ČSN 49 0135 (1984). Prior to the actual testing, the samples were marked according to ISO 9087 (1998) (Fig. 4).

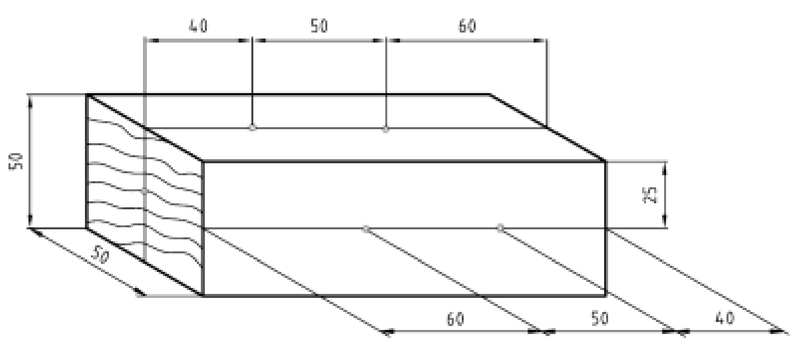

Fig. 4. Marking of test samples for insertion of screws

Two types of steel screws were considered in the research: conventional (Classic Fast FSP-SZ) and self-drilling with extra securing threads (Power Fast FPF-SZ), both with dimensions of 4 × 50 mm (Fig. 5; Table 2). Two alternative uses of conventional screws were chosen for the testing: with pre-drilling (PD) and without pre-drilling (NPD). The pre-drilling was carried out with a diameter of 3 mm and depth of 15 mm.

Fig. 5. Screw type for testing. (a) conventional screw and (b) self-drilling screw

Table 2. Dimensions of Screws

Screw type	Shank diameter (mm)	Root diameter (mm)	Thread length (mm)	Pitch (mm)	Thread height* (mm)	Thread angle (°)	Note
Conventional	4	2.5	35	2	0.75	82	No securing threads
Self-drilling	4	2.5	30	2	0.75	80	Angle-wise securing threads

*Thread height = (Shank diameter – root diameter)/2

Two screws were driven into each plane of the sample: perpendicular to the surface and in the radial, tangential, and axial directions. The depth of the screw insertion (driving) was 20 ± 1 mm. The screws were to be extracted no sooner than 2 h and no later than 3 h after the driving. Then the samples with the screws were placed into an extraction jig of the universal tensile machine UTS 50 (Testsysteme, Germany) with TIRA system and tested (Fig. 6). Extraction of the screws was realized with a continuous movement of the head of the testing machine at a constant rate. The rate of movement was such that the time taken for extraction was between 1 min and 2 min.

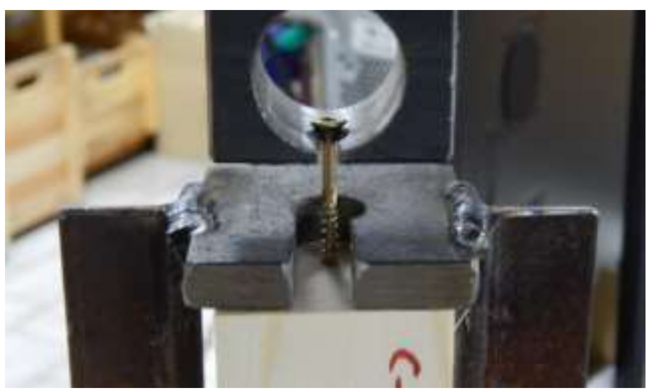

Fig. 6. Placement of the sample in extraction jig

Evaluation and calculation

The influence of various factors on the screw direct withdrawal load resistance was statistically evaluated using ANOVA (Fisher's F-test) analysis, in STATISTICA 12 software (Statsoft Inc.; USA).

Screw direct withdrawal load resistance, also called holding power, withdrawal capacity, or withdrawal resistance, was a primary factor that varied due to thermal treatment. Screw direct withdrawal load resistance was calculated according to Eq. 1 from ISO 9087 (1998) and ČSN 49 0135 (1984),

$$\sigma_w = \frac{F_{\max}}{l} \tag{1}$$

where σ_w is the specific resistance of the wood to the extraction of screws at a certain moisture content w (N/mm), F_{max} is the maximum load force (N), and l is the depth of penetration of a screw (mm). Each final value of specific resistance of the wood to the extraction of a screw is the arithmetic mean of the results of two measurements on each surface of a given sample according to ISO 9087 (1998).

The density was determined as an auxiliary indicator. Density was calculated according to Eq. 2 from ISO 13061-2 (2014),

$$\rho_w = \frac{m_w}{a_w * b_w * l_w} = \frac{m_w}{V_w} \tag{2}$$

where ρ_w is the density of the test sample at a certain moisture content w (kg/m^3), m_w is the mass (weight) of the test sample at certain moisture w (kg), a_w, b_w, and l_w are dimensions of the test sample at certain moisture w (m), and V_w is the volume of the test sample at a certain moisture w (m^3).

The density of the wood after treatment was calculated according to Eq. 3 from ISO 13061-2 (2014),

$$\rho_{tw} = \frac{m_{tw}}{a_{tw} * b_{tw} * l_{tw}} = \frac{m_{tw}}{V_{tw}} \tag{3}$$

where ρ_{tw} is the density of the test sample after treatment (kg/m^3), m_{tw} is the mass of the test sample after treatment (kg), a_{tw}, b_{tw}, and l_{tw} are the dimensions of the test sample after treatment (m), and V_{tw} is the volume of the test sample after treatment (m^3).

Moisture content of samples was determined and verified before and after thermal treatment. These calculations were carried out according to ISO 13061-1 (2014) and Eq. 4,

$$w = \frac{m_w - m_0}{m_0} * 100 \tag{4}$$

where w is the moisture content of the samples (%), m_w is the mass of the test sample at a certain moisture w (kg), and m_0 is the mass of the oven-dry test sample (kg).

Drying to an oven-dry state was also carried out according to ISO 13061-1 (2014), using the following procedure: Wood samples were placed in the drying oven at a temperature of 103 ± 2 °C until a constant mass had been reached. Constant mass was considered to have been reached if the loss between two successive measurements carried out at an interval of 6 h was ≤0.5% of the mass of the test sample.

After cooling the test samples to approximately room temperature in a desiccator, the sample was weighed rapidly enough to avoid an increase in moisture content by more than 0.1%. The accuracy at weighing should be at least 0.5% of the mass of the test sample.

RESULTS AND DISCUSSION

Physical Properties

Average equilibrium moisture content (EMC) and density values of native and thermally modified spruce wood are shown in Table 3. These values were obtained from factorial analysis.

While native spruce wood had moisture content of about 12%, thermal modification reduced the equilibrium moisture content by approximately one half of the untreated wood value, *i.e.*, 4 to 6%, depending on the temperature of modification. This fact was previously confirmed by Mayes and Oksanen (2003).

Table 3. Final Temperature, EMC, and Average Density of Tested Spruce Wood

Samples	Final Temperature of Modification (°C)	Equilibrium Moisture Content (%)	Average Density (kg/m^3)
I. native (control)	-	11.8 (2.11)	421 (8.78)
II. group	140	5.1 (3.42)	414 (3.12)
III. group	180	4.2 (3.09)	409 (5.29)
IV. group	220	3.4 (2.75)	399 (4.11)

Each mean moisture content and density (±SD) represents 20 wood samples

The present experiment identified an average density in spruce wood of 421 kg/m^3. This value is similar to those quoted by other authors. Seeling (1999) found the density of spruce to be 420 kg/m^3, Kučera (1973) measured a higher density of 460 kg/m^3, and Gryc and Horáček (2007) found a density value of 442 kg/m^3. In the present experiment, thermal modification reduced density values by 6% at the highest temperature of 220 °C. This value was confirmed by Arnold (2010), who investigated the impact of 4 h thermal modification at 180 and 220 °C, and found a 5% decrease in density due to thermal modification. However, Yildiz (2002), who investigated 2-, 6-, and 10-h thermal modification, found that thermal modification at 220 °C reduced the density of spruce wood by up to 10.53%.

Screw Direct Withdrawal Load Resistance

Table 4 shows the results of the statistical analysis of the spread of different factors, which indicated that the influence of each factor, as well as their combined influence, was statistically significant.

Table 4. Influence of Factors on Screw Direct Withdrawal Load Resistance

Monitored factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F - Test	Significance Level P
Intercept	1,948,787	1	1,948,787	42,829.73	0.0001
Temperature	37,823	3	12,608	277.08	0.0001
Screw type	13,033	2	6,517	143.22	0.0001
Anatomical direction	27,341	2	13,671	300.45	0.0001
Temperature × screw type × anat. direction	2503	12	209	4,59	0.0001
Error	31123	684	46		

Statistical significance was assessed using Fisher's F-test, which revealed the level of significance for individual factors. The significance level $p < 0.05$ indicated a statistically significant effect.

Figure 7 shows the statistical expression of the influence of temperature on screw direct withdrawal load resistance. The chart clearly shows that increasing the temperature of thermal modification reduces the screw direct withdrawal load resistance, *i.e.*, the lowest values were identified at 220 °C. The reduction occurred evenly as the temperature increased. This effect of temperature on the screw direct withdrawal load resistance was also confirmed by Kariz *et al*. (2013) and Poncsák *et al*. (2006). The decrease in the screw direct withdrawal load resistance of thermally modified wood at 220 °C was around 32% compared to that of native wood. This reduction was partially caused by the overall decrease in wood density, which generally influences a reduction in all mechanical properties (Mayes and Oksanen 2003). The density reduction results from the weakening of the wood structure by the application of a high temperature for a certain period of time. Taj *et al*. (2009) argued that the shear strength is a more accurate factor for the assessment of screw direct withdrawal load resistance than density, because it describes the connection between the wood fibers and screw.

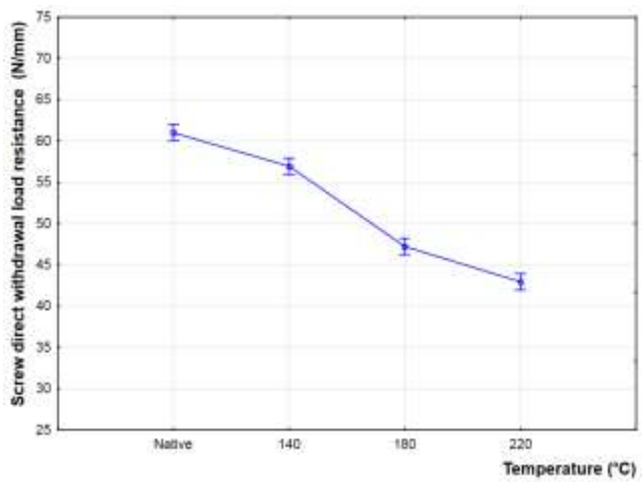

Fig. 7. A 95% confidence interval shows the influence of temperature on screw direct withdrawal load resistance

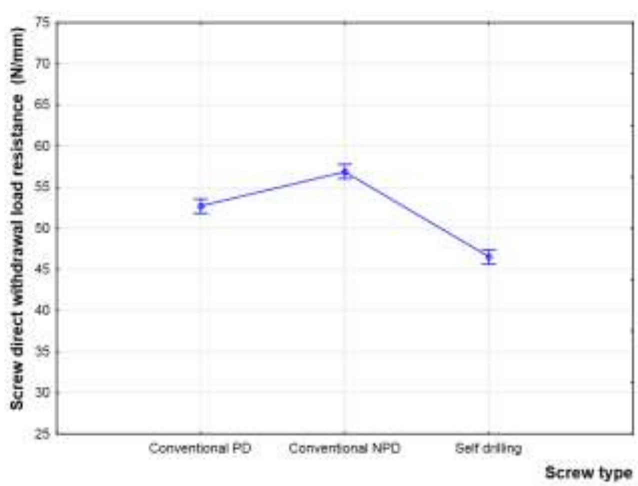

Fig. 8. A 95% confidence interval shows the influence of screw type on screw direct withdrawal load resistance

The statistical expression of the dependence of screw direct withdrawal load resistance on the screw type is shown in Fig. 8. The highest values of screw direct withdrawal load resistance were clearly achieved with conventional screws without pre-drilled holes. These values were almost 8% higher than those for conventional screws with pre-drilled holes and 24% higher than those measured for self-drilling screws. These differences can be explained by the different cohesion between the screw and the surrounding wood.

Pre-drilling does facilitate driving the screws, but it also weakens the wood around the screw, which reduces the joint strength. In contrast, self-drilling screws have a thread designed so that it cuts through wood more easily, thus facilitating its being driven into the wood without the need for pre-drilling. This thread design weakens the wood structure because the different fibers are cut or damaged so much that the overall screw direct withdrawal load resistance of the wood is reduced.

Another factor was the thread angle, which also had a direct effect on the overall joint strength. With a low thread angle, there was insufficient friction between the wood and the screw. The greater the thread angle, the stronger the bond between the screw and the wood.

Figure 9 shows the statistical expression of the influence of the anatomical direction on the screw direct withdrawal load resistance. The highest values were identified in the tangential plane (radial direction), the lowest in the axial direction. The differences between the values for the radial and tangential directions were not remarkable, only about 2%.

Higher values are expected in the radial direction due to the arrangement of cells in the wood and the angle of the wood fibers. This has been confirmed by Aytekin (2008) and Akyildiz (2014), who found the highest values in the radial direction. In general, the lowest values are achieved in the axial direction, as confirmed by our results as well as those of Aytekin (2008).

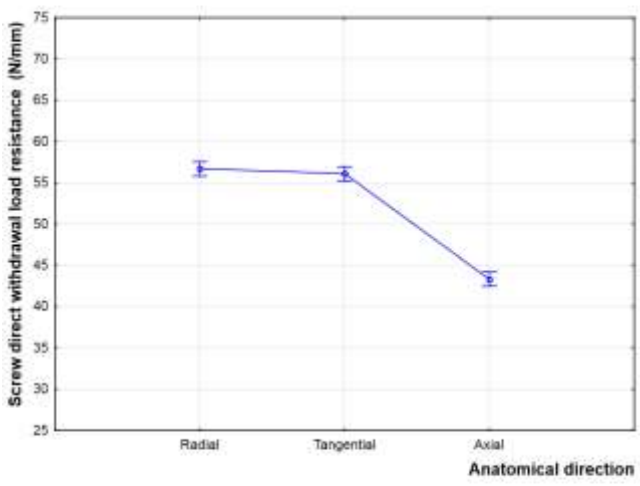

Fig. 9. A 95% confidence interval shows the influence of anatomical direction on screw direct withdrawal load resistance

The final graph (Fig. 10) shows the influence of all combined factors on screw direct withdrawal load resistance. The comparison between the screw types indicates that the conventional screws without pre-drilling achieved the highest values in both native wood and the different thermal modification temperatures (Table 5). Pre-drilling caused similar weakening of the wood in the area around the screw, as was the case with self-drilling screws. However, the diameter of the pre-drilled hole was only as big as the root diameter of the screws so that the threads could create their own space in the wood. Since conventional screws have fewer sharp edges, there was no considerable cutting of wood fibers, only a splaying of fibers.

Table 5. Average Values of Screw Direct Withdrawal Load Resistance

Screw Type	Anatomical directions	Screw direct withdrawal load resistance (N/mm)			
		Native wood	Thermally modified wood		
			140 °C	180 °C	220 °C
Conventional PD	Radial	61.7 (7.84)	63.1 (11.20)	51.5 (4.98)	51.6 (14.11)
	Tangential	58.0 (9.43)	62.8 (7.82)	56.2 (16.02)	48.4 (12.2)
	Axial	54.6 (10.10)	49.0 (13.14)	39.4 (6.94)	35.8 (8.84)
Conventional NPD	Radial	71.0 (5.41)	68.1 (3.98)	55.8 (10.73)	50.0 (11.08)
	Tangential	70.3 (14.74)	62.6 (8.74)	56.3 (5.71)	52.4 (12.01)
	Axial	65.8 (11.36)	53.3 (14.72)	40.2 (8.17)	36.7 (6.69)
Self-drilling	Radial	62.2 (4.21)	58.5 (7.40)	46.9 (9.48)	39.6 (12.45)
	Tangential	62.6 (7.84)	55.6 (6.99)	45.7 (13.44)	42.1 (10.00)
	Axial	42.6 (10.11)	39.5 (3.76)	33.3 (12.14)	29.7 (6.23)

Each mean (±SD) of screw direct withdrawal load resistance represents twenty wood samples

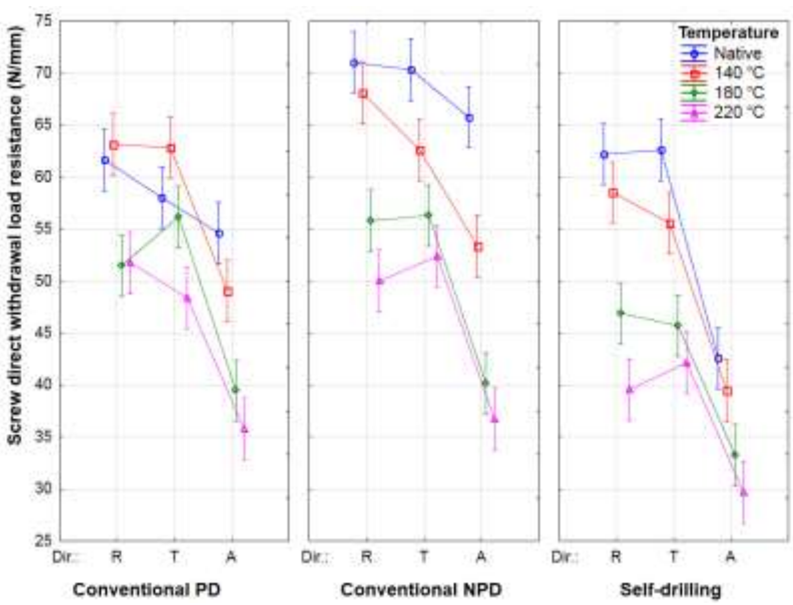

Fig. 10. A 95% confidence interval shows the influence of temperature, screw type and anatomical direction on screw direct withdrawal load resistance

The highest temperature used, 220 °C, had the most significant effect on screw direct withdrawal load resistance. Temperatures above 200 °C are generally regarded as the boundaries at which wood structure changes are the greatest, leading to a reduced wood strength. Poncsák *et al*. (2006) confirmed this fact in their research. They found that thermal modification weakens the structure of wood, making it less strong and more fragile.

Based on these results, the best option for jointing wood is the use of conventional screws without pre-drilling, preferably in the radial direction (tangential plane) for exterior paneling, ceiling paneling, or packaging crates, for example. The use of screws in the axial (longitudinal) direction is practically useless and should therefore be avoided. Thermal modification of spruce wood has to be designed based on the future use of the products made from it. The optimum temperature is up to 180 °C, where the structural degradation is not as significant.

CONCLUSIONS

1. The results of the present study demonstrated a significant decreasing effect of thermal modification on screw direct withdrawal load resistance. The highest screw direct withdrawal load resistance was found in native wood, while the lowest was found in thermally modified wood at 220 °C.
2. The highest screw direct withdrawal load resistances were found, for both native and thermally modified wood, for conventional screws without pre-drilling. The lowest values were achieved by self-drilling screws, namely a 24% decrease compared to conventional screws without pre-drilling. Conventional screws with pre-drilling achieved values 8% lower than without pre-drilling.
3. Various differences were achieved between the directions. The highest decrease of screw direct withdrawal load resistance 44.2% was found in the axial direction and the lowest was achieved in the radial direction 4.1%. The values of screw direct withdrawal load resistance for the radial direction were about 2% higher than those for the tangential direction.

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