

Wood Physics/Mechanical Properties

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Effect of heat and steam bending on the longitudinal and radial mechanical properties and derived acoustical indices of spruce and maple wood

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Abstract: This study investigates the effects of steam and heat bending on the longitudinal and radial vibromechanical properties of spruce (*Picea abies*) and maple (*Acer spp.*). More than 100 thin beams were bent to nominal strain levels of approximately 0.7 % and compared to reference specimens using laser vibrometry and modal analysis combined with finite element model updating. X-ray microtomography (2 μm voxel size) was performed on selected specimens to examine the cellular-scale integrity after bending. After re-conditioning at 50 % RH and 25 $^{\circ}\text{C}$, density showed no statistically significant change. A modest reduction in longitudinal stiffness was observed, more pronounced in spruce, while the longitudinal loss factor increased significantly for both species, leading to decreased radiation ratio and acoustic conversion efficiency indices, particularly in spruce. These results provide quantitative trends relevant to manufacturing of bent wood, the mechanical and vibroacoustical design of bent wood parts and structures.

Keywords: wood mechanics; wood bending; modal analysis; finite element model updating; X-ray microtomography; acoustical indices

1 Introduction

Wood is the material of choice in many industrial sectors, such as furniture making, buildings, packaging, etc. due to its widespread availability, ease of machining and neutral carbon footprint (Ross 2000). Besides, it is a natural composite material, featuring a high stiffness to weight ratio, resulting in remarkable structural properties which make it a good candidate for structural elements (Ashby and Jones 2012). To realize the final objects, which sometimes have complex shapes, the wood needs to be seasoned and then worked on, usually by machining, which involves the loss of a large fraction of material as chips (Sarmin et al. 2023). A complementary process is wood bending: a widely used technique in the production of wooden objects, including furniture pieces, structural beams, and stringed musical instruments such as violins and guitars (Mik  sik et al. 2023; Prekrat et al. 2021; Wright et al. 2013). This method is particularly attractive from both a technological and an environmental point of view, as it allows the shaping of wood rather than carving it, which can lead to reduced material use. This last aspect is gaining importance since environmental repercussions of wood products is being recognized more and more while environmental awareness and demand for forest products expand (Sarmin et al. 2023). In the wood structure, crystalline cellulose microfibrils are embedded in a matrix of hemicellulose and lignin in a complex hierarchical structure making it an anisotropic material (Ross 2000). Lignin in particular, is an amorphous hydrophilic compound with a glass transition temperature around 90–130 $^{\circ}\text{C}$ that can be lowered significantly by heating, moistening or chemical treatment (Olsson and Salm  n 1992), allowing for the plasticisation of wood and making these approaches the usual way to bend wood (Angelski 2014; Wu et al. 2022). Despite the highlighted advantages, bending can significantly affect the mechanical properties of wood, which in turn influences the final characteristics of the manufactured objects (As et al. 2018). Besides being

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hygroscopic, wood is also a viscoelastic material whose stiffness and damping depend on moisture content (including adsorption/desorption hysteresis) (Gerhards 1982; Stöcklein et al. 2024) and temperature (Kelley et al. 1987; Salmén 1988; Sulzberger 1955), as well as loading history (Montero et al. 2012). Therefore, thermo-hygro-mechanical bending may alter the measured dynamic response through reversible viscoelastic effects (relaxation, mechanosorption) and/or irreversible mechanisms (plasticisation, thermal modification), in addition to geometrical curvature.

Although bending has been used extensively through history up to now, the specific impact on its mechanical and damping properties remains underexplored. Only a few studies have analysed the impact of bending on the longitudinal or radial elastic properties using acoustic or ultrasonic techniques (Ümit Büyüksarı and As 2013; Woodhouse and Barlow 1993), highlighting a decrease in the speed of sound and stiffness. In these cases however, the impact of bending on the damping was not assessed, while the variation of the mechanical properties was measured on a small number of samples, making the results of little statistical significance.

1.1 Research aim

This research aims to address this shortfall by investigating how the bending process, involving the application of water, heat, and mechanical force, impacts on the anisotropic elastic and damping properties of spruce and maple wood along the longitudinal and radial directions. These effects were studied experimentally by characterising the samples both before and after the bending process, after conditioning to a constant nominal moisture content, to provide a pairwise comparison for each specimen. Reference samples were characterised before and after heating or steaming without bending to determine whether the observed changes were inherent to bending or to heating/steaming alone, thereby disentangling the two effects. Moreover, by analysing a large set of samples would allow to provide a statistically significant database. This aspect is particularly relevant to structural components making, as well as musical instruments soundboards, where the mechanical and damping properties of the wood have a great influence on the structural and acoustical properties of the manufactured objects. From a mechanical and acoustical perspective, a deeper understanding of wood bending's effect could help establish a direct link between the process parameters and the structural properties and sound radiation of the bent wood items. Additionally, from a technological and environmental viewpoint, it would help determine when wood bending is more advantageous than alternative techniques,

such as carving. By utilising modal analysis and finite element model updating (FEMU), the study seeks to detect changes in the longitudinal and radial modulus of elasticity and loss factors, density, and specific longitudinal modulus of wood. Besides, X-ray microtomography was used to evaluate the microstructural state of the wood structure as a consequence of bending. Spruce (*Picea Abies*) and maple (*Acer spp.*) wood were selected because of their widespread use in furniture making, buildings and musical instruments making.

Specifically, the study seeks to:

- Quantify the physical, mechanical and acoustical properties changes along the longitudinal (L) and radial (R) directions: Determine how bending influences density, the modulus of elasticity, the specific modulus, the loss factor and other derived acoustical merit factors such as the radiation ratio and the acoustic conversion efficiency.
- Contribute to the scientific knowledge on wood bending by reporting effective post-processing changes in stiffness and damping after re-conditioning, while explicitly discussing limitations related to thermo-hygro-mechanical history, moisture state and detection limits of imaging.

By achieving these objectives, the research aims to bridge the gap between traditional craftsmanship, industrial practice and modern scientific inquiry, ultimately enhancing the quality and performance of bent wood objects through a deeper understanding of material properties and their manipulation. As a final remark, the present study focuses on the changes induced by bending on the *effective properties*, i.e. the overall macroscopic properties of wood. This was achieved by conditioning both the pristine and the bent wood samples at 50 % RH and 25 °C until equilibrium was reached, before performing any measurement. The advantages and limitations of this approach will be commented throughout the text.

2 Materials and methods

2.1 Samples preparation and conditioning

Fifty-two samples of red spruce (*Picea abies spp.*) and 60 samples of maple (*Acer spp.*) were cut from wood boards provided by two specialised sawmills: *Le Bois de Lutherie* (France) and *Rivolta S.N.C.* (Italy). The samples consisted of thin rectangular beams with standardised dimensions as follows: length of 15 cm, width of 1.4 cm, and thickness of 2.5–3.5 mm (typical of luthiery stock). The average density of the samples (determined as mass/volume) was 335 kg/m³ for

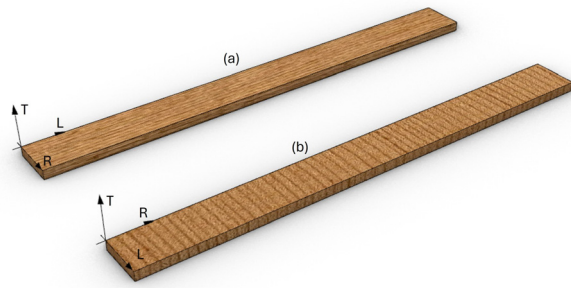


Figure 1: Geometry of the samples used in the study and frame of reference: (a) longitudinal (L) samples, (b) radial (R) samples. The tangential (T) direction is perpendicular to the sample planes. Sample dimensions: $L = 150$ mm, $b = 14$ mm, $h = 2.5\text{--}3.5$ mm.

spruce and 660 kg/m^3 for maple. The samples were cut so that the shortest dimension was aligned with the tangential (T) direction while the longest dimension was aligned with the longitudinal (L) direction or the radial (R) direction, as reported in Figure 1.

As for spruce, 27 samples, coming from one single board and 30 samples coming from another board were analysed. Overall, 29 samples were cut along the L direction and 28 along the R direction. As for maple samples, all samples came from the same board. 22 samples were cut along the L direction and 24 along the R direction.

Although each specimen was characterised before and after the bending process, because spruce originated from two boards while maple originated from one board, and because group sizes are unbalanced, part of the observed variability may be confounded with between-board variability. This limitation is discussed and motivates a randomised blocking/mixed-effects design for follow-up work.

To control the moisture state, the parts were kept in a climatic chamber at stable relative humidity level (50 % RH and 25°C , as in (Pérez et al. 2011)) until their change in mass was less than 0.1 % after 24 h before measuring their properties and performing the bending process, as suggested in (EN 318:2004 *Wood-based panels – Determination of dimensional changes associated with changes in relative humidity*, SIST EN 318 2004). The moisture content (MC, %) was measured using oven-dry mass m_0 , measured after the study, and mass at a given state m_i :

$$MC = \frac{m_i - m_0}{m_0} \quad (1)$$

2.2 Bending processes

Bending was performed according to two of the most common methods, i.e. steam bending and heat bending. These processes were as follows.

2.2.1 Steam bending

In steam bending, the samples were put in a mould with movable parts and the mould was put in a closed container with water on the bottom. The container was heated up until water was boiling, exposing the sample to saturated steam at a temperature of $\sim 98^\circ\text{C}$. After 10 min, the movable mould parts were pressed together with a clamp (see Figure 2(a)), giving the wood samples the desired shape, and re-heated by exposure to steam for five more minutes to stabilise the definitive shape. The samples were then let to cool down and lose humidity at room temperature for a few hours and then transferred to a 3-D printed mould where they were left to condition again at 50 % RH in the climatic chamber until the equilibrium was reached, as described above.

2.2.2 Heat bending

As for heat bending, the wood samples were bent with a *bending iron*, a device commonly used by stringed musical instruments makers to bend wood. This device consisted of an aluminium element with different radii of curvature, heated by an electric resistance. This device is reported in Figure 2(b). The bending iron was heated up to 220°C (a typical temperature used in musical instrument making) and bending was performed by hand, by pressing the samples against the bending iron with the help of a steel strip from the largest radius of curvature up to the desired one. The shape of the bent samples was compared with a reference while bending was carried out progressively until the desired curvature was achieved. Although water is often used to prevent burning and is considered to help wood to reach the desired shape, the bending was performed without moistening the samples. In the case of wavy/flamed maple, water can induce debonding between layers and therefore break the samples. Moreover, moistening the samples induces greater springback, i.e. partial recovery of the initial shape while the samples dry after the bending, and prolong the time required to reach the equilibrium moisture afterwards and was discarded for these reasons. While the complete process lasts approximately 2 min, the contact area between the sample and the hot surface represents only a fraction of the total area; therefore, the localised heating lasts significantly less than the total duration. A thermocouple was inserted into an additional sample to measure the temperature variation during the bending process. A photograph of the sample with the thermocouple, together with the measured temperature as a function of time, is shown in Figure 3. The temperature in the sample reached almost 140°C , but the duration for which it exceeded 100°C is approximately 14 s. No visible charring or discoloration was

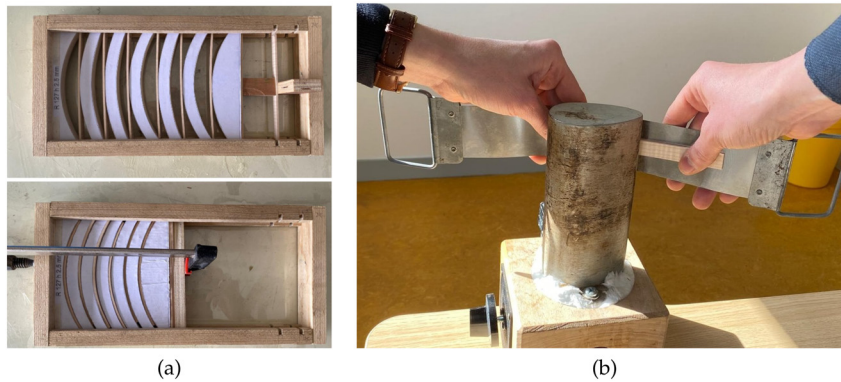


Figure 2: Wood bending process. (a) Steam bending. Above: straight samples in the mould, below: mould clamped. (b) Heat bending with a *bending iron*. The sample is held against the heated surface with a thin steel strip with handles.

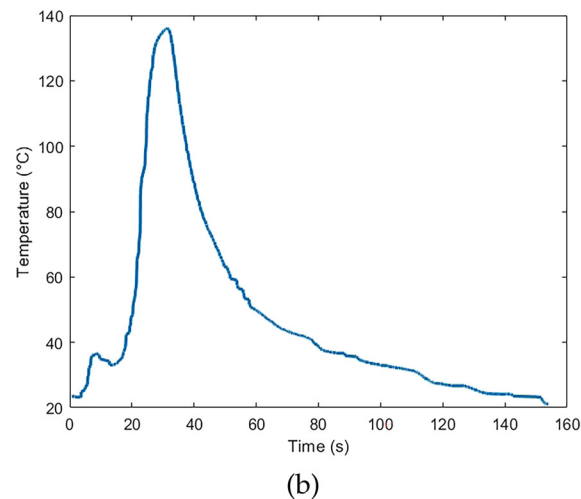
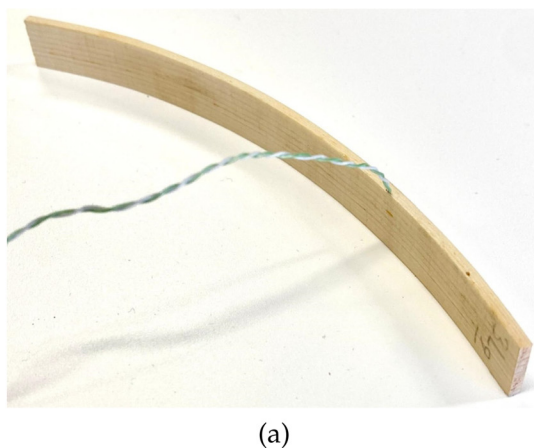


Figure 3: Temperature measurement during the heat-bending process. (a) Positioning of the thermocouple in a spruce sample. The sample size is $2.5 \times 14 \times 145$ mm and the thermocouple is positioned inside the sample at approximately 0.5 mm from the surface in contact with the bending iron. (b) Temperature profile during the bending process.

observed on the processed specimens under normal lighting, but quantitative colorimetry and thermal-dose monitoring were not performed and would be the subject of a future work. Once bent to the desired shape, the samples were put in a 3D-printed mould and left to condition at 50 % RH in the climatic chamber.

2.3 Bending strain and samples shape

The equivalent bending strain was calculated following equation (2) (with ε is the strain, r the radius of curvature and h the thickness).

$$\varepsilon = \frac{h}{2r} \quad (2)$$

Without heating and/or steaming, the bending process would induce an equivalent strain higher than the tensile strain at failure (Glišović et al. 2017). The combination of

water and heat softens the amorphous components of the wood, allowing it to reach such large strains without damage. Samples were bent with both techniques, aiming at a constant radius of curvature. The radius r was calculated to achieve a nominal strain ε of 0.7 %, as per equation (2) and resulted in two different nominal radii: 250 mm for the 3.5 mm thick samples and 180 mm for the 2.5 mm thickness h samples. For the steam bending technique, samples were over curved to take into account the spring back. The over curved radii were calculated empirically and resulted in a mould radius of 177 and 127 mm for the nominal radii of 250 and 180 mm respectively. After bending and conditioning, the samples geometry was retrieved by scanning them with an optical scanner. An average radius of curvature was calculated by fitting a circular arc through five points along the samples length and the geometry of the samples was reconstructed by importing the scan in a 3-D drawing software. The geometry was later used for the FEMU analyses (see below). In the following, the “nominal strain” refers to

the process target strain derived from tooling nominal radius and thickness, while the “measured strain” is computed *a posteriori* from the fitted curvature after conditioning. Neutral-axis shifts and through-thickness hygro-thermal gradients were not measured; thus, the strain field is treated as an effective geometric descriptor rather than an in-process local measurement.

2.4 Reference samples

For each batch of bent samples, a subset of samples was not bent but only exposed to the heat or steam. In heat bending case, the sample was leaned against the bending iron for approximately the same time required to bend a portion of the other samples (see 2.2.2). In steam bending case, the samples were exposed to steam, along with the other samples without pressing them into the mould. These subsets were considered as a reference and were used to determine whether the heating/steaming process alone resulted in a considerable change of the properties, independent from the bending. Test and reference samples were divided as reported in Table 1.

2.5 X-ray microtomography of spruce and maple samples

An *EASYTOM* (RX-SOLUTION) equipment was used to scan portions of spruce and maple samples obtained after bending. These portions had dimensions of $2 \times 2 \times 10$ mm. Although a comparative scan of the same samples before and after bending could, in principle, reveal local damage or deformation, this was not performed due to the difficulty of bending specimens of such small dimensions – required for high-resolution microtomography – under conditions comparable to those applied to the full samples. The specimens were scanned at a resolution of $2 \mu\text{m}$ with a voltage of 60 KV and a current of $80 \mu\text{A}$. The number of projections was fixed at 1,440 over 360° with an exposure time of 500 ms and an average of five images in 4 pass plus reference mode. These parameters lead to a tomography time of 1 h per specimen. The reconstruction based on the radiographs was performed

with *X-act* software to create vertical slice with filtered projection algorithm. The slices were analysed with *VG Studiomax 2024* software.

2.6 Mechanical properties characterisation

2.6.1 Samples vibrometric analysis

Modal analysis was conducted before and after the bending process, measuring the first bending mode with a laser vibrometer PDV-100, exciting the samples with an automated impact hammer. Measurements were carried out with the vibrometer software which allows to identify the frequency, as well as the modal damping by fitting the measured response function in the frequency domain. The loss factor was determined as twice the modal damping of the first bending mode identified. Since the samples were relatively small and their support conditions could significantly influence the measurements, they were suspended using two thin wires positioned at the nodal lines of the first vibration mode of the bar (i.e. approximately 0.224 L from each end), as shown in Figure 4. Although the exact nodal positions were determined for each individual sample, the adopted spacing was based on oscillating beam theory and was consistent with the finite element analysis (FEA) results, including the case of curved samples. Finally, a sensitivity analysis of the vibrometric measurements with respect to sample positioning was carried out, showing that the error in both frequency and damping due to misalignment with respect to the wires was negligible, even in the case of significant misalignment (COV of 0.01 % and 0.3 % on frequency and damping respectively for a batch of 10 measurements on the same sample).

2.7 Calculation of the mechanical properties from the measurements

2.7.1 Analytical model for flat specimens

The mechanical properties of the straight samples were retrieved from the analytical formula that describes the first

Table 1: Wood samples used in this study divided by wood species, bending technique, wood cutting and bending direction. For each combination, the number of samples subject to bending (Bent) or only exposed to heat or steam (Ref.) is reported.

Direction	Spruce – steam bent		Spruce – heat bent		Maple – steam bent		Maple – heat bent	
	Bent	Ref.	Bent	Ref.	Bent	Ref.	Bent	Ref.
L direction	8	4	10	4	6	2	12	4
R direction	15	5	6	2	7	2	6	5

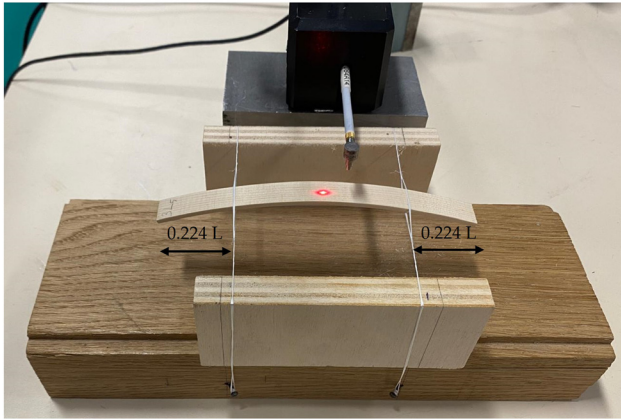


Figure 4: Experimental setup used for the vibrometric analysis of the samples. Each sample was suspended using thin wires positioned at the nodal lines and excited by an automated impact hammer. The local velocity was measured using a laser vibrometer.

vibration frequency of a Euler–Bernoulli free-free beam (Rao 2007):

$$f_1 = \frac{4.73^2}{2\pi} \sqrt{\frac{EI}{\rho AL^4}} \quad (3)$$

where, I is the moment of inertia and A the cross-sectional area, ρ the density, L the length and E the Young's modulus. Assuming a rectangular section, $I = \frac{bh^3}{12}$ and $A = bh$. The elastic modulus E can hence be calculated as:

$$E = 0.9464 \frac{f_1^2 \rho L^4}{h^2} \quad (4)$$

The value 4.73 is associated to the boundary conditions and the hypotheses used to model the beam. In case the h/L ratio increases above 0.002, as for the thicker samples, the conditions are slightly different than Euler and correction was also implemented as per (Kocatürk and Şimşek 2005). While for isotropic materials the identification of mechanical properties can also be performed using higher-order modes, in orthotropic beams the coupling between flexural and torsional modes increases the influence of the shear

modulus in higher modes (Miller and Adams 1975). Therefore, only the first mode was considered both for the analytical and for the FEMU identification (see later).

2.7.2 Finite element model updating (FEMU)

Finite element model updating (FEMU) is an inverse identification approach in which selected model parameters are iteratively adjusted to minimise the mismatch between measured and simulated modal features, such as proposed in (Viala et al. 2018). Here, the first bending eigenfrequency was adjusted to retrieve the elastic modulus, with geometry and density prescribed. A computer aided design (CAD) model of each sample was created using SOLIDWORKS, based on the images retrieved by optical scanning of the edge of the part. Figure 5(a) shows the CAD model of one sample after bending. The parts were then exported in COMSOL under the format parasolid. The orthotropic parameters were implemented and oriented using the curvilinear coordinates features. The coordinate frames are shown in Figure 5(b). The mesh size was defined to display at least six quadratic elements per flexure waves wavelength (mesh convergence is reported in Figure 1 in the Supplementary Materials) and the modal analysis was performed using the MULTifrontal Massively Parallel sparse direct Solver (MUMPS) solver taking into account the first eigenmode, as displayed in Figure 5(c). A sensitivity analysis (see Figure 2 in the Supplementary Materials) was conducted to verify that on bent objects mainly density and longitudinal modulus are influential on the first mode, with a small contribution of ν_{LT} , similarly to (Viala and Cabaret 2024). The same analysis highlighted that, while the first mode of vibration is mainly affected by density and longitudinal modulus, the shear properties slightly affect the high order modes. As a consequence, only the first mode of vibration was considered in the analyses to retrieve the wood properties. By iteratively adjusting the model parameters in the FEMU approach, a close match between simulation and experimental results was achieved, and the elastic modulus

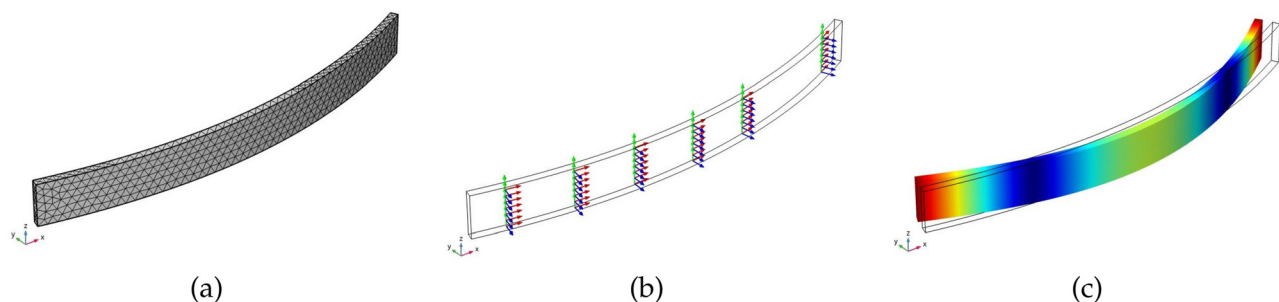


Figure 5: Details of the finite element analyses of a bent wood sample: (a) mesh of the bent samples, (b) associated coordinate frames taking into account wood grain orientation and (c) computed modal shape.

was identified once the relative difference in frequency was lower than 0.1 %, close to the measurement precision. It has to be pointed out that the eigenfrequency analysis assumed a stress-free configuration, while residual stresses after bending, potentially having an influence on frequencies, were not measured and therefore not taken into account. The identified parameters should be hence interpreted as effective properties of the post-processed specimens at the measurement state. This limitation motivates future analyses to quantify residual stresses and their effect.

2.8 Calculation of the acoustical properties from the measurements

Since the results of this study can be interesting for stringed musical instruments makers and industries, two derived figures related to the acoustical properties were also calculated. The radiation ratio RR_i , associated with the acoustic loudness, was calculated for the i direction (in this case L or R) as:

$$RR_i = \sqrt{\frac{E_i}{\rho^3}}. \quad (5)$$

The acoustic conversion efficiency (ACE), a similar figure that takes into account the loss factor of the material and can be associated with the amplitude of the resonance peaks at the eigenmodes (Ono 1996; Wegst 2006), was calculated as:

$$ACE_i = \frac{RR_i}{\eta_i}. \quad (6)$$

2.9 Statistical significance tests

Paired statistical comparisons were performed to evaluate the effect of the treatment between the before and after states measured on the same specimens. For each specimen i , the paired difference was defined as:

$$d_i = X_{i, \text{after}} - X_{i, \text{before}}.$$

The null hypothesis was that the mean paired difference was zero ($H_0 : \mu_d = 0$). This hypothesis was tested using a paired Student's t -test,

$$t = \frac{\bar{d}}{s_d / \sqrt{n}},$$

where $\bar{d}$ and s_d are the mean and standard deviation of the paired differences, respectively, and n is the number of paired specimens. The test statistic was evaluated against a Student t -distribution with $n - 1$ degrees of freedom to

obtain the corresponding p -value. Smaller p -values indicate stronger evidence that the treatment induced a systematic change. A significance threshold of $p < 0.05$ was adopted. As analysis is paired, the result depends on the variability of the within-specimen differences rather than on the difference between the two group means.

3 Results

3.1 Moisture content

The mass of each specimen was measured before and after bending process, and a reference mass were measured after heating in an oven at 103 °C until no significant mass change (<0.5 %) was observed after 1 h. The moisture contents before and after are given for each species and directions in Table 2. The differences in MC ranged from 0 (spruce R direction) to 0.3 % (spruce L, maple L, maple R directions).

3.2 Measured samples strain

The actual strain of the samples was measured from the radii of curvature. The average strain and its standard deviation are reported in Table 3. The complete dataset is reported in the Supplementary Materials.

3.3 X-ray microtomography of spruce and maple samples

X-ray microtomography images of the samples are reported in Figure 6. RT, LT and LR sections are shown for both maple and spruce.

3.4 Effect of bending process on density, mechanical properties and acoustical indices

The results for spruce in L and R directions are given in Table 4 while those for maple are given in Table 5. Results included density ρ , Young's modulus in L and R direction E , loss factors in L and R direction η , specific longitudinal modulus (E in GPa divided by the density) before and after bending process. The derived acoustical indices of both the bent and the reference samples in terms of Radiation Ratio (RR) and Acoustic Conversion Efficiency (ACE) are also reported. These results referred to both bending techniques

Table 2: Annual rings width (ARW), latewood proportion (Lw %) and moisture content (MC) before and after treatment, obtained with dry mass. Values are reported as mean (μ) $\pm$ standard deviation (σ). n denotes the number of samples. p -Value is obtained through pairwise comparison.

Material	Direction	n	ARW	Lw %	MC before ($\mu \pm \sigma$)	MC after ($\mu \pm \sigma$)	p -Value
Spruce	L	18	2.1 ± 0.5	5–10	10.6 ± 0.2	10.3 ± 0.4	$<10^{-4}$
Spruce	R	21	1.9 ± 0.2	5–10	10.3 ± 0.3	10.3 ± 0.3	1
Maple	L	15	4.7 ± 0.8	10–15	10.3 ± 0.3	10 ± 0.5	0.06
Maple	R	17	3.8 ± 0.9	10–15	10.4 ± 0.3	10.1 ± 0.5	0.04

Table 3: Strain measured on the bent samples.

Type of samples	Measured strain (%)
Steam spruce L	0.7 ± 0.05
Heat spruce L	0.65 ± 0.1
Steam spruce R	0.9 ± 0.05
Heat spruce R	0.6 ± 0.1
Steam maple L	0.9 ± 0.05
Heat maple L	0.7 ± 0.1
Steam maple R	0.9 ± 0.05
Heat maple R	0.8 ± 0.05

and include the reference samples. The complete dataset is reported in the Supplementary Materials.

3.5 Comparison by species, directions and methods and interaction of variables

Box and whiskers plots relative to the measured and derived properties are reported in the Supplementary Materials in Figures 3, 4, 5, and 6 for spruce and maple, relative to both bending methods grouped. The comparison considering the two different bending methods separated is reported in Figures 7 and 8 in the Supplementary Data. A two-way analysis of variance (ANOVA) was conducted to examine the effects of the interaction between the method and species on the variables (density, E_L , η , E_{Lspec} , RR , ACE and strain) and for the L and R direction samples. All the numerical results for the ANOVA are presented in Tables 1–4 in the Supplementary Materials. Prior to the analysis, the assumptions underlying ANOVA were carefully evaluated. The normality of residuals was assessed using the Shapiro–Wilk test and visual inspection of Q–Q plots. Homogeneity of variances across groups was examined using Levene’s test. Given that these assumptions were satisfied, the two-way ANOVA was performed. The analysis revealed a significant interaction ($p < 0.05$) for density, E_L , E_{Lspec} and strain. For the R direction samples results, the Shapiro–Wilk tests indicated a significant deviation from normality for density, η (maple, bending

iron) and for RR (spruce, bending iron). For the other variables, the Levene’s tests revealed that the assumption of equal variances was not met ($p < 0.05$). Therefore, the interaction effects could not be assessed. Effect sizes were calculated to estimate the magnitude of the observed effects. When appropriate, *a posteriori* pairwise comparisons were conducted using Tukey’s HSD test. These *a posteriori* comparisons indicated that for the four variables (density, E_L , E_{Lspec} and strain), for spruce, the steam method produced higher values than the bending iron method ($p < 0.001$). In contrast, no significant difference between methods was observed for maple.

4 Discussion

4.1 Moisture content

Average moisture content before and after bending showed only small differences, in accordance with other studies showing that heat treatment of wood at higher temperatures can induce a permanent diminution in moisture content (Quintavalla et al. 2026). A pairwise statistical test however shows that these differences have a little statistical significance. Moreover, even several tenth of percent of change would not be sufficient to explain changes in mechanical properties. Indeed, (Viala et al. 2018), observed on spruce used for tonewood that 1 % MC increase would decrease E_L by 0.75 %, E_R by 2.5 %, and increase η_L by 6 % and η_R by 11 %. Therefore, increase of rigidity and decrease of damping would have been three times small than the measured effects, based on observed changes on moisture content.

4.2 Strain level in the different sets of samples

The average strain, measured on the bent samples indicated a relatively large scatter. Heat-bent specimens showed an average strain level closer to the nominal value (0.7 %), while its standard deviation is relatively high in almost all cases

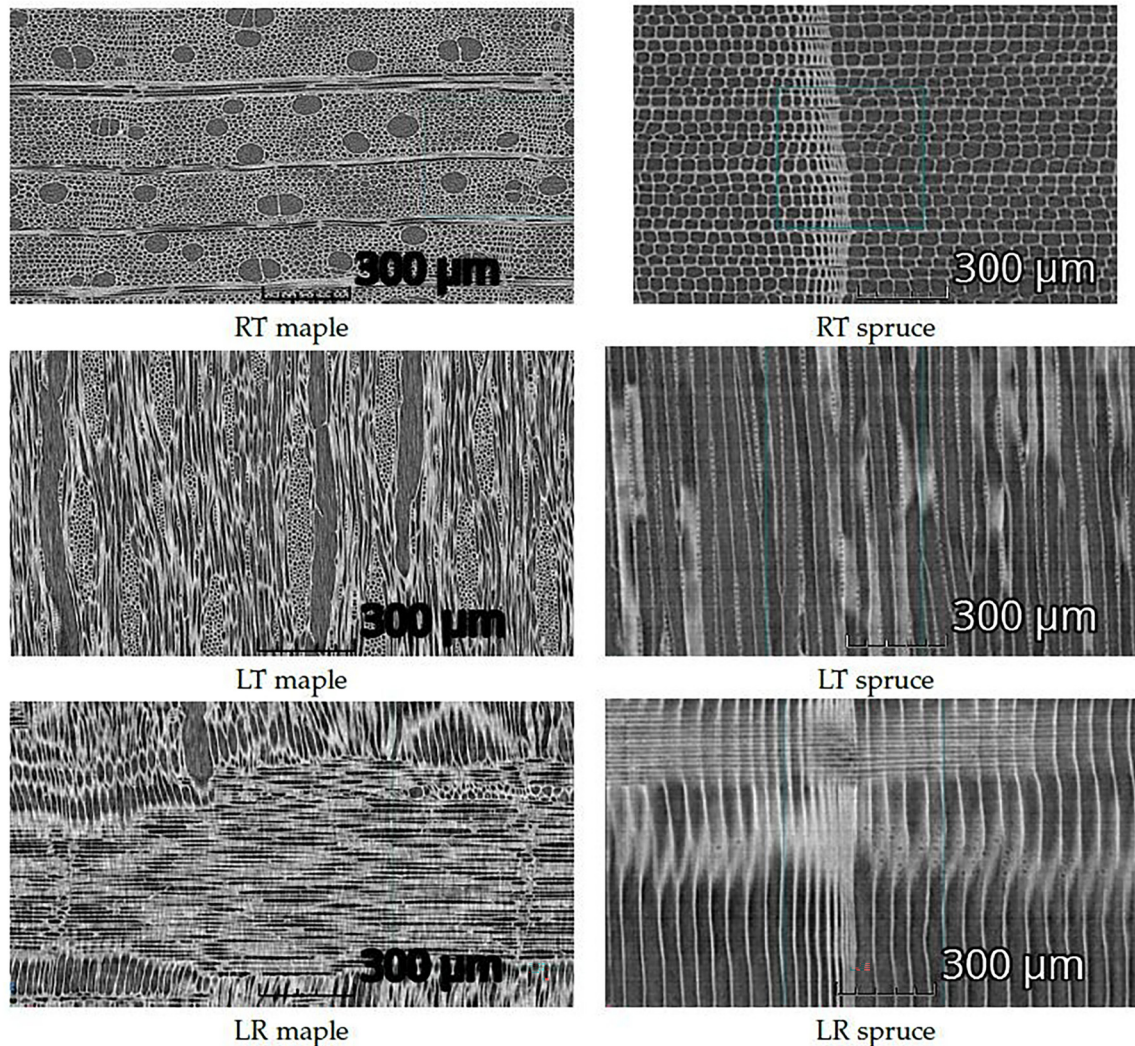


Figure 6: Tomographic reconstruction of maple *Acer spp.* and spruce *Picea abies* after bending.

(with the exception of heat bent maple, R direction). Conversely, for steam bent samples, while the average values of strain level show a larger difference with respect to the nominal value, their standard deviation is lower. These differences reflect the fact that heat bending by hand allows for an immediate control of the object shape which, on average, is closer to the nominal one. Conversely, steam bending is more affected by spring back (which cannot be evaluated immediately after the bending procedure) and depends on the mould shape. On the other hand, heat-bent samples exhibited a larger variability than the steam-treated ones. This suggested that the steam bending process was more controllable and yielded more uniform results. If this difference is due to the inherent process conditions, i.e. due to a more uneven distribution of heat or strain throughout the sample, or to the fact that bending is performed by hand however cannot be ascertained and future research would

be required. A species-specific response was also observed. Maple samples consistently demonstrated higher strain than spruce, particularly under steam treatment. The intrinsic properties of maple, a hardwood with a different cellular structure and chemical composition than the softwood spruce, seem to make it more receptive to the plasticising effects of steam (Awoyemi 2008). This confirms a well known fact among stringed instruments makers and wood workers: that the effectiveness of bending treatments is highly dependent on the wood's inherent characteristics. Finally, regarding steam bent spruce samples, although bending was performed using the same moulds, 'R' samples, showed consistently higher measured strain (and hence less spring back) than 'L' samples. This result suggests that, when heated with steam, spruce wood is consistently more compliant along the R direction than along the L direction, while maple wood shows a very similar behaviour along both directions.

Table 4: Mechanical and derived acoustical indices of spruce samples before and after bending (L = longitudinal, R = radial). Values are reported with reduced significant digits to match measurement uncertainty. Bold values are associated with high statistically significant results.

Spruce		Density (kg/m ³)		E_i (GPa)		η_i (%)		$E_{i\text{spec}}$ (m ² s ⁻²)		RR_i (m ⁴ kg ⁻¹ s ⁻¹)		ACE_i (m ⁴ kg ⁻¹ s ⁻¹)	
		Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
L bent ($N = 18$)	Mean	336	338	8.7	8.0	0.70	1.00	25.7	23.6	15.2	14.4	2,290	1,405
	SD	31	28	1.4	1.1	0.10	0.10	2.3	1.7	1.1	1.1	215	180
	CV (%)	9.3	8.4	16.3	13.3	10.2	9.2	8.9	7.1	7.5	7.4	9.4	12.8
	Δ mean (%)	+0.6		-8.0		+42.9		-8.2		-5.3		-38.7	
	p -Value	0.84		0.10		<0.001		0.003		0.04		<0.001	
L control ($N = 8$)	Mean	325	326	8.4	8.3	0.68	0.79	25.7	25.6	15.7	15.5	2,303	1,993
	SD	26	23	1.0	0.8	0.10	0.10	1.7	1.6	1.2	1.1	235	342
	CV (%)	8.1	7.0	11.5	9.1	8.9	14.7	6.5	6.1	7.4	7.2	10.2	17.2
	Δ mean (%)	+0.3		-1.2		+16.2		-0.4		-1.3		-13.5	
	p -Value	0.89		0.83		0.045		0.90		0.73		0.05	
R bent ($N = 21$)	Mean	345	350	0.70	0.69	1.7	1.9	2.1	2.0	4.2	4.1	262	223
	SD	31	31	0.2	0.2	0.15	0.20	0.71	0.67	1.09	1.04	90	75
	CV (%)	8.9	8.8	28.3	27.5	9.3	10.7	34.2	33.3	26.0	25.4	34.5	33.5
	Δ mean (%)	+1.4		-1.4		+11.8		-4.8		-2.4		-14.9	
	p -Value	0.58		1.00		0.10		0.64		0.76		0.14	
R control ($N = 5$)	Mean	354	357	0.68	0.68	1.7	1.8	2.0	2.0	4.0	3.9	244	237
	SD	30	30	0.2	0.2	0.20	0.40	0.80	0.80	1.13	1.14	97	122
	CV (%)	8.3	8.4	34.2	34.3	10.6	20.7	40.5	40.8	28.6	28.9	39.6	51.4
	Δ mean (%)	+0.8		0.0		+5.9		0.0		-2.5		-2.9	
	p -Value	0.90		1.00		0.63		0.98		0.97		0.92	

Table 5: Mechanical and derived acoustical indices of maple samples before and after bending (L = longitudinal, R = radial). Values are reported with reduced significant digits to match measurement uncertainty. Bold values are associated with high statistically significant results.

Maple		Density (kg/m ³)		E_i (GPa)		η_i (%)		$E_{i\text{spec}}$ (m ² s ⁻²)		RR_i (m ⁴ kg ⁻¹ s ⁻¹)		ACE_i (m ⁴ kg ⁻¹ s ⁻¹)	
		Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
L bent ($N = 33$)	Mean	657	659	10.0	9.5	1.10	1.40	15.3	14.5	5.97	5.81	567	407
	SD	39	46	1.52	0.93	0.12	0.17	2.77	2.01	0.80	0.76	129	70
	CV (%)	6.0	7.0	15.2	9.8	11.5	11.8	17.9	13.7	13.2	12.8	22.1	16.3
	Δ mean (%)	+0.3		-5.0		+27.3		-5.2		-2.7		-28.2	
	p -Value	0.80		0.11		<0.001		0.19		0.39		<0.001	
L control ($N = 5$)	Mean	696	708	9.3	9.9	1.22	1.24	15.8	14.0	5.26	5.28	432	429
	SD	31	32	0.82	1.15	0.10	0.10	2.17	1.12	0.21	0.19	30	37
	CV (%)	4.5	4.6	8.8	11.6	6.4	7.8	13.5	7.6	3.0	2.7	6.6	8.2
	Δ mean (%)	+1.7		+6.5		+1.6		-11.4		+0.4		-0.7	
	p -Value	0.60		0.35		1.00		0.14		0.87		0.63	
R bent ($N = 13$)	Mean	693	699	2.28	2.35	2.20	2.30	3.29	3.36	2.62	2.62	120	115
	SD	31	31	0.17	0.20	0.15	0.20	0.71	0.67	1.09	1.04	90	75
	CV (%)	4.4	4.4	7.5	8.7	3.8	4.3	6.5	7.5	3.1	3.4	4.5	6.2
	Δ mean (%)	+0.9		+3.1		+4.5		+2.1		0.0		-4.2	
	p -Value	0.14		0.38		0.02		0.48		0.96		0.12	
R control ($N = 9$)	Mean	696	702	2.24	2.28	2.22	2.33	3.22	3.25	2.58	2.57	115	109
	SD	9	12	0.20	0.20	0.11	0.18	0.25	0.26	0.11	0.12	10	13
	CV (%)	1.3	1.7	8.4	8.6	5.1	7.6	7.8	8.0	4.3	4.6	9.1	11.5
	Δ mean (%)	+0.9		+1.8		+5.0		+0.9		-0.4		-5.2	
	p -Value	0.26		0.68		0.14		0.81		0.86		0.32	

This can presumably be attributed to the cellular structure of spruce, and likely of other softwoods, but would require further investigation to be properly assessed.

4.3 Microstructure state and detection limits

Microtomography at 2 μm voxel size did not show visible cellular-scale cracks or gross anatomical damage in the scanned regions. However, this resolution did not allow exclusion of sub-micron mechanisms (e.g., cell-wall shear bands, micro-cracks below voxel size) or polymer-level chemical/physical changes. Therefore, the observations were consistent with preserved cellular integrity at the resolved scale, but they do not uniquely identify the underlying softening mechanism nor exclude sub-resolution damage.

4.4 Change of density

As regards density, reference samples did not show significant changes after heating or exposure to steam. As for the other samples, although slight differences in thickness and density were observed before and after the bending process (see the dataset in the Supplementary Material), there is no statistically significant difference in density for both spruce and maple. This holds even when different bending methods are considered. The small average increase observed in all cases can be interpreted primarily as measurement uncertainty (mass and geometry reconstruction for curved samples) and/or sorption hysteresis effects after different moisture/temperature histories, rather than evidence of mass gain at equal conditioning. Another possible cause may be the slightly reduced thickness of the samples as a consequence of bending, however it is difficult to clearly isolate this effect, being the thickness variation at the limit of the measurement uncertainty.

4.5 Modulus of elasticity and specific modulus of elasticity

Reference samples did not show any significant variation, with the exception of maple, L direction. However, a large variability was observed in this case and the statistical significance is small. A diminution in longitudinal stiffness E_L was observed (-8.0% for spruce and -5.0% for maple) but with weak statistical evidence for both species. As for the specific modulus of the wood, which relates stiffness to

density, a significant diminution was observed only for spruce along the L direction (-8.2%), while the values of maple samples did not show significant changes. This suggested that the stiffness-to-weight ratio changed after bending for spruce while there was no evidence of a diminution for maple. This result supports the traditional use of hardwoods to realise bent objects, with respect to softwoods (Awoyemi 2008) and are in agreement with the measurements showing a different softening temperature of lignin in softwood and hardwoods, especially at low moisture content (Östberg et al. 1990). As regards the radial stiffness E_R and the radial specific modulus, there was no evidence of a diminution of the properties for both species, at least at the considered strain. These results may lead to noticeable consequences when using bent spruce wood to realise structural elements, as well as structural elements and stringed instruments where, the elastic properties along the L direction tend to dominate both the structural and the vibrational behaviour (Ashby and Jones 2012; Gore and Gilet 2016; Quintavalla et al. 2022a,b). Even so, this consideration should be tempered by the inherent advantage of bent wood where fibres are typically aligned with the load direction whereas milling involves that the grain orientation is intermediate between longitudinal and radial or tangential, these last having much lower properties in terms of stiffness and strength (Ross 2000), hence result in less rigid and robust objects.

As for the bent samples, overall, along the longitudinal direction, bending was associated with (i) small-to-moderate reductions in E_L and $E_{L,\text{spec}}$ (more pronounced in spruce), and (ii) a consistent increase in η_L for both species, which drove a reduction in ACE . Along the radial direction, stiffness-related metrics variations were generally not significant at the tested nominal strain, while η_R exhibited method- and species-dependent changes. Reference (exposed-only) specimens showed smaller and generally statistically non-significant shifts than bent specimens, suggesting that both hygrothermal exposure and mechanical bending may contribute to the observed evolution, within the limitations imposed by the unbalanced populations of bent and pristine samples, as reported in the literature for some hardwood species (Cetera et al. 2016; Papandrea et al. 2026).

4.6 Internal friction

Reference samples showed an increase of the loss factor after exposure to heat or steam but with little statistical significance in any case. As for the bent samples, while the radial loss factor is not significantly affected at the

considered strain, it was significantly increased along the L direction for both species (+43 % for spruce and +27 % for maple). This suggests that the bending process increases internal friction within the wood and therefore leads to increased energy dissipation during vibrations. Although the X-ray micro tomography does not show any sign of fractures at 2 μm voxel size, the formation of sub micrometer defects during bending, due to the stress applied, evaporation of water, or reorganisation of constituents, can be plausible causes (Russu et al. 2025). Other possibilities can be the modified surface roughness after the bending process, since a part of the wood fibres are straightened normally to the surface of the wood, or the modification of the cell geometry due to plastic deformation. The elastic properties of wood in fact largely depend upon the cell geometry (Kahle and Woodhouse 1994) and minimal changes could lead to significant variation in the properties. Other alternative contributions can also be considered, including (i) thermo-hygro-mechanical viscoelastic relaxation, (ii) sorption hysteresis effects, and/or (iii) thermal modification at the surface, especially during dry heat bending. From a practical perspective however, this increase of internal friction can be favourable for the vibrational behaviour of structural elements where, usually, a large modal damping is desired to avoid uncontrolled oscillation at resonances (Mead 1998). A similar conclusion can be drawn about stringed instruments where too low damping could lead to strong resonance peaks, making them prone to so-called *wolf notes*. An increase in damping could therefore be beneficial (Richardson et al. 2012; Roberts and Richardson 2013).

4.7 Derived acoustical indices

Reference samples show little and statistically not significant variations of *RR*. As for *ACE*, a slight decrease is observed for spruce, L direction where a statistically significant difference was observed ($p = 0.05$), although the result is borderline and should be interpreted with caution. As for the bent samples, *RR* showed a significant decrease only for spruce (−5.3 %), along the L direction, while the *ACE* shows a significant decrease both for species, but only in the L direction

(−38.7 % for spruce and −28.2 % for maple), suggesting an overall decrease of the wood properties in this regard. This effect, in particular, could potentially lead to an influence on the acoustical behaviour of stringed instruments, particularly loudness, especially when their soundboard is designed based on the vibration frequency (Quintavalla et al. 2025). However, since their behaviour is strongly dependent on the design adopted, whose influence can completely overwhelm the effect of material properties (Viala et al. 2021), a screening of this effect would require a specific study.

4.8 Modelling the strain behaviour (scope and limitations)

The work conducted so far aimed at achieving a statistically significant study on the effect of bending on wood properties. For this reason, the study was focused on only one nominal level of strain. Using these data, it is possible to extrapolate a first-order empirical linear relation between strain level and the change in properties for spruce and maple. Table 6 proposes linear coefficients that link the evolution of observables with the level of strain. Only significant evolution ($p < 0.15$) are considered. While this is a crude approximation in this range, rather than a constitutive law capturing non-linearities, gradients, neutral-axis shifts, or plasticised layers, it can be implemented in a model of any structural element or musical instrument to retrieve a rough estimate and evaluate in which way bending can affect the properties of the object. Further studies would be required to investigate the effect of bending at different levels of strain.

4.9 Qualitative comparison of material and energy implications of bending versus milling

The results suggested that, although bending wood resulted in a partial decrease of the mechanical properties, this technique is still advantageous with respect to milling in terms of

Table 6: Mechanical and derived acoustical indices evolution per % ϵ for spruce and maple along longitudinal (L) and radial (R) directions.

Species/direction	Density (kg/m ³)	<i>E</i> (GPa)	η (%)	<i>E</i> _{spec} (m ² /s ²)	<i>RR</i> (m ⁴ kg ^{−1} s ^{−1})	<i>ACE</i> (m ⁴ kg ^{−1} s ^{−1})
Spruce L	–	–1	0.4	–3	–1.1	–1,270
Spruce R	–	–	0.15	–	–	–440
Maple L	–	–0.7	0.4	–1.15	–	–230
Maple R	–	–	0.15	–	–	–8

efficient material usage. This is in line with previous studies that estimate a material saving around 23–64 % (Prekrat et al. 2021). Even when considering an 8 % decrease in specific stiffness – leading to a similar increase in the required cross-section of structural elements – the material savings can still be very high compared to milling for elements produced by bending wood at the strain levels considered here (and likely also beyond). While the precise quantification of energy consumption and the potential economic benefits was beyond the scope of this study, a reasonable economic advantage can nonetheless be expected, together with an environmental benefit related to reduced waste production and lower energy use compared to milling.

4.10 Limitations and recommended additional measurements

Several limitations should be considered when interpreting the present results: discoloration and chemical changes were not investigated; residual stresses after bending were not evaluated and the FE modal analysis assumed a stress-free configuration; micro-tomography at 2 μm voxel size cannot exclude sub-micron damage or polymer-level changes; spruce originated from two boards and treatment groups were unbalanced, so between-board variability may partially confound treatment effects. Moreover, the present study focused on relatively thin specimens typical of lutherie stock and did not consider thicker samples such as those used in furniture making. To address these points, the authors leave as suggestion for future works: standardised photographs/colorimetry to document discoloration, chemical analysis, a blocked design by board/radial position with mixed-effects modelling for treatment comparisons and the study of samples with different thicknesses.

5 Conclusions

This study revealed that steam bending, while presenting an average strain level that deviates more from the nominal value due to spring-back, consistently yielded more uniform and predictable results than heat bending, as evidenced by its lower standard deviation compared to heat bending. This suggested that steam would be a more reliable method for achieving consistent outcomes, especially in mass production. The species-specific response showed that spruce and maple have different suitability for bending. Observed differences between L and R bending were interpreted cautiously because equal nominal strain does not imply equal stress state across directions/species, and additional

radii/strain levels would be required for mechanistic separation. From a micro-structural perspective, X-ray micro-tomography at 2 μm voxel size revealed no visible cellular-scale cracks or gross anatomical damage in scanned regions; however, sub-micron mechanisms cannot be excluded at this resolution. Additionally, density measurements showed no statistically significant change after re-conditioning and only a small decrease in equilibrium moisture content was observed. Regarding mechanical properties, a modest reduction in longitudinal stiffness and specific modulus was observed, particularly for spruce while increased internal friction was observed in both species, mainly in the longitudinal direction. The correspondent increase in damping could be potentially beneficial for both structural elements (mitigating resonance) and musical instruments (reducing excessive peak responses). The comparison of environmental and economic implications was qualitative and literature-based but shows that the bending technique's ability to create complex shapes from a single piece of wood with only a minor diminution of the mechanical properties could help reduce material waste compared to milling, with potential savings of a large fraction of material depending on geometry and process constraints. The study also highlighted that modal analysis, coupled with finite element model updating, is a valuable tool for evaluating the material properties of complex shapes, and therefore the impact of wood bending on effective vibro-mechanical properties of curved specimens after re-conditioning.

While this study provided exploratory results, further research is needed to: quantify moisture content changes and temperature evolution during bending, assess residual stress influence on modal frequencies, and investigate microstructural/chemical changes at finer scales and across additional strain levels to propose predictive models. Future research should also explore the effects of bending on other wood species and compare various bending techniques to provide a more comprehensive understanding of this valuable process, as well as providing predictive models of the mechanical parameters as a function of bending strain.

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Data availability: The data that supports the findings of this study are available within the article. The datasets related to the vibrational measurements are provided in the Supplementary Material. The remaining datasets are available from the corresponding author upon reasonable request. Due to their large size, these data are not publicly available but can be shared in an appropriate format upon request.

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