Properties of Oak Roundwood with and without Frost Cracks

Przemysław Mania 1,*, and Arkadiusz Tomczak 2

1 Department of Wood Science and Thermal Technics, Faculty of Wood Technology, Poznań University of Life Sciences, Wojska Polskiego 38/42, 60-627 Poznań, Poland
2 Department of Forest Utilisation, Faculty of Forestry, Poznań University of Life Sciences, Wojska Polskiego 71A, 60-625 Poznań, Poland; arkadiusz.tomczak@up.poznan.pl
* Correspondence: przemyslaw.mania@up.poznan.pl; Tel.: +48-61-848-7448

Received: 14 April 2020; Accepted: 7 May 2020; Published: 12 May 2020

Abstract: The aim of this study was to examine certain properties of sessile oak wood (Quercus petraea (Matt.) Liebl.) with frost cracks, such as density (\(\rho\)), modulus of rupture (MOR), modulus of elasticity (MOE), and compressive strength in all anatomical directions and to compare it with control trees without frost cracks. Oak with frost cracks had a higher wood density (\(\rho = 765\, \text{kg}\times\text{m}^{-3}\)) than the control (\(\rho = 650\, \text{kg}\times\text{m}^{-3}\)). However, despite its lower density, the control oak was characterized by noticeably better mechanical parameters, with the exception of the compressive strength in radial and tangential directions. Differences in mechanical parameters reached up to 26%. The tests were performed on wood taken from trees with frost cracks that formed over 10 years to several decades ago. Frost cracks can render wood vulnerable to fungi growth, which leads to rotting and discoloration. Differences in strength were found on samples with no visible signs of decay, as they were cut at a distance from the crack. Nonetheless, the observed differences in strength allowed us to conclude that the shreds of fungi, as well as decay, may occur in the entire volume of the frost-damaged log. Such wood is, therefore, of a lower quality than that made of logs without any frost damage. Trees with frost cracks should be progressively be felled during the periodic intermediate cutting, as their wood quality may systematically deteriorate over the years.

Keywords: frost crack; oak wood; mechanical properties

1. Introduction

Oak wood is highly valued for its unique properties and durability. It is characterized by a high proportion of heartwood; clear grain; and wide, high, and numerous medullary rays. Furthermore, oak wood is hard and has a high density and proportionally higher strength than wood of most other temperate zone tree species [1,2]. Oak wood is used to produce valuable veneers and many luxurious everyday objects, mainly furniture.

The main quality indicator of oak wood is the width of its annual growth rings. This can be demonstrated, for example, by different growth rates of a natural forest (slow growth) and intensively managed plantation (rapid growth) [3]. Sessile oak presents ring-porous anatomy, so there is more latewood in the wider rings. Therefore, trees that grow more dynamically in thickness are characterized by higher density wood [4].

Growth rhythm, shaped mainly by the age of the tree, environmental factors, and stand conditions [5–8] may be disturbed. Under natural conditions, plants are exposed to various types of stress. These are defined as factors which impact on organisms and can lead to disturbances of function and structure that are unfavorable to the plant itself. Among multiple abiotic stressors the thermal stress can be named, including the one caused by low temperatures. Frost cracks are among
the specific and irreversible structural disturbances that occur at low temperatures, as they lead to radial-longitudinal splitting in the tree trunks. The size and location of frost cracks vary among individual trees. Frost cracks are usually located within a few meters from the ground longitudinally, and radially often penetrate deep into the tree’s core. In the spring, when frost cracks close, wood and bark callus tissues bridge the crack. In the following winter, however, the crack may open again. As a rule, the cracking and healing repeat for several years and a frost strip develops [9].

The various mechanisms of frost crack formation in trees were described by Kubler [9]. In short, it is the effect of shrinking of the wood under the influence of low temperature and internal drying. In nature, where the temperature drop is generally slow, ice is usually formed in the intercellular spaces, between the cell wall and the protoplast. Therefore, there is an extracellular crystallization of water. The water vapor pressure in the spaces above ice decreases and a gradient of water potential is created between the unfrozen cell interior and the extracellular environment. The water starts to move according to this gradient and crystallizes, leading to dehydration and contraction of the cell. The lower the ambient temperature, the later the balance between the water potential over ice and in cells is established and, therefore, the greater are the effects of cell dehydration [10]. Wood is a good insulator and has a poor heat transfer coefficient [11], so the wood directly under bark shrinks faster than in deeper layers. The tensile strength of wood across the fibers (in radial and tangential directions) is relatively low compared to the tensile strength along the fibers (in longitudinal direction). In shrinking wood, the tangential stress may increase to a certain value, beyond which the wood breaks.

Drought cracks are created in an identical pattern. Drought cracks are initiated by tangential tension as a result of the drying and shrinking of the sapwood in response to moisture deficit [12].

Frost cracks occur most often in solid hardwood, such as oak (Quercus sp.), ash (Fraxinus sp.), elm (Ulmus sp.), and maple (Acer sp.), and less frequently in soft hardwoods and softwood [13–20]. Oak seems particularly susceptible to frost cracks among the aforementioned general species [21]. However, susceptibility to low temperatures is very dependent on the species of oak or its origin [22–26]. For example, Câmpu and Dumitrache [27], according to literature, explain that sessile oak (Q petraea) and common oak (Q. robur) (northern species) are less vulnerable to extreme frost than Turkey oak (Q. cerris) and Hungarian oak (Q. frainetto) (southern species). Oak is characterized by multiple wide and high medullary rays. Perhaps rays are the reason for such physical characteristics. Mattheck and Kubler [28] claim that maximum tangential stress is strongly correlated with the size and number of medullary rays. On the other hand, high moisture content, even in the heartwoods, may also constitute a plausible explanation [29]. We do not know yet why such cracks appear or what may cause them. We know only that such defects do not occur on all trees and that they may affect only a part of the population [30]. Perhaps the phenomenon is related to the individual characteristics of the tree. We also know that there is a risk of oxidative discoloration around the cracked area as well as of a fungus attack. Frost crack becomes a place of increased penetration into the wood of various types of decay fungi. Therefore, in this paper it was assumed that the properties will be the distinguishing features of the wood tested. These are the mechanical parameters that determine the suitability of wood for selected applications, important for round industrial timber. Actually, according to European Standard 1316-1 [31], frost crack is part of those wood defects which are not permitted in quality classes A, B, or C and downgrades round industrial timber to split wood (usually firewood). It should be considered that use of wood is increasing, and there are not many reports of real quality and other ways to use oak wood with frost cracks.

The same determination was, therefore, carried out on wood with and without frost cracks. The aim was to determine the usable value of round wood with and without the aforementioned frost damage, originating from the same habitat with trees of the same age. The research undertaken aimed to make new contributions to the knowledge of the mechanical properties of oak wood affected by frost crack.
2. Materials and Methods

2.1. Site and Model Trees’ Selection

The investigations were performed in 2019, in one sessile oak (*Quercus petraea* (Matt.) Liebl.) stand located in the Murowana Goślinna Experimental Forest Station (Poznań University of Life Sciences, Poland) (geographical coordinates: 52°32′40.797″ N, 17°4′5.132″ S). The age of the stand was 118 years. Ten model trees were selected for testing, including five oak trees characterized by clearly extended frost strips, formed after frost cracks had overgrown, and five trees with no frost cracks (control). The cracked trees were randomly selected. Paired trees of similar diameter at breast height (DBH, diameter at 1.3 m), height, and canopy depth, one frost cracked and one sound in close proximity to counteract the possible effects of differences in soil, were chosen [23]. The aim was to ensure that both trees were nearly identical in size and experienced the same growing conditions.

All 10 trees were measured for height, DBH, and canopy depth (calculated at the last living whorl of branches at the base of the crown). The diameter at breast height of the frost-damaged trees was 4.2 cm higher than for the controls. Other features such as height and canopy depth (m and %) were similar (Table 1).

|                  | Cracked (n = 5) | Control (n = 5) |
|------------------|----------------|----------------|
| Height (m)       | 27.0           | 27.3           |
| DBH (cm)         | 38.2           | 34.0           |
| Canopy depth (m) | 16.8           | 17.2           |
| Canopy depth (%) | 62.5           | 62.2           |

In order to characterize the experimental material, numbers and the width of annual rings were measured on the cross-sections of the wood samples to the accuracy of 0.1 mm. Macrostructure measurements were performed with a BIOTRONIK electronic growth ring device (BEPD-5, Warsaw, Poland).

2.2. Frost Crack Measurement

The cracked trees were randomly selected. To limit the effect of local growing environment, an undamaged tree with similar diameter at breast height (DBH, diameter at 1.3 m), height, and canopy depth as close to that of the damage tree was selected and marked. The aim was to ensure that both trees were nearly identical in size and experienced the same growing conditions. All 10 trees were measured for height, DBH, and canopy depth (calculated at the last living whorl of branches at the base of the crown). The cracked trees also had measurements on the length of the crack (scar on bark), height from the base of the tree to the midpoint on the crack, and the compass orientation of the crack on the stem [12]. Tree height and height of the last living whorl of branches were measured using a Nikon Forestry Pro optical laser rangefinder/hypsometer. DBH was measured using caliper (1 cm accurate). A disc was taken halfway through the length of the frost crack. One side of the disk was finely sanded to highlight the boundaries between the annual rings. In the next step, all the annual rings were counted to determine the cambial age of the section. After that, the annual rings, which were formed after the season in which the frost crack appeared, were counted (Figure 1). In the spring, wood and bark callus tissues formed at the ruptures’ edges of the cambial layer grow together and bridge the crack. Here the characteristic bending/expansion of the annual rings can be seen on the cross-section surface and thus read out the cambial age of the section where the fracture originated.
were measured with digital caliper to the accuracy of ±0.01 mm. Due to the rather small dimensions of the frost damage, which was rarely higher than 30 mm, it was not possible to cut samples of the callus tissue.

**2.3. Sampling Procedure**

From the trees selected for the study, 50-cm-long logs were obtained from the diameter at breast height (DBH). Such fragments were split into four quarters and then a 40-mm-thick plank was cut out in the tangential direction. The material prepared in this way was seasoned in the dry environment for six months to reach the moisture content below fiber saturation point (FSP), and then in laboratory conditions (temperature, \( T = 20 \, ^\circ C \); air relative humidity, \( RH = 65\% \)) to achieve a moisture content of about 10%. In the case of logs harvested from trees with frost cracks, the boards were cut at such a distance that there was no visible wood decay (Figure 2) which would directly affect the mechanical parameters of the wood. Due to the rather small dimensions of the frost damage, which was rarely higher than 30 mm, it was not possible to cut samples of the callus tissue.

**2.4. Wood Properties’ Measurement**

Wood density was determined for wood samples of the size 20 × 20 × 30 mm on each sample, intending to determine the compressive strength of wood. The sample densities were determined according to the method recommended by ISO 13061-2 [32]. The mass of each sample was measured on an analytical balance (Sartorius GmbH, Göttingen, Germany) (±0.001 g accuracy). The dimensions were measured with digital caliper to the accuracy of ±0.01 mm.
Experimental tests were made using the equipment ZWICK ZO50TH (Zwick/Roell, Ulm, Germany) wood testing machine, whose software allowed calculating, e.g., modulus of elasticity (MOE), work to maximum load (WML), and modulus of rupture (MOR). The four-point bend test was carried out in accordance with PN-77/D-04103 [33]. The samples (20 × 20 × 300 mm), after their conditioning in laboratory at temperature $T = \sim 20$ °C and air relative humidity $RH = \sim 60\%$, were placed on the machine support pins, separated by a distance of 240 mm in such a way that the forced deflection was always in the tangential direction.

Modulus of rupture (MOR) was calculated as follows:

$$\text{MOR} = \frac{3F_{\text{max}}L}{2bh^2} \text{ (MPa)},$$  

where $F_{\text{max}}$ is the maximum (breaking) force (N), $L$ is the distance between supporting span (mm), and $b$ and $h$ are the width and height of the test samples (mm), respectively.

Modulus of elasticity (MOE) was calculated according to the equation:

$$\text{MOE} = \frac{3(F_{n+1} - F_n)L^3}{64bh^3(f_{n+1} - f_n)} \text{ (MPa)},$$  

where $F_{n+1} - F_n$ is the increment in load within the linear region of the load-deflection curve (N) and $f_{n+1} - f_n$ is the increment in deflection (corresponding to $F_{n+1} - F_n$) (mm).

The work to maximum load (WML) defines the amount of energy absorbed by the sample until it is destroyed. Its value is equal to the area under the curve $\sigma$-$\epsilon$, and is expressed by the equation:

$$\text{WML} = \int_0^{\epsilon_{\text{max}}} \text{MORd}\epsilon \text{ (J)},$$  

where $\epsilon_{\text{max}}$ is the maximum strain (mm).

The specific modulus of elasticity (MOE$_{sp}$) was defined as follows:

$$\text{MOE}_{sp} = \frac{\text{MOE}}{\rho} \text{ (kN} \times \text{m} \times \text{kg}^{-1}).$$  

where $\rho$ is the wood density (kg × m$^{-3}$).

After measuring the bending strength, the moisture content (MC) of the wood was gravimetrically measured according to the ISO 13061-1 [34] standard.

The compressive strength in longitudinal direction was determined in accordance with ISO 13061-17:2014 [35] on 20 × 20 × 30 mm rectangular samples. It was decided to additionally perform compression tests of wood in tangential and radial directions on analogous samples, where the 30-mm dimension was corresponding to the direction of the compressive force applied to the sample (Figure 2). The value of the compressive strength of wood in transverse directions was read at the proportionality limit and presented as compressive stress perpendicular to grain, so called “relative strength”. Knowing the values of wood’s compressive strength in all basic anatomical directions will determine to what extent frost cracks affect the mechanical parameters of oak wood. All mechanical parameters were determined on 50 samples made of frost-damaged oak and 50 control samples. All the samples for determining the strength of the wood were cut from the mature wood zone, the heartwood [36].

2.5. Statistical Analysis

The experimental data were analyzed using the DellTMStatisticaTM13.1 (TIBCO Software Inc., Palo Alto, CA, USA) software with the analysis of variance (ANOVA). Significant differences between mean values of the parameters describing the properties of oak samples were determined using Tukey’s honest significant difference (HSD) test. The comparison tests were performed at a 0.05 significance
level. Identical superscripts, e.g., a and b, denote no significant difference between mean values of the investigated properties.

3. Results

3.1. Frost Cracks' Characteristic

There was one frost crack on two trees, and three to five frost cracks on the others, mainly in the lower part of the trunk. The length of frost cracks ranged from several tens of centimeters to several meters. At the breast height there were one to five frost cracks (Table 2). Compass direction of the cracks on the stems indicates that the northern side of the stems had fewer cracks than other directions.

Table 2. Number, length of crack (measured on scar on bark), height to midpoint of crack (from the tree base), compass direction of the cracks, and cambial age *.

| Tree Number | Total Number of Cracks | Length of Crack (m) | Height to Mid-Point of Crack (m) | Number of Cracks at the Breast Height | Cambial Age * | Cambial Age of the Crack * | Compass Direction |
|-------------|------------------------|---------------------|----------------------------------|--------------------------------------|--------------|---------------------------|------------------|
| 1           | 1                      | 3.3                 | 1.65                             | 1                                    | 109          | 13                        | S                |
|             |                        | 5.0                 | 2.50                             |                                      |              |                           |                  |
|             |                        | 1.9                 | 0.95                             | 2                                    | 100          | 51                        | W                |
|             |                        | 1.8                 | 5.30                             |                                      | 114          | 12                        | SW               |
|             |                        | 2.8                 | 6.00                             |                                      |              |                           |                  |
| 2           | 4                      | 5.0                 | 2.50                             |                                      | 0.95         | 56                        | NW               |
|             |                        | 1.7                 | 1.80                             |                                      |              |                           |                  |
|             |                        | 1.5                 | 0.75                             |                                      | 5.00         | 42                        | NE               |
|             |                        | 0.8                 | 0.42                             |                                      |              |                           |                  |
| 3           | 1                      | 3.6                 | 1.80                             |                                      | 1.90         | 29                        | NW               |
|             |                        | 1.5                 | 0.75                             |                                      | 0.50         | 12                        | NE               |
|             |                        | 0.8                 | 0.42                             |                                      |              |                           |                  |
|             |                        | 0.6                 | 0.30                             |                                      |              |                           |                  |
|             |                        | 1.6                 | 0.80                             |                                      |              |                           |                  |
| 4           | 3                      | 0.8                 | 0.42                             |                                      |              |                           |                  |
|             |                        | 1.0                 | 0.50                             |                                      |              |                           |                  |
|             |                        | 0.4                 | 0.20                             |                                      |              |                           |                  |
|             |                        | 1.8                 | 0.90                             |                                      |              |                           |                  |
| 5           | 5                      | 5.4                 | 4.30                             |                                      |              |                           |                  |

* Measured at the midpoint of the crack, only for cracks at the breast height.

3.2. Wood Density and Moisture Content

Oaks obtained from the same habitat, having similar age, were characterized by different densities. The density of wood of oak trees with frost cracks was over 100 kg × m⁻³ higher than that of control oak trees. The differences obtained were statistically significant. The moisture of the control samples was only about 0.4% higher than samples obtained from frost-damaged trunks. There were no statistically significant differences between the average MC values (Table 3).

Table 3. Basic statistical parameters of the density (ρ) of oak wood species with and without frost cracks (standard deviation, SD; coefficient of variation, CV).

| Properties               | Material   | Statistical Parameters |
|--------------------------|------------|------------------------|
|                          | min | mean | max | ±SD | CV (%) |
| Density (kg × m⁻³)       | Frost crack | 560 | 765 ᵃ | 875 | 76 | 9.9 |
|                          | Control    | 530 | 650 ᵇ | 720 | 47 | 7.2 |
| Moisture content (%)     | Frost crack | 7.9 | 8.4 ᵃ | 9.4 | 0.62 | 7.4 |
|                          | Control    | 8.1 | 8.8 ᵃ | 9.3 | 0.74 | 8.3 |

ᵃ,ᵇ Different superscripts denote a statistically significant (p < 0.05) difference between mean values according to Tukey’s HSD test.

3.3. Mechanical Properties

Control oak wood had a higher bending strength (MOR) and a higher work to maximum load (WML) value. The differences were statistically significant. The modulus of elasticity (MOE) was also
higher for control oaks, but in this case the difference was not statistically significant. The specific modulus of elasticity (MOE<sub>sp</sub>), on the other hand, differed statistically significantly between the compared samples.

The compressive strength of wood was analyzed in basic anatomical terms: Along the fibers (R<sub>cL</sub>), radial (R<sub>cR</sub>), and tangential (R<sub>cT</sub>) directions. The control tree wood was characterized by a higher compressive strength along the fibers, while in the tangential and radial directions, the frost-damaged wood had higher values. The differences received in each case were statistically significant (Table 4).

| Properties | Material       | Statistical Parameters |
|------------|----------------|------------------------|
| MOE (MPa)  | Frost crack    | 6526 10021<sup>a</sup> | 12368 1280 12.77 |
|            | Control        | 7165 10221<sup>a</sup> | 12799 1334 13.05 |
| MOR (MPa)  | Frost crack    | 66 108<sup>b</sup>    | 133 13.8 12.77  |
|            | Control        | 87 115<sup>a</sup>    | 148 14.0 12.17  |
| WML (J)    | Frost crack    | 0.896 1.810<sup>b</sup>| 2.545 0.384 21.21|
|            | Control        | 1.286 2.292<sup>a</sup>| 5.697 0.857 37.39|
| MOE<sub>sp</sub> (kN × m × kg<sup>−1</sup>) | Frost crack | 9.44 13.15<sup>b</sup>| 17.03 1.58 12.02 |
|            | Control        | 12.75 15.45<sup>a</sup>| 18.00 1.27 8.22 |
| R<sub>cL</sub> (MPa) | Frost crack | 43.6 52.9<sup>b</sup>| 69.6 6.4 12.09  |
|            | Control        | 57.3 66.9<sup>a</sup> | 75.8 4.9 7.32  |
| R<sub>cR</sub> (MPa) | Frost crack | 6.76 8.37<sup>b</sup>| 10.31 0.84 10.03 |
|            | Control        | 5.69 6.92<sup>a</sup> | 8.37 0.44 6.35  |
| R<sub>cT</sub> (MPa) | Frost crack | 4.72 6.02<sup>b</sup>| 7.94 0.77 12.79  |
|            | Control        | 4.46 5.66<sup>a</sup> | 6.89 0.75 13.25  |

<sup>a, b</sup> Different superscripts denote a statistically significant (p < 0.05) difference between mean values according to Tukey’s HSD test.

4. Discussion

Although the research was based on a relatively small number of trees, it provided useful information on the quality of round wood with frost cracks. The reason why cracks only occur on some trees, in different places (height and compass direction), or have different lengths is still unclear. These are as variable as the properties of the wood in the trunk (within-stem). Sessile oak presents ring-porous anatomy. Its characteristic feature is the annual ring width variability from pith to bark. As the width of annual growth increases, the width of the earlywood zone does not change significantly, but the width of the latewood increases. So, if the annual ring is narrow, the density of wood is low, unlike in conifers [11]. Oaks with frost cracks were characterized by an air-dry density higher by more than 100 kg × m<sup>−3</sup> than the control oaks. Both values of the discussed quantity are within the average density values described in the literature [37]. One of the reasons for this is perhaps the difference in the width of annual increments. Control oaks had a smaller trunk diameter and, thus, narrower annual growths. The average annual increment width, determined on compressed samples and on which the wood density was determined, was 1.14 mm for control wood and 1.67 mm for wood with frost cracks.

The mechanical parameters of wood are positively correlated with its density [11]. It can, therefore, be expected that the wood of oak trees with a lower density will have a lower strength. However, it turned out that the opposite was true. Control oak wood was characterized by all of the mechanical properties better than the frost-damaged one, despite lower density. For modulus of elasticity and MOR, the difference between the averages was small and amounted to 2 and 6% respectively. This difference was only statistically significant for the bending strength. In the case of modulus of elasticity, the differences between individual tissues were statistically insignificant.

The tests were performed mainly on wood taken from trees with frost cracks that formed several or several dozen years ago. As a result of the frost crack, the decay developed, mainly along some medullary rays (Figure 3). Visibly, decay did not occupy a large area. Moreover, in the case of a frost
crack, no extensive areas of its occurrence was visible. On the cross-sections of some of the trees, signs of decay were not visible (Figure 4).

![Sample tree number 5; DBH cross-section with frost cracks and decay: (a) example of a disc with two frost damage and decay; (b) discoloration and decay shape.](image)

**Figure 3.** Sample tree number 5; DBH cross-section with frost cracks and decay: (a) example of a disc with two frost damage and decay; (b) discoloration and decay shape.

![Sample tree number 1; DBH cross-section with frost crack: (a) example of a disc with one frost damage; (b) no discoloration and decay.](image)

**Figure 4.** Sample tree number 1; DBH cross-section with frost crack: (a) example of a disc with one frost damage; (b) no discoloration and decay.

Differences in strength were found on samples where the presence of decay could not be visually detected, as the samples were cut out at a certain distance from the crack itself. However, the observed differences in the modulus of elasticity allowed us to conclude that fungal fragments, as well as decay, may occur in the entire volume of the log with a distinct frost damage. This, therefore, demonstrated the high impact of frost damage on the elastic properties of oak wood. Frost crack becomes a place of increased penetration into the wood of various types of decay fungi. Decomposition of the cell wall through the action of fungi can lead to changes in mechanical parameters. Schwarze et al. [38] studied the effect of decay fungi on the wood properties of spruce and maple. The decrease of MOE in these species was 20 and 16%, respectively. This can also be indicated by the large difference in work to maximum load (WML), which determines how much energy a sample of wood can take until it is destroyed by an applied force. A 21% lower reading for wood with frost cracks indicates its increased brittleness. Fungal fragments and decay can increase wood brittleness and decrease mechanical parameters [39,40].

The difference in modulus of elasticity for both groups of oaks was small and amounted to about 2%, as confirmed by statistical analysis. In order to eliminate the influence of density on mechanical parameters, it was decided to calculate the specific modulus of elasticity (MOEsp) being a product of modulus of elasticity and density of wood (MOE/\( \rho \)).
parameters, it was decided to calculate the specific modulus of elasticity (MOE<sub>sp</sub>) being a product of modulus of elasticity and density of wood (MOE/ρ). Analysis of the correct modulus of elasticity allowed us to conclude that the differences between frost-damaged and the control oak were much higher. The average specific modulus of elasticity of the control wood obtained from 50 samples was 15.45 kN × m × kg<sup>-1</sup>, while for the frost-damaged oak it was 13.15 kN × m × kg<sup>-1</sup>. The average MOE/ρ value was, therefore, 15% higher for control oaks. The difference in minimum values was more than 26%. Determination of the value of this parameter confirmed the high influence of frost cracks on the mechanical parameters of oak wood.

The compressive strength of oak wood along the basic anatomical directions is shaped according to a known rule, where the highest values are in the longitudinal direction, smaller in the radial direction, and the smallest in the tangential direction. Their values did not differ from the average values described in other literature [37,41]. In control oaks, the compressive strength of wood along the fibers was over 26% higher. This may confirm previous observations of the presence of both fungus, mold, and decay in samples obtained from oak trees with a clear frost damage. The opposite was true for the transverse directions. Oaks with frost cracks showed 21% higher compression strength in the radial and 6% higher in the tangential direction. The compression strength of oak wood in transverse directions was positively correlated with the proportion of wide medullary rays in the sample [11]. Tests carried out in 2001 showed that the prepared medullary ray subjected to a tensile strength test could reach over 100 MPa [42]. In the case of the samples used for tests described in this paper, a higher proportion of wide medullary rays in oaks with frost cracks could not be clearly indicated. If the oak samples did, in fact, differ significantly in the number of wide medullary rays, this could explain the differences in strength that were detected.

When the wood was compressed in the transverse directions, the destruction of the large vessels in the earlywood occurred first. The smaller vessels in the latewood were destroyed afterwards. The higher strength in transverse directions was also positively correlated with the width of the annual growth and the proportion of latewood [11]. In the case of oak, a change in the width of the annual growth is most often associated with a change in the width of the latewood zone, as the width of the earlywood zone does not change significantly. Oaks with frost cracks, as mentioned earlier, were characterized by wider annual growth rings. The average annual ring width, determined on compressed samples, was 1.14 mm for control wood and 1.67 mm for wood with frost damage. For samples of similar dimensions, such a large difference in the widths of annual rings was associated with a variable number of annual increments in the samples. The samples made from control oak, therefore, contained more annual growth and more earlywood zones than those with frost cracks. Thus, in these oaks a larger collapse of large vessels occurred, which resulted in lower strength in the aforementioned directions. Such narrow annual growth in oak wood was due to the harvesting of samples from the mature wood zone where a lower annual ring width was observed for ring-vascular genera.

Sessile oak (Q. petraea) is an important species in Polish forests. In terms of participation, it is second to Scots pine. Frost crack is a wood defect that affects the quality of roundwood, because it is a direct cause of the development of decay, which in turn reduces the strength of the wood. Unlike other species, the decay surface on the trunk cross-section with frost damage is relatively small. The design of the experiment did not involve measuring the surface of decay, nor correlating it with the cambial age of frost rib. In fact, the results obtained from this study are relatively unsophisticated, because the study did not account directly for cambial age of frost damage, but only for selected properties of wood. This was a simplification, because the main goal was to determine the usable value of round wood with frost damage, originating from the same habitat with trees of the same age. The research undertaken aimed to make new contributions to the knowledge of the mechanical properties of oak wood affected by frost crack. Samples for strength tests were without decay. The assumption was that they would not have any visible defects that could reduce strength. The wood of trees with frost damage was characterized by higher density and lower strength, compared to the wood of control trees. Density and strength are strongly correlated [11]. High density indicates high strength, and this
only showed in the results obtained for control trees. Perhaps, in oak wood, decay develops for a long time without visible symptoms. This is very important for the industrial use of oak wood. This seems possible because, for some properties, the differences were not statistically significant. This means that oak roundwood with frost damage, despite its lower quality, is not completely worthless. However, this should be more accurately determined in future experiments, which will, inter alia, correlate the age of cambial frost crack with the area of decay and with the mechanical properties of wood. Currently, trees with frost damage are gradually removed during intermediate cutting, but not all. In addition, the occurrence of the defect was not correlated with the age of the trees. An equally interesting problem was the mechanism of the formation of frost cracks. We know that sensitivity depends on the oak species, but we do not know individual factors. Perhaps, based on the analysis of wood properties as well as studies of selected morphological features of trees, it will be possible to determine features indicating less or greater sensitivity to frost.

5. Conclusions

The tests were performed on wood taken from trees with frost cracks that formed several or several dozen years ago. Frost cracks make the wood vulnerable to fungi growth that leads to rotting and discoloration. Differences in strength were found on samples with no visible signs of decay. Oak with frost cracks had a higher wood density ($\rho = 765 \text{ kg}\times\text{m}^{-3}$) than the control ($\rho = 650 \text{ kg}\times\text{m}^{-3}$). However, despite its lower density, the control oak was characterized by noticeably better mechanical parameters, with the exception of the compressive strength in radial and tangential directions. Differences in mechanical parameters reached up to 26%. Observed differences in strength allowed us to conclude that the shreds of fungi may occur in the entire volume of the frost-damaged log. Such wood is, therefore, of a lower quality. However, it is not completely worthless, because some differences were not statistically significant. This is very important for the industrial use of oak wood. Trees with a frost damage should progressively be felled during the periodic intermediate cutting, as their wood quality may systematically deteriorate over the years. Perhaps future experiments will determine which features of the frost bar can be useful in making such decisions. Actually, the reason why cracks only occur on some trees, in different places (height and compass direction), showing different lengths is still unclear.

**Author Contributions:** Conceptualization, P.M. and A.T.; methodology, P.M. and A.T.; performing the experiments P.M. and A.T.; writing—original draft preparation, P.M. and A.T.; writing—review and editing, P.M. and A.T.; supervision P.M. and A.T. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was financed within the framework of the Ministry of Science and Higher Education program ‘Regional Initiative of Excellence’ in years 2019-2022, Project No. 005/RID/2018/19.

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**

1. Pázsíthy, Z.; Börcsök, Z.; Ronyecz, I.; Mohácsi, K.; Molnár, S.; Kis, S. Oven dry density of sessile oak, turkey oak and hornbeam in different region of Mecsek Mountain. *Wood Res.* **2014**, *59*, 683–694.
2. Longuetaud, F.; Mothe, F.; Santenoise, P.; Diop, N.; Dlouha, J.; Fournier, M.; Deleuze, C. Patterns of within-stem variations in wood specific gravity and water content for five temperate tree species. *Ann. For. Sci.* **2017**, *74*, 64. [CrossRef]
3. Genet, A.; Auty, D.; Achim, A.; Bernier, M.; Pothier, D.; Cogliastro, A. Consequences of faster growth for wood density in northern red oak (*Quercus rubra* Liebl.). *Forestry* **2013**, *86*, 99–110. [CrossRef]
4. Vavrčík, H.; Gryc, V. Analysis of the annual ring structure and wood density relations in English oak and Sessile oak. *Wood Res.* **2012**, *57*, 573–580.
5. Zhang, S.Y.; Owoundi, R.E.; Nepveu, G.; Mothe, F.; Dhôte, J.F. Modelling wood density in European oak (*Quercus petraea* and *Quercus robur*) and simulating the silvicultural influence. *Can. J. For. Res.* **1993**, *23*, 2587–2593. [CrossRef]
6. Lebourgeois, F.; Cousseau, G.; Ducos, Y. Climate-tree-growth relationships of Quercus petraea Mill. stand in the Forest of Bercé (“Futaie des Clos”, Sarthe, France). *Ann. For. Sci.* 2004, 61, 361–372. [CrossRef]

7. Bergès, L.; Nepveu, G.; Franc, A. Effects of ecological factors on radial growth and wood density components of sessile oak (*Quercus petraea* Liebl.) in Northern France. *For. Ecol. Manag.* 2008, 255, 567–579. [CrossRef]

8. Guada, G.; Vázquez-Ruiz, R.A.; García-González, J. Meteorological conditions control the cessation rather than the beginning of wood formation in a sub-Mediterranean ring-porous oak. *Agric. For. Meteorol.* 2020, 281, 107833. [CrossRef]

9. Kubler, H. Origin of frost cracks in stems of trees. *J. Arboric.* 1987, 13, 93–97.

10. Kacperska, A. Plant responses to stressful environmental factors. In *Fizjologia Roślin*; PWN: Warszawa, Poland, 2012; pp. 634–708.

11. Kollmann, F.; Côté, W.A. *Principles of Wood Science and Technology*; Springer: Berlin, Germany, 1968.

12. Cameron, A.; Orr, D.; Clark, J. Variation in the incidence and severity of drought crack in three conifer species in North East Scotland. *Scand. J. For. Res.* 2017, 32, 658–662. [CrossRef]

13. Burton, J.I.; Zenner, E.K.; Frelich, L.E. Frost crack incidence in northern hardwood forests of the southern boreal–north temperate transition zone. *North. J. Appl. For.* 2008, 25, 133–138. [CrossRef]

14. Hart, J.H.; Dennis, G.K. Effect of tree wrap on the incidence of frost crack in Norway maple. *J. Arboric.* 1971, 4, 226–227.

15. Kula, E.; Buchta, I.; Stránský, P. Frost cracks and their effect on the stability of birch stands in the Krušné hory Mts. *J. For. Sci.* 2006, 52, 348–356. [CrossRef]

16. Persson, A. Stem cracks in Norway spruce in southern Scandinavia: Causes and consequences. *Ann. Sci. For.* 1994, 51, 315–327. [CrossRef]

17. Richter, C. Overview of Cracks/Shake Forms and Causes. In *Wood Characteristics*; Springer: Cham, Switzerland, 2015; pp. 199–208.

18. Viherä-Aarnio, A.; Velling, P. Growth, wood density and bark thickness of silver birch originating from the Baltic countries and Finland in two Finnish provenance trials. *Silva Fenn.* 2017, 51, 18.

19. Wagener, W.W. *Frost Cracks—A Common Defect in White Fir in California*; Forest Service, US Dept. of Agriculture, Pacific Southwest Forest and Range Experiment Station: Berkeley, CA, USA, 1970.

20. Richter, C. *Wood Characteristics: Description, Causes, Prevention, Impact on Use and Technological Adaptation*; Springer Internationale Publishing: Basel, Switzerland, 2015.

21. Sakai, A.; Larcher, W. *Frost Survival of Plants: Responses and Adaptation to Freezing Stress*; Springer: Berlin, Germany, 2012.

22. Butin, H.; Shigo, A.L. *Radial Shakes and “Frost Cracks” in Living Oak Trees*; U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station: Broomall, PA, USA, 1981.

23. Danielewicz, W.; Kiciński, P.; Antosz, L. Turkey oak (*Quercus cerris* L.) in Polish forests. *Acta Sci. Pol. Silv. Coendar.* 2014, 13, 5–22.

24. Kovács, I.P.; Czigány, S. The effect of climate and soil moisture on the tree-ring pattern of Turkey oak (*Quercus cerris* L.) in Central Transdanubia, Hungary. *Q. J. Hung. Meteorol. Serv.* 2017, 121, 243–263.

25. Savill, P.S.; Kanowski, P.J. Tree improvement programs for European oaks: Goals and strategies. *Ann. Sci. For.* 1993, 50, 368–383. [CrossRef]

26. Campu, V.R.; Dumitrache, R. Frost crack impact on European beech (*Fagus sylvatica* L.) wood quality. *Not. Bot. Horti Agrobot. Cluj-Napoca* 2015, 43, 272–277. [CrossRef]

27. Mattheck, C.; Kubler, H. Cracks. In *Wood—The Internal Optimization of Trees*; Springer Series in Wood Science; Springer: Berlin/Heidelberg, Germany, 1997.

28. Tomczak, A.; Tomczak, K.; Smarul, N.; Rutkowski, K.; Wenda, M.; Jelonek, T. The gradient of wood moisture within-stem of sessile oak (*Quercus petraea* (Matt.) Liebl.) in summer. *Wood Res.* 2018, 63, 809–820.

29. Sano, Y.; Fukazawa, K. Timing of the occurrence of frost cracks in winter. *Trees* 1996, 11, 47–53. [CrossRef]

30. CSN EN 1316-1 Hardwood Round Timber—Qualitative Classification—Part 1: Oak and Beech; European Committee for Standardization: Brussels, Belgium, 2012.

31. Cinotti, B. Winter moisture content and frost-crack occurrence in oak trees (*Quercus petraea* Liebl. and *Q. robur* L.). *Ann. Sci. For.* 1989, 46, 614–616. [CrossRef]

32. ISO 13061-2. *Physical and Mechanical Properties of Wood—Test Methods for Small Clear Wood Specimens—Part 2: Determination of Density for Physical and Mechanical Tests*; International Organization for Standardization: Geneva, Switzerland, 2014.
33. PN-77/D-04103 Wood. *Determination of Static Bending Strength*; Polish Committee for Standardization: Warsaw, Poland, 1977.
34. ISO 13061-1. *Physical and Mechanical Properties of Wood—Test Methods for Small Clear Wood Specimens—Part 1: Determination of Moisture Content for Physical and Mechanical Tests*; International Organization for Standardization: Geneva, Switzerland, 2014.
35. ISO 13061-17:2017. *Physical and Mechanical Properties of Wood—Test Methods for Small Clear Wood Specimens—Part 17: Determination of Ultimate Stress in Compression Parallel to Grain*; International Organization for Standardization: Geneva, Switzerland, 2014.
36. Helinśka-Raczkowska, L. Variation of vessel lumen diameter in radial direction as an indication of the juvenile wood growth in oak (*Quercus petraea* Liebl.). *Ann. Sci. For.* 1994, 51, 283–290. [CrossRef]
37. Wangenführ, R. *Holzatlas. 6., Bearbeitete und Erweiterte Auflage*; Fachbuchverlag: Leipzig, Germany, 2007.
38. Schwarze, F.W.M.R.; Spycher, M.; Fink, S. Superior wood for violins—Wood decay fungi as a substitute for cold climate. *New Phytol.* 2008, 179, 1095–1104. [CrossRef] [PubMed]
39. Winandy, J.; Morrell, J. Relationship between incipient decay, strength, and chemical composition of douglas-fir heartwood. *Wood Fiber Sci.* 1993, 25, 278–288.
40. Ibach, R.; Lebow, P. Strength loss in decayed wood. In *The McGraw-Hill Encyclopedia of Science & Technology*; McGraw-Hill: New York, NY, USA, 2014; pp. 368–371.
41. Kollmann, F.; Kuenzi, E.; Stamm, A. Principles of wood science and technology. In *Wood Based Materials*; Springer: Berlin, Germany, 1975; Volume II, pp. 139–149.
42. Burgert, I.; Eckstein, D. The tensile strength of isolated wood rays of beech (*Fagus sylvatica* L.) and its significance for the biomechanics of living trees. *Trees* 2001, 15, 168–170. [CrossRef]