Electric guitar neck from densified poplar? Experimental and numerical analysis

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ABSTRACT

Electric guitar necks (EGNs) and parts are usually made of hardwoods (i.e., maple, ash, etc.), including protected exotic species coming from overseas (mahogany, etc.), due to their aesthetics, high stiffness and density. Additionally, EGNs typically include a truss rod – a metal bar stiffening the neck against bending caused by string tension. In order to reduce the environmental impact of guitar production, we believe that EGNs can be made from local and fast grown plantation wood modified using a thermo-hydro-mechanical (THM) process. In this paper, we analyze the potential of using THM densified poplar wood as a substitute material for EGN. We believe our approach for EGN production may be (i) more convenient due to higher mechanical properties of densified wood while preserving similar vibrational performance; (ii) more economical due to local and cheap resources use and absence of a truss rod; (iii) more environmentally friendly due to reduced logistics and energy costs. To analyze the hypothesis resulting from (i), we performed both experimental tests and numerical analyses. Experiments consisted of poplar wood densification (dens. ratio 2) to obtain the elastic orthotropic material model of densified poplar suitable for finite element analyses (FEA). We carried out compression tests accompanied with digital image correlation which provided a set of elastic material coefficients – 3x normal elastic moduli (E_L, E_R, E_T), 3x Poisson's ratios (μ_{LR}, μ_{RT}, μ_{LT}); 3x shear elastic moduli (G_{LR}, G_{RT}, G_{LT}) were calculated from measured values. Developed material models were employed in FEA of (i) guitar neck deflection induced by string tension and (ii) modal analysis of a neck including sensitivity study for the role of density and elastic moduli on eigenfrequencies. FEA showed the highest 1st principal stress (PS1) is located on the bottom of the neck. Further, PS1 changes with change of E_L – deflection decreased 40 % and PS1 increased ~ 11 % as E_L increased from 12.4 GPa to 22 GPa. Eigenfrequencies decrease with density but increase as E_L increases (1st freq 17.4 %, 2nd freq. 21.4 % and 3rd about 27 %).

INTRODUCTION

A broad range of wood types are used in the production of musical instruments. In case of many instruments, such as strings or guitars, the selection of wood has been defined trough centuries of craftsmanship leading to the evolution of musical instruments as we know today. Depending on the part of the instruments, very diverse mechanical and dynamical properties are favored for the wood used. A large amount of research has been devoted to the understanding of the relation between the wood properties and the performance of the instrument in sense of structural requirements, playability and acoustic character.

Parts like guitar fretboard or violin pegs are built from very durable woods, such as ebony or rosewood. Those wood species are endangered meaning that suitable alternatives with similar mechanical properties are needed. Furthermore, in many instrument components the wooden part must be reinforced by other materials to achieve the desired strength. An example of this is the truss rod in the electric guitar's neck which is required to sustain the high torque produced by the strings. Could the truss rod be avoided if the neck would be built from densified wood with a higher MOE?

The mentioned cases are just some examples where modified wood could be a suitable alternative or building improvement for producing musical instruments. Our hypothesis is, that many more exist. Some pioneering work and research have been already performed to support this idea, but the full potential of using modified wood in musical instruments still has to be studied to a greater extent.

MATERIALS AND METHODS

Our work aimed on a comparison of native and densified poplar wood (*Populus* Sp.) originated from poplar plantation in Serbia. The comparison was based on mechanical properties of both materials and their performance in numerical modal analysis of EGN. The work consisted of the following steps: (i) densification; (ii) compressive tests coupled with visual data acquisition; (iii) experimental data evaluation and (iv) numerical static structural and modal analysis of EGN with use of experimental data.

Densification

Densificatication was carried out at the hot press (Langzauner LZT-UK-30-L) with heated plates. The sawn timber (Fig. 1 left) of 60 mm thickness was planned to final 53 mm. The planned boards were densified to a thickness of 27 mm, which give a general densification ratio (ρ ratio) about 2 (Fig. 1 right). The densification process was conducted under the following steps: wood specimens were put in the press at room temperature. Heating plates were heated to 60°C with 5°C /min heating rate and held pressed for 10 minutes. After that, heating was increased to 170 °C with a 5°C/min heating rate with addition of 300 kN force for 3 minutes. This step was followed by increasing the temperature to 200 °C with 20 °C/min heating rate for 2 additional minutes. The process was completed by cooling the press to 40°C, holding the temperature for 30 minutes and releasing the press.
The densification process on thick boards caused different density profiles, where middle parts got densified more than boundaries. The specimens for testing were cut out from the boards, so the parts with the highest density were used. This explains why the ρ ratio in the Table 1 is higher than 2.

Figure 1: Poplar wood in raw material (left) and in boards before and after densification (right)

Compression testing

Compression tests were performed using the Universal Testing Machine – UTM (Zwick Roell Z100, Zwick Germany) equipped with a 100 kN load cell. Preload was set to 10 N and speed of loading was controlled by a displacement rate of 5 mm/min. Compression specimens were loaded in longitudinal (L), radial (R) and tangential (T) direction and, at the same time, they were filmed using a 1 Mpx camera (Logitech) with a 30 fps acquisition rate synchronized with the UTM. 2D digital image correlation (2D-DIC) implemented in Mercury software (Sobriety Ltd., Czech Republic) was used to track markers on three planes of deformation to obtain active and passive strains and, consequently, three Poisson's ratios (ν_{LR}, ν_{RT}, ν_{TL}) from an elastic range of deformation (see Fig. 2). DIC algorithm assumed full-affine transformation, subset size was set to 35 px with a step of 5.

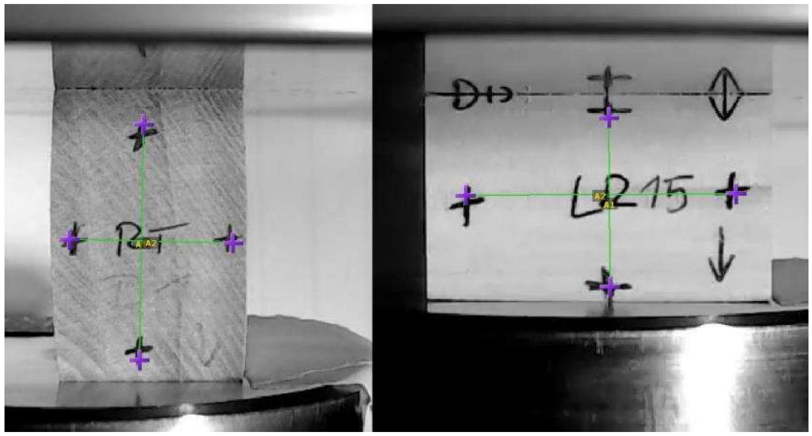

Figure 2: Specimens in compression tests of densified wood in tangential (left) and radial (right) directions with virtual strain gauges for obtaining strains and Poisson's ratios

Other three Poisson's ratios were derived from Hooke's law for orthotropic material, which can be written using Voigt's notation as follows:

$$\begin{bmatrix} \varepsilon_{LL} \\ \varepsilon_{RR} \\ \varepsilon_{TT} \\ 2\varepsilon_{RT} \\ 2\varepsilon_{TL} \\ 2\varepsilon_{LR} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_L} & \frac{-\nu_{LR}}{E_R} & \frac{-\nu_{LT}}{E_T} & 0 & 0 & 0 \\ \frac{-\nu_{RL}}{E_L} & \frac{1}{E_R} & \frac{-\nu_{RT}}{E_T} & 0 & 0 & 0 \\ \frac{-\nu_{TL}}{E_L} & \frac{-\nu_{TR}}{E_R} & \frac{1}{E_T} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{RT}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{TL}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{LR}} \end{bmatrix} = \begin{bmatrix} \sigma_{LL} \\ \sigma_{RR} \\ \sigma_{TT} \\ \sigma_{RT} \\ \sigma_{TL} \\ \sigma_{LR} \end{bmatrix} \tag{1}$$

where E_i is elastic modulus, G_{ij} is shear modulus, ε_{ij} is strain and ν_{ij} is Poisson's ratio. Indices *i* and *j* may be *L*, *R* and *T* that stand for longitudinal, radial and tangential anatomical directions, respectively. Because of the assumed material symmetry in compliance matrix (Eq. 1), we can derive following $\nu_{LR}/E_R = \nu_{RL}/E_L$, $\nu_{LT}/E_T = \nu_{TL}/E_L$, and $\nu_{TR}/E_R = \nu_{RT}/E_T$. These relationships were used to calculate Poisson's ratios complementary to those measured ones and these were used to calculate shear elastic moduli at three shear planes. Shear elastic moduli were calculated using approach given by Saint-Venant (1863), its successful use and analysis was demonstrated on walnut wood in Bachtiar et al. (2017), the calculation is as follows:

$$G_{ij} = \left[\frac{\nu_{ji}+1}{E_i} + \frac{\nu_{ij}+1}{E_j}\right]^{-1} \tag{2}$$

where i, j can be L, R, T, and $i \neq j$.

Finite element model

Geometrical and finite element model of the EGN was obtained from a publicly accessible database (https://cockrum.net/lutherie.html) and is depicted in Fig. 3. The numerical model was developed in Ansys 2019 R2 (Ansys Inc., USA). The numerical model considered pretension simulating pulling strings and in total, force equal of 306 N was used and applied on head of neck (red area in Fig. 3) in a direction of a nut where strings are bent. For all computations, a free mesh created by 3D quadratic finite element SOLID186 was used. FE model was used for both static structural evaluating bending of a neck due to strings pulling and modal analysis evaluating eigenfrequencies and modal shapes of EGN in dependence on elastic parameters and density.

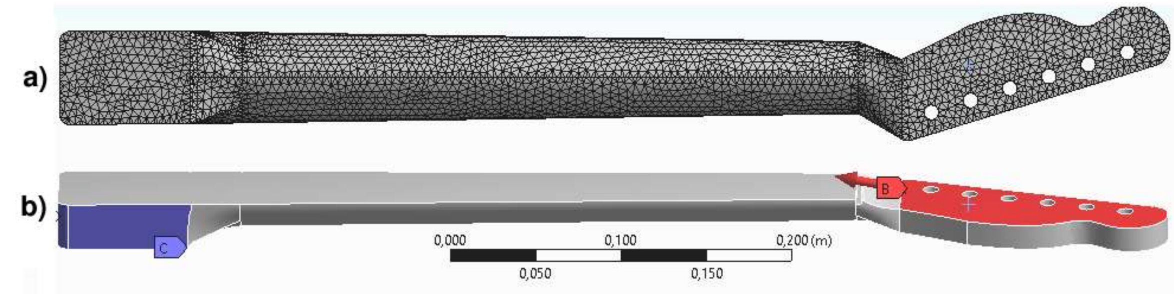

Figure 3: Numerical model of EGN, a) finite element mesh; b) geometrical model with boundary conditions where blue color denotes full constraint, red color denotes pretension simulating pulled strings

RESULTS

Results from the compression testing in a form of stress-strain diagrams for all tested groups are depicted in Fig. 4. By comparing diagrams of groups before and after the modification, it is clear that the densification substantially modified stress-strain response of wood, mostly by increasing strength and elastic modulus, but also by a global character of the stress-strain curve.

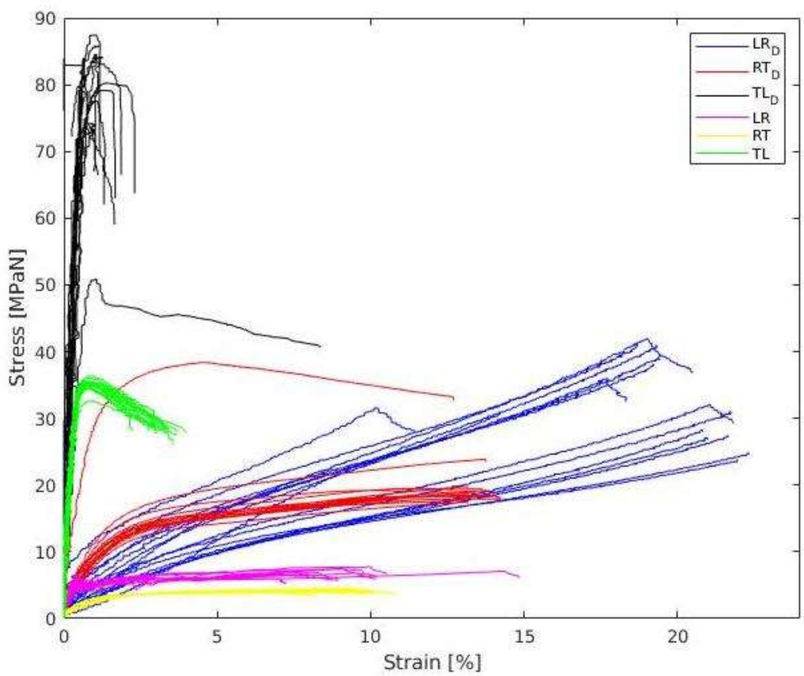

Figure 4: Stress-strain diagrams for native and densified wood (index "D"), the second letter denotes the force direction, strain is obtained from the marker tracking.

The descriptive statistics with removed outliers of obtained stress-strain diagrams is showed in Table 1. It shows that densification ratio (ρ ratio) for all tested specimen ranges between 2.32 and 2.45, but individual mechanical parameters have very different DP/NP ratios, the lowest for Poisson's numbers (0.06-0.28) and the highest for G_{LT} and E_T (3.55-3.6). The ratio of DP/NP with respect to longitudinal strength (σ_L) is very alike to ρ ratio (2.3 *vs.* 2.45). Elastic moduli in longitudinal and tangential direction increased substantially, except the radial one that decreased 3times. The shear moduli that were calculated using eq. 2 also show interesting change because G_{LR} decreased 66%, but G_{LT} increased 3.55times due to change of normal elastic moduli (E_T and E_R). In general, the presented DP/NP ratios show that the poplar densification has very different impact on its each individual parameter, so the coefficients of anisotropy might be modified too. This could impact a global behavior of wood not only in acoustic applications such as EGN.

Table 1: Descriptive statistics of material data for native (NP) and densified (DP) poplar, * denotes computed values

	E_L [MPa]	E_R [MPa]	E_T [MPa]	G_{LR} [MPa]	G_{LT} [MPa]	G_{RT} [MPa]	ν_{TR} [-]	ν_{TL} [-]	ν_{LR} [-]	σ_L [MPa]
NP mean	6408	1052	147	612*	139*	85*	0.29	0.63	0.18	35.1
CoV	20	43	11				4	41	215	2
n	15	13	15				15	13	11	15
DP mean	12479	278	524	266*	496*	178*	0.048	0.17	0.011	81.4
CoV	11	38	13				6	38	126	5.2
n	13	14	14				9	13	14	13
DP/NP	1.9	0.34	3.6	0.44*	3.55*	2.1*	0.16	0.28	0.06	2.3
ρ ratio	2.45	2.32	2.35	-	-	-	2.35	2.45	2.32	2.45

Finite element model

First, static structural FEA was performed to investigate location of stress allocation due to bending caused by pulled strings. The result of this analysis can be presented as total deformation which expresses bending (Fig. 4a). From legends in Fig. 4 it is clear that EGN made with densified poplar has 1.8x lower deflection due to 1.95x higher longitudinal elastic modulus (E_L) which is the main contributing material parameter in bending problems. The maximal 1st principal stress (PS1), which represents the tensile stress (Fig. 4b and c) is 1.14x higher for densified EGN compared to one from native, and it is also due to higher E_L.

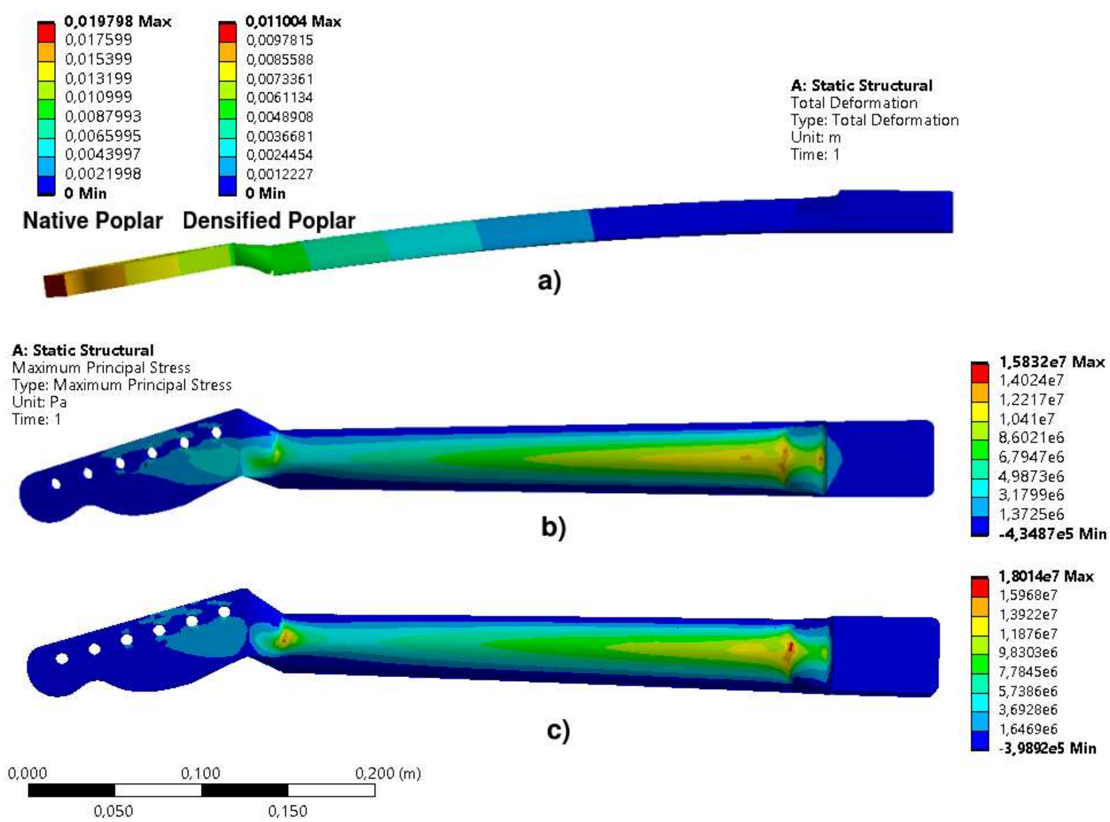

Figure 4: a) Bending of the EGN due to string pretension where NP and DP differs only by legend; b) 1st principal stress of NP and c) 1st principal stress of DP

The result of numerical modal analysis of both variants of EGN is showed in Table 2 that lists first twenty eigenfrequencies including their ratios. It says that densification changed all eigenfrequencies in different manner in a range of 2-18%. Every frequency is influenced by all material properties, but each of them has a different participation to the obtained frequencies which explains the differences between them. Because the model has simplified geometry by not considering frets, tuning pets and truss rod, the frequencies will not match real guitar. Instead, the analysis aims only on an investigation of EGN behavior when material is changed.

Table 2: Eigenfrequencies of EGN made of native (NP) and densified (DP) poplar and ratios

Mode shape #	1	2	3	4	5	6	7	8	9	10
NP – freq [Hz]	39.7	80.6	163.3	250.2	328.7	516.7	662.9	726.7	919.5	1092.9
DP – freq [Hz]	36.5	76.5	151.2	223.2	335.0	423.5	617.1	766.4	792.4	985.4
DP/NP	0.92	0.95	0.93	0.89	1.02	0.82	0.93	1.05	0.86	0.90

Mode shape #	11	12	13	14	15	16	17	18	19	20
NP – freq [Hz]	1265.1	1416.4	1589.0	1635.6	1868.7	2045.2	2227.7	2330.9	2352.2	2796.7
DP – freq [Hz]	1146.2	1328.0	1403.9	1570.6	1638.4	1787.1	2061.8	2110.1	2142.7	2438.5
DP/NP	0.91	0.94	0.88	0.96	0.88	0.87	0.93	0.91	0.91	0.87

Then, we performed the sensitivity analysis to investigate an effect of increased longitudinal stiffness (E_L) on a deflection and PS1 without changing other material properties. This analysis showed in Fig. 5 left tells that increased E_L causes substantial lowering of deflection and increase of PS1. The impact of density increase on first three eigenfrequencies for two E_L (12 GPa and 20 GPa) is showed in Fig. 5 right. It shows that increase of density lowers eigenfrequencies, meanwhile E_L highers it and the higher the frequency is, the higher the impact.

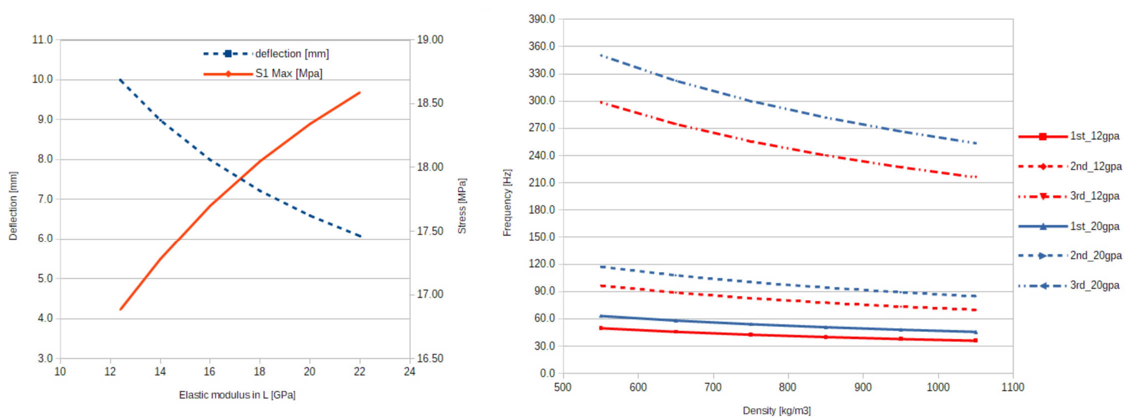

Figure 5: left – Principal stress and deflection depending on E_L, right – dependency of the first three eigenfrequencies on density for E_L =12.4 GPa and 22 GPa

CONCLUSIONS

In this paper, we analyze the potential of using THM densified poplar wood as a substitute material for electric guitar necks. Such substitution contributes to the preservation of endangered exotic wood species and reduces the financial and environmental production costs, while preserving similar vibrational performance. Our experimental tests and numerical analyses show that in general, the increase of density due to densification has higher impact on vibrational properties than the increase of elastic parameters. Through FE modal analysis, we also show that orthotropic mechanical properties of densified poplar wood exhibit substantial increase in most of elastic parameters as well as in mutual ratios, and that most of eigenfrequencies decrease by using densified wood compared to native poplar.

As future work, we deem appropriate to explore how particular elastic properties participate on individual eigenfrequencies; how and what wolf tones to avoid in this EGN design; how the fully equiped EGN (frets, pegs etc.) differs in its response to currently simulated version; and what is our simulation error with respect to experimental modal analysis.

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