Laser bending of wood veneers: phenomenological and Machine-Learning approaches case study

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Abstract

Wood is a noble, versatile, and renewable material which plays an important role in sustainable manufacturing. The present study shows that it is feasible to laser bend veneers of different wood species by applying infrared energy in the form of a scanned laser beam. Bending height, i.e., deflection of the veneer measured as the vertical elevation of its edge points from the horizontal plane; were achieved on three wood types, namely: beech, yesquero, and ulmo. Process parameters and wood properties considered relevant to the response variable are laser energy, moisture content, water loss, density, and wood species. Experimental results indicate that specimens 15 cm long, 3.5 cm wide and 1.5 mm thick achieved bending heights ranging from 0.35 cm (beech) up to 4.8 cm (yesquero). Largest average height of 4.45 cm was achieved in beech veneers at equilibrium moisture content of 13% under maximum laser energy of 1061 J. On the other hand, ulmo specimens having 0% moisture content, after oven drying for 72 hour at 40ºC, also showed considerable average deflection height of up to 3.1 cm. This reaffirms that free water loss is not the only mechanism for fibre contraction, but that cell wall bound water loss during the laser wood interaction also causes considerable shrinkage, as expected. Machine-Learning analysis of the experimental data suggests the algorithm that better suited the response variable was the Gaussian Process regression since it showed the highest correlation coefficient and the lower RMSE. Confirming that moisture content explains almost 45% of the model's predictability, followed by laser energy with 35%, while water loss (both free and bound) was ranked third.

1. Introduction

Throughout history, wood has been one of the most used construction materials by man. It is an easy to shape material, due to its viscoelastic properties. This can be appreciated when used for the construction of furniture, marquetry, boats, skates and skis, all of which take advantage of its resistance, flexibility, weight, and other constructive benefits (Meier 2007; Açık 2022). Today, in developed countries, ca 90% of houses with less than four floors are built using timber (Sterley et al. 2021). Many wood properties have already been studied thoroughly, however given the significant variability of its mechanical properties, wood still is an interesting material for advanced research. Its related manufacturing processes are known, achieving a certain homogeneity in their results and use, despite the significant variability of wood’s mechanical properties. (Ramage et al. 2017). Considering modern manufacturing processes, lasers have been used before to cut, mark, and surface process wood products by means of a controlled combustion reaction mechanism, such as those at the kerf zone (Barcikowski et al. 2006; Letellier and Ramos-Grez 2008; Rezaei et al. 2022). Nonetheless, research considering the deformation of wood material by lasers has apparently not been pursued yet to the best knowledge of the authors.

1.1 Microconstituents and Properties of wood

Wood is a non-homogeneous organic material with differences in its physical and mechanical properties, which are defined by the species, age, type of soil, geographical location of growth, the section of the tree from which wood is extracted (trunk, branches, roots, among others). Its cellular structure is complex and
principally formed by hollow longitudinal wall cells. The interior of the cell is the lumen, while the cell wall consists of three regions: the middle lamella, the primary wall, and the secondary wall. In each region, the cell wall has three components: cellulose microfibrils, hemicelluloses, and a matrix of pectin in primary walls and lignin in secondary walls (Panshin and deZeeuw 1980). Cellulose can be understood as a long string-like molecule with high tensile strength; microfibrils are collections of cellulose molecules into even longer, stronger thread-like macromolecules. The hemicelluloses are smaller, branched molecules that link the lignin and cellulose together in each layer of the cell wall (Ross et al. 2010). All the latter distributed along the longitudinal growth axis and arranged radially (Rezaei et al. 2022). Moreover, cellulose consists of a crystalline polymer with amorphous regions (Rowell 2012); it is a biopolymer made out of β-glucose molecules, which makes up approximately 50% of the weight of wood. Hemicellulose is a heteropolysaccharide that covers the cellulose bers, it represents about 25% of the weight of the wood. Finally, lignin is a brittle matrix material classified as an amorphous polymer (Rowell 2012; Chávez and Domine 2013), whose composition changes depend on the species and represents the remaining 25% of the weight of the wood (the percentage of weight may vary depending on the species). Cellulose and hemicellulose are hydrophilic materials, while lignin is a hydrophobic material (Chávez and Domine 2013). The hydrophilic constituents are responsible for holding water in the form of liquid and vapor. The water intake can be divided into free water, stored in cell lumina and void spaces, and bound water stored in cell walls. The former is easier to remove by simply heating the wood specimen above the temperature at the vapor pressure; centrifuging can also be an effective mechanism in removing free water according to Choong et al. (1989). On the other hand, cell bound water has a lower vapor pressure and therefore it requires more energy and time to be removed, thus it may still be present after heating the wood above the boiling point of water under atmospheric conditions; removal of bound water causes shrinking of wood.

Concerning thermal properties of wood constituent’s, cellulose and lignin, the former has a glass-transition temperature that ranges between 145 and 175 ºC, depending on its water content (Wang et al. 2012). Cellulose will undergo a thermal expansion with a coefficient of 5.5 x 10\(^{-4}\) ml/(g ºC), and a density of 1.55 g/ml (Ramiah and Goring 1965). Lignin, on the other hand has a glass-transition temperature of 140 ºC and a thermal expansion coefficient of 10 x 10\(^{-5}\) ml/(g ºC), and a density of 1.26 gm/ml. (Ramiah and Goring 1965; Wang et al. 2012). Thermal expansion coefficients for parallel-to-grain values ranged from 3.1–4.5 x 10 \(-6\) / ºC, while across the grain (radial and tangential) are proportional to specific gravity and range from about 5 to more than 10 times the parallel-to-grain coefficients (Ross et al. 2010).

1.2 Moisture content in wood

Moisture can exist in wood as free water (i.e., liquid water or water vapor in cell lumina and cavities) or as bound water (i.e., held by intermolecular attraction within cell walls). The moisture content at which only the cell walls are completely saturated (all bound water) but no water exists in cell lumina is called the fiber saturation point, MC\(_{FS}\). The fiber saturation of wood averages about 30% moisture content. Conceptually, fiber saturation distinguishes between the two ways water is held in wood. However, a more
gradual transition occurs between bound and free water near the fiber saturation point. For small pieces of wood without moisture gradients, shrinkage normally begins at about the fiber saturation point and continues in an almost linear manner until the wood is completely dry. However, in the normal drying of lumber, the surface of the wood dries first, causing a moisture gradient. When the surface MC drops below the fiber saturation point, it begins to shrink even though the interior can be wet and not shrink. Because of moisture gradients, shrinkage of lumber can occur even when the average moisture content of the entire piece of lumber is above fiber saturation. Moreover, in freshly sawn wood (i.e., green wood) the cell walls are completely saturated with water and additional water may reside in the lumina. The moisture content of green wood can be higher than 30% (Ross et al. 2010).

1.3 Wood capability to deform

Wood is dimensionally stable when moisture content is greater than the fiber saturation point (MC_{FS}). Below this content wood changes dimension as it gains or loses moisture, swelling and shrinking respectively, because volume of the cell wall depends on the amount of bound water. This shrinking and swelling can result in warping of the wood (Ross et al. 2010). With respect to dimensional stability, wood is an anisotropic material. It shrinks in the direction of the annual growth rings, about half as much across the rings, and only slightly along the grain. Greater shrinkage is associated with higher density of the wood. The size and shape of a piece of wood can affect its shrinkage, as well as the rate of drying for some species. (Ross et al. 2010). Regarding the capability to deform wood, thermo-hydro and thermo-hydro mechanical processing have been used to enhance wood properties, dissipate internal stresses, dry, and soften the material. Thermo-hydro processes can heat treat wood-based composites and veneer products under high temperatures. Conversely, thermo-hydro mechanical processes have been employed in wood shaping, bending and molding, welding wood by friction, or improving wood densification (Navi et al. 2012; Sandberg et al. 2013). The deformation effect is expected to be generated by the applied heat on the wood lignin, cellulose, and hemicellulose. These are expected to behave mechanically in different manners due to their different glass-transition temperature and thermal expansion moduli (Wang et al. 2012). In addition, shrinkage due to water loss (both free and bound) in hydrophilic sections within the wood microstructure must be considered (Ramiah and Goring 1965). When moist wood is heated, it tends to expand because of normal thermal expansion and to shrink because of loss in moisture content. Unless the wood is dry (3% moisture content or less), shrinkage caused by moisture loss on heating will be greater than thermal expansion, so the net dimensional change on heating will generate an upward deflection. Wood at intermediate moisture content levels (8% – 20%) will expand when first heated, and then gradually shrink to a volume smaller than the initial volume as the wood gradually loses water while in the heated condition (Ross et al. 2010). Chandra and Batthacharya (2018), evaluated the spring-back and spring-forward of the 3-ply laminates, using a single curvature vee-bending test on commercially available radiata pine veneer plywood, in which the veneer was pre-softened in water. The forming temperature and pre-forming moisture content were found to have the highest influences. More recently Chanda et al. (2020) developed an equation to model the spring-back phenomenon during the thermoforming process of veneer plywood. They studied the formation of multiple bends and their
interactions using four-point bending tests. Their empirical equation performed well regarding again forming temperature and pre-forming moisture content allowable ranges.

## 1.4 Laser processing of wood products

To evaluate the deflection achieved by heat fluxes, wood specimens can be subjected to the irradiation of a laser system, which delivers its energy over the surface of one of the faces of the laminate. In this study, the bending generated in veneers, by temperature difference induced by a scanning infrared CO\textsubscript{2} laser beam operating in continuous wave (CW) was considered. Wood with moisture content close to its equilibrium moisture content (EMC) that is heated above 100ºC results in a wood with greatly decreased moisture content. The high temperature degrades the hemicellulose sugars to furan-based intermediates and volatile gasses. The furan intermediates have a lower EMC than the sugars and increase bonding of the wood structure. At a weight loss of approximately 25%, the EMC is lowered by almost the same percentage. On the other hand, heating wood under drying conditions at higher temperatures (above 95°C) produces a decrease in the hygroscopicity and subsequent shrinking of the wood appreciably (Ross et al. 2010).

Concerning the recent advancements in laser processing of wood materials. Fukuta et al. (2016) used an ultraviolet nano seconds pulsed laser for processing wood, particularly hole drilling and incising machining. In contrast to CO\textsubscript{2} lasers, a short wavelength, short pulse-width laser was tested successfully for its performance on wood. More recently, Jurek and Wagnerová (2021), achieved a larger palette of engraved shades of burned wood using a continuous controlled chemical process by laser and wood interaction with a combination of laser power and optical focus. Their color engraving process was divided into wood burning and wood carbonization by variation of laser beam focus. Additionally, Li et al. (2021) showed that laser surface treatment could be applied to change the wood properties of color, wettability, surface roughness, due to the high efficiency, flexible moving trajectory, and good controllability. These surface properties directly affect the wood products coating performance, such as coating adhesion and surface gloss. However, the bending effect induced by a laser has not been studied previously in wood but in other materials systems, such as metals (Vásquez-Ojeda and Ramos-Grez 2009; Steen and Mazumder 2010).

The final objective of this present work is to observe how laser energy, moisture content, water loss, density, and wood species affect the thermally-induced deformation of the selected veneer specimens. For this, samples of three different wood species were studied, namely beech, yesquero, and ulmo; all were subjected to different levels of laser energy and moisture content to identify how these two parameters affect their deformation. The results were analyzed through Machine-Learning regressors models to provide meaning to the data obtained. In this study, deformation will be interpreted as the bending height (as measured vertically up from the bottom horizontal plane) achieved at both edge points of the wood veneer pieces.

## 2. Materials And Methods
2.1 Veneer wood products

Wood from tree logs can be processed in several ways. The cut of interest considered in this work is one commonly known as veneer, which consists of thin slices of wood, which can be obtained by rotary-cut, slicing or swan. Rotary-cut veneer is produced by rotating a log by its ends against a knife, which results in continuous sheets of flat-grain veneer. Sliced veneer is produced in long strips by moving a squared log, called a fitch, against a knife. Sawn veneer is produced in long narrow strips from fitches that have been selected and sawn for attractive grain patterns. These sheets have a thickness of about 1–2 mm. Details about the process of obtaining the veneer can be found elsewhere (Gutiérrez Rojas and Silva Sandoval 2000; Rowell 2004; Ross et al. 2010; Ramage et al. 2017). Veneers are used intensively in industry, mostly for producing plywood sheets and lumbers. The rectangular laminates obtained from these peels are cut off so that the longitudinal direction is perpendicular to the fibers' orientation. Regions in which the lignin joins with the cellulose fibers, forms a structure that controls the mechanical properties in the longitudinal direction. In contrast, fibers themselves control properties in the transverse direction. This translates into a flexible laminate in the longitudinal direction and a more rigid one in the transverse direction, as shown in Fig. 1.

2.3 Selected wood species

Species selection was based primarily on the availability of veneers. To be able to study if the species type has any influence on the bending heights achieved, three wood species were selected and evaluated:

2.3.1 Beech (Fagus sylvatica)

This tree is native to central and eastern Europe and belongs to the Fagaceae family. Density at 12% moisture content corresponds to 0.71 g/cm$^3$. This wood is classified as heavy, hard, strong, high in resistance to shock, and suitable for steam bending. Beech shrinks substantially and therefore requires careful drying. Percentage shrinkage from green to ovendry moisture content in the radial, tangential and volumetric corresponds to 5.5, 11.9 and 17.2, respectively (Ross et al. 2010).

2.3.2 Yesquero (Cariniana lanarensis)

This species is native to the central and southern Amazon, it belongs to the Lecythidaceae family and is also known as Jequitiba or Albarco (Justiniano and Fredericksen 1999). Its green density corresponds to 0.48 g/cm$^3$, ovendry density corresponds to 0.58 g/cm$^3$ and density at 12% moisture content corresponds to 0.78 g/cm$^3$. Primarily used for general construction and carpentry wood, but it can also be used for furniture components, shipbuilding, flooring, veneer for plywood, and turnery. Shrinkage (%) from green to ovendry moisture content radial 2.8, tangential 5.4 and volumetric 9.0. (Ross et al 2010)

2.3.3 Ulmo (Eucryphia Cordifolia)

Chilean and Argentine indigenous species from the Andes southern mountain range that grows below 700 meters above sea level. It belongs to the Eucryphiaceae family. Density of ca. 0.73 g/cm$^3$ at 12% MC
2.4 Laser–veneer interaction

The heat from a moving infrared laser source can couple to the wood surface mainly by the absorption interaction with water molecules if the latter are present in the form of moisture. Infrared energy is readily absorbed by water which undergoes a liquid-to-vapor phase change. This process maintains the temperature at the water boiling point (e.g., 100°C), preventing cellulose fibers and lignin calcination. The water (both free and cell bound) loss at the veneer's surface caused by the laser irradiation induces a differential volumetric shrinkage across the laminate thickness, being larger at the surface than at the bottom. This differential evaporation causes the cellulose fibers to contract at the surface (along the longitudinal direction of the veneer), thus bending the veneer towards the laser beam motion direction, thus elevating the endpoints of the veneer. The thermal expansion of the cellulose and lignin due to the vaporization temperature then takes place below their glass transition temperatures, making the former not large enough to counteract against the volumetric shrinkage due to the water loss. This new geometric deflection height configuration remains up until the veneer is saturated with water again. If little or no bound water is present in the specimen, then differential heating could act over the amorphous microstructure of the lignin, causing its contraction due to an increase in configurational entropy with temperature. However, this has not been demonstrated or measured yet.

2.5 Laser processing system

The equipment used during the experiments consisted of a Synrad 57 – 1 Evolution CO₂ laser, with a maximum power of 70W and a wavelength of 10.6 µm with a TEMₐ₀₀ mode, operating under atmospheric conditions. The system runs under a Cambridge Series 6030 dual-axis galvanometric mirror system. All the elements are integrated into a PC and can be directed by a proprietary program coded in C++ language. The laser generates an infrared beam that passes through a collimating lens, the galvanometric mirrors, and finally through an F-theta lens with a focal length of 36 cm. For this study, it was necessary to defocus the laser beam and expand its irradiation area. The specimen can be located underneath the optical system at a distance larger than the focal length of the lens to achieve defocusing of the beam. In this way, it was possible to apply the heat from the laser without burning the wood, especially at low speeds, and thus not affect its resistance or mechanical properties. The assembly is schematically shown in Fig. 2.

The laser output power is measured with a manual power meter. As expected, energy losses occur throughout the optical system due to absorption. The first loss occurs inside the collimator and is close to 44% of the output power of the laser. The second loss is attributed to the travel distance between the laser output and the specimen and the passage through both the X-Y mirror and focal lens. This adds an extra 18% energy loss. For example, a 48 W output power will deliver only 17.5 W at the surface of the specimen.

2.6 Process variables
2.6.1 Laser energy

The applied energy is considered as the total amount of joules that have been irradiated onto the specimen, defined as the laser power times the actual irradiation time. The irradiation time is defined as the ratio between the defocused laser beam diameter $f$ and the traverse speed of the laser scan pattern $v_t$.

2.6.2 Moisture Content

It is considered as the water retained by the specimen (both free and bound water) and the percentage that it represents of the total absorption capacity of the material; this can be computed from Eq. 1.

$$\text{MC} = \frac{m_{0\%} - m}{m_{0\%} - m_{100\%}}$$

where, $m_{0\%}$ is the mass of the dried specimen; $m_{100\%}$ is the mass of the specimen at complete surface moisture content. Both $m_{100\%}$ and $m$ are the specimen's masses measured at ambient conditions recorded at 55% humidity and 20º C.

2.6.3 Weight loss

The weight loss of each wood species was measured in grams and computed as the difference in mass between the initial and final MC condition after the laser treatment process. It consisted mainly in water loss, both free and bound, but also it included hemicellulose sugars degrading to volatile gasses.

3. Density

The density was reported in g/ml after having the specimen been irradiated by the laser beam and undergoing the corresponding water loss, divided by its volume.

4. Wood Species

As described previously in 2.3, three indigenous species were considered: beech, yesquero, and ulmo.

Finally, Table 1 summarizes all five variables considered in the experiments, with their mean, standard deviation, and range of values, and those of the response variable, deflection height.
Table 1
Experimental variables definition, average, standard deviation, and range

<table>
<thead>
<tr>
<th>Notation</th>
<th>Definition</th>
<th>Unit</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_1$</td>
<td>Laser energy</td>
<td>J</td>
<td>794.40</td>
<td>251.18</td>
<td>439–1061</td>
</tr>
<tr>
<td>$x_2$</td>
<td>Moisture Content</td>
<td>%</td>
<td>35.20</td>
<td>43.08</td>
<td>0–100</td>
</tr>
<tr>
<td>$x_3$</td>
<td>Water loss</td>
<td>g</td>
<td>0.10</td>
<td>0.10</td>
<td>0.01–0.34</td>
</tr>
<tr>
<td>$x_4$</td>
<td>Mass density</td>
<td>g/cm$^3$</td>
<td>0.78</td>
<td>0.20</td>
<td>0.55–1.11</td>
</tr>
<tr>
<td>$x_5$</td>
<td>Wood species</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-1: Beech</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>0: Ulmo</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1: Yesquero</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$y$</td>
<td>Bending height</td>
<td>cm</td>
<td>2.18</td>
<td>1.11</td>
<td>0.55–4.8</td>
</tr>
</tbody>
</table>

2.7 Machine Learning algorithms

This paper proposes three ML methods (i.e., fully-connected feedforward artificial neural network (NN), gaussian process regression (GPR), and support vector regressor (SVR)) to model the behavior of the wood bending height. As no single model is always the best fit for a particular problem, in this study, three representative techniques are analyzed and compared to establish the most accurate tool that describes the nature of the response variable within the boundaries of the experimental design conducted. These models were all trained and tested through the cross-validation approach to avoid bias during training and therefore decrease the chances of over or underpredicting values. Also, to achieve the highest accuracy, the hyperparameters of each ML algorithm were tuned by applying Bayesian Optimization (BO) since it's a well-documented and satisfactory method to do this task (Awal et al. 2021; Ban et al. 2017; Putatunda and Rama 2019). The idea behind BO is to examine the hyperparameter search space and try to find the optimal combination of values that minimize the root mean squared error (RMSE). The most significant hyperparameters are depicted in Table 2. Additionally, ML algorithms' precision is evaluated using two well-known error-based metrics: RMSE and the determination coefficient $R^2$. Once identified the algorithm with superior accuracy (lower RMSE, and higher $R^2$), predictor contribution is carried out by means of the permuted feature importance procedure (PFI) (Gómez-Ramírez et al. 2020). PFI shuffles an input parameter and sees how the model changes its prediction; hence the relationship between the input feature and the response is broken. If the model score drops, this indicates a strong dependence on the permuted input. Since this so-called permutation feature importance is a model-agnostic procedure, it can be applied to any ML (Mi et al. 2021).
The NN models mimic how the human brain processes information through a structured series of neurons arranged in layers. The structure of a feedforward fully connected neural is composed of five main blocks. First is the input layer, where each neuron corresponds to a specific design variable (independent variable or predictor). Then, the first fully connected layer, in which the number of neurons is one of the key parameters that need to be carefully chosen (or optimized) to obtain agreeable results. Next, the activation function block, here the Rectified Linear Unit function (ReLU), is usually used; however other functions like sigmoid type can be specified as well. This layer is linked to the final fully connected layer, where the number of neurons here is primordial again. Additionally, this layer has only one output that corresponds to the predicted response values.

On the other hand, GPR is a nonparametric approach with a Bayesian focus. So instead of estimating the probability distribution of parameters of a specific function, GPR computes the probability distribution over all admissible equations that fit the data. Similar to the NN, this model has some hyperparameters that need to be tuned, like the kernel function, kernel scale, etc. GPR is a powerful technique for deriving analytical models from a relatively small data set and provides uncertainty measurements on the predictions (Saunders et al. 2022).

Finally, SVR is a type of ML method that splits the data by finding the so-called hyperplane in N-dimensional space (N-number of features) that classify in two categories all data points. This algorithm per se aims to find the plane that has the maximum distance between data points of each category. The process of assigning new samples to one or the other side of the hyperplane turns SVR into a non-probabilistic binary linear method. The data characteristics determine their location, and no stochastic element is involved. If the information supplied to the SVR is not linearly separable, a loss function is used to penalize points on the wrong side of the hyperplane. To do so, SVR applies kernel-based transformations to convert nonlinearly separable data into higher dimensions where it is possible to find a linear decision plane. Therefore, the main hyperparameters to consider when constructing an SVR-based regressor are the kernel function, the kernel scale, the margin of tolerance where no penalty is given to errors (epsilon), and the standardization of the input data.
<table>
<thead>
<tr>
<th>ML algorithm</th>
<th>Hyperparameter ranges</th>
</tr>
</thead>
</table>
| NN           | Hidden Layers: [1, 2, 3]  
   The number of neurons in each hidden layer: 1...300  
   Activation function : ['sigmoid', 'tanh', 'ReLU'] |
| GPR          | Basis function: ['none', 'constant', 'linear']  
   Kernel function: ['exponential', 'matern32', 'matern52', 'rationalquadratic', 'ardmatern32', 'ardmatern52', 'ardrationalquadratic']  
   Fit method: ['none', 'exact'] |
| SVR          | Kernel function: ['gaussian', 'polynomial', 'linear']  
   Kernel scale: ['auto', 1]  
   Epsilon: [0, 0.9]  
   Standardize: ['false', 'true'] |

* See Matlab help to know more details about each model's hyperparameters.

### 3. Experimental Setup

#### 3.1 Specimen dimensions

Considering the characteristics of the laser beam (power, focal spot area) and the scanning area within which the latter does not suffer major variations in power density (e.g., W/cm²), it was decided that the specimens should have a length of 150 mm, a width of 35 mm and a thickness $e$ of 1.5 mm (thickness defined by the wood cut used). Given the fragility of the veneer, it was necessary to size the specimens with a laser cutter. The samples were confined between two thicker and more resistant wooden plates to avoid thermal deformations during the cutting process. The nominal dimensions of the veneer are illustrated in Fig. 3.

#### 3.2 Laser scan pattern

The specimens were laser scanned with a scan width ($w$) of 50 mm under a zig-zag-type scan pattern, a 3 mm hatch space ($\Delta\partial$), and a scan length ($L$) of 190 mm. The scan strategy is illustrated in Fig. 4. For a zig-zag scan pattern, the traverse speed can be related to the scan speed and the scan width, such that:

$$v_t = \frac{\Delta\partial}{\Delta t} = \Delta\partial x \left( \frac{v_s}{w} \right)$$
A scan pattern width greater than the width of the veneer specimen (i.e., \(w > b\)) was considered so that the scan advance is generated outside the specimen, thus not irradiating certain areas more than others (e.g., locations where the direction of the zig-zag path changes abruptly). All the samples were placed in the same position so that they were irradiated equally, and the results were not affected by power fluctuations due to different orientations. The F-theta lens allows the focal position to remain constant within a 25x25 cm area horizontal plane.

### 3.3 Laser energy levels

To study how the different energies supplied by the laser beam can affect the bending height of the specimens, it was decided that the power and scan strategy would be fixed for all the samples. The parameter that varied was then the traverse speed of the scan pattern. This allows for modification of the interaction time and, thus, the laser beam's energy. It was decided to use a nominal power range between 17 and 18 W applied at three traverse speeds: 49.5 mm/s, 61 mm/s, and 119.5 mm/s. These speeds were selected since, at lower speeds, the specimens calcinated, and at higher speeds, no results were achieved (e.g., laser irradiation was too low to achieve any effect on the specimen). To calculate the energy levels, the applied laser power was multiplied by the effective scanning time, which was defined as the effective scanning distance divided by the traverse speed \(v_t\) of the laser scan pattern. The effective scanning distance thus corresponds to the width of the specimen \(b\) times the total length of the scan \(L\) divided by half the hatch spacing \(D\). Considering the fixed dimensions of the specimens and a final average power of 17.5 W, the energy levels delivered to the specimens for each speed were calculated as 1061, 861, and 439 J. For every five specimens, laser power measurements using the power meter were taken to ensure that the nominal power was kept constant.

### 3.4 Bending height measurements

The specimens were laid on a fixed wooden surface, then irradiated by the laser beam acting perpendicularly to the upper surface, corresponding to the inside of the lumber at the time of unwinding the peels. As the specimens do not naturally return to their original curvature and are perfectly horizontal at the time of irradiation, this face has a greater ease of curvature given its initial natural fibrous microstructure. The irradiation is theoretically perpendicular to the specimen. Still, as it becomes curved, the irradiation will vary its angle since the surface is free to bend and is not constrained at any edge points.

Immediately after being irradiated, the height achieved at both edge points and the horizontal distance between them were recorded in mm scale. The experimental height of each specimen was defined as the average of the heights achieved by its two edge points. The latter corresponded to the difference between the lowest point in the specimen and each of its edge points (left and right). This was measured using a mm scaled graph paper located onto a vertical plate, while the specimen rested freely on the horizontal face; this setup can be observed in Fig. 5. The difference in heights between the left and right edge points is caused by the relative sliding of the veneer with respect to the horizontal surface as it is not
constrained; thus, the average between both heights was considered a good representation of the total deformation of the laminate.

All the specimens were weighed before going through the laser irradiation process and immediately after the heights achieved were measured. This way, it was possible to quantify the water loss in g from each specimen after receiving the energy radiated from the laser. All this weight loss can be attributed to water evaporation both free and bound, since in this process, the wood was not burned, and only the upper face was heated, so it is known that there was no weight loss due to a structural change in the material (e.g., burned wood is not the same as natural wood, both in weight, microstructure, and mechanical properties).

It is important to mention that the spring-back effect (Chandia and Bhattacharyya 2016, Chadia et al. 2021, Navi and Sandberg 2012) due to ambient moisture absorption after the laser treatment has finished was not included or recorded in this present work.

### 3.5 Moisture content

For this study, three different moisture contents were defined: ovendry (MC$_{OD}$), equilibrium moisture content, and moisture content at complete or maximum surface saturation (MC$_{MAX}$). The ovendry sample was obtained by heating the specimens inside an oven drying at a temperature of 40º C for 72 hours. Several weight measurements were taken during the drying process. After 4 hours, between 89 and 100% drying of the samples was achieved. After 48 hours, no further weight loss was observed, so it could be assumed that the pieces were 100% dry in terms of the removal of at least all the free water. The EMC is defined as that moisture content at which the wood is neither gaining nor losing moisture, and it corresponded to a moisture content of the specimen at experimental ambient conditions (temperature of 20 ºC and relative humidity of 55%); while MC$_{MAX}$ corresponded to a moisture content at which the surface of the veneer was completely saturated. Beech, yesquero and ulmo samples had EMC values of 13%, 18% and 8% at ambient temperatures of 20 ºC and 55% relative humidity.

Table 3. shows the density values in g/cm$^3$ of the wood species at the different moisture contents: ovendry, equilibrium and maximum as well as for 12% obtained from literature. It can be noticed that yesquero is able to lose a larger amount of bond water during oven drying while its capacity to absorb moisture is the lowest at the highest % content. Additionally, the density at maximum surface moisture content is almost the same for the three species.
Table 3

Density values of wood species in g/cm$^3$ at different MC

<table>
<thead>
<tr>
<th>Density (g/cm$^3$)</th>
<th>Beech</th>
<th>Yesquero</th>
<th>Ulmo</th>
</tr>
</thead>
<tbody>
<tr>
<td>@ MC$_{12%}$</td>
<td>0.71</td>
<td>0.78</td>
<td>0.73</td>
</tr>
<tr>
<td>@ MC$_{OD}$</td>
<td>0.64</td>
<td>0.49</td>
<td>0.64</td>
</tr>
<tr>
<td>@ EMC</td>
<td>0.70@MC$_{13%}$</td>
<td>0.61@MC$_{18%}$</td>
<td>0.68@MC$_{8%}$</td>
</tr>
<tr>
<td>@ MC$_{MAX}$</td>
<td>1.14</td>
<td>1.13</td>
<td>1.12</td>
</tr>
</tbody>
</table>

4. Results And Discussion

Experimentally, resulting heights were observed in all species at the three considered moisture content levels. Figure 6 shows the height progression sequence and deflection evolution achieved throughout the laser scanning process of a yesquero veneer; the red arrow represents the direction of the traversing laser beam.

4.1 Bending heights as a function of laser energy and moisture content

From the three plots shown in Figs. 7–9, the ulmo veneers reach the largest bending height for the same energy level, except for EMC and high energy level case. Regardless of the latter, ulmo veneer has greater deformation capacity than the other two veneer types. Its density at 12% MC is larger than beech but lower than yesquero.

4.2 Water loss as a function of laser energy and moisture content

Figures 10 and 11 show that the water loss is practically the same for all the species under EMC and MC$_{MAX}$ at different energy levels. These comparisons indicate a correlation between the laser energy level and water loss, in addition to the ability of ulmo to achieve greater heights compared to the other species for the same level of either of the two parameters.

From Table 4 it can be seen that yesquero is the species that deflects to a higher height followed by beech and then ulmo. Regarding average values, beech shows the higher height followed by yequero and then ulmo.
Table 4
Bending heights achieved by wood species in mm

<table>
<thead>
<tr>
<th>Bending height (cm)</th>
<th>Beech</th>
<th>Yesquero</th>
<th>Ulmo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td>4.65</td>
<td>4.8</td>
<td>3.85</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.35</td>
<td>0.4</td>
<td>0.55</td>
</tr>
<tr>
<td>Average maximum</td>
<td>4.37</td>
<td>4.25</td>
<td>3.55</td>
</tr>
<tr>
<td>Average minimum</td>
<td>0.42</td>
<td>0.41</td>
<td>0.56</td>
</tr>
</tbody>
</table>

4.3 Bending heights as a function of water loss and moisture content

From these results, a difference between ulmo, yesquero, and beech is again observed in Figs. 12 and 13. With significant similarity to Figs. 10 and 11, ulmo presents superior bending heights for the same level of water loss, while the other two species have similar and inferior results. Bending height increase has a behavior with a decreasing trend against water loss than when compared against laser energy gain (Figs. 10 and 11).

5.4 Moisture content effects

a) Oven dry moisture content

Results indicate that the bending height is related to the loss of water and the thermal expansion of the cellulose and lignin, considering that the surface temperature only rises to 100°C while free water is present. In this regard, the veneer in the dry state should curve oppositely; however, it curved in the same direction as the specimens having some moisture content level. This could be attributed to the temperature gradient induced in the specimens and the presence of wall cell bound water. The bending heights measured in the dry specimens (MC_{OD}) are attributed to these latter phenomena; these heights were achieved with a curvature in the same direction as those with moisture content. Laser energy was adjusted so as not to reach the calcination temperatures of wood, 400–600°C (higher than the glass temperatures of lignin and cellulose, 140–175°C). These specimens also experienced weight loss from the cell bound water being released; however, given the conditions described above at MC_{OD}, the polymeric wood constituents could also shrink due to an increase in the configuration entropy of the polymer chains of their amorphous sections (e.g., entropy change of elastomers) instead of the expected thermal expansion in a linearly elastic solid.

c) Maximum moisture content

Like the oven dry specimens, the EMC (specimen at ambient saturation) and MC_{MAX} (specimen at complete surface saturation), samples are exposed to the effect of the induced temperature gradient by the laser beam. The difference is that by having water in the system, the energy is used to heat the
specimen and evaporate the free water, so it does not affect it in the same way as in the previously dried specimens. The upper layers are exposed to a temperature higher than 100ºC. It is possible to see that the \( \text{MC}_{\text{MAX}} \) specimens have the lowest deformations of the sample, which is attributed to two factors: first, the specimen, having \( \text{MC}_{\text{MAX}} \), has far more free water and evaporates about several times more water than the specimens under EMC. This indicates that the laser energy does not penetrate much the surface of the veneer as it is being used to evaporate excess free water out of them. Secondly, \( \text{MC}_{\text{MAX}} \) specimens contain more water mass. Thus, its density is higher given the amount of water it has absorbed previously, so it will finally show greater opposition to deflection by weight than in the specimens with less moisture content.

d) Equilibrium moisture content
As it can be analyzed from the results obtained in all species, the maximum heights are achieved when they are under EMC and maximum energy level processing. When comparing these maxima and their moisture content, we can see that the Yesquero at 18% EMC has a maximum average height of 4.25 cm, the Beech at 13% EMC a height of 4.36 cm, and the Ulmo at 8% EMC achieves a maximum average height of 3.55 cm. With these results, we can assume that there is a tendency for bending height to increase with increasing moisture content, but the height/MC curve for each species is unknown. Moreover, all samples achieved a certain bending height at ovendry MC, due to some bound water still being evaporated, and in all cases, there is an increase between this latter height and that achieved at EMC, regardless of the species or energy delivered by the laser beam. This suggests a relationship between MC and height, which should have an optimal value per species. In all the species, it is noted that the minimum bending height and the minimum average obtained occurred at \( \text{MC}_{\text{MAX}} \); all the results associated with this MC are lower than the results with \( \text{MC}_{\text{OD}} \).

4.5 Laser energy effect
For all saturations and any species, the higher the energy, the higher the bending height. The height augments with the increase in energy almost linearly, some have exponential trends, and others a decreasing trend, but they seem not to be pronounced curves.

4.6 Water loss effect
It can be concluded that the greater the water loss, the greater the bending height. However, when analyzing the \( \text{MC}_{\text{MAX}} \) cases, it can be noticed that significant water losses do not generate great bending heights, which can be attributed to the saturated specimen having much more water in the upper layers, facilitating its evaporation. Still, the remaining weight of the sample is larger, so the work required to lift the mass to a certain height must be greater than that of a lower MC specimen. This is a general observation, but there are differences between the species, noting that the bending heights of the ulmo at \( \text{MC}_{\text{MAX}} \), compared to the other two species, achieved greater heights with near similar water losses. For EMC, they all behave similarly regardless of their different % moisture content; the weight loss generated is even in all three species.
4.7 Exploratory Data Analysis

The experimental dataset of 90 observations (Ramos-Grez 2022) was used to model the bending height of 3 types of wood. Five experimental variables were modified to study their influence on the response, four of those variables are numeric, and the wood classification was numerically coded to include it in the prediction model.

The first assessment when dealing with experimental raw data prior to any further decision is an exploratory analysis to study the behavior of the variable(s) under study. First, the data is rescaled according to the $z$-score metric, which is a parametric outlier detection method that normalizes the values following Eq. 3, where $x_i$ is the specific value, $\mu$ is the mean of all $x_i$, and $\sigma$ is the standard deviation. Then the normalized points are compared to a pre-defined threshold value, usually in the range [-3, 3]. As a rule of thumb, this method has been tested and proven its effectiveness (Aggarwal et al. 2019; Anagnostou et al. 2021; Urolagin et al. 2021) in outliers’ identification.

$$z_i = \left( \frac{x_i - \mu}{\sigma} \right)$$

Figure 14a indicates that there are no strong outlier points, even when some measurements have atypical behavior. Additionally, Fig. 14b shows that the response variable doesn't follow a normal distribution since the extremes are widespread from the line trend in the quantile-quantile plot. Therefore, applying modeling techniques like Machine Learning-based ones capable of handling these patterns is justified since these types of non-linear regressors can capture the intrinsic relationship between inputs-output variables.

On the other hand, the correlation analysis between wood bending height and the five experimental factors is carried out. The Pearson (PCC), Kendall (KCC), and Spearman (SCC) correlation coefficients (Urolagin et al. 2021) are shown in Table 5. The PCC is a metric of the strength of linearity between two variables; from Table 3, it can be observed that the highest absolute valor magnitude of the correlation is with $x_2$ and $x_4$ indicating an inverse relationship with $y$ as well as for $x_3$. Moreover, the KCC and SCC measure the dependency and the degree of association among variables, respectively. The maximum KCC and SCC between wood bending height and a feature are 0.406 and 0.508, respectively, agreeing on both indicators that laser energy is the better-correlated variable. The lowest correlation values are those between the response and the type of wood.
Table 5

Three correlation coefficients of predictors to wood bending height

<table>
<thead>
<tr>
<th>Predictors</th>
<th>PCC</th>
<th>KCC</th>
<th>SCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_1$</td>
<td>0.515</td>
<td>0.406</td>
<td>0.508</td>
</tr>
<tr>
<td>$x_2$</td>
<td>-0.575</td>
<td>-0.224</td>
<td>-0.337</td>
</tr>
<tr>
<td>$x_3$</td>
<td>-0.368</td>
<td>-0.049</td>
<td>-0.175</td>
</tr>
<tr>
<td>$x_4$</td>
<td>-0.563</td>
<td>-0.274</td>
<td>-0.438</td>
</tr>
<tr>
<td>$x_5$</td>
<td>0.073</td>
<td>0.056</td>
<td>0.070</td>
</tr>
</tbody>
</table>

4.8 ML-modeling

The core of any ML algorithm is the data to be modeled, so the previous section proved the need for this tool to reveal the intrinsic relationships among input parameters ($x_i$) and the response, in this case, the wood bending height ($y$). To predict the mentioned variable, three types of the most powerful ML regressors were implemented, e.g., NN, GPR, and SVR. The final optimized hyperparameters for their respective regressor are reported in Table 6.

Table 6

Optimized hyperparameters

<table>
<thead>
<tr>
<th>ML algorithm</th>
<th>Hyperparameter ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>NN</td>
<td>Hidden Layers: 3</td>
</tr>
<tr>
<td></td>
<td>The number of neurons in each hidden layer: [284, 41, 11]</td>
</tr>
<tr>
<td></td>
<td>Activation function: 'sigmoid'</td>
</tr>
<tr>
<td>GPR</td>
<td>Basis function: ['none', 'constant', 'linear']</td>
</tr>
<tr>
<td></td>
<td>Kernel function: ['exponential', 'matern32', 'matern52', 'rationalquadratic', 'ardmatern32', 'ardmatern52', 'ardrationalquadratic']</td>
</tr>
<tr>
<td></td>
<td>Fit method: ['none', 'exact']</td>
</tr>
<tr>
<td>SVR</td>
<td>Kernel function: 'gaussian'</td>
</tr>
<tr>
<td></td>
<td>Kernel scale: 1.507</td>
</tr>
<tr>
<td></td>
<td>Epsilon: 0.004</td>
</tr>
</tbody>
</table>
Once the training process through 5-folds cross-validation is complete, the metric results are presented in a boxplot graph. From Fig. 15 can be noted that the three models have a similar accuracy performance when the mean of the determination coefficient and the RMSE are analyzed for the training phase. However, when the testing stage of all ML methods is assessed, there is evidence that the GPR outperforms the other two techniques having a $92.53 \pm 0.04\%$ and $0.23 \pm 0.06$ of $R^2$ and RMSE, respectively. So, this GPR-based model is selected as the ML technique that best fits the analyzed variable. However, overall, the three considered techniques show good accuracy for predicting the bending height. Figure 16 presents the performance evaluation of the prediction for the training and testing set obtained by GPR. Moreover, a careful analysis of the model residual depicts a random behavior about the zero line and no trend in the data along the axes, even when some particular predictions can be labeled as outliers. All in all, this is a good sign of the general quality of the fitted model since there is strong evidence in favor of homoscedasticity in the studentized residuals.

Figure 17 shows the contribution of each predictor to the modeled response variable, where saturation scores the highest value, 44.78%, while the type of wood is the less significant for the model, 4.84%, which doesn't mean that it can be neglected because even when the feature importance is low, it plays its role in the final predicted accuracy.

5. Conclusions

The experimental procedure presented here verified that it is possible to bend wood veneers of different species at different MC by irradiating heat onto the upper faces of the specimen by means of a scanning laser beam. It was successful and viable to standardize a wood laser bending procedure defining five variables: energy, MC, water loss, density, and species type.

- Direct analysis shows that the energy level and the water loss are strongly related to the bending heights achieved by the specimens suggesting that density affects the evaporation capacity and, therefore, the water loss, affecting the final bending height of the sample. On the other hand, EMC is directly related to the water absorption capacity of the species, so the resulting bending height also responds to the MC conditions of the veneer.
- Furthermore, applying ML makes it possible to accurately predict the obtained wood bending height with more than 90% precision. This technique can fit the experimental parameter to ensure feasible relationships between input-outputs.
- The algorithm that better suited the response variable was the Gaussian Process regression since it showed the highest correlation coefficient and the lower RMSE. This technique was recommended to predict the bending height in the analyzed woods.
- The feature importance analysis procedure determined the factor with the higher contribution and therefore dominated the model prediction ability. The MC is the variable that explains almost 45% of the model's predictability. These results corroborated the direct analysis of the measured data and reaffirmed that saturation alone could not explain all the phenomena involved. In the MC_{OD} state,
remaining cell wall bound water loss is the mechanism responsible for fibrous contraction resulting in a bending height, instead of the shrinkage induced by free water content loss as observed in higher % MC. Nonetheless, entropy change due to differential temperature increase of the amorphous polymeric microconstituents regions, could also have an effect in the observed contraction, however it remains to be measured or verified.

- The properties hereof studied are relevant in the resulting curvature of the veneer, and this experimental system does verify the property of deformation due to thermal differences in the wood. To the best knowledge of the authors, this specific laser-based process had not been standardized before.

**Declarations**

**Disclosure statement**

The authors report there are no competing interests to declare.

**Data availability statement**

The data that support the findings of this study are openly available in HARVARD Dataverse at https://doi.org/10.7910/DVN/FRPHBE, reference number (Ramos-Grez 2022).

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**References**


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Image that exemplifies the flexibility of a wood beech veneer along its longitudinal axis (perpendicular to its fibers).
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Experimental laser processing setup scheme.

Figure 3

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Figure 5
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Figure 7

Graph of average bending height vs. laser energy for three different species at MC_{OD}.

Figure 8
Figure 9

Plot of average bending height vs. laser energy for three species at EMC

Plot of average bending height vs. laser energy for three species at MCA_{MAX}.
Figure 10

Plot of water loss vs. laser energy for three different species at EMC.
Figure 11

Plot of water loss vs. laser energy for three species at MC\textsubscript{MAX}.
Figure 12

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Figure 13

Graph of average bending heights vs. water loss for three different species at $MC_{\text{MAX}}$. 
Figure 14

Primary raw data analysis: a) z-score, and b) QQ plot of sample data versus standard normal.
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Predictors contribution.