Short Term Scientific Mission Report

COST Action FP1302

Topic: Microstructure-property relationship in varnished wood of string instruments

Submitted by: Sarah Louise Lämmlein

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1. Purpose of the STSM

One part of my doctoral thesis on the "microstructure-property relationship in varnished wood of strings instruments" is the influence of varnish on the vibro-mechanic properties of wooden musical instruments. To measure the changes in the vibration behavior and to identify the material parameters that lead to these changes, it is aimed at a combined experimental-numerical and non-destructive approach for the investigation.

The main objective of the STSM was the introduction to the combined experimental-numerical setup used at FEMTO-ST for the investigation of vibrations and the determination of material parameters. Beside an experimental modal analysis with a 3D laser vibrometer, numerical post-processing is used to define the Eigen-frequencies and the corresponding loss factors and to determine material properties by optimizing a numerical model. The STSM should enable a state-of-the-art understanding so that the PhD thesis is conducted on an up-to-date level.

Within the frame of this STSM it should also be evaluated, whether this combined approach is suitable to measure the influence of varnish on the vibro-mechanic behavior of wooden musical instruments. Therefore, first experimental measurements and their numerical post-processing should be conducted.

2. Description of the work carried out during STSM

In the process of getting to know the combined experimental-numerical setup and evaluating the influence of different varnishing steps on the vibro-mechanic properties, twelve samples were investigated. Always three samples were cut out in longitudinal direction at a time. For samples cut out one above each other, the macroscopic structures (sequence of annual rings etc.) are quite similar. This results in comparable material properties and therefore these samples are often called 'twin samples'. Hence we had four sets, consisting of each three twin samples, with a size of 140 x 100 x 5 mm. For each twin set, two samples have been pretreated with the following steps:

- Priming with sodium nitrite
- Sealing with Mastic Varnish
- Grounding with pumice powder and clear oil varnish

As shown in Figure 1 and Figure 3, the samples can also be distinguished by their color.

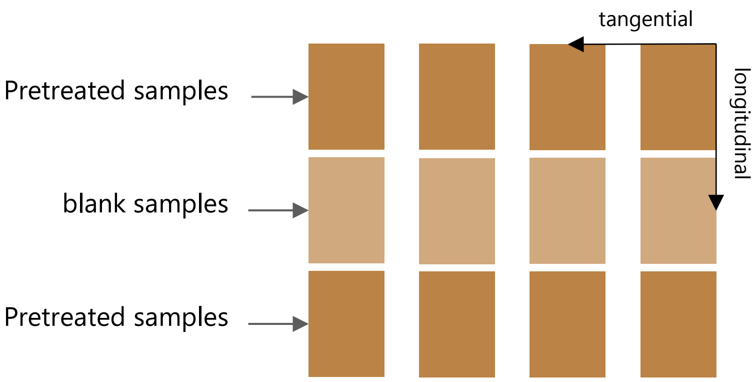

Figure 1: Samples for the laser vibrometry measurements

All samples were stored in a climate chamber at 24.5 °C and 50% RH.

For the investigation of the changes induced by the pretreatment steps, all samples were measured with a Polytec PSV-500-3D Scanning Vibrometer. A typical test setup can be seen in Figure 2.

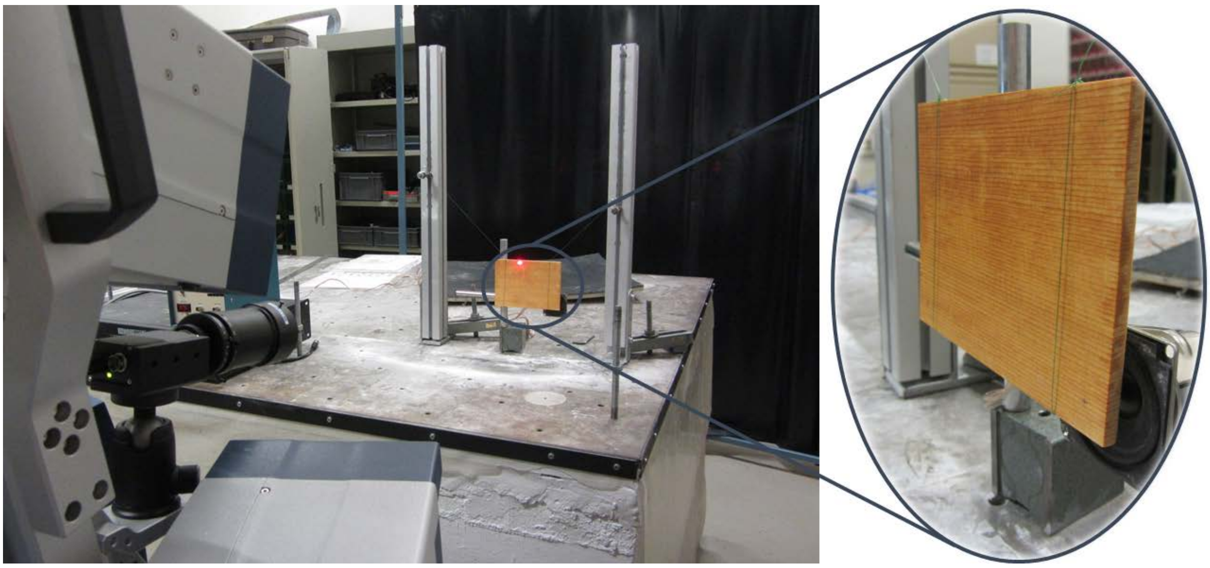

Figure 2: Laser vibrometry setup. The loudspeaker for the excitation of the vibrations is positioned behind the plate.

The free plate vibrations were excited with a loudspeaker, positioned behind the bottom right corner of the plate. The measurements were taken at 160 points, distributed equally over the plate. For each measurement point, nine measurements were conducted in a range from 400 – 10000 Hz. The complete measurement of one plate took approximately 45 – 55 min.

For the investigation of the varnish step itself, it was decided to cook an alcohol varnish, as it dries faster compared to oil varnishes. The varnish chosen for the investigation consists of:

- 45 g shellac
- 7.5 g elemi gum
- 180 ml alcohol
- 9 ml aspic oil

Two sets of each three twin samples (in total: six samples) were varnished with the alcohol varnish, as it can be seen in Figure 3. The varnished samples had a thickness of 5.2 mm.

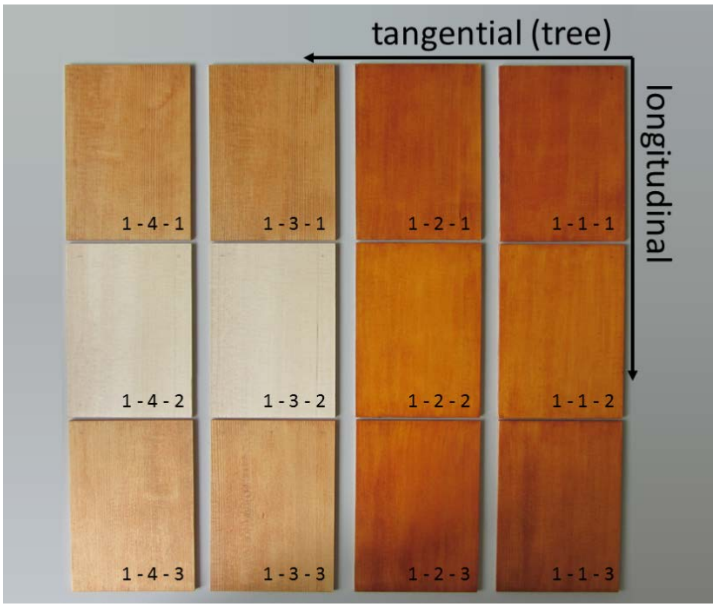

Figure 3: Unvarnished (1-3&4-Z) and varnished (1-1&2-Z) samples for the laser vibrometry measurements

These six samples were then again measured with the scanning vibrometer. In addition, all samples were weighed before and after varnishing.

The material density was calculated out of the measured mass and dimensions. The Eigen-frequencies and loss factors could directly be determined out of the experimental results. As 'getting to know the numerical post-processing' was also one of the objectives, the numerical determination of the remaining parameters is explained in the third (3.2) part.

3. Description of the main results obtained

Based on the chosen samples, two different evaluations can be made:

- For the unvarnished plates, the pretreated eight plates can be compared to their blank twin plates to evaluate the influence of the pretreatment.
- With the measurement of the exactly same but varnished plates (six measurements), the effect of the varnish can be estimated.

During the discussion of the results, it should always be considered, that the number of investigated samples is small. Furthermore one has to distinguish 'varnished blank sample' from 'varnished pretreated sample' to avoid mixing up the influences of the separate steps.

Considering the number of samples and measurements, all the following results are rather useful to evaluate trends than to make any quantitative statements.

3.1. Direct results out of experimental measurements

The results for the measured masses and the thereof calculated density $\left(\rho = \frac{m}{V}\right)$ are shown in Table 1. The lines having a blue color are the pretreated samples. The values of the already pre-pared samples are in the same order as the completely blank results. Therefore, the pretreatment seems not to have any influence on the density

Sample label	Twin number	Mass [g] (unvarnished)	Density [kg/m³] (unvarnished)	Mass [g] (varnished)	Density [kg/m³] (varnished)
01-1-1	1	29.4	413.39	31.1	427.20
01-1-2	1	29.1	409.17	31.3	429.95
01-1-3	1	29.1	409.17	30.6	420.33
01-2-1	2	29.3	411.98	30.9	424.45
01-2-2	2	29.1	409.17	31.2	428.57
01-2-3	2	29.0	407.76	30.9	424.45
01-3-1	3	29.2	410.57	-	-
01-3-2	3	29.3	411.98	-	-
01-3-3	3	29.4	413.39	-	-
01-4-1	4	29.4	413.39	-	-
01-4-2	4	29.1	409.17	-	-
01-4-3	4	29.0	407.76	-	-

Table 1: Mass and density results

Varnishing on the other hand clearly influences the mass and density. On average, varnishing increases the mass by 1.83 g; 1.675 g for the pretreated plate and 2.150 g for the blank plates. Even though only two blank plates have been varnished, these results show a tendency that the pretreatment reduces the varnish penetration into the wood. The density of the varnished plates is slightly increased compared to the unvarnished plates.

An in-house post-processing software at Femto-ST automatically calculates the Eigen-frequencies and the corresponding loss factors for each mode. The loss factors η_L, η_R and η_{LR} result out of the fourth, second resp. first mode. Figure 4 and Figure 5 show the results for the unvarnished resp. varnished plates. Figure 4 indicates that the grounding increases the loss factor in radial direction and also, alt-hough even less certain, in the LR-plane. Comparing the absolute values in Figure 4 and Figure 5, it can clearly be said that the applied varnish increases the loss factors, especially in radial direction and in the LR-plane. The influence of the pretreatment step on the other hand, seems to be gone.

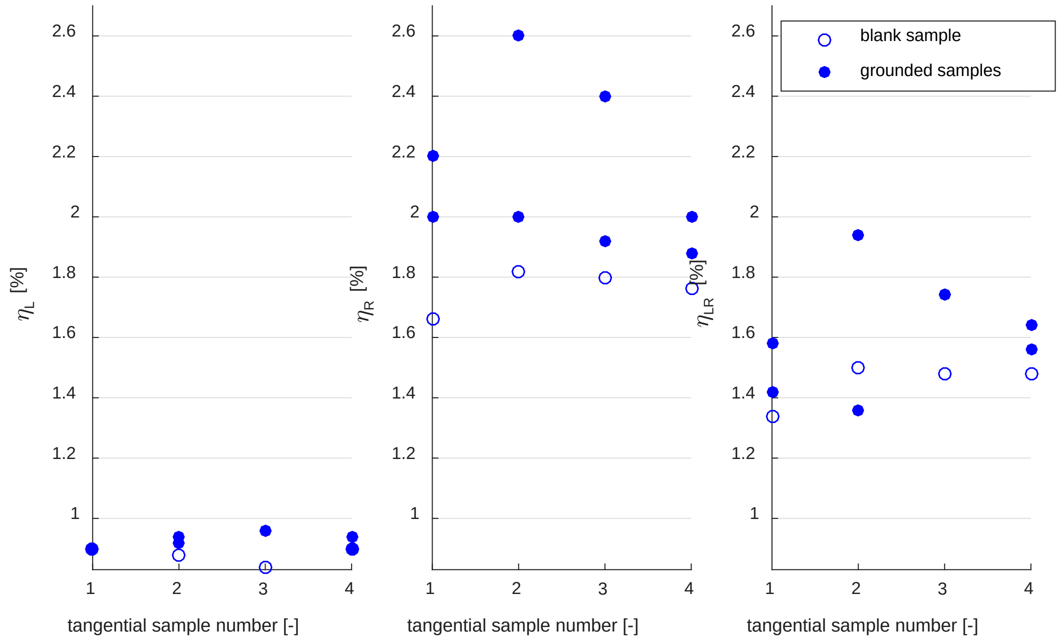

Figure 4: Loss factors for unvarnished plates in longitudinal (left), radial direction (middle) and LR-plane (right)

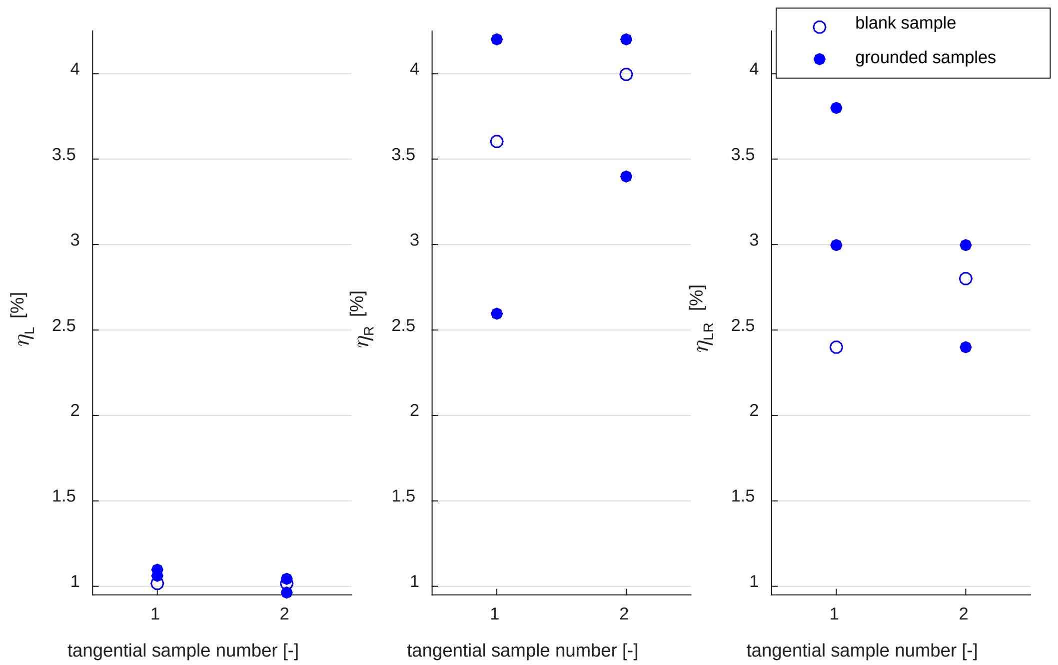

Figure 5: Loss factors for varnished plates in longitudinal (left), radial direction (middle) and LR-plane (right)

3.2. Numerical optimization

Compared to the direct measured respectively determined material parameters (mass, density, Eigen-frequencies and loss factors), the remaining material parameters can be determined via a numerical optimization. The general procedure of such an optimization is shown in Figure 6. For the numerical results, a FEM model is set up, having linear elastic material properties. As starting values, average spruce tone wood material properties, adapted to temperature and RH, are taken. The experimental and numerical results are commonly compared in two ways: either by comparing the Eigen-frequencies values or by comparing the Eigen-frequency mode shapes (MAC-values).

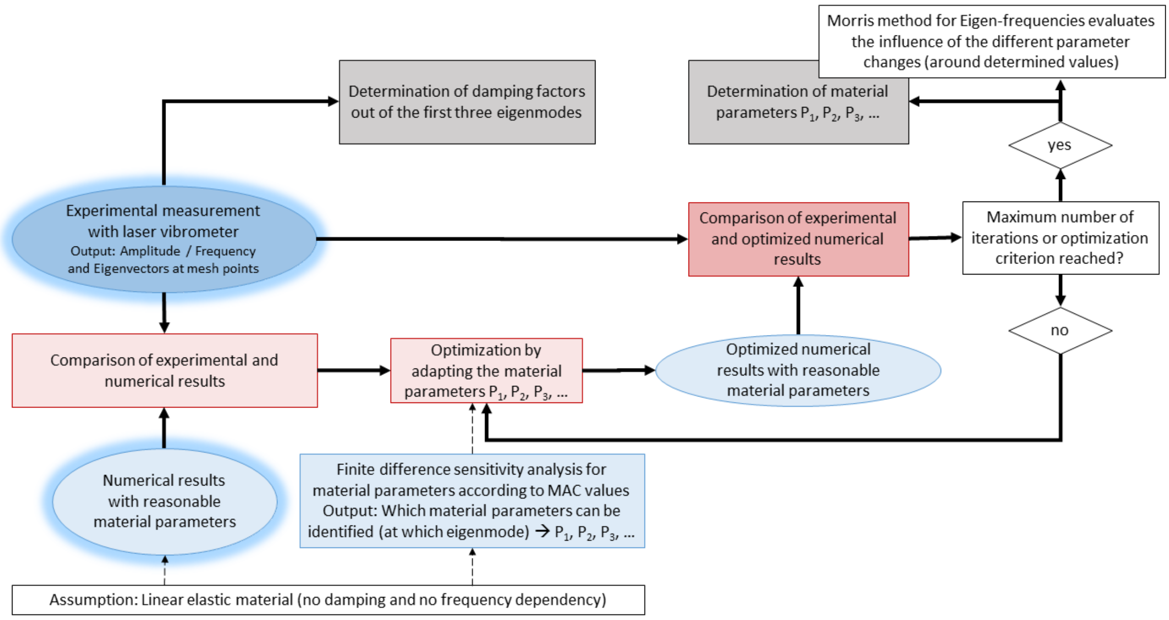

Figure 6: Optimization process: By trying to minimize the difference between the experimental and numerical results, optimized material parameters can be defined.

A finite difference sensitivity analysis for the given FEM-model reveals the material properties that influence the numerical results and therefore can be determined within the optimization of the numerical material parameters. Figure 7 shows that for the given plate geometry with average spruce tone wood parameters, the numerical result are influenced by

- The stiffness in longitudinal direction E_L (mode 4)
- The stiffness in radial direction E_R (mode 2)
- The in-plane shear stiffness G_{LR} (mode 1)
- The out-of-plane shear stiffness G_{TR} (modes 14 and 15)

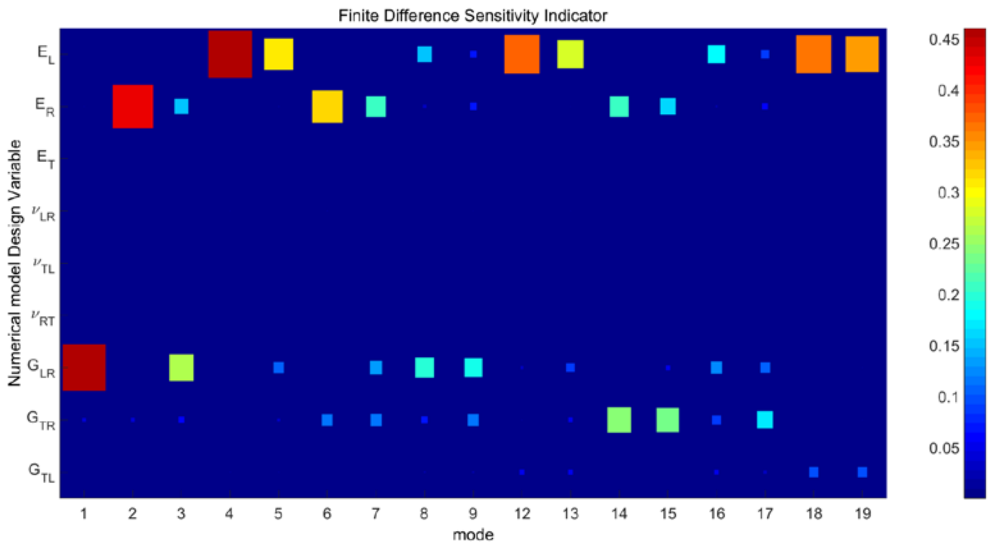

Figure 7: Finite difference sensitivity analysis showing the "importance" of different material parameters for the first 19.th modes

By adapting these values, the numerical results can be changed. During the optimization E_L, E_R, G_{LR} and G_{TR} are changed to minimize the difference between the experimental Eigen-frequency values and the numerical ones. When this difference reaches a certain value or when the maximum number of iterations is reached, the final values of E_L, E_R, G_{LR} and G_{TR} correspond to the optimized material parameters.

Compared to the already derived material parameters (density and loss factors), the usage of a FEM model and numerical optimization implies additional uncertainties.

For a statement over the absolute values, a comparison to material parameters derived from other experimental methods should be considered. Nevertheless, the applied FEM model and numerical optimization are not changed for the different measurements. Therefore, the results obtained by this method can fairly well be compared among themselves and more general statements about parameter tendencies can be made.

3.3. Optimized material parameters

In Figure 8 and Figure 9 the optimized results for the axial and shear moduli are displayed. Out of the conducted measurements, and also considering the limited amount of experiments, the pretreatment seems to influence the stiffness in radial direction E_R and the in-plane shear modulus G_{LR}.

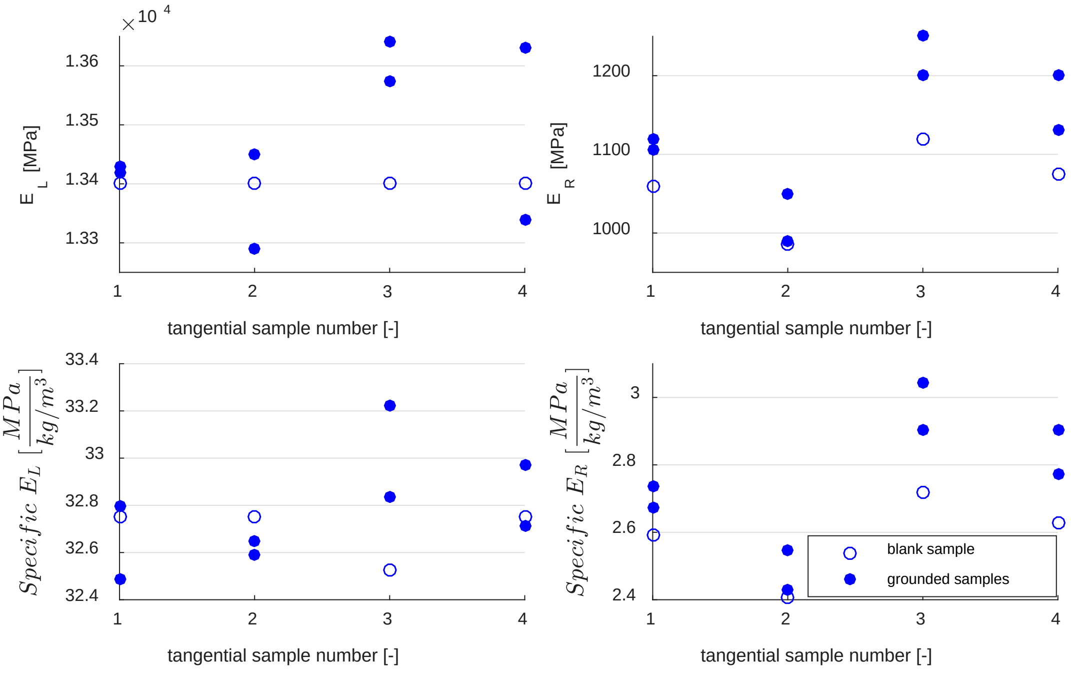

Figure 8: Optimized stiffnesses (top) and specific stiffnesses (bottom) for the unvarnished plates in longitudinal (left) and radial (right) direction.

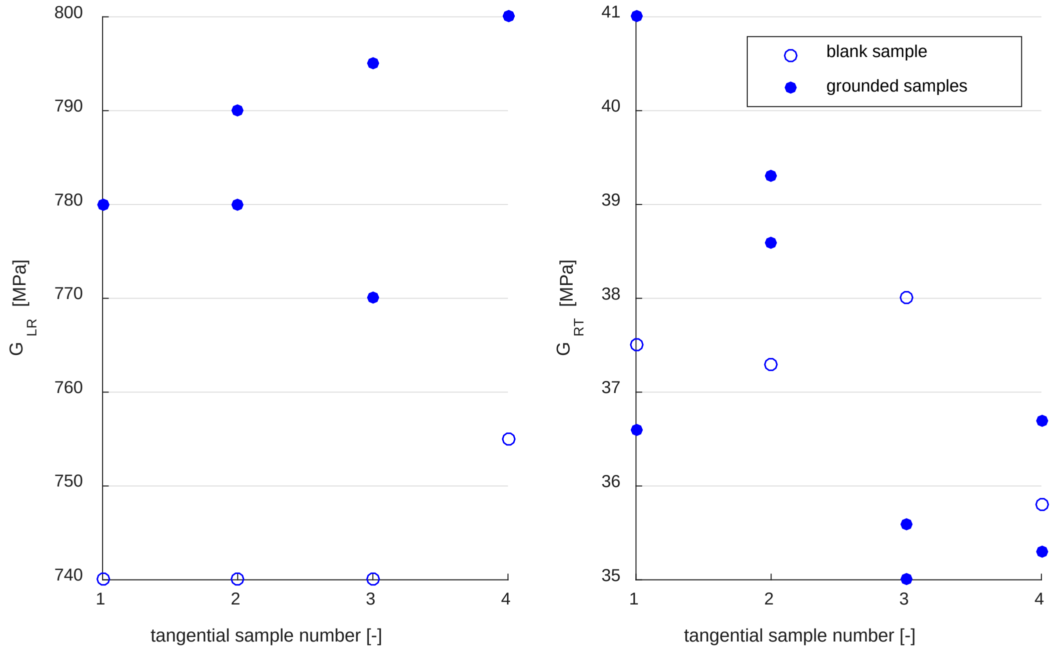

Figure 9: Optimized shear moduli for the unvarnished plates

The percentage change of all parameters due to the applied pretreatment can be seen in Figure 10. The mean values of the changes (black dots) indicate, that the pretreatment increases all parameters (and also their variability) having at least one compound in radial direction. The loss factor in radial direction experiences the strongest and most noticeable change of all parameters.

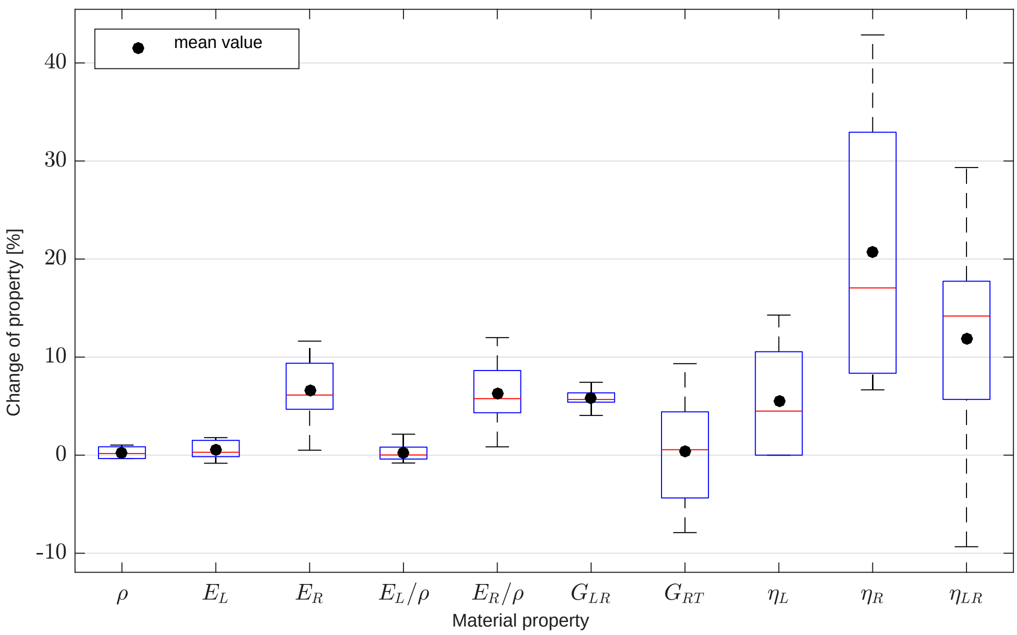

Figure 10: Percentage changes of material properties due to the pretreatment

Figure 11 till Figure 13 display the results for the varnishing step. As only half of the samples have been varnished, it is even more difficult, to determine any tendencies for material property changes.

According to the few measurements, the pretreatment step seems not to have any influence on the stiffness and shear moduli of the finally varnished plates.

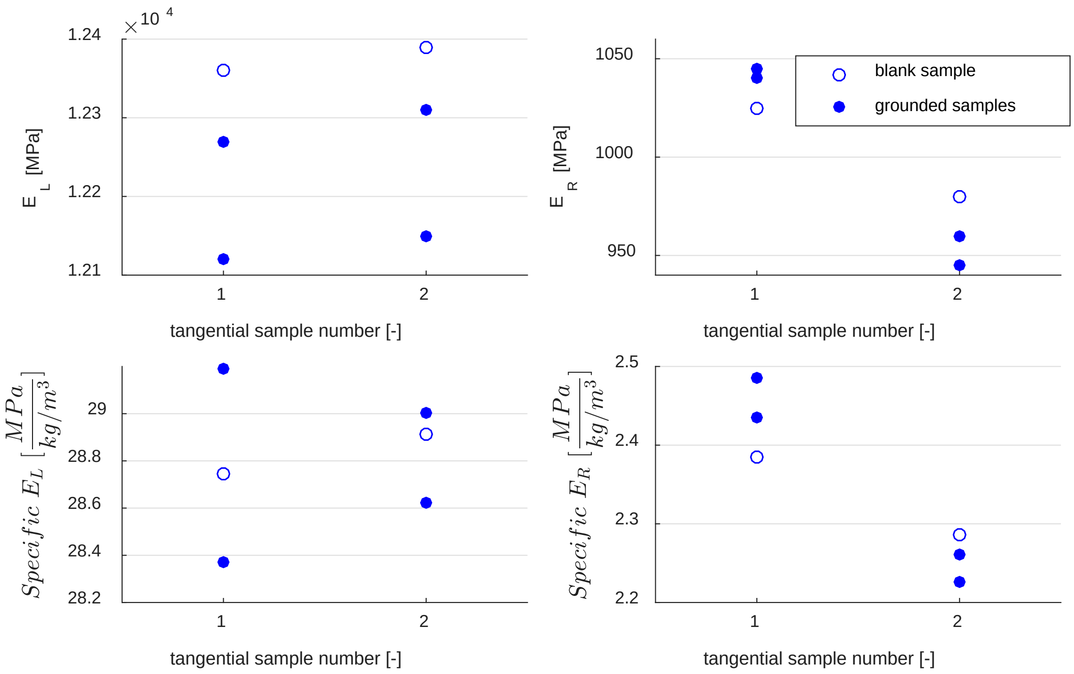

Figure 11: Optimized stiffnesses (top) and specific stiffnesses (bottom) for the varnished plates in longitudinal (left) and radial (right) direction.

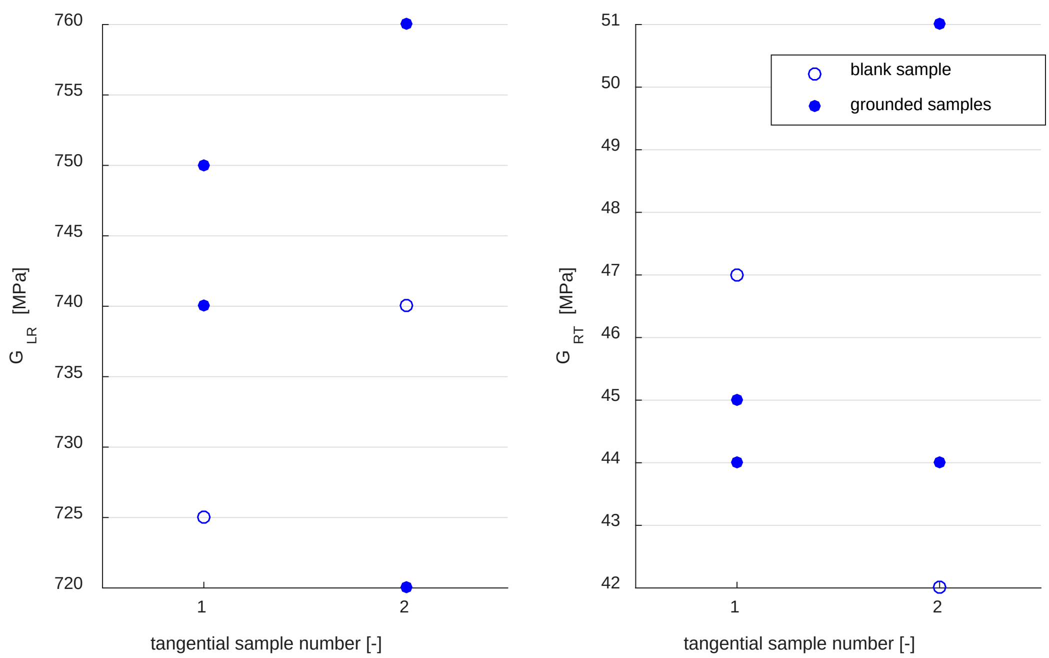

Figure 12: Optimized shear moduli for the varnished plates

Figure 13 shows the changes of the material properties compared to the exactly same, but unvarnished samples (before and after varnishing). The optimized parameters indicate that the varnishing increases the loss factors, especially in radial direction and in the LR-plane, and G_{RT}. For the loss factor in radial direction, the varnishing appears to have a greater influence on the blank samples. Furthermore, the (specific) stiffness in longitudinal and also radial direction seems to be decreased slightly – this time a little more pronounced for the pretreated samples.

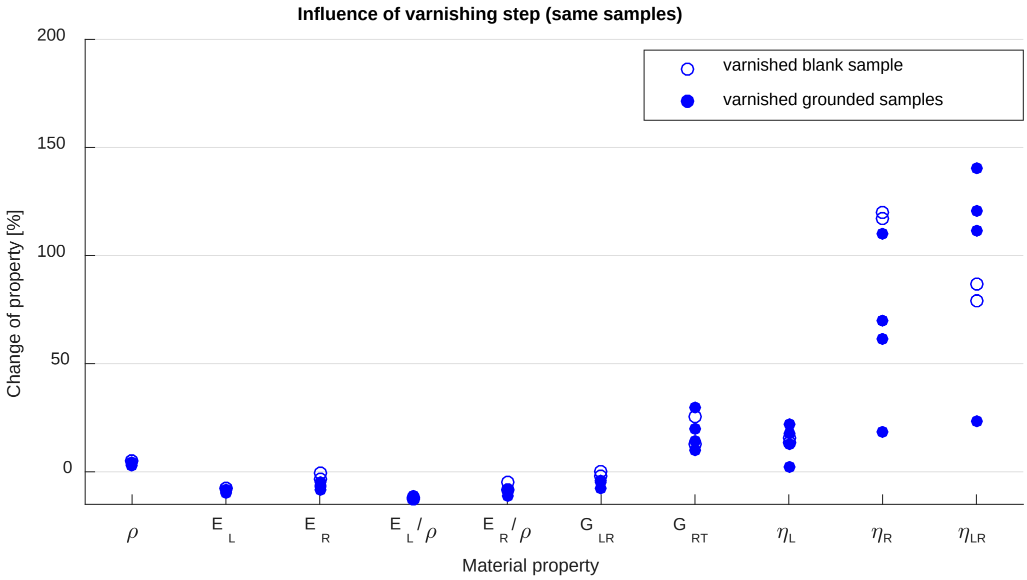

Figure 13: Percentage changes of material properties due to varnishing

In general it can be said that the different steps of varnishing have a greater influence on the loss factors than on the stiffness and shear moduli.

For more precise statements and trends, many more experiments are needed.

4. Future collaboration with host institute

Different possibilities for further collaboration exist. Besides conducting many more experiments in order to receive more quantitative statements, other aspects such as viscoelastic properties and RH, T and frequency dependencies of the materials can be discussed.

Femto-ST offered me the possibility to conduct more vibrometry measurements, use their post-processing software and perform other experiments (e.g. nanoindentation) at their facilities.

Furthermore, a collaboration considering the modelling of a complete violin, including also the aspect of varnish influences, seems possible.

The STSM at Femto-ST has proven the applicability of the described method for investigations of changes in the vibro-mechanic properties induced by the different steps of varnishing. Further experiments will hopefully lead to a paper on this topic, written in collaboration with Romain Viala, Scott Cogan and all other persons involved.