# The influence of freezing on the nail withdrawal capacity of Norway Spruce and European Larch wood

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# Abstract

Environmental conditions and temperature oscillations can influence wood properties. Accordingly, the performance of wood connections such as nails could be affected by freezing and heating temperature. Thus, in the present work, the impact of freezing/heating temperatures on the nail withdrawal power of Norway Spruce (*Picea abies* (L.) H. Karst.) and European Larch (*Larix decidua* Mill.) has been studied. Three types of the wood nail; smooth, helically threaded, and annularly threaded were studied, and two different freezing heating steps have been implemented (-15°C/70°C and − 25°C/70°C). Withdrawal capacity was distinguished on two various anatomical directions; radial and tangential surfaces. The freezing could cause a considerable destructive impact on the nail withdrawal capacity of both wood species. The highest drop has found for smooth nail (A) for larch wood in the tangential direction with 73% and 69% decrease and radial direction, with 70% and 63%, at temperatures − 15°C/70°C and − 25°C/70°C, respectively. Furthermore, spruce wood exhibited a meaningful reduction for both tangential (69% and 63%) and radial (54% and 56%) directions and smooth nail (A), at temperatures − 15°C/70°C and − 25°C/70°C, respectively. The highest reduction was found for annularly threaded nails (C).


# 1. Introduction

Wood is an environmentally friendly substance and is considered a symbol of nature. Today, wood is the most arbitrary material in the design of green or sustainable buildings. The construction of wooden structures or wooden houses employing timber is more out-dated than the construction with other materials. The point to be made is the different surroundings. This subject should be taken into account before starting to make a building with wood. Surrounding temperatures can effectively influence the mechanical properties of wood. In a climate with extremely low temperatures below 0°C, stashed timbers with high moisture content in outdoor conditions start to freeze (Szmutku et al. 2013), whereas between 0°C and − 30°C free water freezes in the wood (Cividini 2000; Marinescu 1980). Two different moisture conditions are distinguished in the wood below 0°C; in the non-frozen conditions and frozen conditions, while the content of non-frozen moisture content is contingent on the total moisture content and freezing temperature (Torgovnikov 1993).

Previous studies investigated the impact of low temperatures on wood mechanical properties (Kollmann and Côté 1968; Jiang et al. 2014; Niemz et al. 2014). Their studies have shown that by reducing the temperature, there would be an increase in some mechanical properties, including modulus of elasticity, compression, and bending strength. However, the shear strength of wood decreased remarkably (Wang et al. 2015). Erickson et al. (1968)d bler (1962) have investigated the impact of freezing on the physical properties of wood, and they indicated freeze-drying could reduce collapse and defects. They investigated the possibility of applying pre-freezing as a treatment to decrease wood shrinkage due to freezing temperature. Wood freezing causes cell wall constriction and, subsequently, water motion toward the lumen. Thought, transmutation of water into ice inner side the lumen could cause volume enhancement and accordingly lead to cell wall shrinkage (Ilic 1995). Ispas and Campean (2014) have reported the results of their research on changes during sawing of frozen and unfrozen wood. Considering the freezing rate, they have found that a slower freezing rate results in bigger ice formed in crystal forms. Thence, more micro-fissures generate (Szmutku et al. 2011). A study on the impact of freezing rate on the mechanical properties of conditioned Spruce wood (12% equilibrium moisture content) induced that wood strength can be negatively affected by slow freezing rate (1°C/h) (Szmutku et al. 2013). In comparison, the variation of temperatures (freezing and thawing) during cold seasons results in the strength reduction of wood (Caceres and Hernández 2019).

According to previous works, the mechanical properties of frozen wood in green conditions increase as the temperature reduces below 0°C (Mishiro and Asano 1984; Hernández et al. 2014). During freezing, water transformation into ice inside the lumen is combined by increased volume, which can exert pressure upon cell walls. This stress most likely procreates micro-cracks in the membrane, which can cause reduced mechanical strengths of frozen wood (Ilic 1995).

Wood constructions are made of different wood and its composite products together with a range of different fasteners, including different adhesives and mechanical joints which they can be divided into two groups: dowel type (lag screw, wood screw, nail) and bearing type (split ring, shear plate) (Taj et al 2009). Forasmuch as each wood species has its properties, nail withdrawal resistances vary for different wood species. As regards, withdrawal strength depends on the natural properties of wood, such as its density, so the specification of withdrawal capacity of different wood species is of great importance (Aytekin 2008). According to Helinska-Raczkowska (1993), there is a positive correlation between nail withdrawal capacity and wood density. Hence, the nail withdrawal resistance is in a linear relationship with humidity (Kim 1979).

Since freezing can affect wood mechanical properties (Ilic 1995; Szmutku et al. 2011), accordingly wood nail withdrawal strength can be influenced by freezing. The influence of low temperature on the joint glued of different adhesives has been studied before (Wang et al. 2015). Furthermore, an investigation on the effect of freezing on the nail withdrawal strength of Spruce wood concluded that freezing lowers the nails withdrawal resistance in all three directions, while MOE, tensile strength, and compressive strength were not significantly affected by low temperatures (Szmutku et al. 2011), thought the nail type and different loading treatments have not been investigated in this study. Although the reference works of literature investigate the mechanical properties of wood in frozen and normal states with the same moisture content (Bodig and Jayne 1993), there is no literature published about the effect of different freezing/heating temperatures on the nail withdrawal capacity of wood by considering different nail types. Accordingly, in the current study, the nail withdrawal capacity of Norway spruce and European Larch wood have been investigated for three types of wood nails (smooth, helically threaded, and annularly threaded) and two levels of freezing temperatures (15°C/70°C and − 25°C/70°C). Furthermore, the second aim of the current study was to investigate the impact of anatomical direction and nail types on the withdrawal holding power of wood under freezing/heating conditions.

# 2. Materials And Methods

## 2.1. Material

### 2.1.1. Wood

The experiment of the present study was performed on Norway Spruce (*Picea abies* (L.) H. Karst.), and European Larch (*Larix decidua* Mill.) lumbers, which were supplied from a market. A total of 360 conditioned samples, consisting of 180 samples for each group of species with dimensions of 50 mm × 50 mm × 150 mm (t × w × l) and with no defect were provided (Fig. 1) based on the standard ČSN EN 1382 (2018). The nail withdrawal power could be impressed by straight grain orientation, and accordingly, samples were chosen based on the standard CSN EN 1309-3 (2018) with an approximate 5% inclination.

The wood lumbers kiln dried. Prepared samples were placed in climatic chamber HPP 750 (Memmert GmbH, Germany) to be stabilized and reach an equilibrium moisture content of 12% under standard conditions (relative humidity of 65% ± 3%, and temperature of 20°C ± 2°C). Samples of each group of species were classified into three groups according to thermal loading temperature; Reference samples, freezing/heating samples at temperature − 15°C/70°C, and freezing/heating samples at temperature − 25°C/70°C.

### 2.1.2. Nails

Three commercially available steel wood nails were used (Fig. 2). The dimensions and manufacturers of wood nails are given in Table 1. All nails had the same dimensions of shank diameter, while the overall length of the annularly threaded nail is less than the smooth nail and helically nail. Hence, nails were with no coating (Table 1). Material properties of wood nails were not determined and are not expected to be relevant to the presented experiment focused on withdrawal capacity. The nails were driven to a penetration depth of 30 mm in the tangential and radial surface according to the ČSN EN 1382 (2018), without prior pre-drilling, and 20 replications were considered for each anatomical direction (Fig. 3).

Table 1
Wood nails

| | **Nail type** | | |
|---|---|---|---|
| **Parameters** | **Smooth nail** (A) | **Helically threaded nail** (B) | **Annularly threaded nail** (C) |
| **Dimensions (mm)** | 2.8 × 63 | 2.8 × 63 | 2.8 × 60 |
| **Coating** | no | no | no |
| **Producer** | Chalko Příkrý s.r.o., Czechia | Chalko Příkrý s.r.o., Czechia | Hašpl a.s., Czechia |

## 2.1.3. Thermal loading

The freezing/heating was carried out based on the standard ČSN EN 321 (2002) to determine the moisture resistance of wood under cyclic temperature measures. The laboratory freezer MediLine LGT 3725 (Liebherr GmbH, Germany) was fixed to the necessary temperature (-15°C or -25°C), and the samples were left in the freezer for 12 h at the desired temperature.

After freezing, the weight of samples was measured to calculate physical properties (Table 2). After, the frozen samples were situated in a thermal chamber SolidLine ED-S 115 (Binder GmbH, Germany) with a temperature of 70 ± 2°C for 12 hours. Following heating, the samples were weighed. Subsequently, measurement was performed. Finally, the samples were prepared for the pull-out test.

## 2.2. Methods

## 2.2.1. Physical properties

The moisture content and density demonstrate the significant function. Since these two features are the principles to confirm the effectiveness of thermal loading on wood properties, these properties were measured after each step of the experiment (conditioning, freezing, heating), and according to the standards ISO 13061-1 (2014) and ISO 13061-2 (2014).

## 2.2.2. Withdrawal capacity

Nail withdrawal capacity was carried out according to the ČSN EN 1382 (2018) standard and by a universal testing machine UTS 50 (TIRA Germany) in partnership with the TIRA test software. The nail extraction was done between 2 hours and 3 hours after the driving. According to the ČSN EN 1382 (2018) standard, the loading speed was specified to extend that the time to achieve the maximum force ($F_{max}$) did not exceed 60 ± 15 seconds. After overreaching the leading pulling power and when the ultimate pressure decreased by more than 20%, the test was terminated, and the fixtures were returned to the initial position (Fig. 4). The same procedure was applied for both tangential and radial directions.

Nail withdrawal capacity is determined as equal to the maximum withdrawal (pull-out) force. The maximum required power to pull out the nails were considered to compute the withdrawal parameter $f_{ax}$ (Eq. 1) according to ČSN EN 1382 (2018) as well as the withdrawal resistance $R_{ax}$ (Eq. 2) according to ČSN 49 0135 (1984).

The withdrawal parameter $f_{ax}$ was calculated using Eq. 1,

$$f_{ax} = \frac{F_{max}}{d \times l_p}$$

1

where $F_{max}$ is the maximum force (N), $d$ is the nail diameter (mm), $l_p$ is the penetration depth of nail (without sharp tip)(mm).

The withdrawal resistance $R_{ax}$ was calculated using Eq. 2,

$$R_{ax} = \frac{F_{max}}{l_p}$$

2

where $F_{max}$ is the maximum force (N), $l_p$ is the penetration depth of nail (without sharp tip)(mm).

The withdrawal parameter and withdrawal resistance values were evaluated by Statistica 13 (TIBCO Software Inc., Palo Alto, USA) software using ANOVA.

## 3. Results And Discussion

# 3.1. Moisture content and wood density

The effect of freezing/heating on the wood density and moisture content are presented in Table 2. The provided table reveals that freezing and heating could not generate noteworthy modification in the density and moisture content. The coefficients of thermal expansion and contraction of wood are self-determining of temperature in the range of − 51.1°C to 54.4°C (Simpson and TenWolde 1999). Therefore, the explained consequences are being expected since wood is long lasting against thermal variations. This result is in line with investigations by earlier researchers in the literature (Missio et al. 2016).

The freezing operation hinges on wood moisture content. Free water freezes effortlessly and results in ice growth in the cell lumen. Hence the rate of ice formation in wood is affiliated with the moisture content resulting in fracture of the cell wall. Consequently, in the present study, the low moisture content of the wood (approximately 12%) during freezing is expected to have no considerable influence on nail withdrawal power. The low preliminary moisture content in the wood expresses no free water in the cell lumen and represents the existence of only bound water. Bound water freezes at a slow pace and, though part of it, stays in a liquid shape (Simpson and TenWolde 1999). Even if the wood with low moisture content were subjected to extremely low temperatures for a long period, bound water freezing occurs only slightly (Karenlampi et al. 2005). Further studies by researchers revealed that wood with higher moisture content (above fiber saturation point) tends to be more influenced by temperature (Comben 1964). Hence this tendency is more noticeable for cold temperatures (Gerhards 1982).

In the current work, the density stayed without change since there was no considerable loss in moisture content and volume change.

Table 2
Average density and moisture content of spruce and larch wood

| Wood species | Thermal loading | Moisture content (%) | | | Density (kg/m$^3$) | | |
|---|---|---|---|---|---|---|---|
| | | Initial | After freezing | After heating | Initial | After freezing | After heating |
| Spruce | Reference | 11.8 | - | - | 382.6 | - | - |
| | -15°C/70°C | 12.3 | 12.4 | 4.2 | 381.9 | 382.6 | 369.4 |
| | − 25°C/70°C | 12.2 | 12.3 | 5.8 | 381.7 | 382.5 | 369.3 |
| Larch | Reference | 11.9 | - | - | 621.6 | - | - |
| | -15°C/70°C | 12.4 | 12.1 | 6.6 | 619.9 | 621.8 | 603.4 |
| | − 25°C/70°C | 12.0 | 12.1 | 7.9 | 617.3 | 618.5 | 601.3 |

## 3.2. Nail type, temperature and anatomical direction

In the current study, $R_{ax}$ was defined by dividing $F_{max}$ with the penetration length of the nails, which was invariant for all the nail types (30 mm). Anyhow, the nail withdrawal parameter ($f_{ax}$) could be more instructive since it considers the diameter of the nails. Tables 3 and 4 show the average values relevant to the three parameters ($F_{max}$, $R_{ax}$, and $f_{ax}$), though only $f_{ax}$ has been considered for investigation in the present study. Tables 3 and 4 demonstrate the mean values of nail withdrawal force, parameter, and resistance. The relative results of nail withdrawal parameters of spruce and larch and for both radial and tangential directions are presented in Tables 3 and 4, respectively. Nail holding powers were determined both on the tangential and radial sides.

A perusal of results indicated a higher nail withdrawal parameter in the radial direction as compared to the tangential direction in both spruce and larch wood (Tables 3 and 4). Thermal loading (altering temperature) could cause a detrimental impact on the nail holding power in both species, though the degree of the detriment for withdrawal parameters varied depending on the wood species.

The results of the effect of nail type on the withdrawal parameter of reference wood (without thermal loading) in all the three types of nail ranged between 12.2 and 2.6 N/mm$^2$ in spruce, and the decrease in the withdrawal parameter due to thermal loading ranged between 14% and 73% from the reference values. The results of pooled data indicate that the average withdrawal resistance exhibited by annularly threaded (C) type nails was significantly higher than those exhibited by smooth (A) and helically treaded (B) type nails. The highest average withdrawal parameter was 12.2 N/mm$^2$ with the lowest percentage of decrease for both tangential (14.7% and 19.6%) and radial (16.4% and 21.3%) direction and for both loading treatments. This result shows no significant detrimental impact for annularly threaded (C) type nails. Maximum decrease values were obtained in smooth (A) nail subjected to both thermal loadings in both tangential (73% and 69%) and radial (70% and 63%) directions, which are statistically significant ($p < 0.05$).

The pooled data of larch wood presented in Table 4 shows a higher withdrawal parameter of larch wood compared to spruce wood. The average reference values (without thermal loading) range between 5.4 and 25.9 N/mm$^2$. Annularly threaded (C) nail exhibited the highest average withdrawal parameter in the tangential and radial direction (21.4 and 25.9 N/mm$^2$) followed by helically treaded (B) (6.8 N/mm$^2$). Smooth (A) type nail exhibited the least withdrawal parameter in both tangential and radial directions (5.4 and 5.9 N/mm$^2$). The average withdrawal parameter exhibited by annularly threaded (C) nails was significantly higher than that exhibited by smooth (A) and helically treaded (B) type nails ($p < 0.05$). The highest mean withdrawal parameters after thermal loading for larch wood was found for annularly threaded (C) type nail with no significant decrease for both tangential (21%) and radial (27% and 30%) directions, and both thermal loadings. Thought, smooth (A) nail type with the lowest mean value obtained the highest significant ($p < 0.05$) decrease for both tangential (69% and 63%) and radial (54% and 56%) directions, followed by a significantly decreased value obtained for helically treaded (B) type nail in both tangential (60% and 51%) and radial (54% and 34%) directions. The presented results for both spruce and larch wood are in concurrence with the results published by previous researchers who reported that freezing reduces certain mechanical properties of wood (Ilic 1995; Liu et al. 2015).

Table 3
Withdrawal parameter, resistance and force of spruce wood

| Wood nail type | Anatomical direction | Thermal loading | Withdrawal parameter $f_{ax}$ ($N/mm^2$) | Withdrawal resistance $R_{ax}$ (N/mm) | Withdrawal force $F_{max}$ (N) |
|---|---|---|---|---|---|
| Smooth (A) | Tangential | Reference | 2.6 (0.53) | 7.2 (1.47) | 215.5 (44.21) |
| Smooth (A) | Tangential | -15°C/70°C | 0.7 (0.39) | 2.0 (1.08) | 60.9 (32.36) |
| Smooth (A) | Tangential | -25°C/70°C | 0.8 (0.31) | 2.3 (0.88) | 68.8 (26.41) |
| Smooth (A) | Radial | Reference | 3.0 (0.26) | 8.3 (0.71) | 248.7 (21.43) |
| Smooth (A) | Radial | -15°C/70°C | 0.9 (0.27) | 2.6 (0.74) | 78.6 (22.33) |
| Smooth (A) | Radial | -25°C/70°C | 1.1 (0.26) | 3.2 (0.71) | 95.7 (21.39) |
| Helically treaded (B) | Tangential | Reference | 2.8 (0.51) | 7.8 (1.42) | 234.0 (42.54) |
| Helically treaded (B) | Tangential | -15°C/70°C | 1.0 (0.26) | 2.9 (0.73) | 87.3 (21.91) |
| Helically treaded (B) | Tangential | -25°C/70°C | 1.2 (0.25) | 3.2 (0.69) | 97.4 (20.70) |
| Helically treaded (B) | Radial | Reference | 3.1 (0.45) | 8.6 (1.26) | 259.3 (37.85) |
| Helically treaded (B) | Radial | -15°C/70°C | 1.4 (0.33) | 3.9 (0.91) | 117.9 (27.31) |
| Helically treaded (B) | Radial | -25°C/70°C | 1.4 (0.34) | 4.0 (0.94) | 119.4 (28.23) |
| Annularly threaded (C) | Tangential | Reference | 10.2 (2.28) | 28.6 (6.38) | 859.3 (191.42) |
| Annularly threaded (C) | Tangential | -15°C/70°C | 8.7 (2.23) | 24.3 (6.24) | 728.3 (187.08) |
| Annularly threaded (C) | Tangential | -25°C/70°C | 8.2 (2.41) | 23.1 (6.75) | 692.7 (202.58) |
| Annularly threaded (C) | Radial | Reference | 12.2 (1.29) | 34.0 (3.61) | 1020.7 (108.22) |
| Annularly threaded (C) | Radial | -15°C/70°C | 10.2 (1.51) | 28.5 (4.22) | 856.2 (126.54) |

The values in parentheses are the standard deviations (SD).

| Wood nail type | Anatomical direction | Thermal loading | Withdrawal parameter $f_{ax}$ (N/mm$^2$) | Withdrawal resistance $R_{ax}$ (N/mm) | Withdrawal force $F_{max}$ (N) |
|---|---|---|---|---|---|
| Annularly threaded (C) | Radial | -25°C/70°C | 9.6 (1.67) | 27.0 (4.69) | 809.0 (140.66) |
| The values in parentheses are the standard deviations (SD). | | | | | |

Also, the results of pooled data for two different wood species irrespective of anatomical direction nail types, and thermal loading reveals that the nail holding power of larch wood (9.2 N/mm$^2$) is significantly higher (52%) as compared to spruce wood (4.4 N/mm$^2$). It could be anticipated that the specific gravity is a good indicator of the nail withdrawal parameter and there is a linear relationship between the withdrawal strength of nails and the specific gravity (Cassens and Eckelman 1985).

Table 4
Withdrawal parameter, resistance and force of larch wood

| Wood nail type | Anatomical direction | Thermal loading | Withdrawal parameter $f_{ax}$ ($N/mm^2$) | Withdrawal resistance $R_{ax}$ (N/mm) | Withdrawal force $F_{max}$ (N) |
|---|---|---|---|---|---|
| Smooth (A) | Tangential | Reference | 5.4 (1.16) | 15.0 (3.26) | 451.0 (97.75) |
| Smooth (A) | Tangential | -15°C/70°C | 1.7 (0.46) | 4.8 (1.28) | 143.7 (38.27) |
| Smooth (A) | Tangential | -25°C/70°C | 2.0 (0.58) | 5.7 (1.64) | 170.0 (49.10) |
| Smooth (A) | Radial | Reference | 5.9 (1.34) | 16.6 (3.76) | 498.6 (112.88) |
| Smooth (A) | Radial | -15°C/70°C | 2.7 (0.92) | 7.5 (2.59) | 225.6 (77.62) |
| Smooth (A) | Radial | -25°C/70°C | 2.6 (0.61) | 7.4 (1.71) | 222.6 (51.69) |
| Helically treaded (B) | Tangential | Reference | 6.8 (2.14) | 19.2 (5.99) | 575.3 (179.73) |
| Helically treaded (B) | Tangential | -15°C/70°C | 2.7 (0.86) | 7.5 (2.40) | 224.6 (71.92) |
| Helically treaded (B) | Tangential | -25°C/70°C | 3.3 (0.94) | 9.2 (2.63) | 275.2 (78.93) |
| Helically treaded (B) | Radial | Reference | 6.8 (2.17) | 19.1 (6.06) | 573.0 (181.93) |
| Helically treaded (B) | Radial | -15°C/70°C | 3.1 (1.27) | 8.6 (3.57) | 258.8 (106.97) |
| Helically treaded (B) | Radial | -25°C/70°C | 4.5 (1.22) | 12.5 (3.42) | 374.5 (102.74) |
| Annularly threaded (C) | Tangential | Reference | 21.4 (4.59) | 59.9 (12.85) | 1795.8 (385.43) |
| Annularly threaded (C) | Tangential | -15°C/70°C | 16.8 (3.32) | 46.9 (9.30) | 1407.9 (278.98) |
| Annularly threaded (C) | Tangential | -25°C/70°C | 17.0 (2.79) | 47.5 (7.82) | 1425.9 (234.63) |
| Annularly threaded (C) | Radial | Reference | 25.9 (5.01) | 72.5 (14.02) | 2174.9 (420.51) |
| Annularly threaded (C) | Radial | -15°C/70°C | 19.0 (4.84) | 53.3 (13.54) | 1598.2 (406.21) |

The values in parentheses are the standard deviations (SD).

| Wood nail type | Anatomical direction | Thermal loading | Withdrawal parameter $f_{ax}$ (N/mm$^2$) | Withdrawal resistance $R_{ax}$ (N/mm) | Withdrawal force $F_{max}$ (N) |
|---|---|---|---|---|---|
| Annularly threaded (C) | Radial | -25°C/70°C | 18.1 (4.72) | 50.6 (13.21) | 1518.9 (396.25) |
| The values in parentheses are the standard deviations (SD). | | | | | |

The data pertain to the nail holding power for both anatomical directions, irrespective of wood species, nail types and thermal loading is shown in Fig. 5. It could be deduced that the withdrawal parameter values in the radial direction are marginally higher than that in the tangential direction, though there is not a significant difference between these two directions. It was expected that thermal loading affect the nail holding power of wood in both anatomical directions. According to the pooled data presented in Table 2, there was reduced moisture content after the heating phase, which was about 6.4% – 8.1% in spruce wood and 4.1–5.8% in larch wood, which consequently could cause differential shrinkage in the radial and tangential directions. Thus, this could affect the contact area between the nail and wood fibers.

Figure 6 illustrates the effect of nail types on the withdrawal resistance of wood irrespective of anatomical direction, wood species, and thermal loading. The higher withdrawal strength pertains to the annularly threaded nail (C) (14.8 N/mm$^2$), while smooth nail (A) shows the lowest withdrawal parameter (2.4 N/mm$^2$). The nail withdrawal power hinges mainly on nail diameter, its driven length, grain anatomical direction, and wood density. A nail shank could generally be modified to helical or annular threads. Smooth shank nail power depends only on the attrition between the nail shank and the wood, which supplies holding power. But holding strength of helically and annularly threaded nails could be reached mainly by gripping threads into the wood fibers. They provide holding power by wood fibers lodged between the threads. Thought to pull out threaded nails from the wood, these lodged wood fibers must be broken (Rammer and Zelinka 2015).

Hence, threaded nails seem to demonstrate higher nail withdrawal power. Therefore, after withdrawing the smooth shank nail, stress relaxation of the wood fibers results in loss of withdrawal power. Whereas during driving of threaded nails, the wood fibers slide over the threads into the annular grooves like wedges, and they release harder than smooth shank nails (Stern 1956a). Therefore, the reduction in withdrawal strength of ring-shank nails over time is small when compared to that of smooth-shank nails (Stern 1956b). So, the achieved result is expected and is in line with the previous literature discussing the effect of nail types on withdrawal resistance (Rammer and Zelinka 2015; Stern 1956b; Quackenbush 1977).

The overall finding of the study on the effect of anatomical direction, nail type, and thermal loading on the nail withdrawal parameter in spruce and larch wood has been presented in Fig. 7 and Fig. 8, respectively. It can be summarized that thermal loading could cause a detrimental effect on the nail withdrawal parameter for both spruce and larch wood. The influence of thermal loading on the withdrawal parameters in larch wood was almost similar to that obtained in spruce wood though the nail types influence the values. Annularly threaded nails have higher withdrawal parameters and are less affected by thermal loading, while smooth nails with the lowest nail holding power have the maximum significant decreased values in the withdrawal parameter. However, there is no significant difference in the effects of two different thermal loadings. The effect of freezing at 30°C for one week followed by drying at 50–60°C for 129 h on the nail withdrawal strength of spruce wood reported a marginal decrease, though not statistically significant (Szmutku et al. 2011), which is in line with the results presented in the current study.

As the moisture content of the wood is very critical during freezing, the reduced mechanical properties, including nail withdrawal power, have been reported to be expected and can be attributed to the micro-cracks in the cell walls. The pressure originating from the expansion of ice during freezing in the cell lumens constructs these micro-cracks (Ilic 1995; Szmutku et al. 2011). Since free water is liable to freeze easier, the higher moisture content in the wood can act as a controlling factor in determining the degree of expansion of ice and, consequently, cell wall rupture. Though in the current study, the moisture content of wood during freezing was very low (~ 12%), and the exposure time during freezing was also less (12 h) as compared to the exposure times, which was 72 h and stated in the prior study (Szmutku et al. 2011; Liu et al. 2015), but results reveal a noteworthy impact of freezing on the nail withdrawal parameters. In comparison, bound water freezes only to a small amount for wood subjected to very low temperature for a lengthier period (Karenlampi et al. 2005).

## 3.3. Statistical Analysis

The statistical analysis of the effect of the factors and their combinations on the withdrawal parameter is given in Table 5. Indicating the level of significance ($p < 0.05$), it can be concluded that the parameters including wood type, thermal loading, anatomical direction and nail types reveal a significant impact on the withdrawal power ($p < 0.05$).

Table 6 shows Spearman’s correlation, which expresses the general interdependence between factor groups, withdrawal parameter, and withdrawal resistance.

According to the table, the highest correlation was found between withdrawal parameter and withdrawal resistance (0.981). There is also a moderately significant correlation between wood species and withdrawal parameter (0.0.384) and withdrawal resistance (0.384). Although, there was a general correlation between thermal loading and withdrawal parameter (-0.256) and withdrawal resistance (-0.256), the correlation is not significant. The presented correlation results also exhibit no significant correlation between nail types and withdrawal power.

**Table 5**. Statistical evaluation of withdrawal parameter $f_{ax}$

| Factors | Sum of squares | Degrees of freedom | Variance | *Fisher's* F - Test | Significance level P |
|---|---|---|---|---|---|
| Intercept | 33,295.66 | 1 | 33,295.66 | 7795.693 | 0.000000 |
| Wood species | 4154.93 | 1 | 4154.93 | 972.815 | 0.000000 |
| Temperatures | 1491.98 | 2 | 745.99 | 174.663 | 0.000000 |
| Nail type | 22,924.12 | 2 | 11,462.06 | 2683.674 | 0.000000 |
| Anatomical direction | 185.96 | 1 | 185.96 | 43.539 | 0.000000 |
| Wood species * Temperature * Nail type * Anatomical direction | 24.38 | 4 | 6.09 | 1.427 | 0.223324 |
| Error | 2921.39 | 684 | 4.27 | | |

The blue highlighted lines show statistically significance $p < 0.05$

Table 6
Spearman's correlation of factors and withdrawal characteristics

| | Wood species | Thermal loading | Nail type | Anatomical direction | Withdrawal parameter $f_{ax}$ | Withdrawal resistance $R_{ax}$ |
|---|---|---|---|---|---|---|
| Wood species | 1.000 | 0.000 | 0.000 | 0.000 | 0.384 | 0.384 |
| Thermal loading | 0.000 | 1.000 | 0.000 | 0.000 | -0.256 | -0.256 |
| Nail type | 0.000 | 0.000 | 1.000 | 0.000 | 0.107 | 0.107 |
| Anatomical direction | 0.000 | 0.000 | 0.000 | 1.000 | 0.088 | 0.088 |
| Withdrawal parameter $f_{ax}$ | 0.384 | -0.256 | 0.107 | 0.088 | 1.000 | 0.981 |
| Withdrawal resistance $R_{ax}$ | 0.384 | -0.256 | 0.107 | 0.088 | 0.981 | 1.000 |

# 4. Conclusions

In this study, the nail withdrawal capacity of spruce and larch wood was investigated under thermal loads (freezing and heating) of −15 °C/70 °C and −25/70 °C.

1. Freezing and heating (thermal loading) lead to a destructive impact on the nail withdrawal capacity of spruce and larch wood.

2. Annularly threaded nails exhibited a significantly higher withdrawal power in both wood species, while smooth nails had the lowest withdrawal strength.
3. Smooth nails had the highest noteworthy diminished values, whereas annularly threaded nails exhibited the descending decrease in nail withdrawal capacity in both species, with no substantial variation.
4. Though there were variations in the withdrawal parameter in the two anatomical directions (radial and tangential) in both species, the difference was not statistically considerable.
5. Freezing did not exhibit any meaningful variation in the density and moisture content of the wood.
6. The different densities of spruce and larch wood result in a differential nail holding power irrespective of nail types and thermal loading. Accordingly, the nail withdrawal capacity of larch wood was higher than that for spruce wood, which is due to its higher density and a significant difference has been found for annularly threaded nails.

The determinations could be of great importance for employing wood products that are periodically subjected to surroundings characterized by extreme temperatures. Interchangeable, the present investigation exemplifies the consequences of one freezing heating cycle, while wood products could be exposed to such extreme circumstances for a longer period in-service condition.

## Declarations

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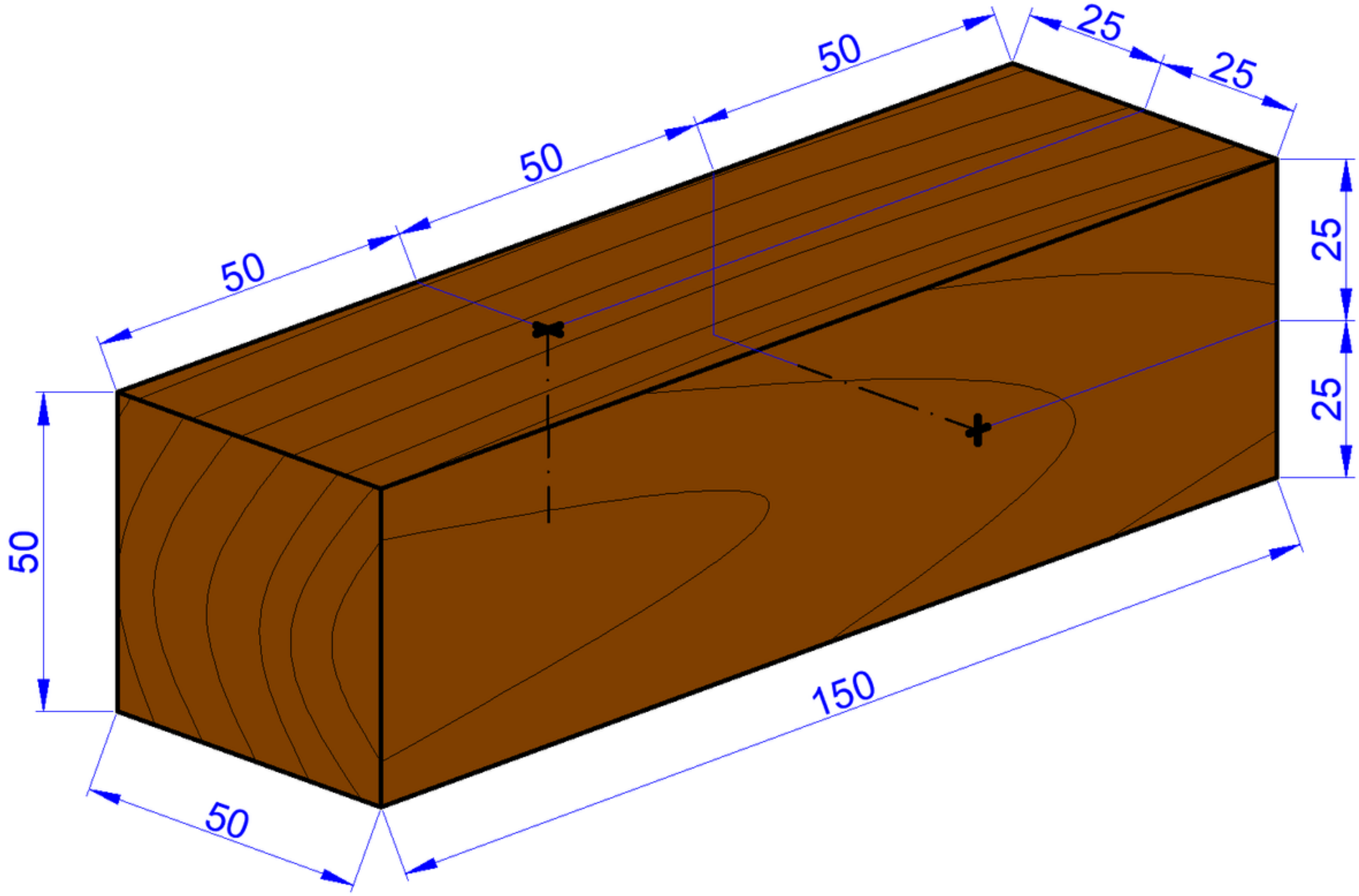
# Figures




### Figure 1

Sample with locations for nails

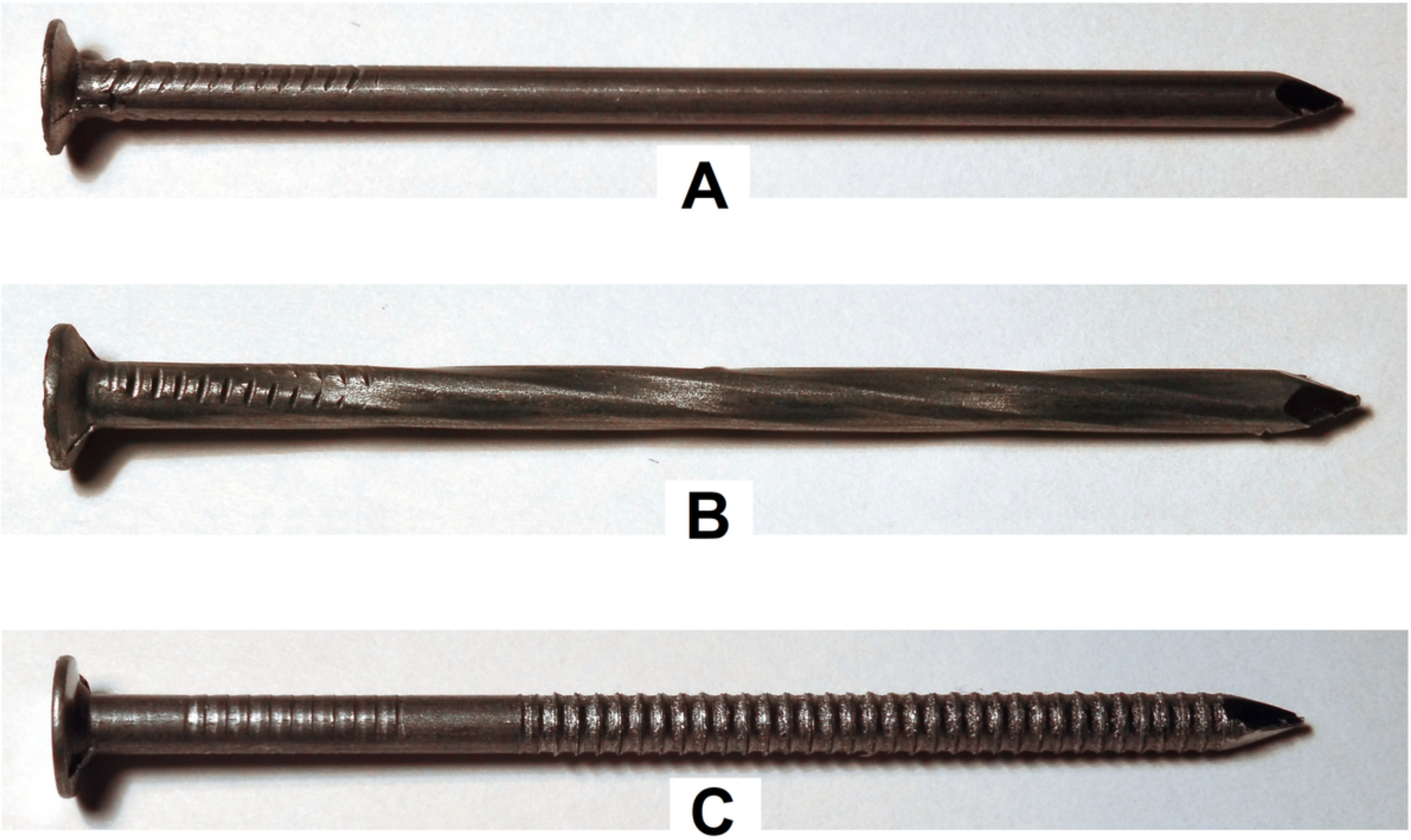



**Figure 2**

Wood nails

(A – smooth nail, B – helically threaded nail, C – annularly threaded nail)

**Figure 3**

Sample with nails

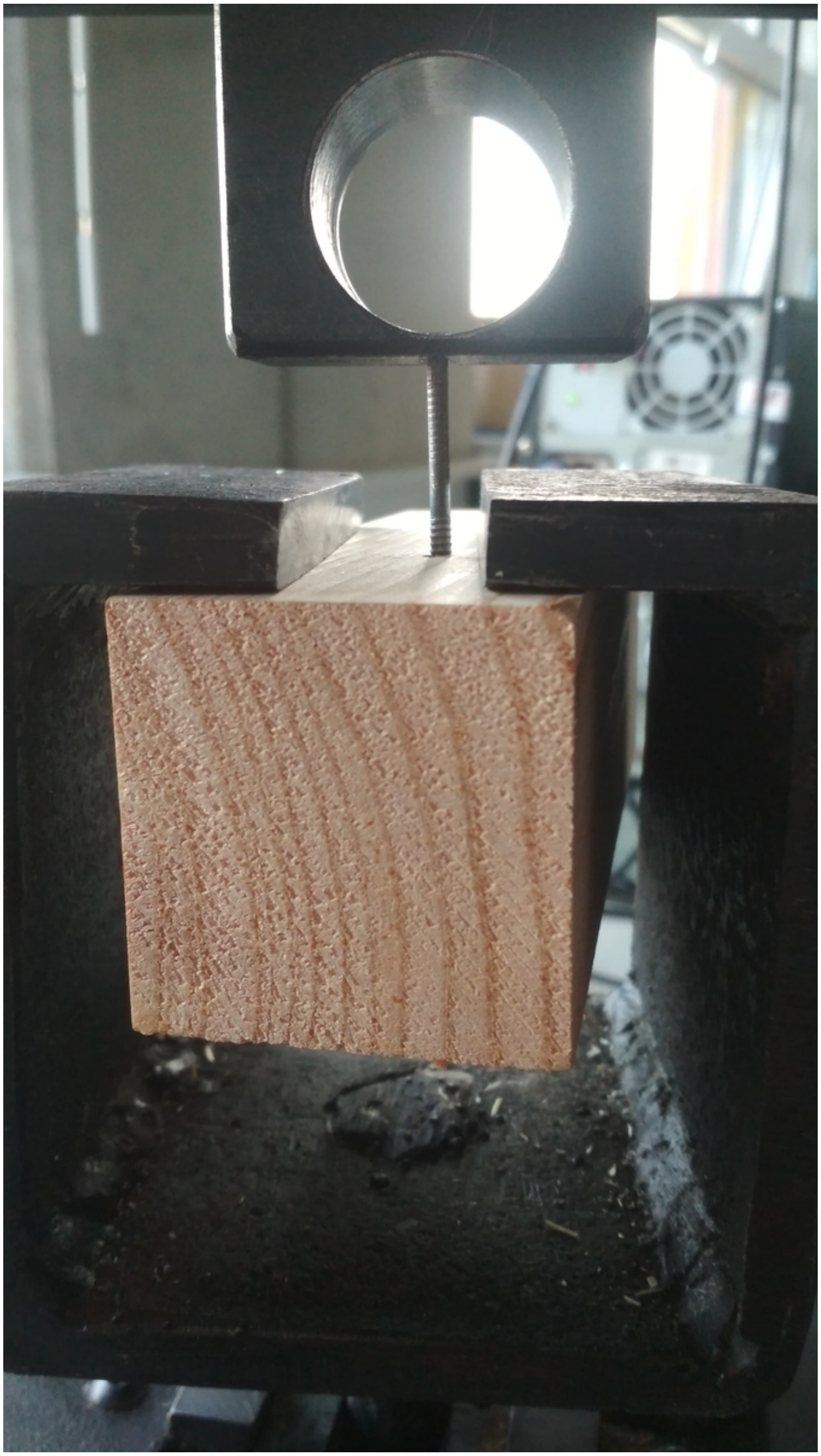


**Figure 4**

Nail withdrawal test

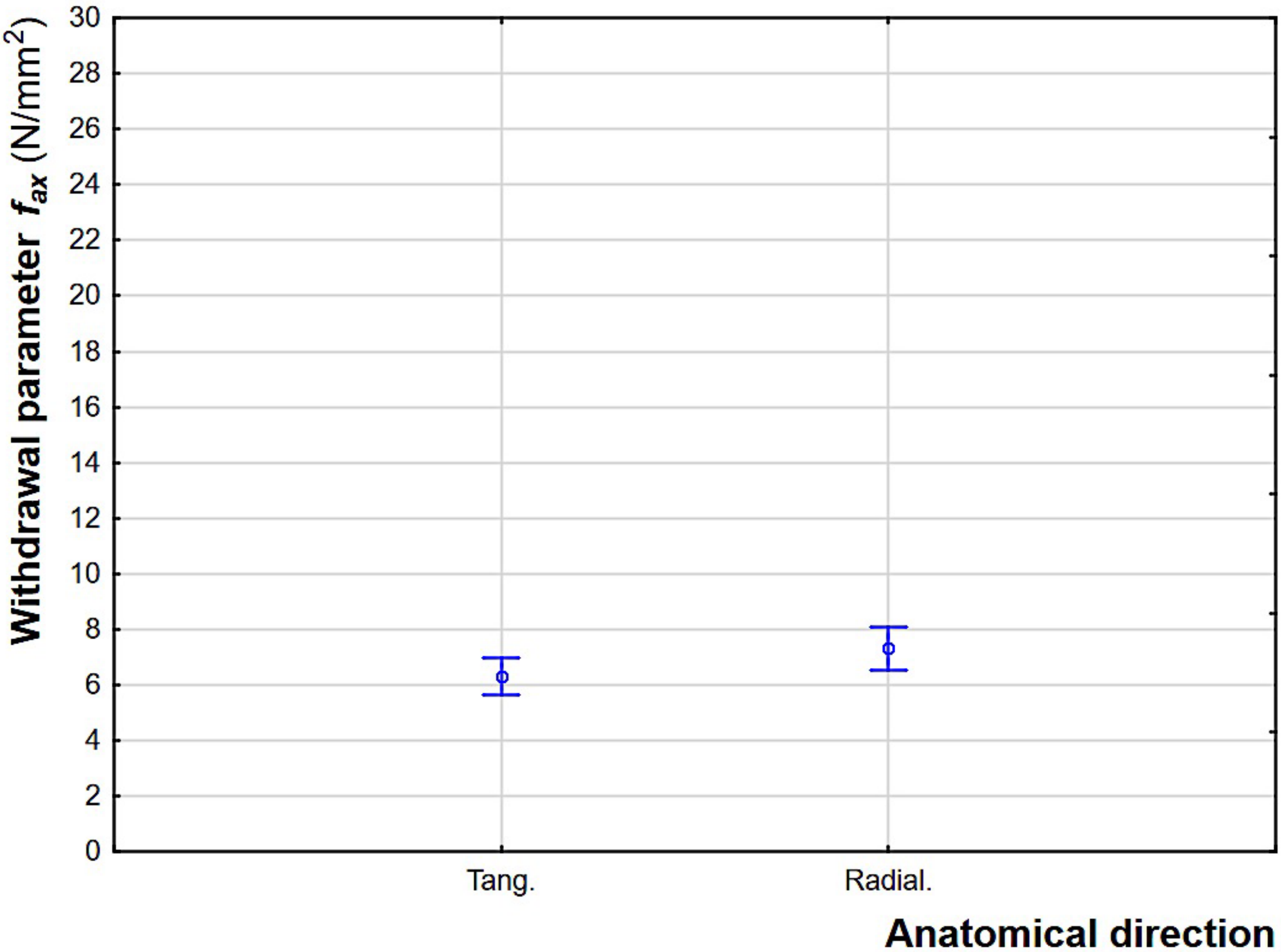



**Figure 5**

The effect of the anatomical direction on the withdrawal parameter

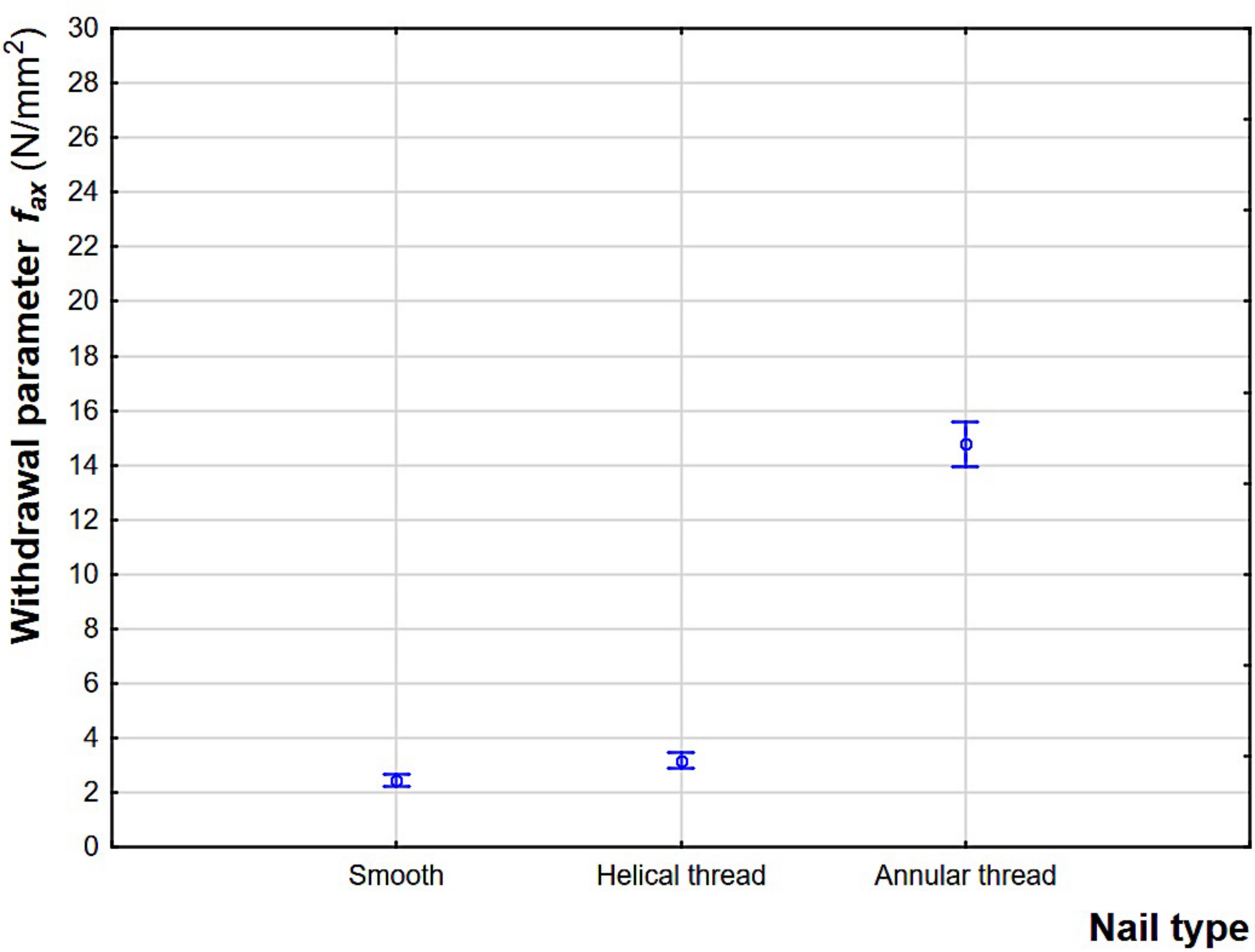



**Figure 6**

The effect of the nail type on the withdrawal parameter

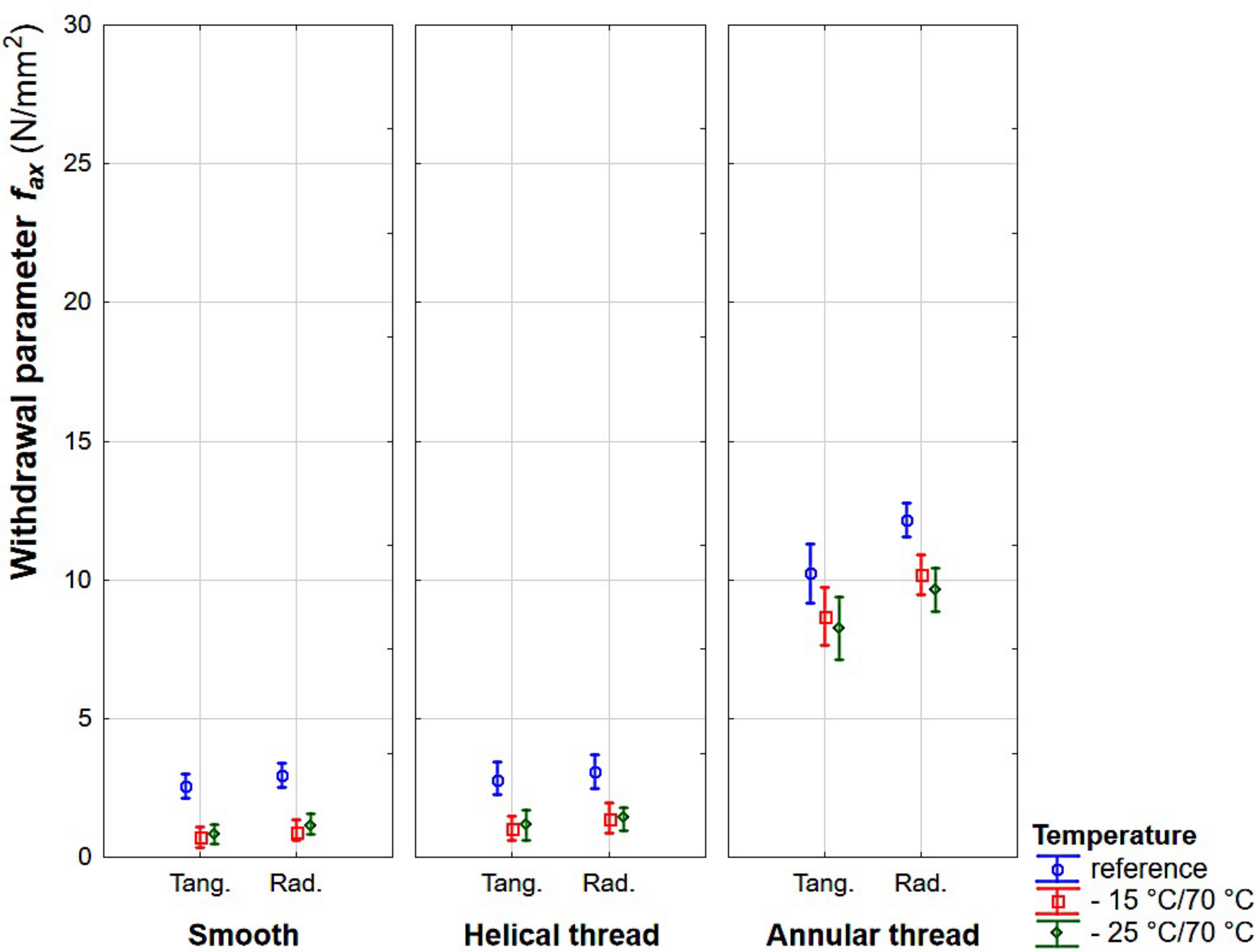



**Figure 7**

The effect of the nail type, temperature and anatomical direction on the withdrawal parameter of spruce wood

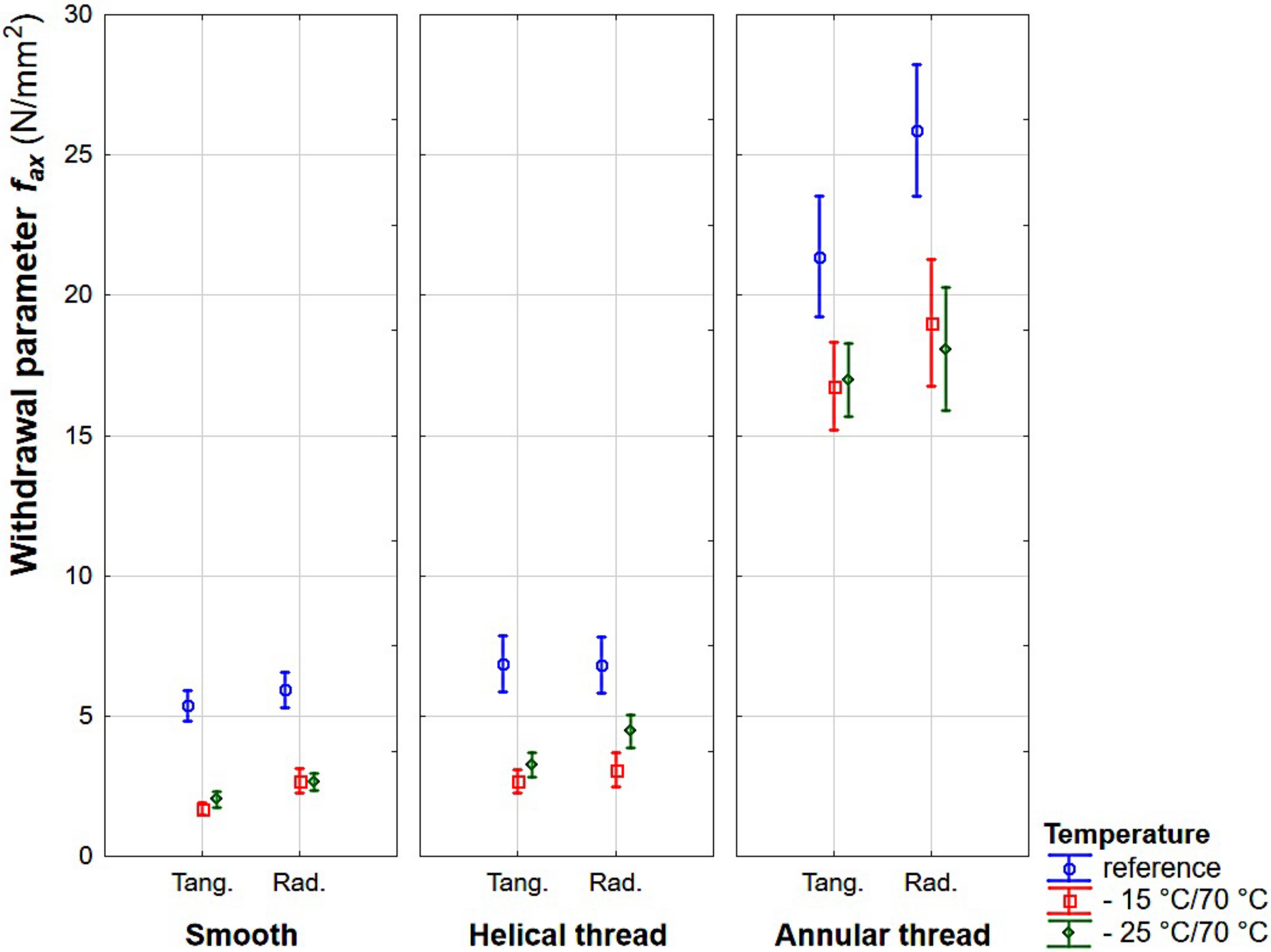



**Figure 8**

The effect of the nail type, temperature and anatomical direction on the withdrawal parameter of larch wood