

# Effect of thermal modifications on the anisotropic acoustic properties of spruce and their relevance for stringed instruments

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Thermal modification alters wood properties and helps improving dimensional stability against humidity changes, making it a promising treatment for wood used in stringed instrument construction. Its effects on the anisotropic mechanical and acoustical properties, however, remain incompletely understood. In this study, spruce samples were analyzed to quantify changes in physical, mechanical, and acoustical properties following thermal modification at 160 °C. Density, orthotropic viscoelastic constants, and damping were measured using non-destructive techniques, while microstructural effects were examined via X-ray microtomography. Finite element analysis of a guitar soundboard assessed impacts on eigenfrequencies, mode shapes, and acoustic radiation. Results indicate that thermal treatment causes a slight reduction in density, a modest increase in longitudinal and radial stiffness, and a significant decrease in damping, leading to enhanced radiation ratio and acoustic conversion efficiency. Microstructural observations suggest that removal of resins and volatile extractives may underlie these changes. Finite element analysis shows that eigenmodes shapes remain largely unchanged, with only minor shifts in eigenfrequencies. The combination of improved radiation efficiency and reduced damping could influence sound radiation and string-to-soundboard coupling.

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## I. INTRODUCTION

Wood is a material of choice for the realization of musical instruments, artifacts and industry products due to its widespread availability, workability and low carbon footprint<sup>1</sup>. Being a bio-based material coming from living trees, where water fills the cells to transport nutrients, it requires seasoning to lose the free water and subsequent bound water to achieve a relative geometrical stability before its use<sup>2</sup>. Wood for musical instruments, in particular, is believed to need at least several years of natural seasoning before it is possible to use it<sup>3,4</sup>. Nevertheless, even after long seasoning, wood remains hygroscopic and undergoes changes in dimensions, shape, density and mechanical properties with relative humidity and temperature variations. For these reasons, thermal treatments were developed to ensure improved stability, since they allow the wood to dry in a controlled manner as well as reducing its hygroscopic behavior. In particular, while thermal treatment leads to the evaporation of volatile components such as resins and terpenes, it also reduces its hemicellulose content and its associated

hydroxyl groups which are responsible for the bound water. As a consequence, wood hygroscopicity is strongly reduced and dimensional stability improved<sup>5</sup>. A technologically important consequence of thermal treatment is the destruction of nutrients that make it much less sensitive to fungi and xylophagous insects attack, increasing the durability of wood intended for exterior use<sup>3,6</sup>. Another important consequence in thermal treatment is the improved specific storage modulus ( $E'/\rho$ , where  $E'$  is the storage modulus and  $\rho$  the density)<sup>7</sup> and the modification of the absorption coefficient of sound waves and the speed of sound propagation<sup>8</sup>. This type of treatment is also becoming more common in the field of stringed musical instruments where so-called *torrefied* wood is sometimes used<sup>9,10</sup>. Although some wood suppliers and musical instrument makers claim that thermally modified wood has similar properties to those of well seasoned wood, only a limited amount of information is currently available about its physical properties and their change as a consequence of the thermal treatment. The available literature in fact focuses mainly on density, aesthetics, moisture content<sup>11</sup> or on the chemical modifications deriving from the treatment, typically performed with FT-IR or Raman spectroscopy<sup>12,13</sup>. Only a few studies have investigated the changes in the mechanical and acoustical

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properties measured along the longitudinal direction of timber<sup>3,14–16</sup>. These studies typically report a decrease in density and either unchanged or slightly increased longitudinal storage modulus, as well as minor variations in the acoustic behavior of rectangular boards<sup>17</sup>. In some cases, an increase in density has been observed when oil treatment was applied<sup>7</sup>. Very limited data are available regarding wood damping:<sup>17</sup> reports a decrease in the logarithmic decrement following thermal treatment at 160°C in spruce (*Picea* spp.) plates but with uneven results among the considered samples. Although the anisotropic properties of wood may also play an important role, particularly in stringed instruments<sup>18,19</sup>, little information is currently available on how these properties are affected by thermal treatment.

### A. Aim of the work

The aim of this work is to evaluate the effect of STYL+WOOD<sup>®</sup> thermal modification on the physical, mechanical, and acoustical properties of wood. A set of 24 spruce (*Picea abies*) boards, selected based on seasoning time, is considered. Density is determined, and the anisotropic storage moduli and loss factors are measured using non-destructive acoustical techniques. Acoustical merit factors are derived, their changes due to thermal treatment are evaluated, and their statistical significance is assessed. The reliability of the results is examined by considering both the propagation of measurement errors and the statistical significance of the measured and calculated values across the studied population. The wood microstructure is also analyzed by X-ray microtomography. Finally, the potential effect of these property changes on musical instruments is assessed by means of finite element analysis (FEA) of a guitar soundboard, through the calculation of eigenmodes, eigenfrequencies, and their variations, as well as the sound radiation from the soundboard surface.

The paper is organized as follows: Section II describes the materials and methods, Section III presents the results of the measurements and simulations, Section IV discusses the results, and conclusions are drawn in Section V.

## II. MATERIALS AND METHODS

### A. Wood boards

Wood boards were selected from the wood stock of Rivolta S.N.C., Desio, Italy, an international supplier of tonewood for musical instruments<sup>20</sup>. The spruce wood considered in this study came from the Paneveggio forest in the Italian Alps. The logs were first sawn into boards, which were then stored for natural air seasoning before undergoing a subsequent *quarter-sawn* cut, i.e., radial cutting from the log. The resulting *quarters* were re-sawn longitudinally into two parts to form bookmatched pairs, which were again left to air dry. If used for guitar making, each pair is subsequently joined with glue to form

the soundboard or the back of the instrument. Twelve spruce boards were selected, resulting in 12 bookmatched pairs and 24 samples. Since natural air seasoning can induce significant changes in the physical and mechanical properties of wood<sup>21</sup>, the boards were chosen based on the time elapsed since log re-sawing and were divided into three groups:

1. Group 1 – boards sawn prior to more than 20 years (2002-2003)
2. Group 2 – boards sawn prior to 5-6 years (2018-2019)
3. Group 3 – boards sawn prior to 2 years (2022)

The boards were cut to a rectangular plate form (500 x 200 mm approximately) and sanded to a final uniform thickness of approximately 3.5 mm to remove all the saw marks.

### B. Thermal treatment

The thermal treatment was performed by BIGonDRY S.R.L. according to the STYL+WOOD<sup>®</sup> proprietary process. The treatment was carried out in a sealed chamber with a volume of approximately 10 m<sup>3</sup>, where both temperature and oxygen concentrations were continuously monitored and controlled by a dedicated software. In this treatment type, temperature is regulated by adjusting the heating/cooling rate, while oxygen concentration is controlled primarily by a slight overpressure resulting from the natural release of gases from the wood (water vapour and gases from pyrolysis) and, if necessary, by the injection of a small amount of saturated steam<sup>14</sup>. Starting from room temperature, the temperature is gradually and uniformly increased, while monitored using temperature probes in direct contact with the wood, until the maximum process temperature (160 to 230°C) is reached. At this stage, the cooling and stabilization phase begins. The final stage of the process consists in a controlled re-moisturization of the spruce. This step reintroduces water into the wood after the high-temperature process step, allowing the material to reach a new equilibrium moisture content with the environment. While this process accepts wood with an initial moisture content of 12% - 18%, the final moisture content of the wood is reduced to 5-10%. The cycle time varies between 2 and 6 days, depending on the process temperature, the wood species and the thickness of the boards and is determined by the process condition of the batch to ensure a correct oxygen concentration and an optimized temperature distribution. For this reason, the parameter that characterizes the treatment is its maximum temperature. At the end of the process, the boards are considerably darker than at the beginning. More information about the process can be found in the provided reference. A simplified representation of the process time-temperature cycle is shown in Figure 1.

In this study, the “low temperature” process was used, with a maximum temperature of 160°C. Moreover,

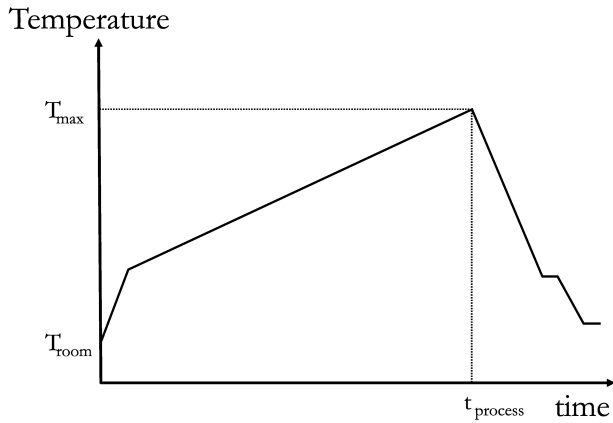


FIG. 1. Example of time-temperature cycle of STYL+WOOD<sup>®</sup> thermal modification process.

the wood boards that were considered in this study had a narrower moisture content dispersion ( $12\pm 1\%$ ) than that admissible for this treatment. An example of comparison between a pristine and a thermally modified soundboard is reported in Figure 2.



FIG. 2. An example of two different bookmatched spruce boards similar to those considered in this study in their pristine state (left) and thermal treated at  $160^{\circ}\text{C}$  (right). Boards thickness is 5 mm. Photo Courtesy Wood 'n' Tones<sup>22</sup>.

### C. Hygrometric stabilization and moisture content measurement of the boards

The wood boards were left to stabilize in a humidity-controlled environment (RH 50%) for at least two weeks before measuring their properties. This climatization procedure was applied to both pristine and heat-treated boards, allowing them to reach equilibrium with the environment and enabling a comparison of wood properties under identical climatic conditions. This aspect is of pri-

mary importance, as heat-treated wood is intended to be used under the same conditions as pristine wood, and any differences between the two would therefore manifest under identical environmental conditions. Wood moisture content was measured with a portable 2-points contact probe wood moisture meter and was  $12\pm 1\%$  in the pristine boards and  $7\pm 1\%$  in the heat treated boards.

### D. Measurement of physical and mechanical properties

Boards dimensions were measured with a measuring tape and a digital caliper to retrieve the overall length, width and thickness. Since thickness strongly influences the determination of the properties, it was measured at four points on each board and averaged. As the boards were reduced to a uniform thickness using an industrial sander, the authors found that averaging across four positions provided sufficient accuracy. The board weight was measured with a digital scale and the density  $\rho$  was retrieved as the ratio of mass/volume. The board orthotropic storage moduli were measured from the frequency of the low order, free-edges plate vibration modes, according to the method developed in<sup>23,24</sup>. The storage modulus  $E'$  characterizes the elastic (energy-storing) component of a viscoelastic material under harmonic loading, with complex modulus  $E^* = E' + iE''$ . The associated loss factor is  $\eta = E''/E' = \tan \delta$ , where  $\delta$  is the phase lag between stress and strain and quantifies material damping. The aforementioned method allows for the identification of the dynamic storage moduli, which are generally different from the static ones, but was chosen because it is a non-destructive test that can provide accurate results and can be easily performed even in a guitar maker's workshop. Furthermore, the dynamic and static storage moduli are highly correlated and can be predicted from one another<sup>25,26</sup>. In the following, the authors refer to the wood main directions as: Longitudinal (L), Radial (R) and Tangential (T). The Longitudinal  $E'_L$ , the radial  $E'_R$  and the shear  $G'_{LR}$  storage moduli (in pascals) were retrieved using the following formulas:

$$E'_L = 0.94625 \frac{\rho f_L^2 L_L^4}{h^4}, \quad (1)$$

$$E'_R = 0.94625 \frac{\rho f_R^2 L_R^4}{h^4}, \quad (2)$$

$$G'_{LR} = \frac{3}{(\pi/2)^2} \frac{\rho f_{LR}^2 L_L^2 L_R^2}{h^4}, \quad (3)$$

where  $L_L$  and  $L_R$  are the overall length and width of the board (in meters, see Figure 2) for a board quarter sawn,  $h$  is the thickness (in meters),  $\rho$  the density (in  $\text{Kg}/\text{m}^3$ ) and  $f_L$ ,  $f_R$  and  $f_{LR}$  are the frequencies of the first longitudinal, radial and torsional modes respectively (in Hz). The shape of these modes and the plate geometry is reported in Figure 3. To measure the frequencies, the boards were suspended with thin wires, placed in correspondence to the nodal lines of the modes and then gently tapped with a hand-held hammer. The sound produced by the tap was measured with a microphone and

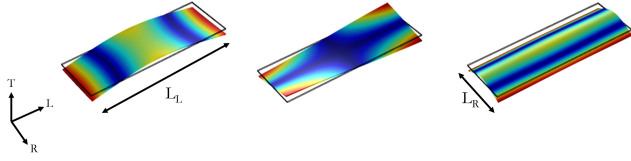


FIG. 3. Shape of the first longitudinal, torsional and transversal eigenmodes of a rectangular spruce plate with the same dimension of the boards considered in this study. The frame of reference indicating the three main direction of wood is also reported.

the frequency was retrieved with a spectrum analyzer (frequency accuracy of  $\pm 0.06$  Hz).

### E. Measurement of damping

The damping characteristics of the plates were measured by suspending them on thin wires and exciting vibrations with a loudspeaker placed beneath an antinodal region of the mode of interest. The loudspeaker was driven through an amplifier with a sinusoidal signal at the same frequency as the considered mode. Once the plate began vibrating, the excitation was abruptly stopped, leaving the plate free to vibrate while the sound was recorded with a microphone. The decaying sound was fitted with an exponentially decaying sinusoid of the form  $A(t) = A_1 \sin(A_2 t + A_3) e^{-A_4 t}$ , where  $A_1$  is the amplitude,  $A_2$  is the angular frequency,  $A_3$  is the phase and  $A_4$  is the exponential decay, from which the damping coefficient was obtained as  $\eta = 2/(A_2 A_4)$ . This method allows the excitation of a single vibration mode and the direct measurement of its damping by fitting the recorded signal, without the need for post-processing or more complex measurements and signal treatment to exclude modal overlap. This approach has proven more reliable than common alternatives, such as measuring the amplitude of successive oscillation cycles or the bandwidth of the excited frequency peak, since it averages over a larger amount of data and is not limited by the finite frequency resolution of FFT measurements. It is also easier to implement in makers' workshops and provides an objective and repeatable characterization method. This method was developed in a previous work by one of the authors<sup>18</sup> where more details can be found. Three loss factors were measured:  $\eta_L$ ,  $\eta_R$  and  $\eta_{LR}$  (adimensional), that characterize the wood damping along its main directions. The correspondent quality factors  $Q_L$ ,  $Q_R$  and  $Q_{LR}$  were also calculated, as they are frequently used in musical instrument making. Although they describe the behavior of a complete vibrating system rather than the material alone, for materials with low damping such as wood, they are related to the loss factors by  $Q_i = 1/\eta_i$  with negligible error<sup>27</sup>. An example of least square fitting of the recorded signal is reported in Figure 4.

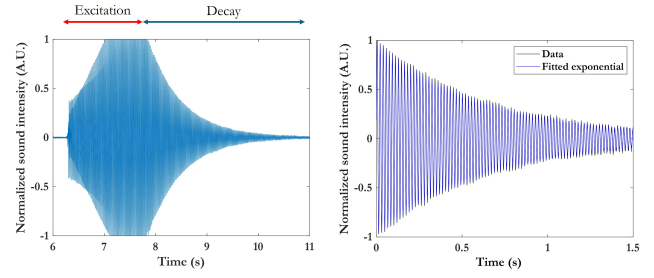


FIG. 4. Example of the audio signal recorded and fitted to retrieve the damping. Left: Sound intensity as a function of time showing the excitation and decay, right: least square fitting of the decay.

### F. Acoustical properties

To quantify the effect of the heat treatment on the acoustical properties of wood, the isotropic merit factors Radiation Ratio (RR) and Acoustic Conversion Efficiency (ACE) were determined:

$$RR = \sqrt{\frac{E'_L}{\rho^3}}, \quad (4)$$

$$ACE = \frac{RR}{\eta}. \quad (5)$$

These merit factors are correlated to the sound radiation of plates and particularly to the sound loudness and duration after excitation<sup>28</sup>. Since, in some cases, the anisotropy of the material is very important for the sound radiation, the anisotropic merit factors  $RR_{eq}$  and  $SRC_{eq}$  were also calculated as<sup>18</sup>:

$$RR_{eq} = \sqrt{\frac{E'_{eq}}{\rho^3}}, \quad (6)$$

$$ACE_{eq} = \frac{RR_{eq}}{\eta_{eq}}, \quad (7)$$

where  $E'_{eq}$  and  $\eta_{eq}$  are the equivalent storage moduli and the equivalent material loss factor, described below. These quantities express the overall stiffness and damping of an orthotropic thin plate. These figures take into account the geometry of the board, as well as the anisotropic wood properties and the considered vibration mode. Herein, they were calculated for the monopole-type vibration mode and for two geometries, corresponding to two families of instruments, namely guitar-like (superscript  $G$ ) and violin-like (superscript  $V$ ) instruments:

$$E'^G_{eq} = \frac{E'_L + E'_R + 2E'_L \nu_{RL} + 4\lambda G'_{LR}}{4}, \quad (8)$$

$$E'^V_{eq} = \frac{E'_L + 16E'_R + 8E'_L \nu_{RL} + 16\lambda G'_{LR}}{25}, \quad (9)$$

$$\eta^G_{eq} = 0.76 \eta_L + 0.05 \eta_R + 0.15 \eta_{LR}, \quad (10)$$

$$\eta^V_{eq} = 0.32 \eta_L + 0.36 \eta_R + 0.25 \eta_{LR}. \quad (11)$$

with  $\lambda = 1 - \nu_{RL} \nu_{LR}$ , where  $\nu_{ij}$  are the Poisson's coefficients. The reader may refer to<sup>18</sup> for further details.

## G. X-Ray microtomography of the wood samples

Three spruce specimens of matchstick dimensions were scanned with an EASYTOM scanning equipment, considering specimens sizes, 3  $\mu\text{m}$  voxel size. The scanning conditions were 60 kV, 80  $\mu\text{A}$ , 1440 images per turn, 500 ms exposure, 5-frame averaging. These parameters led to a scanning time of 1 hour per specimen. The reconstruction based on the radiographs was performed with *X-act* software with the filtered projection algorithm. Reconstructions yielded RT, LR and LT slices for pristine and thermally modified states. The slices were analyzed with *VG Studiomax 2024* software, allowing for the direct comparison of the sample scanned before and after the thermal treatment. A pairwise comparison was performed, at the same location, between the “before treatment” to the “after treatment” volume. This enabled evaluation of through-thickness distance maps on the registered RT slice. A histogram of local normal displacements and a quantitative dimensional comparison was performed. This approach was used to provide quantitative shrinkage metrics.

## H. Finite element analysis of guitar soundboard

To determine the effect of using thermally modified wood on a stringed instrument soundboard, namely the front board of the instrument and its bracing, a guitar top was simulated using finite elements analysis. Simulations were run in COMSOL Multiphysics considering the geometry of a Antonio De Torres classical guitar soundboard, whose geometry was retrieved from<sup>29</sup>. The geometry is reported in Figure 5.

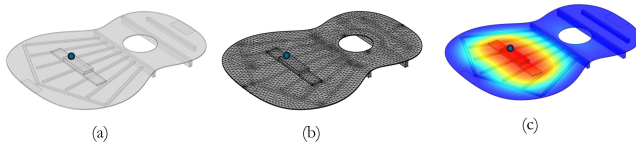


FIG. 5. (a) Geometry of the guitar soundboards, (b) FEA mesh and (c) example of the first eigenmode. The dots indicate the excitation point.

The soundboard alone was simulated for the following reasons: i) with some limitations, a guitar soundboard can be considered as a plate with clamped edges, ii) the authors wanted to highlight the impact of the choice of the variation of the materials properties alone, excluding the contribution of air resonance and damping, which adds complexity to the results and iii) to keep the computational cost low. FEAs were performed on the geometry reported in figure 5. Two FEAs were run: a first analysis was used to retrieve the eigenmodes and eigenfrequencies by solving the complex eigenvalue problem for the damped frequencies:

$$(-\omega_i^2 M + i\omega_i C + K) \phi_i = 0, \quad (12)$$

where  $M$ ,  $C$  and  $K$  are the mass, damping and stiffness matrices respectively and  $\omega_i$  and  $\phi_i$  are the  $i^{\text{th}}$  eigensolutions. A total of 20 vibration modes, covering a frequency range up to 1400 Hz were considered in the analysis. The difference between modal shapes of thermally modified and pristine wood soundboards were evaluated using the Modal Assurance Criterion (MAC)<sup>30</sup>, an indicator used to quantify the degree of correlation or similarity between two mode shapes. MAC was calculated as:

$$\text{MAC}_{ij} = \frac{|\phi_i^T \phi_j|^2}{(\phi_i^T \phi_i) (\phi_j^T \phi_j)}, \quad (13)$$

where  $\phi_i$  and  $\phi_j$  are the modal shapes to be compared. Its value ranges from zero (no correlation between the two modal shapes) to 1 (perfect match). A second analysis was performed to retrieve the frequency response. In this case, a vertical oscillating force (applied along the  $z$  direction, perpendicular to the soundboard surface, see Figure 5) of 1 N was applied to the bass side of the bridge. The bridge velocity in the same point was evaluated to retrieve the bridge admittance  $Y(f) = v(f)/F$  (in  $\text{ms}^{-1}\text{N}^{-1}$ ), a figure that is related to sound radiation, where  $v$  is the velocity along the  $z$  direction and  $F$  the applied force. Sound Pressure Level (SPL) was evaluated by numerical evaluation of the Rayleigh integral across the soundboard surface<sup>31</sup>. The listener’s point in this case was located 0.5 m away from the soundboard, slightly off-axis to evaluate the transversely symmetrical eigenmodes contribution. The spectral centroid (SC), defined as the center of mass of the spectrum and reflecting the distribution of energy across frequencies, was computed to highlight differences related to material properties. As it correlates with perceived brightness<sup>32</sup>, it can serve as an indicator of potential perceptual differences. The normalized spectral centroid (NSC), obtained by dividing the SC by the maximum considered frequency, was also calculated to allow a relative comparison between the spectra. Regarding the material properties, modeling wood as an orthotropic material required the definition of nine mechanical constants: three storage moduli ( $E'_L, E'_R, E'_T$ ), three shear moduli ( $G'_{LR}, G'_{RT}, G'_{LT}$ ) and three Poisson’s ratios ( $\nu_{LR}, \nu_{RT}, \nu_{LT}$ ) as well as six loss factors: ( $\eta_L, \eta_R, \eta_T, \eta_{LR}, \eta_{RT}, \eta_{LT}$ ). Implementing such a material model in COMSOL Multiphysics required all these constants to be specified. However, only a subset significantly affects the vibrational and damping behavior of thin plates such as a guitar soundboard, namely the three storage moduli  $E'_L, E'_R$  and  $G'_{LR}$  and the corresponding loss factors  $\eta_L, \eta_R, \eta_{LR}$  which were measured in this work. The remaining constants have been shown to have a negligible influence on the response<sup>19,23,24,33</sup>; therefore, their values were selected from literature data reported in<sup>1</sup>.

### III. RESULTS

#### A. Dimensional variation

The dimensional variations of the samples, averaged across the considered population, are reported in Table I.

TABLE I. Percentage variations and standard deviations of the measured dimensions and mass. Values represent averages across the samples.

	Average variation (%)
Length	$0.0 \pm 0.0$
Width	$-1.0 \pm 0.2$
Thickness	$-0.9 \pm 0.7$
Mass	$-5.3 \pm 0.8$

#### B. Variation of the physical, mechanical and acoustical properties

To quantify the effect of the thermal treatment on the wood, the physical and mechanical properties were compared before and after the treatment. Error propagation was performed for density, mechanical, and acoustical properties, and the associated measurement uncertainties are reported alongside the calculated values. Table II reports the measured and calculated values averaged across the samples, along with the standard deviation (STD) and the coefficient of variation (COV) providing an indication of variability within the population in absolute and relative terms. The CoV is defined as  $COV = \sigma/\mu$ , where  $\sigma$  is the STD and  $\mu$  is the mean of the population. The variations between the average values before and after the treatment are also reported. In all measurements, the observed variations were greater than the associated uncertainties, confirming the physical significance of the results. A paired Student's t-test was also performed to assess the statistical significance of the observed differences in individual samples and showed that all variations, except for  $G'_{LR}$ , were statistically significant in addition to being physically meaningful. The anisotropy, expressed as  $E'_L/E'_R$  is also reported in Table III.

#### C. Variation of the acoustical properties

The variation of the acoustical properties is reported in Table III. The anisotropic Radiation Ratio and Acoustic Conversion Efficiency, calculated as per Eq. 7 are also reported for the guitar and violin cases.

The observed differences in the acoustical properties are also both physically and statistically meaningful.

#### 1. Effect of thermal treatment on spruce boards with different degree of natural seasoning

The variation observed in density and mechanical properties of the spruce boards after thermal treatment, sorted by seasoning groups, are shown in Figure 6.

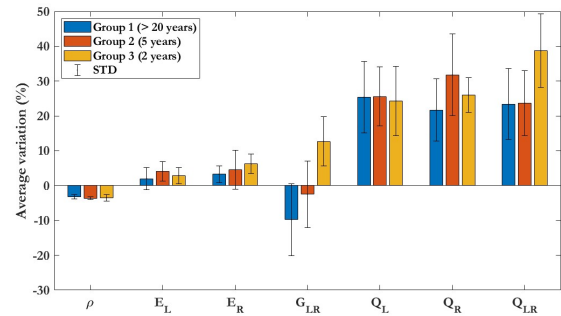


FIG. 6. Variation of the density and of the anisotropic mechanical properties of the boards after the thermal treatment. Data are sorted by three groups of seasoning.

#### D. X-Ray microtomography

The X-ray microtomography observations were performed by direct visual comparison of the reconstructed volumes before and after thermal treatment. RT and LT slices were inspected using equivalent rendering parameters (contrast, brightness, and voxel scaling) to allow a consistent qualitative comparison of microstructural features. In particular, the absence of high-attenuation material inside resin canals was evaluated by visual inspection of multiple slices per specimen. Dimensional changes could not be reliably inferred from visual inspection alone (Fig. 7). Therefore, a quantitative comparison was performed by registering the pristine and thermally modified volumes in VG Studiomax 2024. The reconstructed geometries were used to compute voxel-to-voxel displacement maps and associated displacement histograms. Figure (Fig. 8), left, shows a displacement map obtained after superposition of the pristine volume onto the thermally modified one. Colors and associated vectors represent the local normal displacement between the two registered RT sections, with negative values indicating contraction relative to the pristine geometry. Figure 8, right, reports the histogram of these local displacements over the analyzed section, providing a statistical description of the dimensional variations distribution along the surface. The histogram peaks at negative values, consistent with contraction. For the representative sample shown, the mean shrinkage is around  $-2 \mu\text{m}$  across the section. Canal interiors change from high-attenuating content to air-filled lumen. Given the voxel size ( $3 \mu\text{m}$ ) and  $N = 3$ , specimens were interpreted semiquantitatively; nevertheless, they aligned with macroscopic trends reported in Table I.

TABLE II. Average density and mechanical properties of the spruce samples before and after the thermal treatment.  $E'_L$ ,  $E'_R$  and  $G'_{LR}$  are respectively the longitudinal, radial and shear storage moduli.  $Q_L$ ,  $Q_R$  and  $Q_{LR}$  the the longitudinal, radial and shear quality factors. Values represent averages across the samples. p-value is referred to a paired Student's T-test.

Statistic	Density $Kgm^{-3}$		$E'_L$ GPa		$E'_R$ GPa		$G'_{LR}$ GPa		$Q_L$ -		$Q_R$ -		$Q_{LR}$ -	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
Average	388±2	374±2	10.5±0.2	11.0±0.2	0.8±0.04	0.9±0.04	1.1±0.04	1.1±0.04	122±2	152±2	54±2	68±2	72±2	92±2
STD	13	13	1	1	0.1	0.2	0.1	0.2	8	10	3	5	7	7
COV (%)	3	4	9	10	17	18	11	16	7	7	6	8	9	8
Avg. variation (%)	-3.4		4.4		4.7		-0.1		25		26		28	
p-value	0.00		0.00		0.00		0.50		0.00		0.00		0.00	

TABLE III. Average acoustical properties of the spruce samples before and after the thermal treatment. Anisotropy is expressed as the ratio of the storage moduli in the longitudinal and radial direction  $E'_L$  and  $E'_R$ .  $RR$  is the Radiation Ratio and  $ACE$  the Acoustic Conversion Efficiency as defined in the main text. Subscripts  $G$  and  $R$  refer to the figures calculated for guitar and violin families of instruments respectively, as per<sup>18</sup>. Values represent averages across the samples. p-value is referred to a paired Student's T-test.

Statistic	$E'_L/E'_R$ -		RR $m^4Kg^{-1}s^{-1}$		ACE $m^4Kg^{-1}s^{-1}$		$RR_G$ $m^4Kg^{-1}s^{-1}$		$RR_V$ $m^4Kg^{-1}s^{-1}$		$ACE_G$ $m^4Kg^{-1}s^{-1}$		$ACE_V$ $m^4Kg^{-1}s^{-1}$	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
Average	12.7±0.7	12.7±0.7	13.4±0.1	14.4±0.1	1634±20	2197±20	8.4±0.1	9.0±0.1	5.5±0.1	5.9±0.1	1008±20	1356±20	432±9	584±9
STD	2.4	2.4	0.9	0.8	176	245	0.4	0.4	0.2	0.3	91	120	32	47
COV (%)	19	19	6.6	5.6	11	11	5.1	4.2	4.3	4.5	9.1	8.9	7.4	8.1
Avg. variation (%)	0.1		7.6		34		7.0		6.8		35		35	
p-value	0.47		0.00		0.00		0.00		0.00		0.00		0.00	

## E. FEA analyses

The first ten modal shapes with their relative frequencies of the pristine spruce soundboard are reported in Figure 9. Mode frequencies of pristine and thermally modified soundboards, along with their differences are reported in Figure 10. The average difference in frequency is 1.7% and spans between 1.4 and 2.0%. The mode overlap between pristine and thermally modified spruce, calculated according to the modal assurance criterion, is reported in Figure 11 for the first twenty modes. All diagonal values exceed 0.95, whereas off-diagonal values remain below 0.04. The calculated bridge admittance  $Y$  and the SPL are reported in Figure 12. The calculated admittance reflects the slight eigefrequency shift and shows a higher peak admittance at resonance (+0.82 dB on average across the first 20 peaks). SPL shows an average difference of +2.2 dB in peak amplitude across the first 20 peaks while the average difference between the two SPLs across the whole considered range is +1.3 dB. The spectral centroid shows a shift of +1.8 Hz (+0.0045 for the normalized spectral centroid) between the thermally modified and pristine spruce soundboards.

## IV. DISCUSSION

The observed variations in sample dimension were consistent with those reported in the literature. In particular, no measurable shrinkage was detected in the longitudinal direction, suggesting that any variation may have been below the measurement precision, whereas shrinkage was observed in the radial and tangential directions, with greater dispersion in the latter - presumably due to the larger measurement uncertainty associated with the thinness of the samples in this direction. Similarly, the observed mass reduction agrees with literature values. The values of the physical, mechanical, and acoustical properties indicate that thermal modification at 160 °C produced systematic and statistically significant changes in spruce wood. A modest but consistent reduction in density was observed. This decrease is compatible with the volatilization of resin, as confirmed by the X-ray microtomography images and with additional mechanisms such as partial loss of bound water, as previously reported for thermally modified wood<sup>5</sup> and for this process in particular<sup>14</sup>. In parallel, longitudinal and radial stiffness increased by +4.4 % and +4.7 %, respectively, while the shear modulus and wood anisotropy remained

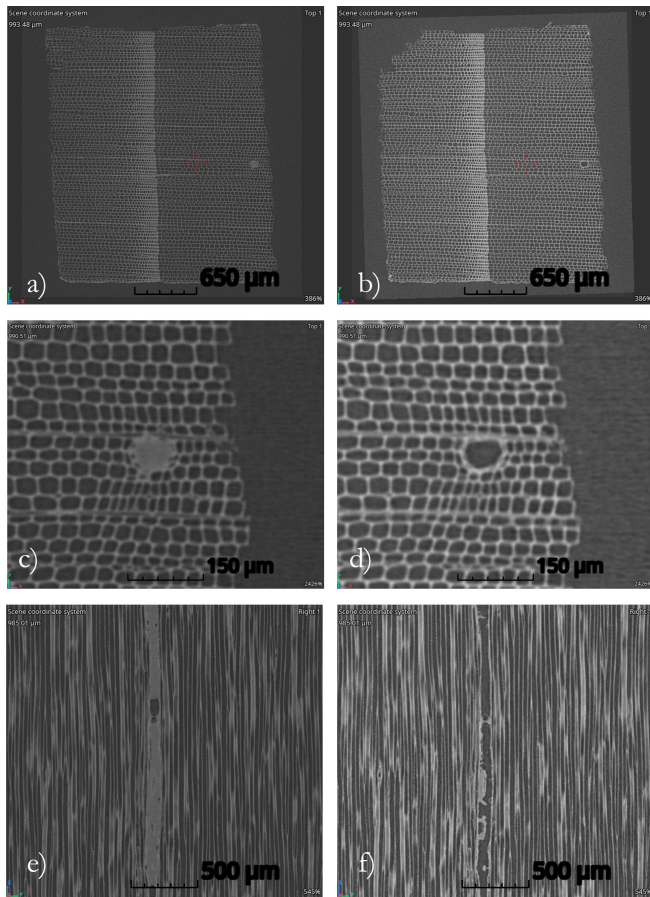


FIG. 7. X-Ray microtomography reconstruction of a spruce sample - RT section. Left column: pristine wood, right column: thermally modified wood. a),b) RT section of the sample, c),d) RT section detail of a resin canal, e),f) LT section detail of a resin canal.

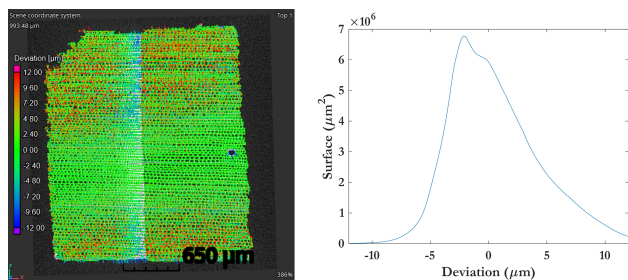


FIG. 8. Dimensional comparison between pristine and thermally modified samples obtained from registered X-ray microtomography volumes. Left, color map of local normal displacements across the RT section (units:  $\mu\text{m}$ ), where negative values indicate contraction. Right, histogram of the displacement distribution showing the surface fraction associated with each displacement value.

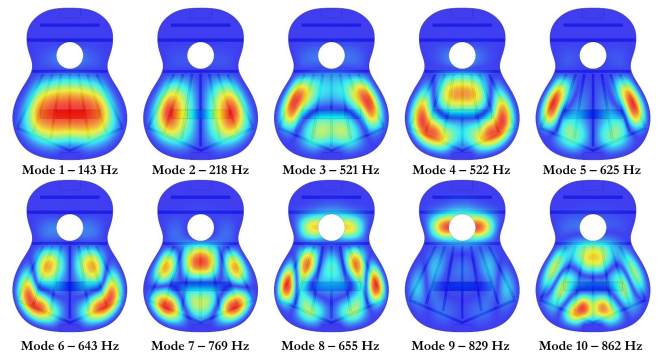


FIG. 9. The first ten eigenmodes and eigenfrequencies of the guitar soundboard calculated by FEA. Pristine spruce properties were used for the soundboard and bracing.

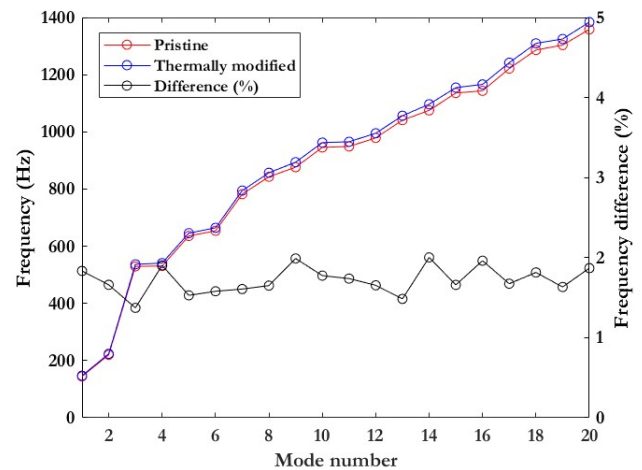


FIG. 10. Comparison between the eigenfrequencies of the pristine and thermally modified spruce soundboards.

essentially unaffected on average. This finding is also consistent with the literature, both for this specific process and for other treatment types<sup>15,16</sup>. A marked reduction in damping was detected in all directions ( $-25$  to  $-28\%$ ). While the trend is consistent with previous findings<sup>17</sup>, the decrease observed in this study is notably more pronounced. These changes are reflected in the acoustical properties: the enhanced stiffness-to-density ratio resulted in a significant increase in the radiation ratio, and the reduced damping resulted in a remarkable enhancement of the acoustic conversion efficiency (ACE). The anisotropic forms of radiation ratio and ACE exhibited a very similar trend, consistent with the absence of appreciable changes in anisotropy. These findings imply that, when heat-treated wood is used to build an instrument there is a potential increase in the sustain, although its practical relevance may be limited<sup>34</sup>. When samples were grouped by degree of natural seasoning, the overall trends induced by thermal treatment remained consistent, across density, storage moduli, and loss fac-

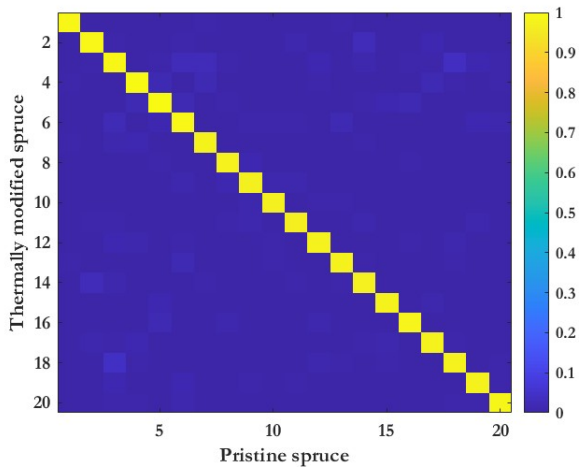


FIG. 11. MAC plot for the guitar soundboard relative to the first twenty mode shapes calculated assuming pristine and thermally modified spruce properties as per Table II.

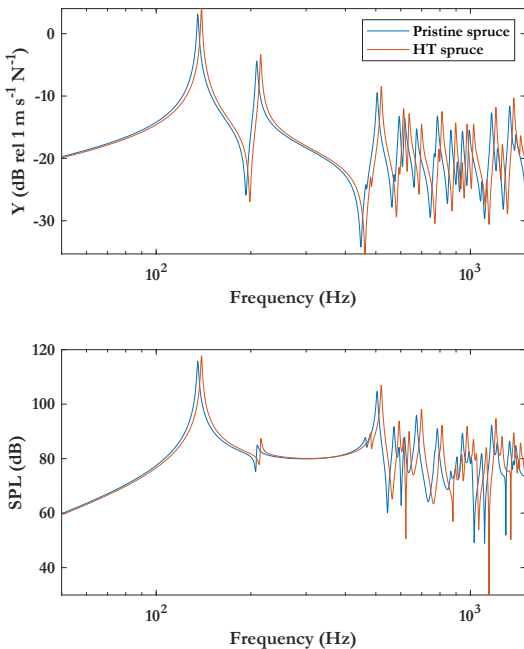


FIG. 12. Variation of bridge admittance  $Y$  and sound pressure level obtained by finite element analysis of a classical guitar soundboard realized with pristine and thermally modified spruce wood.

tors, though the magnitude of variation was slightly different across groups. The only exception regards the shear properties where larger variations were observed for samples that underwent a shorter natural seasoning, presumably due to the presence of free water in the wood. These properties however showed a large variability and their comparison before and after the treatment a low statistical significance. Overall, the results

suggest that thermal modification exerts its effects beyond the differences introduced by natural aging, and may even homogenize material response across boards of different histories. X-ray microtomography revealed the emptying of resin canals in spruce, as well as measurable dimensional shrinkage. These micro structural modifications provide a plausible explanation for the reduced density and damping, as volatile extractives and resins are eliminated while cell-wall stiffness is preserved or enhanced. Confirmation of these mechanisms however would require further, more specific analyses. Finite element analysis of a guitar soundboard suggests that the observed property modifications can translate into measurable, albeit subtle, effects on the assembled plate and, potentially, the finished instrument. Modal frequencies increased slightly (+1.7 % on average), while mode shapes remained virtually unchanged (MAC > 0.95 for all modes). This finding is in line with the experimental data of rectangular boards reported in<sup>17</sup> and indicates that, while the distribution of modes is preserved, their frequencies are only marginally affected, and such small differences would be difficult to detect experimentally. A simple statistical analysis based on Lehr's rule of thumb<sup>35</sup> suggests that, given a typical frequency measurement uncertainty of 1.5 Hz, at least five pairs of guitars would be required to discriminate two instrument populations differing by the observed modal frequency shifts with 95 % confidence by taking into account the monopole type mode of vibration which largely characterizes the guitar timbre<sup>36</sup>. Moreover, the coupling of the soundboard with air, sides and back, typically tends to mitigate the dispersion of the monopole frequency induced by modified stiffness or mass in a complete instrument<sup>37,38</sup>, likely making these differences even more subtle. This finding is consistent with the small variations measured in the spectral centroid of the SPL that, along with the correspondent slight change of the normalized spectral centroid, indicates that a change in the perceived overall timbre of the instrument is unlikely to be observed. Previous studies on just noticeable differences in SC and NSC in fact have shown that the perception threshold is at least one order of magnitude higher with respect to the calculated value<sup>39,40</sup>. It also aligns with previous studies showing that the influence of bracing patterns on vibrational behavior generally outweighs that of variations in material properties<sup>33</sup>. As for the simulated bridge admittance and SPL, the increase observed both in the average response and at the resonance peaks is consistent with the enhanced RR and ACE. It also suggests that instruments designed with identical soundboard geometry but using heat-treated wood are likely to exhibit stronger coupling between the strings and the soundboard, potentially resulting in a slightly louder initial attack. Studies on differential thresholds indicate that SPL differences as low as 1 dB can be perceptible, particularly in the 100 Hz–1 kHz range<sup>31</sup>, suggesting that the predicted changes may likewise be perceptible. While this effect may contribute to a louder instrument, especially near resonance frequencies, it may also increase the risk of over-coupling,

leading to unwanted effects and uneven tonal qualities from one note to another, commonly referred to as wolf notes<sup>41–43</sup>. However, damping in real instruments is influenced by several factors beyond the intrinsic material properties, including varnish, air coupling, energy dissipation through the sides and back, and interaction with the player’s body. This suggests that the contribution of decreased internal friction, though relevant, may be overshadowed by other mechanisms, as reported in a recent experimental study<sup>34</sup>. Finally, it is worth noting that these observations are based on a soundboard design where geometry was kept constant while wood properties varied. If a design approach explicitly accounting for material property differences was adopted, the outcomes could be expected to differ<sup>44</sup>. These results indicate that, while thermal modification effectively affects the wood properties, its perceptible effect at the level of a complete instrument may be limited and may on the contrary exacerbate problems such as wolf notes.

## V. CONCLUSIONS

Thermal modification at 160 °C was shown to systematically alter the physical, mechanical, and acoustic properties of spruce wood. The considered treatment produced a modest reduction in density, accompanied by a slight increase in stiffness and markedly reduced damping, leading to physically and statistically significant enhancement of radiation ratio and acoustic conversion efficiency. Microstructural observations support these macroscopic trends, revealing the volatilization of resins and extractives while preserving the cellular structure. Finite element analysis of a guitar soundboard suggests that these property changes can translate into subtle but potentially perceivable effects in a complete instrument, including a slightly louder attack and an increased prominence of resonance peaks. However, the overall vibrational patterns remain largely unaffected, and the practical influence of reduced internal friction is likely moderated by other instrument-specific factors. Luthiers may therefore value thermal treatment primarily for its improvements in dimensional stability and aesthetics, while expecting only little differences in acoustic output compared to pristine wood.

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## AUTHOR DECLARATIONS

The author have no conflicts to disclose. The data that support the findings of this study are available within the article.

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