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Assessment of the Impact Strength Properties of Thermally Modified Wood by Non-Destructive Testing

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Abstract
This article examines the effectiveness of non-destructive testing (NDT) in assessing wood under impact loadings. Our research was to evaluate the feasibility of using the frequency resonance technique (FRT), to predict the behaviour under impact of thermally modified timber (TMT) compared with a control sample of untreated wood. Wooden planks from five different species were subjected to a thermal modification process (TMP) under two different regimes. Both the TMT and control samples were evaluated using NDT to measure their dynamic modulus of elasticity (MOED), logarithmic decrement of damping (LDD) and acoustic conversion efficiency (ACE). Subsequently, wood samples from the same species were tested using drop-weight impact tests to measure their inflicted maximum force and impact bending strength (IBS), while high-speed cameras recorded the impacts to measure the maximum deflection of the specimens. The results revealed that the only relatively efficient prediction of FRT was the relationship between MOED and IBS. The ACE and LDD results did not show any acceptable correlations with impact tests, indicating that NDT is not reliable for assessing maximum force and deflection in the wood species under impact. Our study also found that the efficiency of the results and predictions were influenced by the wood species and the TMP conditions, necessitating a large number of samples for each species and heat modification temperature to achieve accurate NDT results. Our study found that the efficiency of NDT predictions was significantly influenced by both wood species and the TMP conditions. Specifically, oak showed a relatively higher coefficient of determination, while ash had the lowest. The thermal treatment also had a varied effect on NDT's ability to determine IBS, increasing its efficiency for larch specimens while decreasing it for ash and beech, with no significant effect on oak and spruce. These findings imply that future NDT methodologies must be developed with a species-specific approach and calibrated for each unique modification condition. Consequently, achieving accurate NDT results will require comprehensive data sets with a large number of samples for each species and heat modification temperature.

Keywords Wood · Thermal modification · Non-destructive test · Impact test · Frequency resonance technique · Digital image correlation method

1 Introduction

Wood modification describes all the various methods, processes and operations employed to improve the performance of wood. One such method is thermal modification [1]. In the thermal modification process (TMP), applicable to a wide range of species, wood is exposed to temperatures above 160 °C in the absence of oxygen, which is replaced with steam, nitrogen or oil [2]; the process alters the composition of the wood's cell walls and its physical properties. Thermal modification improves the dimensional stability, water vapour sorption and biohazard resistance making the wood more durable against environmental effects [3]. TMP also increases resistance to weathering agents such as

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sunlight, moisture gradients, temperature changes, chemical agents, atmospheric pollution and abrasion from windblown particles [4]. Despite its advantages, TMP has several detrimental effects on wood, including damage to its tensile, bending and impact strength; it also intensifies the negative effects of knots and defects in the wood [5]. TMP changes the wood's chemical properties, drastically reducing the hemicellulose content and relatively doesn't decrease the content of cellulose, lignin and extractives. It also causes de-acetylation and forms new carbonyl and carboxyl groups due to oxidation [6]. The results of TMP depend on several variables, such as its duration, temperature, treatment atmosphere, wood species, moisture content before TMP and the wood dimensions; among these parameters, the temperature and treatment time are the most critical [7]. The severity of the negative effect of TMP on mechanical properties at lower temperatures (up to around 160 °C) is minimal [8], but as the temperature increases, the mechanical properties decrease significantly, the effect becoming catastrophic at 200 °C [9].

Non-destructive testing (NDT) using dynamic loading can be employed to determine the mechanical properties of wood such as its Young's modulus of elasticity (E), bending modulus of elasticity (MOE) and shear modulus of elasticity (G) [10–12]. Using this method, it has proved possible to detect defects inside wood [13] and can determine the lifespan of timber poles by identifying internal damage without the need for sampling or service interruptions [14]. This approach is suitable for materials with limited availability, such as modified materials, as it allows the same specimens to be tested at various stages of modification [15] or even during the modification process [16, 17] as well as under different types of loading (axial, bending, shear) [18]. Anisotropic materials can be tested in multiple structural-anatomical directions simultaneously [19]. One commonly used method is the frequency resonance technique (FRT), in which the specimen is vibrated and the natural frequencies of individual vibration modes (longitudinal, flexural, torsional) are determined [18, 20, 21]. Based on these frequencies, along with geometry and density, the dynamic moduli of elasticity (Edyn, MOED, Gdyn) are calculated, which show a strong correlation with the static moduli of elasticity [22, 23].

Another parameter that can be determined non-destructively using FRT is internal friction, represented by a damping coefficient such as the logarithmic decrement of damping (LDD) [11, 12, 24, 25]. Although elastic moduli and damping coefficients are generally related [21, 26], their relationship is not easily determinable since the damping coefficient exhibits high variability and is significantly influenced by micro-structural modifications such as heat treatment, chemical treatment, dynamic loading of the specimen, temperature, moisture content and extractive content [27, 28]. Since the damping coefficient indicates the material's ability to absorb dynamic energy, determining the relationship between LDD and impact strength is a key aspect of this study. When using FRT, the summary parameter called the acoustic conversion efficiency (ACE) is often also determined, expressing the ratio of stiffness, density and the damping coefficient in one variable [29–31].

Various impact testing devices have been proposed over the years for assessing the impact behaviour of different materials under loadings with different loading rates in shape of tensile, compression, shear, punch and bending tests [32]. Compared with other materials, wood can absorb tremendous amounts of energy inflicted during an impact loading; another advantage is its damage tolerance by crack isolation and the weak interface between fibres [33]. In assessing the efficiency of materials under impact loadings, impact bending strength (IBS) shows the ability to absorb and dissipate energy through impact loading. IBS refers to the amount of work required to break the wood under given conditions divided by the cross-section area [34]. Some studies have showed that the absorption of energy is directly related to the amount of inflicted energy [35], while others have found their values irrelevant [36]. Generally, the IBS of wood increases with its density while it decreases with the width of rings [37]. The angle of the grain can affect the IBS of wood by affecting its crack initiation strength [38]. In general, a wide range of material and environmental properties can affect the impact behavior of wood [39, 40].

TMP significantly reduces two key mechanical properties of wood: its resistance to bending under static (modulus of rupture) and dynamic (IBS) loadings. The degree of reduction varies with the wood species and the specific conditions of the treatment process [41]. Hemicellulose acts as a bonding agent between the wood's fibres, giving an overall integrity to the material, thereby enhancing its resistance to sudden shocks and impacts. Since TMP deteriorates hemicellulose much more than other materials in the wood, it makes the wood weaker against impact loadings [42]. In some cases, the dynamic bending strength can decrease by half, showing the devastating effect of TMP on the IBS [43]. Some studies have stated that IBS is the mechanical property most affected by TMP [44]. However, the severity of IBS deterioration strongly depends on the temperature; at lower temperatures it is much less than at higher temperatures (in some cases it even increases) [45–48]. The effect of temperature on the impact strength of wood is not only at the high temperatures of TMP; much lower temperatures can also affect the impact strength of wood [49]. Some studies have stated that IBS has no clear relation to MOED and whether they are related or not is defined by the species [50], however, studies showed that the NDT effectively can detect the defects around the impacted zone of wooden composites [51]. TMP decreases the deflection, maximum normal strain and IBS of the TMT and this decrease is intensified by increasing the temperature of the TMP [52]. Table 1 presents a list of the selected sources of the literature review about on the key studies that are most relevant to this research—especially those related to non-destructive testing (NDT), impact loading, and thermally modified timber (TMP).

The effect of TMP on the mechanical properties of wood, particularly related to impact loadings such as IBS, is significant. For this study we aimed to determine if NDT methods could accurately predict the impact-related mechanical properties of wood. Specifically, we investigated which parameters could be predicted using NDT, which could not, and the accuracy of these predictions. We also examined how different wood species and types of heat modification influenced the efficiency of NDT in assessing TMT. Our study provides a clear and comprehensive view of the effectiveness of NDT in evaluating various aspects of the impact-related behaviour of TMT from different species under different TMP.

2 Materials and Methods

2.1 Thermal Modification and Preparation of the Specimens

Air-dried boards with a thickness of 5 cm were obtained from various trees of five species within enterprises of the South Moravia region, Czech Republic. All stages of sample preparation and testing were conducted at the Josef Ressel Research Centre, affiliated with Mendel University in Brno, Czech Republic. The selected species were ash (*Fraxinus excelsior* L.), oak (*Quercus robur* L.), beech (*Fagus sylvatica* L.), larch (*Larix decidua* L.) and spruce (*Picea abies* L.).

The boards from each species were placed into three groups: Group N—the unmodified control group; Group L—subjected to thermal modification at a final temperature of 180 °C for two hours; and Group H—subjected to thermal modification at a final temperature of 220 °C for two hours. The TMP was done in a superheated steam environment at atmospheric pressure in a small-scale laboratory closed system heat modification chamber (Katres s.r.o., Czech Republic). The steps of the thermal modification process are outlined below:

A. Initially, the boards were heated for around 3.5 h at a rate of 10 °C/h up to 103 °C to reduce the moisture content to zero.
B. Following drying, the weight of each group was immediately measured, without allowing for cooling, to determine the dry weight of the unmodified material, which is essential for determining the mass loss.
C. The material underwent monitored controlled re-heating at a rate of 30 °C/h for around 3.5 h to reach the maximum temperature (180 and 220 °C), with cautions to prevent combustion within the chamber.
D. The thermal-modification temperatures (180 or 220 °C) were maintained for two hours, after which the materials were gradually cooled to around 100 °C over approximately two hours and the risk of combustion dissipated.
E. The weight of the planks was once again measured to get the dry weight of the TMT for determination of the mass loss.

The mass loss serves as a valuable criterion for evaluating the effectiveness of TMP, and was measured by calculating the difference in mass of the materials before and after undergoing the thermal modification process.

Rectangular beam test specimens (20 × 20 × 300 mm) were cut from the boards, ensuring they were specially orthotropic. These specimens underwent thorough inspection, and those exhibiting visible defects – mainly knots and cracks (partially attributed to thermal modification) – were discarded. Finally, 318 samples were selected as test specimens and were placed in an environmental room set at 20 °C and 65% relative humidity. Table 2 shows the number of specimens for each group. The equilibrium moisture content of the specimens was monitored until stability was reached, confirmed through periodic weighing of the specimens. Figure 1 depicts the thermal modification chamber before and after the thermal modification.

2.2 Non-destructive Tests

The frequency resonance technique (FRT) was used in compliance with ASTM standards E1875 and E1876 to determine the dynamic modulus of elasticity (MOED). Vibration excitation was applied at the centre of each sample using a rubber hammer while it was positioned on foam supports at the nodes of the first bending mode, which corresponded to 22.4% and 77.6% of the specimen length. Each specimen received ten hits in the tested direction in both longitudinal-tangential (LT) and longitudinal-radial (LR) bending directions. Vibrations of the specimens were detected at the centre of the specimen using a laser vibrometer (PDV-100, Polytec, Inc., Baden-Württemberg, Germany) with signal recording done using the dynamic signal acquisition module DEWE-41-T-DSA and DEWESoft software (DEWETRON Inc., Grambach, Austria) at a sampling frequency of 20 kHz. Resonant frequency was determined by analysing the entire ten-hit signal using fast Fourier transform in MATLAB (The MathWorks, Inc., Natick, USA). Figure 2 shows the setting of the test.

The $\mathrm{MOED}_{\mathrm{LT}}$ and $\mathrm{MOED}_{\mathrm{LR}}$ (for LT and LR direction of bending) was then calculated from the frequency of the first bending mode, as per Eq. 1.

Table 1 Summary of key literature on NDT and thermally modified wood

Author(s) and Year	Wood Species	Treatment(s)	Main Method(s)	Key Findings
Boonstra et al. 2007	Softwood species	Thermal modification	Static and dynamic tests	TMP leads to a reduction in the strength properties of softwoods due to changes in wood's structure
Menezzi et al. 2014	Tropical species	Thermal modification	Non-destructive testing (NDT)	All evaluated properties of TMT could be modeled at a reasonable level
Kutnar et al. 2013	Norway spruce and Beech	Thermal modification	Non-destructive testing (NDT)	DMA can be used to TMP and simultaneously provide data about the modification process
Hassan et al. 2013	Scots pine	No modification	Non-destructive testing (NDT)	All three studied dynamic MOE methods correlated well with the static MOES and MOR
Viala et al. 2020	Norway spruce	No modification	Non-destructive testing (NDT)	The study found that material anisotropy decreases as the wood grade decreases
Nop et al. 2024	Beech and Oak	No modification	Non-destructive testing (NDT)	The beech generally has higher values for MOED, MOE, and Aw
Fernández-Serrano and Villasante 2021	Scots Pine	No modification	Non-destructive testing (NDT)	The vibration techniques showed a better MOES prediction than the ultrasound techniques
Chauhan and Sethy 2016	Tropical species	No modification	Non-destructive testing (NDT)	All three dynamic methods showed a near-perfect correlation with the MOE, making them suitable for prediction
Mania and Skrodzka 2020	Norway spruce	Thermal modification	Non-destructive testing (NDT)	The treatment decreased the logarithmic decrement in the highest quality spruce wood
Brémaud et al. 2010	Different species	No modification	Non-destructive testing (NDT)	By combining data on a species' specific modulus of elasticity, moisture-related properties, and color, it's possible to create simple predictive models
Brémaud et al. 2009	Different species	No modification	Non-destructive testing (NDT)	morphological and biochemical taxonomic markers can affect dynamic mechanical properties of wood
Baar et al. 2016	Tropical species	No modification	Non-destructive testing (NDT)	woods with longer fibers and more slender rays tend to have better acoustic properties
Gašparík et al. 2016	Beech and aspen	Thermal densification	Impact test and hardness test	Wood densification did not have a significant effect on IBS
Yamada et al. 2018	Japanese Cedar	No modification	Impact test	Determination of methods for improvement of roof panels against impacts
Bučar and Merhar 2015	Norway Spruce	No modification	Impact test	The accelerometer-based method is a comparable and effective way to determine impact bending strength

Table 1 (continued)

Author(s) and Year	Wood Species	Treatment(s)	Main Method(s)	Key Findings
Hassan Vand and Tippner 2024	Scots Pine	No modification	Impact test	At high moisture content, both sapwood and heartwood of scots pine are equally strong
Leijten 2004	Different species	Thermal modification	Impact test	The TMP affects toughness
Borůvka et al. 2018	Beech and Birch	Thermal modification	Static and dynamic tests	Comparing the effect of TMP on beech in comparison to birch
Rautkari et al. 2014	Scots Pine	Thermal densification	Static and dynamic tests	Measurement of effect of heartwood vs sapwood in pine TMP
Gaff et al. 2019	Oak and spruce	Thermal modification	Chemical analysis and impact tests	Correlation of IBS to chemical change of TMTs
Bragov et al. 2022	Aspen	Temperature elevation	Compressive impact test	the effect of elevated temperature on strength and deformation properties of aspen is estimated
Hassan Vand and Tippner 2023	different species	Thermal modification	Impact test	The duration of modification can affect toughness of wood

Table 2 The number of specimens for each groups

Number	Ash	Beech	Larch	Oak	Spruce	Treatments
Group N	28	20	29	20	22	No Treatment
Group L	21	21	30	8	29	Thermal Modification at 180 ℃ for 2 h
Group H	20	19	15	17	19	Thermal Modification at 200 ℃ for 2 h

Fig. 1 The thermal modification chamber before and after the thermal modification

$$MOED = \frac{4\pi^2 f^2 L^4 \rho}{\beta^4 i^2} \quad (1)$$

where f is frequency of the first bending mode, L is the length of the specimen, ρ is the density, β is the constant corresponding to the first bending mode ($\beta = 4.73$) and i is

Fig. 2 Vibration sensing setup of a freely supported specimen, excited by a rubber hammer

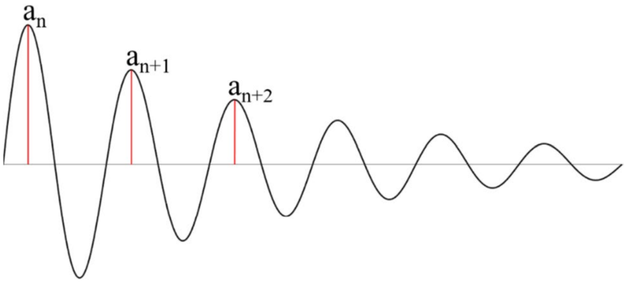


Fig. 3 Amplitudes of successive vibration cycles, used for LDD calculation

the radius of gyration which, for a specimen with rectangular cross-section, can be calculated using Eq. 2.

$$i^2 = \frac{h^2}{12} \tag{2}$$

where h is the side of the square. For each hit, both the maximum amplitude and the amplitude closest to 5% of the maximum were identified. Amplitudes of individual oscillation cycles within this range were identified (Fig. 1), and their LDDs were computed as the logarithm of the ratio of two successive amplitudes, following Eq. 3. The LDD for one hit was determined as the median of these LDDs. The specimen's resulting LDD was calculated as the median of the LDDs from ten hits (Fig. 3).

$$LDD_1 = \ln\frac{a_n}{a_{n+1}}\ LDD_2 = \ln\frac{a_{n+1}}{a_{n+2}}\ LDD_m = \ln\frac{a_{n+m-1}}{a_{n+m}} \tag{3}$$

The ACE was determined by using the ratio of stiffness, density and the damping coefficient in one variable by Eq. 4 [29].

$$ACE = \frac{\pi\sqrt{\frac{MOED}{\rho^3}}}{\mathrm{LDD}} \tag{4}$$

2.3 Impact Tests

A DPFest 400 impact testing machine (Labortech s.r.o., Czechia) was used for the three-point impact bending test in compliance with standards ČSN 490115 (1979) and ČSN 490117 (1980). The tests were done at room temperature (20 °C). The testing machine's 4.55 kg hammer was released from a height of 815.7 mm, reaching a velocity of 4 m/s at the point of impact with the longitudinal centre of the specimens, thereby delivering 36.4 J of energy. The position and reaction force on the hammer were measured with an accuracy of 0.01 mm and a sample frequency of 1 MHz. The testing machine recorded both the maximum reaction force and the IBS of the specimens. It is important to note that some samples of unmodified ash and beech did not break, thus the definition of IBS may not exactly align with the generally accepted definition. In such cases, the total energy absorbed by the specimens without failure was considered as their IBS.

To record the results of the impact tests, a high-speed camera FASTCAM SA-X2 1000K-M2 (Photron Cameras, Japan) was used to capture images at a resolution of 1,024 × 512 pixels in grey scale, with a frame rate of 50,000 frames per second. Additionally, a Micro-Nikkor G lens (Nikon, Japan), two high-speed MultiLED QT equipment and two teleconverters (Nikon, Japan) were integrated into the set-up. The camera was positioned perpendicular to the surface of the specimens. The specimens were painted with a grey-scaled random speckled pattern, with the aim of increasing the contrast between points on the surface of the specimens and consequently enhance the efficiency of the digital image correlation (DIC) method. Figure 4 presents a representative image recorded by the camera following crack initiation. Figure 5 depicts a schematic diagram of the DIC software's process for measuring sample deflection, with a specific example shown at a deflection of 6 mm.

The recorded images were processed using Vic-2D v. 2010 DIC software (Correlated Solutions Inc., USA). A 1D-scale calibration method was employed to determine the conversion factor. A simple scale calibration was conducted to determine the conversion factor. The strain tensor was computed using the Lagrange notation. The displacement field and strain filter size were set at 3 × 3 points and 5 × 5 points, respectively. Through DIC analysis, the software successfully determined the deflection of the beams up to crack initiation, allowing the measurement of each specimen's flexibility.

3 Results and Discussion

Sample measurements and the results of the non-destructive and impact tests are presented in Table 3, showing median values alongside their standard deviations for all groups.

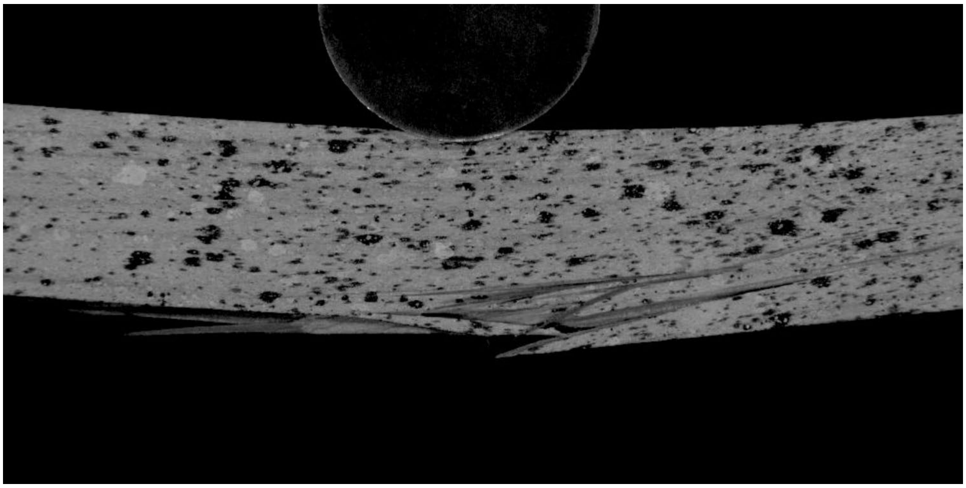


Fig. 4 An output recorded image of the impact

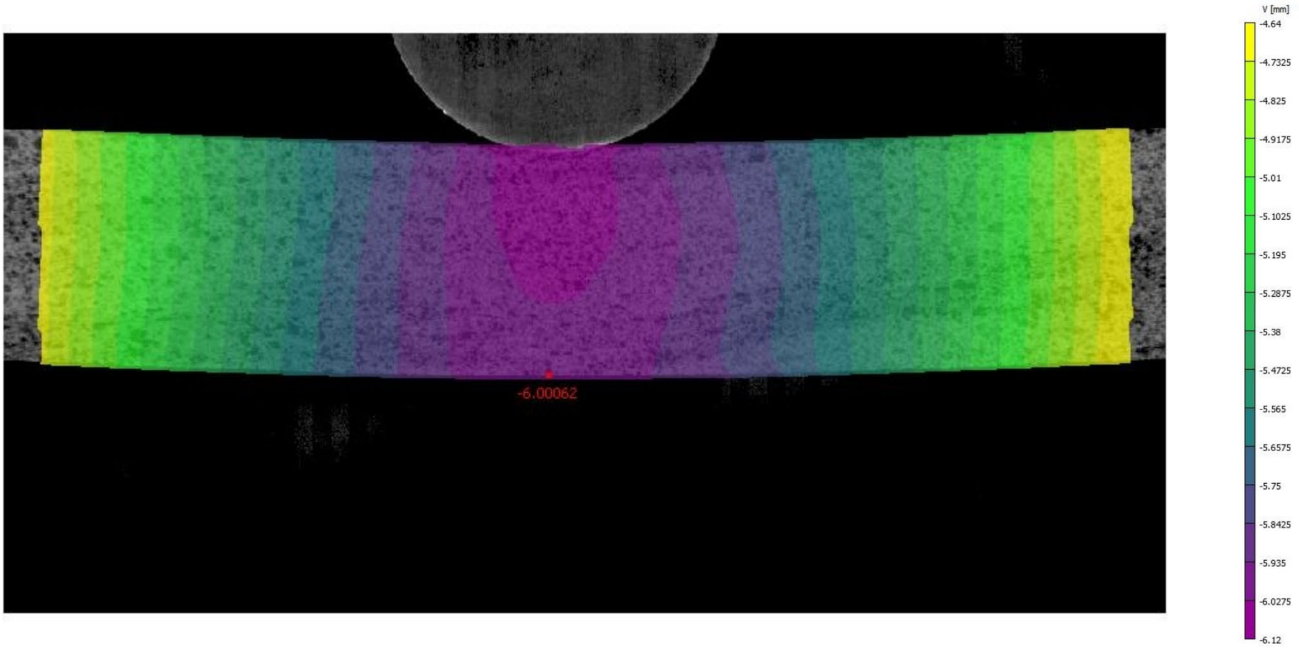


Fig. 5 A schematic of DIC software's process for measuring deflection

The impact bending strength (IBS) results from this study show both similarities and differences when compared to previous research on thermally modified wood. For spruce, the 15% decrease in IBS for the L-group in our study is significantly better than the 57% decrease reported by Boonstra et al. (2007) for the same temperature but a longer treatment duration (6 h). The absolute IBS values of the modified spruce between our study and theirs have 27% difference. The IBS of non-treated spruce in our research differed by only 13% from the value reported by Bučar and Merhar (2015), indicating good agreement for the baseline property. When comparing our results for beech to those of Borůvka et al. (2018), who used a 210 °C treatment for 3 h, we found a more significant decrease in density but a less significant decrease in IBS. Their study reported a 55% decrease in density and an 80% decrease in IBS, while our results showed a less drastic reduction in IBS. Finally, our findings for IBS change for spruce (14.5% decrease for L groups and 40% decrease for H group) are consistent with the study by Gaff et al. (2019), showing a 18.5% decrease in IBS for the L-group and a 39% decrease for the H-group. However, there was a considerable difference in the IBS of oak between the two studies. Both our study and Gaff et al. (2019) agree that the decrease in oak's IBS is relatively similar for both the L and H groups, while spruce's IBS decreases more significantly for the H group.

Table 3 Median values and standard deviations of results

Median (STDV.S)	No of samples	Density (kg/m^3)	Moisture content (%)	MOED$_{LT}$ (GPa)	MOED$_{LR}$ (GPa)	LDD$_{LT}$ (%)	LDD$_{LR}$ (%)	ACE (m^4/kg.s)	Fmax (N)	IBS (kJ/m^2)	Deflection (mm)
ASH N	28	707 (27)	10.66 (0.44)	15.25 (1.17)	15.67 (1.40)	2.77 (0.52)	2.74 (0.57)	5,523 (903)	3,442 (1,593)	45.4 (1.6)	8.17 (0.68)
ASH L	22	691 (15)	6.08 (0.69)	15.95 (0.99)	16.45 (0.96)	2.69 (0.73)	2.68 (0.87)	6,434 (1,012)	3,776 (1,189)	44.4 (2.9)	6.61 (0.47)
ASH H	20	614 (22)	3.22 (0.29)	14.06 (1.23)	14.48 (1.15)	2.14 (0.54)	2.31 (1.01)	10,060 (2,119)	5,850 (1,925)	20.3 (8.2)	4.43 (0.84)
BEECH N	20	735 (29)	12.2 (0.19)	14.76 (0.97)	15.12 (1.25)	3.47 (0.70)	3.86 (1.43)	3,653 (1,070)	3,257 (653)	45.9 (1.5)	7.88 (0.66)
BEECH L	21	728 (16)	6.1 (0.46)	17.49 (0.94)	18.28 (1.09)	3.24 (1.57)	2.95 (0.66)	5,373 (1,053)	5,374 (1,725)	42.0 (4.2)	6.59 (0.6)
BEECH H	19	619 (57)	4.02 (0.37)	14.23 (2.65)	14.61 (2.77)	2.43 (0.37)	2.62 (0.77)	7,436 (1,656)	2,861 (1,164)	30.9 (13.8)	4.54 (0.96)
LARCH N	28	539 (20)	11.28 (0.33)	12.48 (1.57)	12.31 (1.79)	2.95 (0.92)	2.81 (0.89)	10,116 (2,356)	4,319 (1,108)	24.1 (10.2)	5.37 (0.82)
LARCH L	29	504 (21)	5.66 (0.63)	12.9 (1.78)	12.96 (2.13)	3.0 (1.06)	2.72 (0.46)	12,525 (2,428)	2,659 (913)	28.4 (9.5)	4.91 (0.66)
LARCH H	14	483 (23)	4.29 (0.94)	11.05 (3.86)	11.52 (3.71)	4.94 (3.19)	5.47 (5.99)	1,2633 (5,240)	2,274 (1,097)	11.8 (8.1)	3.51 (0.6)
OAK N	19	715 (45)	13.26 (2.36)	11.29 (2.24)	11.65 (2.24)	3.80 (1.82)	3.46 (0.96)	3,531 (1,098)	3,396 (1,280)	28.2 (11.6)	6.08 (1.03)
OAK L	9	639 (27)	4.8 (1.1)	10.71 (2.21)	11.85 (1.72)	3.70 (1.92)	3.27 (0.95)	4,219 (992)	3,374 (963)	14.2 (3.3)	4.13 (0.67)
OAK H	18	560 (39)	3.83 (1.05)	7.95 (2.5)	9.62 (1.83)	5.72 (3.96)	4.00 (2.93)	6,910 (3,538)	1,085 (343)	11.6 (4.3)	3.23 (1.05)
SPRUCE N	23	450 (55)	10.34 (0.67)	13.39 (2.25)	13.57 (2.26)	2.43 (0.46)	2.54 (1.03)	18,223 (6,587)	2,150 (586)	38.5 (11.8)	5.94 (1.23)
SPRUCE L	30	455 (65)	5.6 (0.82)	13.91 (3.66)	13.99 (2.81)	2.87 (1.00)	2.90 (1.35)	19,186 (6,316)	2,720 (1,449)	32.9 (16.3)	4.44 (1.27)
SPRUCE H	31	431 (40)	3.66 (0.67)	12.66 (2.46)	12.92 (2.55)	2.87 (1.00)	2.79 (1.28)	20,345 (6,159)	1,430 (1,807)	22.9 (11.2)	2.64 (1.33)

We determined the density and moisture content of samples by measuring their weight before and after testing and depict these in Figs. 6 and 7. It is evident that TMP decreased both moisture content and density. In ash, beech and spruce, the density of the H group was significantly different from the control N group, while the L group was not, indicating the limited influence of TMP on density at the lower temperature. However, in the moisture content chart, the N group is notably distant from the other two,

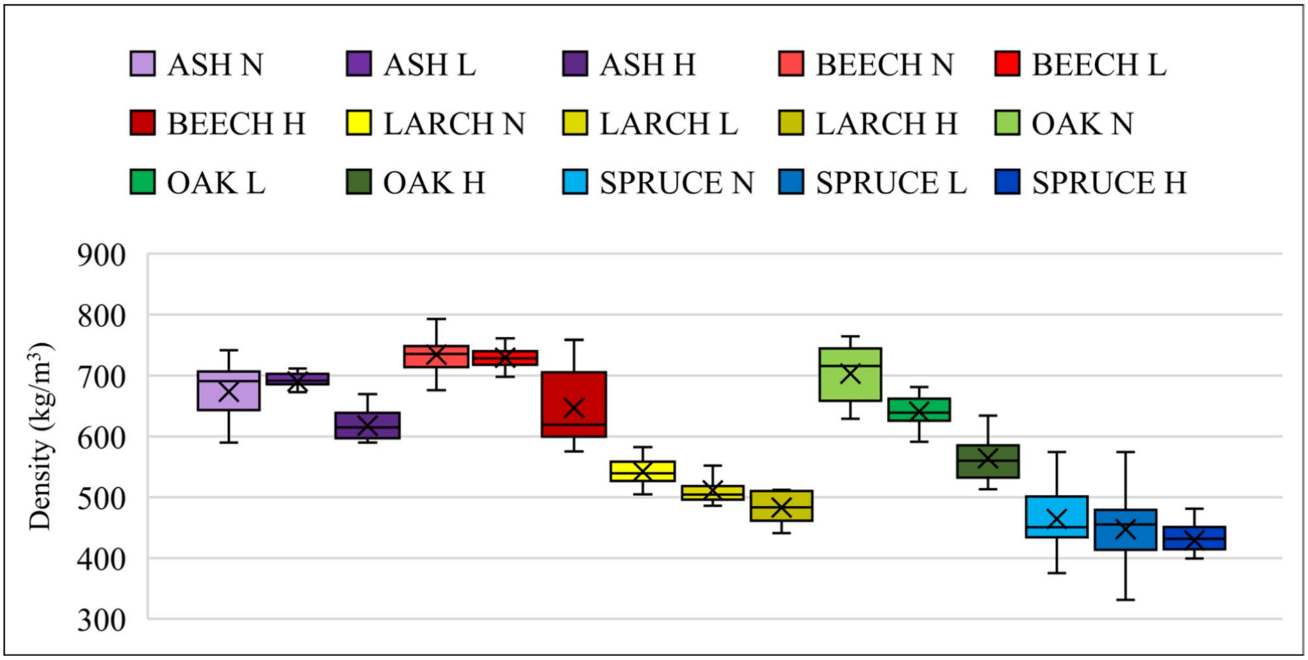


Fig. 6 Densities of wood samples by species with different levels of TMP

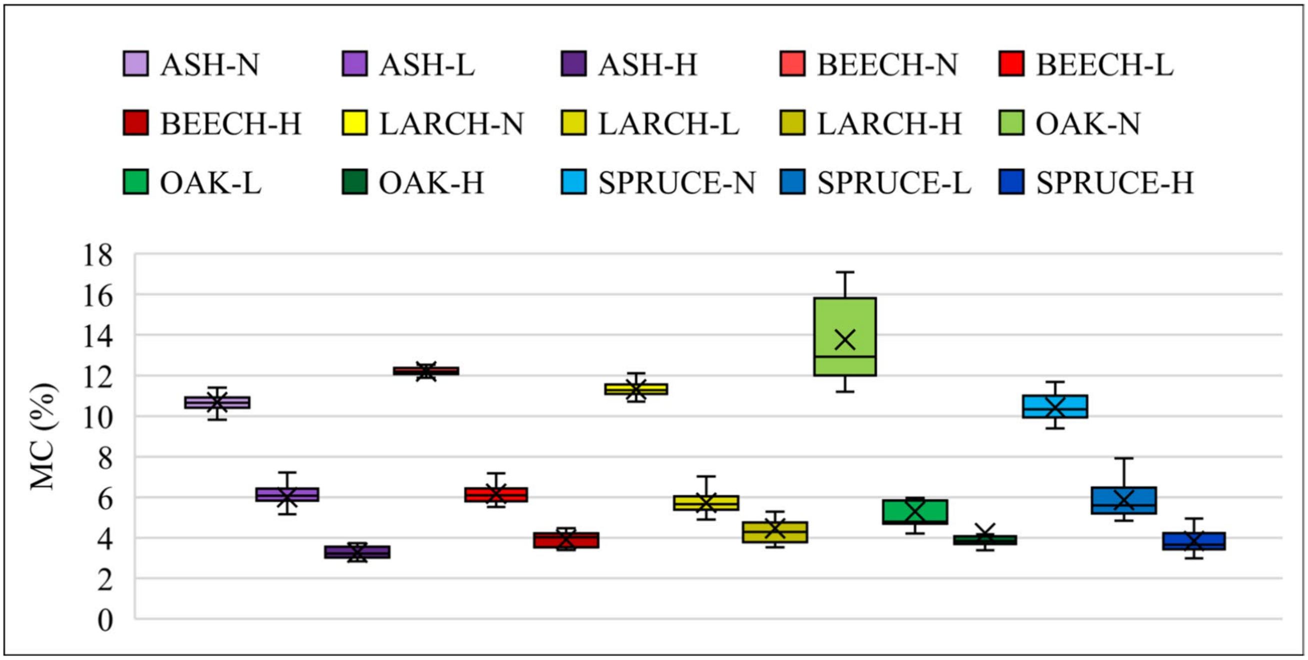


Fig. 7 Moisture content of wood samples by species with different levels of TMP

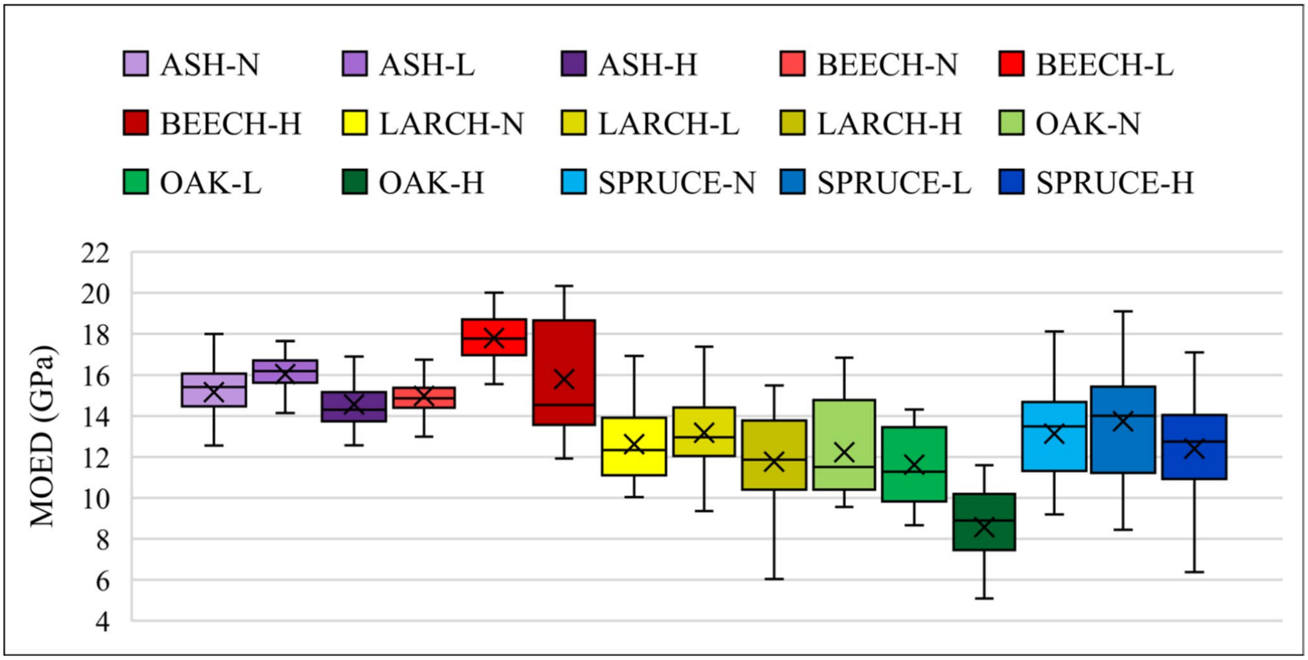


Fig. 8 MOED of wood samples by species with different levels of TMP

indicating the substantial effectiveness of TMP in reducing the wood's moisture content even at the lower temperature.

An ANOVA test confirmed that the size of each group did not significantly affect any of the parameters measured, and the results were independent of the number of specimens in the groups.

Furthermore, the p-values derived from ANOVA tests on all groups (N, L and H), as well as their combination (H + L + N) about their MOED_{LT} and MOED_{LR}, were

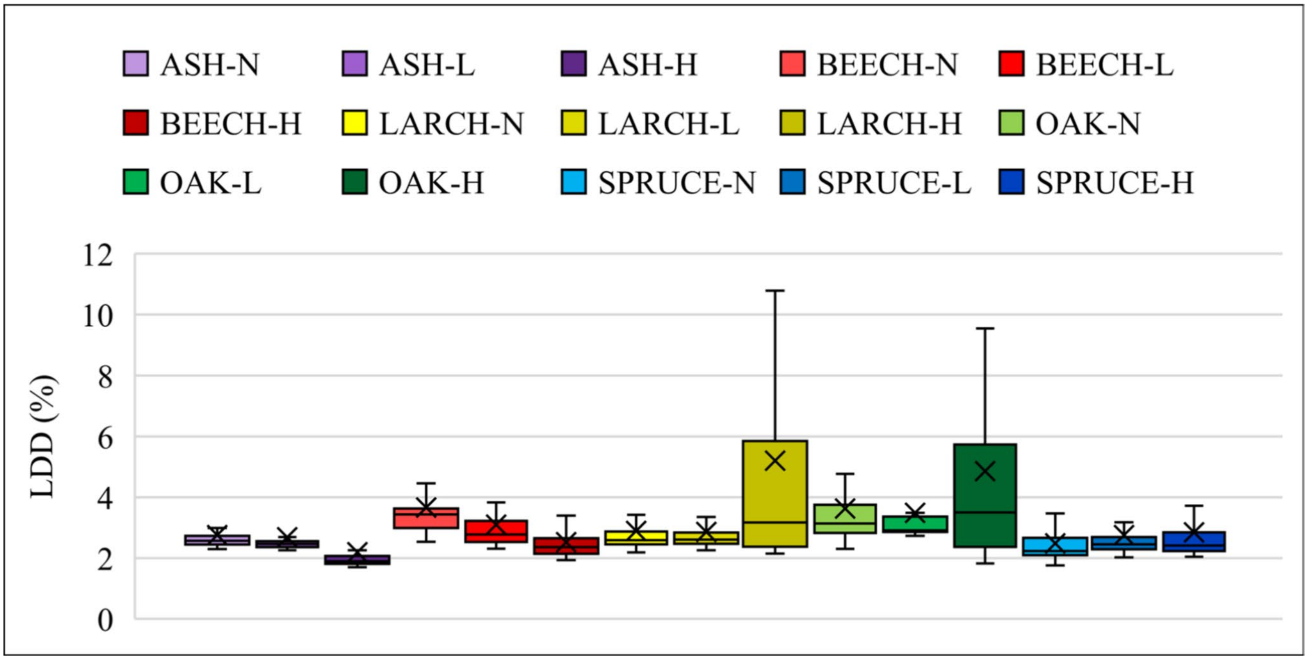


Fig. 9 LDD of wood samples by species with different levels of TMP

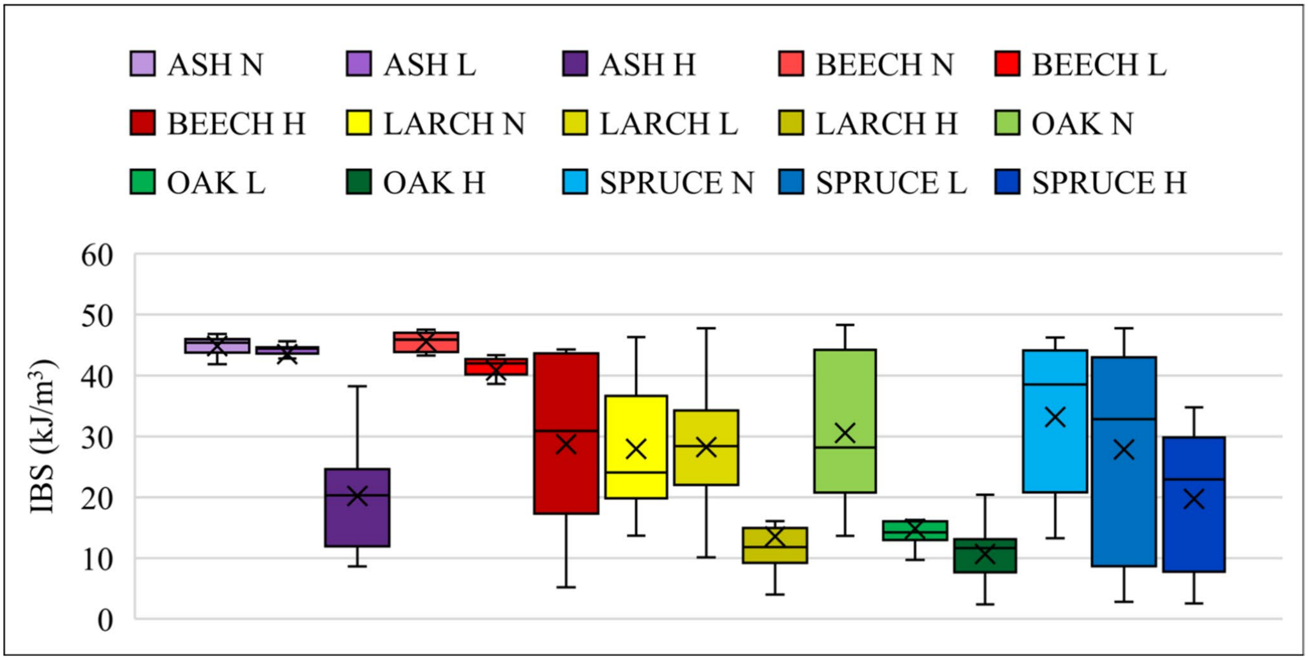


Fig. 10 'IBS of wood samples by species with different levels of TMP

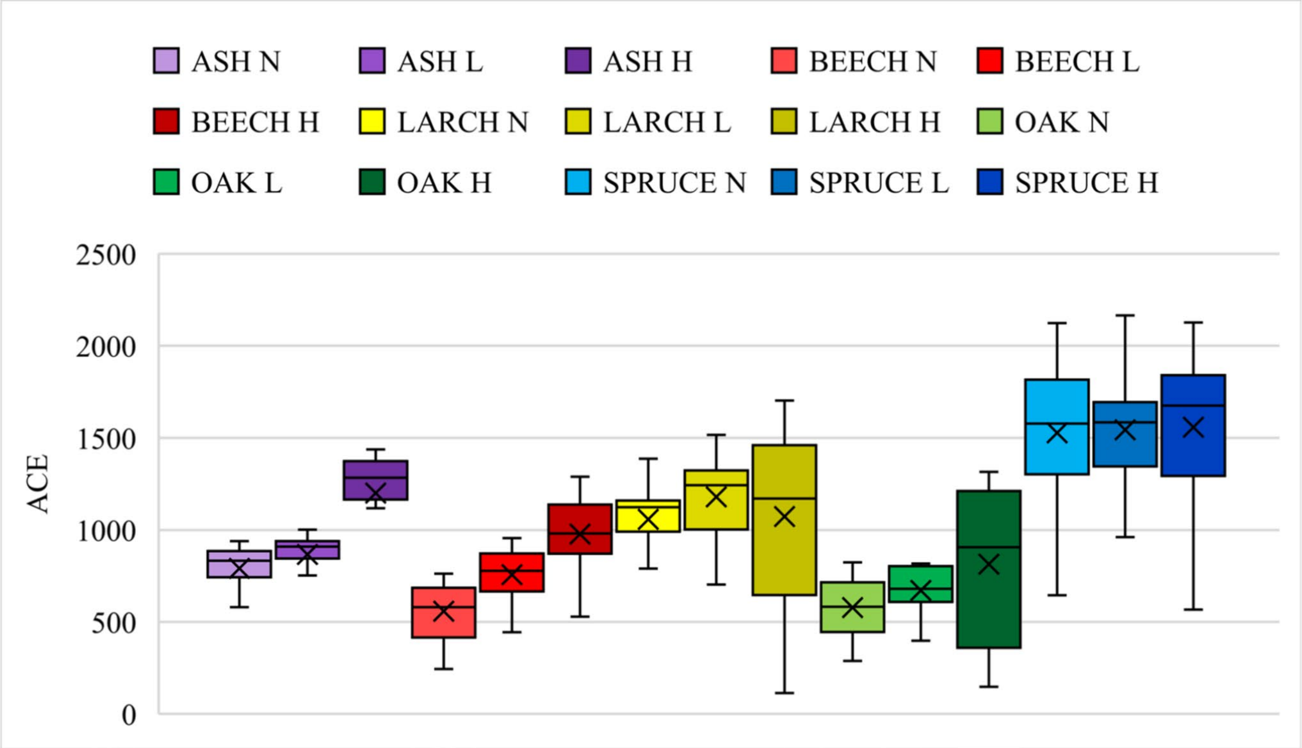
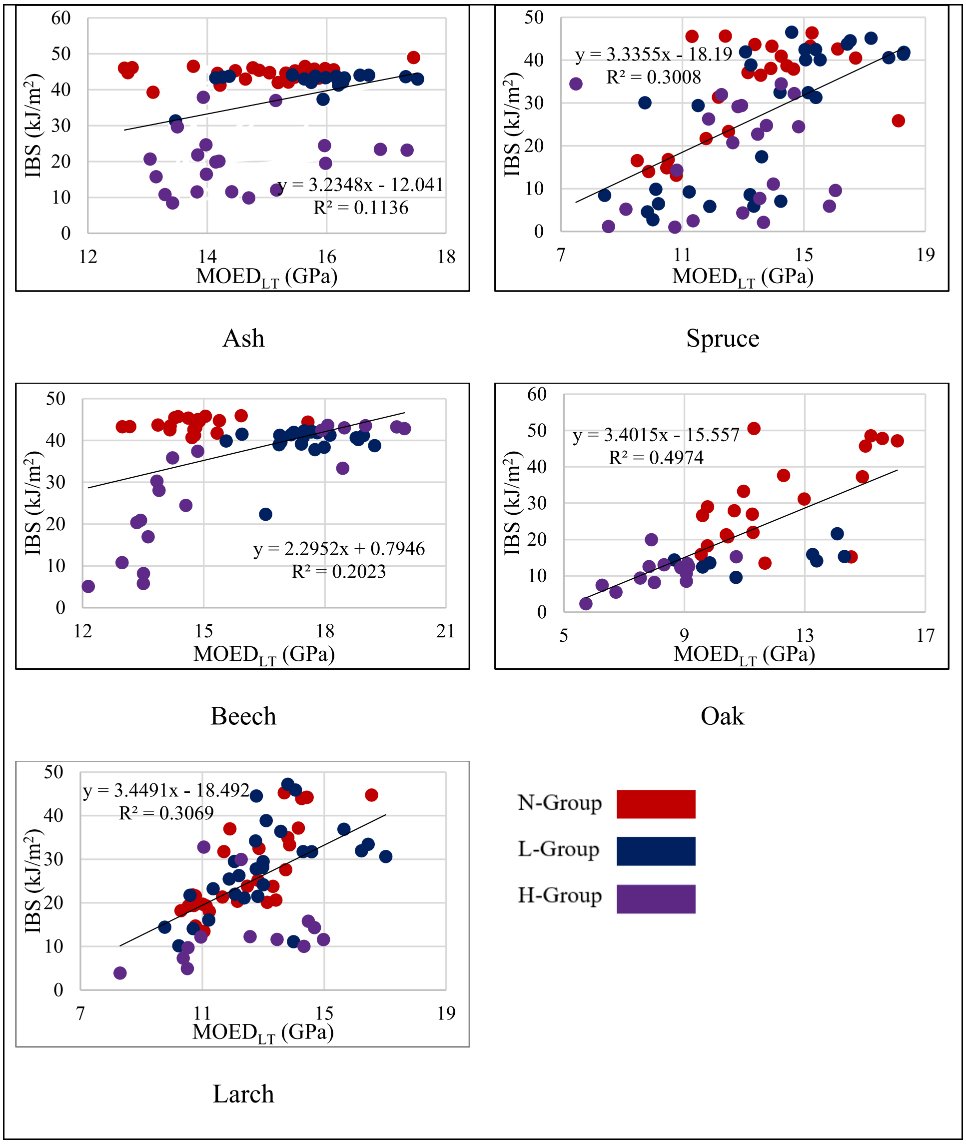


Fig. 11 ACE of wood samples by species with different levels of TMP

Fig. 12 IBS vs MOED for wood samples by species



observed to exceed 0.05, except for the oak H group. This outcome suggests that the $MOED_{LT}$ and $MOED_{LR}$ exhibited statistically equivalent values, and there is no necessity to distinguish between $MOED_{LT}$ and $MOED_{LR}$.

The p-values derived from Kruskal–Wallis tests on all groups (N, L and H), as well as their combination (H + L + N) about their LDD_{LT} and LDD_{LR}, were observed to exceed 0.05, except for three groups (larch N). Thus, the assumption of the equality of LDD_{LT} and LDD_{LR} is correct. For LDD, the Kruskal–Wallis test was used because of the non-normal distribution within all groups.

Figures 8 and 9 are box-plot charts representing the MOED and LDD of each species, as well as their combination categorised as hardwood, softwood, and all wood species included in this study. The MOED of the L groups (except for oak) was higher than N groups, indicating a slight improvement of MOED by low-temperature TMP, while for higher temperatures, the MOED decreased significantly. The LDD showed different behaviour in different species. It decreased in ash and beech and increased in larch, oak and spruce.

IBS test results for each specimen are given as box-plots in Fig. 10 to allow species to be compared. It should be noted that the IBS for ash-N and beech-N are not exact as most of the specimens did not break; they simply absorbed the impact energy.

Table 4 Regression analysis of MOED, LDD, and ACE with maximum deflection and maximum force

R^2	For determining Max Deflection			For determining Max Force		
	MOED	LDD	ACE	MOED	LDD	ACE
ASH N	0.024	0.028	0.036	0.047	0.040	0.007
ASH L	0.213	0.013	0.025	0.001	0.018	0.013
ASH H	0.010	0.087	0.065	0.035	0.166	0.134
ASH ALL	0.042	0.087	0.505	0.001	0.110	0.136
BEECH N	0.155	0.328	0.261	0.284	0.033	0.021
BEECH L	0.011	0.001	0.000	0.000	0.080	0.233
BEECH H	0.082	0.022	0.008	0.610	0.242	0.051
BEECH ALL	0.047	0.163	0.569	0.358	0.038	0.048
LARCH N	0.086	0.050	0.112	0.005	0.037	0.064
LARCH L	0.004	0.031	0.001	0.027	0.008	0.050
LARCH H	0.010	0.002	0.002	0.423	0.325	0.262
LARCH ALL	0.001	0.030	0.013	0.086	0.092	0.002
OAK N	0.121	0.141	0.216	0.397	0.031	0.000
OAK L	0.233	0.083	0.009	0.190	0.066	0.301
OAK H	0.040	0.036	0.000	0.000	0.005	0.033
OAK ALL	0.158	0.011	0.067	0.544	0.032	0.008
SPRUCE N	0.042	0.264	0.481	0.414	0.060	0.102
SPRUCE L	0.364	0.079	0.022	0.186	0.002	0.129
SPRUCE H	0.019	0.116	0.168	0.160	0.070	0.036
SPRUCE ALL	0.091	0.155	0.037	0.148	0.011	0.015
WOOD ALL	0.128	0.008	0.104	0.255	0.039	0.038

Acoustic conversion efficiency results are given in Fig. 11 and show the difference between the species tested. TMP increased the ACE for all species, and at the higher temperature, ACE results were more variable.

We plotted charts depicting IBS and maximum deflection versus MOED, LDD and ACE to assess the linear regression between these variables. The regression analysis revealed a correlation between IBS and MOED. However, the other parameters did not demonstrate any significant correlation, particularly LDD, which exhibited not even a remote relationship with deflection and IBS at any level. The scatter graphs are given in Fig. 12 and the regression equations and their coefficients of determination are presented in Table 5. The coefficients of determination of LDD, ACE and MOED with Maximum deflection and reaction force were also presented in Table 4 as a form of null results. The Table 4 depicts that the NDT surely is not able to measure the max deflection and reaction force robustly. Almost all of the coefficients of determination for the regressions of the charts are less than 0.5, indicating a weak relationship

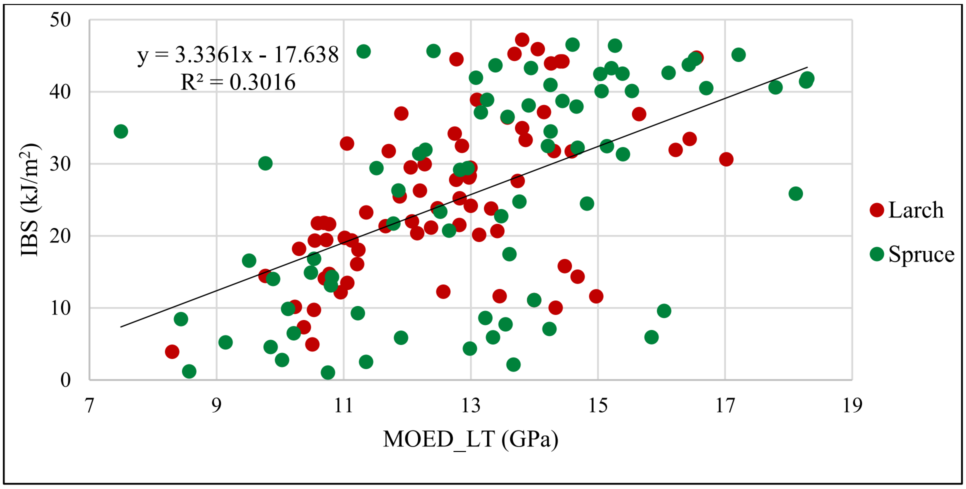


Fig. 13 IBS vs MOED for the softwood species

Fig. 14 IBS vs MOED for the hardwood species

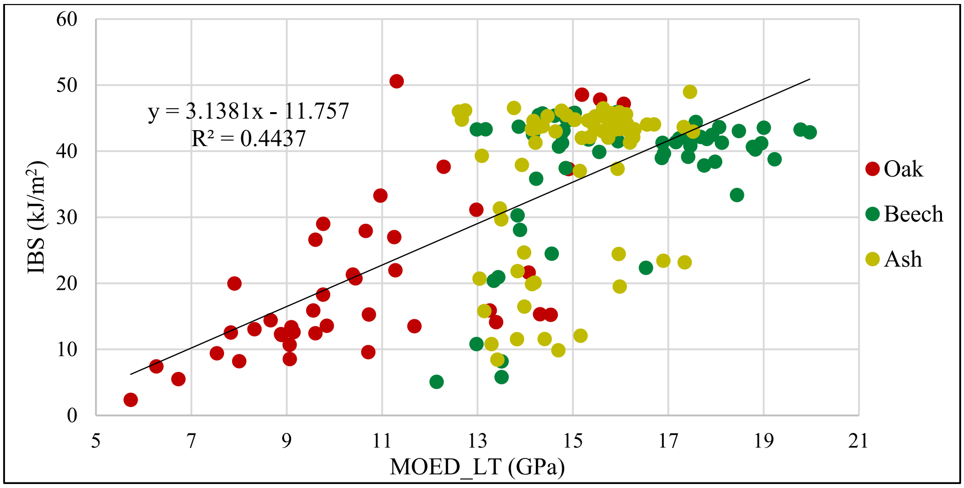
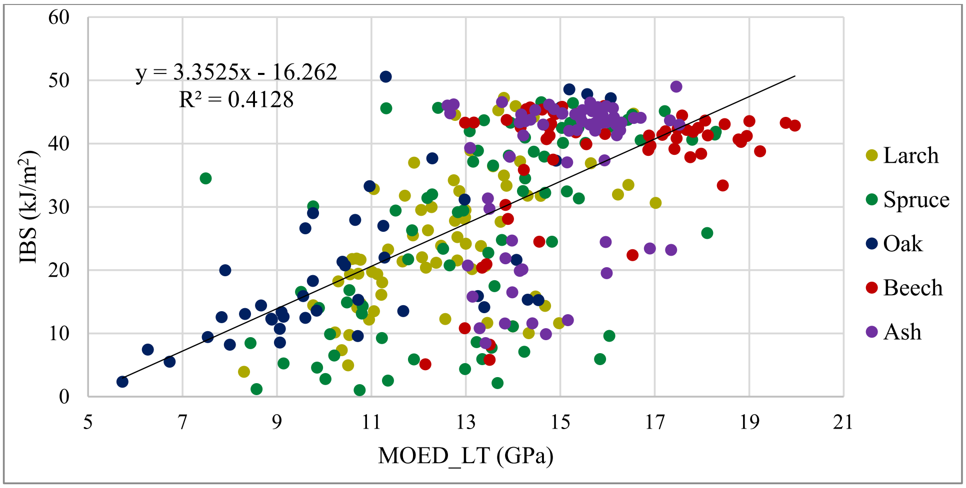


Fig. 15 IBS vs MOED for the all wood species



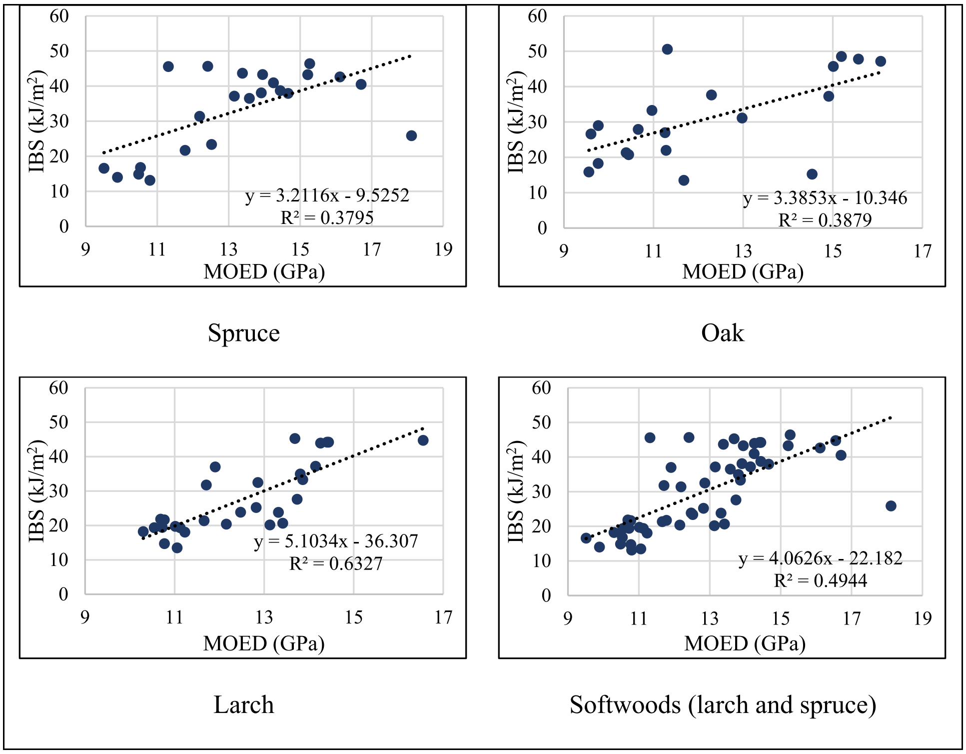
between IBS and MOED. Nonetheless, regression analysis can still assist in assessing the impact strength of wood to some extent via NDT, albeit with low precision.

Due to some similarities between the softwood species and hardwood species, each in aggregate, we examined whether their combined groups could offer any information about the relationship between MOED and IBS. Figures 13, 14 and 15 show the results for these aggregations. Larch and spruce show a good matching pattern and overall have similarities; however, among the hardwoods, oak seems to behave differently from ash and beech, which have similar patterns in their scatter graphs.

Additionally, NDT proved to be useful for assessing the IBS of non-modified oak, larch and spruce. In Fig. 16, scatter charts depict the relationship between IBS and MOED for these species, as well as for both softwood species in this study (larch and spruce).

By linear regression of the relationship between IBS and MOED, equations determining the IBS through MOED can be achieved. Table 5 presents the equations and coefficients of determination R^2. The efficiency of the linear regression of the relationship between IBS and MOED showed a considerable variation between the groups and species.

Fig. 16 IBS vs MOED for non-modified specimens of oak and the two softwoods (larch and spruce) separately and together



Spruce

Oak

Larch

Softwoods (larch and spruce)

Table 5 Regression equation and coefficients of determination between MOED and IBS of the samples

	Treated	Untreated	All
Ash	y = 5.4896x—51.84 R^2 = 0.3034	y = 0.3784 x + 38.918 R^2 = 0.0534	y = 3.2348x—12.041 R^2 = 0.1136
Beech	y = 4.3735x—38.333 R^2 = 0.6793	y = 0.3207x + 39.153 R^2 = 0.0396	y = 2.2952x + 0.7946 R^2 = 0.2023
Larch	y = 2.8335x—12.57 R^2 = 0.2218	y = 5.1034x—36.307 R^2 = 0.6327	y = 3.4491x—18.492 R^2 = 0.3069
Oak	y = 1.2039x + 0.8207 R^2 = 0.4417	y = 3.3853x—10.346 R^2 = 0.3879	y = 3.4015x—15.557 R^2 = 0.4974
Spruce	y = 3.3964 x—22.167 R^2 = 0.3252	y = 3.2116x—9.5252 R^2 = 0.3795	y = 3.3355x—18.19 R^2 = 0.3008
Ash, beech and oak (hardwood)	y = 3.2507x—18.664 R^2 = 0.6149	y = 3.3794x—7.2297 R^2 = 0.5254	y = 3.1381x—11.757 R^2 = 0.4437
Spruce and larch (softwood)	y = 3.1657x—18.056 R^2 = 0.284	y = 4.0626x—22.182 R^2 = 0.4944	y = 3.3361x—17.638 R^2 = 0.3016
All species	y = 3.301x—15.461 R^2 = 0.4048	y = 4.1098x—19.796 R^2 = 0.5499	y = 3.3525x—16.262 R^2 = 0.4128

4 Conclusions

The NDT methods used in this study successfully evaluated the impact-related properties of thermally modified wood, though with significant limitations. In line with our objectives, our findings provide a clear understanding of NDT's predictive capabilities for this application. The MOED was found to be effective for predicting the IBS. However, as hypothesized, the accuracy was species-dependent, with strong correlations observed for oak while proving less effective for larch and spruce, and no useful for assessing ash and beech. Also, this study revealed a key limitation of NDT: it failed to provide reliable estimations for maximum deflection and force during impact loading. The poor results from regression analysis of MOED, LDD, and ACE with these parameters indicate that NDT alone cannot fully characterize the dynamic fracture behavior of the wood. This highlights a critical gap in NDT's application for impact assessment. This study provides a comprehensive view of the effectiveness of NDT for evaluating the impact-related behavior of thermally modified timber and also it shows how the efficiency of NDT is influenced by both the wood species and the specific thermal modification process. Based on these findings, we recommend further research into the use of different NDT techniques to broaden the application of NDT in this field.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Ethical Approval Not applicable.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process During the preparation of this work the authors used Grammarly and ChatGPT by OpenAI software in order to find the primary English language grammatical mistakes in the text. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article. However, in the end, the authors decided to send the text to an expert firm to be inspected for improvement of the English language.

Competing interests The authors declare no competing interests.

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