Experimental determination of stress and strain states of the guitar’s wood structure

M D Stanciu¹, P Bârsănescu², V Goanță² and A Savin³

¹Mechanical Engineering, Transilvania University of Brasov, 29 Eroilor Blvd, 500036, Brasov, Romania
²Gheorghe Asachi Technical University of Iasi, Romania, B-dul Dimitrie Mangeron 65, Iasi 700259
³National Institute of Research and Development for Technical Physics, -dul Dimitrie Mangeron 49, Iasi, Romania

E-mail: mariana.stanciu@unitbv.ro

Abstract. During the playing, the wood from guitar structure is subjected to stresses due to the strings tension. The paper aims to determine the stresses and strain states of wood from guitar structure in different stage of strings tension. So, a classical guitar made from Romanian factory was investigated. For experiment, the method of electrical resistance tensometry was used. On the top of guitar, near of bridge and sound hole were applied two stacked rosette type C2A-06-062WW-350 and two on the neck of guitar. The strings were tensioned to the specific value of producing the musical note. The signals of sensors were captured by Vishay P3 Input Strain Indicator / Recorder. Applying the elasticity theory of orthotropic materials as wood, the main strains and stresses were determined. The results emphasized that tensile and compression stresses are produced in guitar body and the higher values of strains are recorded in the bridge area and in the guitar neck, the 8th fret.

1. Introduction

The most studies about guitar are related to acoustic and vibration characteristics of guitar body, being researched theoretical or experimental, the modal shapes of plates as individual structures or whole acoustic box made from guitar plates [1-5]. The numerous references describe the dynamical behaviour of guitar body (classical, acoustic or electric guitar), in different stage of construction, with different shapes of guitar plates and different bracing systems of top plate of guitar [6-8]. Other researches deals with interaction between wood and fluid from inside of the guitar body, measured the vibrational characteristics [1-3]. The literature is relatively poor in terms of studies on the stresses and deformations that occur in the body and neck of the guitar during string tension. Some previous studies performed by the authors of this paper approached the stability of guitar necks with different reinforcement or at moisture content variation [9–11]. The aim of this paper is to study the stresses and strain of wood plate from guitar structure in different stage of strings tension, using the method of electrical resistance tensometry.

The guitar is a complex mechanical system consists of three subassemblies: the acoustic box, the neck, the strings as can be seen in figure 1(a). The main function of this mechanical system is to generate and amplify the sounds from strings through guitar body. The transfer of the vibration energy of the strings is done through the solid system (s1 – string) - solid (s2 – bridge) - solid (s3 – sound
board) – fluid (f1 – the air from the cavity) - solid (s4 - back) - solid (s5 - side) - fluid (f1 – the air from the cavity and the sound hole) (figure 1(b)) [4]. For this reason, the guitar body is carefully manufactured from two types of wood species: for top plate are used softwood such as resonance spruce (Picea abies); Cedar (Cedrus atlantica, Cedrus brevifolia - Cedrus deodara, Cedrus libani; sitka spruce (Picea sitchensis); Red spruce (Picea rubens); Red pine (Pinus resinosa); Silver fir (Abies alba). For back plates and sizes, the hardwood species are: curly maple (Acer pseudoplatanus); mahogany (Swietenia macrophylla); indian rosewood, Brazilian rosewood (Dalbergia nigra, Dalbergia sissoo, Dalbergia latifolia); walnut (Juglans regia); cocobolo (Dalbergia retusa); cherry (Prunus Avium); bubinga (Guibourtia Arten ) etc. The guitar neck is an important part of mechanical system having the role to sustain the stiffness of whole system under strings tension and to obtain different sounds by variation of string length. Thus, the neck is made from hardwood charaterized by high rigidity and wear resistance, as maple or mahogany for neck and ebony or black locust for fingerboard.

![Figure 1. The mechanical and dynamical system of guitar: (a) the main parts of guitar; (b) the dynamic transfer from strings vibration to guitar body.](image)

**2. Theoretical foundation of the stresses and strain state of wood**

The wood is an anisotropic material, with three perpendicular planes of elastic symmetry with respect to the cylindrical coordinates of tree trunk, denoted with L – longitudinal direction along fibres (along the trunk), R radial direction, T - tangential direction. The elastic properties of solids can be defined by generalized Hook’s law relating the volume average of stress $[\sigma_{ij}]$ to volume average of strains $[\varepsilon_{ij}]$ by the elastic constants $[C_{ij}]$ in the form $[12–14]$ . In case of wood, the stress and strain states of wood pieces are represented by stresses tensor and strains tensor as can be seen in equations (1) and (2):

$$T_{\sigma} = \begin{pmatrix}
\sigma_L & \tau_{RL} & \tau_{TL} \\
\tau_{RL} & \sigma_R & \tau_{TR} \\
\tau_{TL} & \tau_{TR} & \sigma_T
\end{pmatrix}.$$  (1)
where \( \sigma_L, \sigma_R \) and \( \sigma_T \) are normal stresses on longitudinal (L), radial (R) and tangential (T) direction; \( \gamma_{LR}, \gamma_{RT} \) și \( \gamma_{LT} \) – tangential stresses in planes LR, RT și LT; \( \varepsilon_L, \varepsilon_R \) și \( \varepsilon_T \) – strains; and \( \gamma_{LR}, \gamma_{RT} \) și \( \gamma_{LT} \) – shearing strain. Using the tensor of elasticity modulus E and the tensor of Poisson coefficients, results (3):

\[
\begin{align*}
\varepsilon_L &= \frac{1}{E_L} (\sigma_L - \nu_{LR} \sigma_R - \nu_{LT} \sigma_T); \gamma_{TR} = \frac{\tau_{TR}}{G_{TR}}, \\
\varepsilon_L &= \frac{1}{E_R} (\sigma_R - \nu_{RL} \sigma_L - \nu_{RT} \sigma_T); \gamma_{RL} = \frac{\tau_{RL}}{G_{RL}}, \\
\varepsilon_L &= \frac{1}{E_T} (\sigma_T - \nu_{TL} \sigma_L - \nu_{TR} \sigma_R); \gamma_{LT} = \frac{\tau_{LT}}{G_{LT}}.
\end{align*}
\]

where \( \nu_{LR}, \nu_{LT}, \nu_{RL}, \nu_{RT} \) are coefficients of transverse contraction (first index represents the direction of transverse contraction and the second, the direction of the stress which produces the elongation).

Applying the substitution of the parameters: \( E_L \nu_{RL} = E_R \nu_{LR}; E_L \nu_{LR} = E_T \nu_{TL}; E_R \nu_{TR} = E_T \nu_{VR}; \) the expressions of stresses on the main three direction are (4):

\[
\begin{align*}
\sigma_L &= \frac{(1-\nu_{RT} \nu_{TR}) E_L \nu_{LR} + (\nu_L + \nu_{LR} \nu_{TR}) E_R \nu_{LR} + (\nu_{LT} + \nu_{LR} \nu_{RL}) E_T \nu_{LR}}{E_L \nu_{LR} + (1-\nu_{RT} \nu_{TR}) E_R \nu_{LR} + (\nu_{LT} + \nu_{LR} \nu_{RL}) E_T \nu_{LR}}, \\
\sigma_R &= \frac{(1-\nu_{RT} \nu_{TR}) E_R \nu_{LR} + (\nu_L + \nu_{LR} \nu_{TR}) E_L \nu_{LR} + (\nu_{LT} + \nu_{LR} \nu_{RL}) E_T \nu_{LR}}{E_R \nu_{LR} + (1-\nu_{RT} \nu_{TR}) E_L \nu_{LR} + (\nu_{LT} + \nu_{LR} \nu_{RL}) E_T \nu_{LR}}, \\
\sigma_T &= \frac{(1-\nu_{RT} \nu_{TR}) E_T \nu_{LR} + (\nu_L + \nu_{LR} \nu_{TR}) E_L \nu_{LR} + (\nu_{LT} + \nu_{LR} \nu_{RL}) E_R \nu_{LR}}{E_T \nu_{LR} + (1-\nu_{RT} \nu_{TR}) E_L \nu_{LR} + (\nu_{LT} + \nu_{LR} \nu_{RL}) E_R \nu_{LR}}, \\
\tau_{TR} &= G_{TR} \gamma_{TR}; \tau_{RL} = G_{RL} \gamma_{RL}; \tau_{LT} &= G_{LT} \gamma_{LT}.
\end{align*}
\]

3. Experimental set-up

The principle of the use of resistive electrical tensometry is based on the measurement of linear deformations by means of resistive electrical transducers (TER) that transform the variation of mechanical deformations into the variation of the electrical resistance of the element [15, 16]. In the analysed case, on a guitar used as a sample, 4 electro – tensometric transducers, type C2A-06-062WW-350, stacked rosette, with attached cables, each having three tensometric strain gauge with electrical resistance 350Ω, were fitted.

By orienting the rosettes, it was measured the effects of the bending / torsion of the guitar in the four areas (in the area of the cord - area A, in the area of the sound hole - zone B, on the neck - in the area of the 8th fret on the upper part (denoted CS) on the neck - in the area of the 8th fret on the lower part (denoted CI) by means of the strain gauges oriented 90° to each other (strain gauge 1 - oriented parallel to the longitudinal axis of the guitar, respectively parallel to the wood fibre, gauge 2 - oriented to 45 degrees and gauge 3 oriented to 90 degrees with respect to gauge 1, respectively perpendicular to the fibres) (figure 2). Electrical-tensometric transducers are introduced in Wheatstone bridge measuring circuits with quarters of bridge configurations, which means that each tensometric mark is balanced according to the circuit in the tensometric bridge [15 – 18]. The tensometric mark signals were gathered using a Vishay P3 bridge. By means of automatic data collection on the tensometric Vishay bridge, the latter memory card records the data file containing specific longitudinal and transverse deformation variation with time, when the specimen stress is applied on a particular direction (figure 3).
Figure 2. The position of tensometric marks on guitar: mark A, near the bridge; mark B, near the sound hole; mark CS – on upper part of neck, on 8th fret; mark CI - on bottom part of neck, on 8th fret, symmetric with mark CS.

Figure 3. The experimental instrumentation.

The classical guitar model with five radial bracing on inner part of top plate, polyurethane varnish and nylon strings, was subjected to this experiment. First, the guitar's loading was made by means of the strings which were tuned successive at the value of the frequency emitted by each free string. The values of frequencies and tension from strings are presented in table 1. Then, all strings were tuned as for playing, measuring the size of the instantaneous deformations. The micro-strains were measured by each strain gauge ($\varepsilon = 10^{-6}\mu e$).

Table 1. The input data for strings tune of guitar.

| Musical note/symbol | Frequency [Hz] | Load for each string [N] |
|---------------------|----------------|--------------------------|
| Mi/E1               | 82.41          | 61.2                     |
| La/A                | 110            | 74.5                     |
| Re/D                | 146.8          | 74.5                     |
| Sol/G               | 196            | 57.9                     |
| Si/B                | 246.9          | 61.1                     |
| Mi/E2               | 329.6          | 76.7                     |
4. Results and discussion

The micro strains measured with the all tensometric marks, for each of the six strings tensioned successively and in total, are presented in tables 2, 3 and 4. Thus, in table 2 are presented the results provided from the positional tensometric marks parallel to the wood fibers (in longitudinal direction of wood) denoted with index 1, in the four measured areas A1, B1 and CS1 and C1. In table 3 are presented the micro strains measured at 45° related to longitudinal axis, by means of marks denoted with index 2 (A2, B2, CS2, C1) and in table 4, micro-strains measured in the four areas with the gauges arranged perpendicular to longitudinal axis (in radial direction of wood), denoted with index 3 (A3, B3, CS3, CI3). Based on the mathematical relations (5 – 11) between the measured values of strains on the tree direction, the following mechanical characteristics were determined:

• maximum strain, \( \varepsilon_{\text{max}} \):
  \[
  \varepsilon_{\text{max}} = \frac{1}{2} \left[ (\varepsilon_1 + \varepsilon_3 + \sqrt{2(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2}) \right]
  \]  

• minimum strain, \( \varepsilon_{\text{min}} \):
  \[
  \varepsilon_{\text{min}} = \frac{1}{2} \left[ (\varepsilon_1 + \varepsilon_3 - \sqrt{2(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2}) \right]
  \]

• angle of the direction of maximum principal strain, \( \theta \):
  \[
  \theta = \frac{1}{2} \arctg \left[ \frac{2\varepsilon_2 - \varepsilon_1 - \varepsilon_3}{\varepsilon_1 - \varepsilon_3} \right] \text{ [rad]}
  \]

• maximum shear strain, \( \gamma_{\text{max}} \):
  \[
  \gamma_{\text{max}} = \sqrt{2(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2}
  \]

• maximum normal principal stresses, \( \sigma_{\text{max}} \):
  \[
  \sigma_{\text{max}} = \frac{E}{2(1+\nu)} \left[ (1+\nu)(\varepsilon_1 + \varepsilon_3) + (1-\nu)\sqrt{2((\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2)} \right]
  \]

• minimum normal principal stresses, \( \sigma_{\text{min}} \):
  \[
  \sigma_{\text{min}} = \frac{E}{2(1-\nu)} \left[ (1+\nu)(\varepsilon_1 + \varepsilon_3) - (1-\nu)\sqrt{2((\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2)} \right]
  \]

• and the maximum shear stress, \(\tau_{\text{max}}\):
  \[
  \tau_{\text{max}} = \frac{E}{2(1+\nu)} \left[ \sqrt{2((\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2)} \right]
  \]

Where \(E\) is the Young’s elasticity modulus, \(\nu\) - Poisson coefficient.

Table 2. Micro-strains measured in the four areas with the gauges arranged parallel to the longitudinal axis of the guitar (parallel with wood fibers).

| Strings | Micro strain με |
|---------|-----------------|
|         | A1 | B1 | CS1 | C1 |
| Mi/E1   | -21 | -4 | -6 | 3  |
| La/A    | -5  | -1 | -2 | 1  |
| Re/D    | -3  | 0  | -1 | 0  |
| Sol/G   | -31 | -4 | -6 | 5  |
| Si/B    | -39 | -6 | -6 | 4  |
| Mi/E2   | -128| -18| -17| 18 |
Table 3. Micro-strains measured in the four areas with the gauges arranged at 45° related to longitudinal axis.

| Strings | Micro strain με | A2 | B2 | CS2 | CI2 |
|---------|-----------------|----|----|-----|-----|
| Mi/E1  | -5              | -8 | -4 | 1   |     |
| La/A   | 1               | -1 | -1 | 0   |     |
| Re/D   | -1              | 1  | 0  | 1   |     |
| Sol/G  | -15             | -8 | -4 | 3   |     |
| Si/B   | -23             | -11| -3 | 3   |     |
| Mi/E2  | -83             | -33| -9 | 11  |     |

Table 4. Micro-strains measured in the four areas with the gauges arranged perpendicular to longitudinal axis (in radial direction of wood).

| Strings | Micro strain με | A3 | B3 | CS3 | CI3 |
|---------|-----------------|----|----|-----|-----|
| Mi/E1  | -4              | -3 | -1 | -2  |     |
| La/A   | -1              | -1 | -1 | 0   |     |
| Re/D   | -1              | -1 | -1 | 0   |     |
| Sol/G  | -13             | -3 | -1 | 0   |     |
| Si/B   | -16             | -5 | 0  | 0   |     |
| Mi/E2  | -45             | -12| 0  | -1  |     |

In figure 4(a) and (b) are presented the calculated values of maximum and minimum strains produced by each string, based on the formulas (5-11). In figure 4(c), the variation of overall strains obtained after all strings were tuned is presented. Analysing the variation of micro-strains from charts presented in figure 4, it is observed that the extreme values are obtained in case of tension of the 6th string E2 (with the highest frequency), and from area point of view, the maximum deformations are obtained in the area of the bridge area (denoted A) and in the area of the 8th fret on the neck, the lower part subjected to compression. The top plate made from spruce recorded strain with 120% higher than the neck strains, a phenomenon explained by the different rigidity of the two structures. From the values of deformations, it can be seen that the plate between the bridge and the neck is subjected to compression, and the neck, being subjected to bending, has the tension part (CI); and the compressed part (CS) (figure 4). From the point of view of the values of the minimum and maximum stresses, the calculated stresses are below the limit of the allowable stresses of the wood (<10 MPa), being compression stresses (negative values) for the areas A, B and CS and tensile stresses (positive) for the CI area. It can be noticed that the stresses of the 8th fret vary linearly in section from the value +0.64 MPa to -0.64 MPa.

Based on these results, during playing, under strings tensions, the guitar deformed in elastic domain. The deformed shapes of guitar can be noticed in figure 5.
5. Conclusions
The paper presents the experimental investigation of strains of some parts of guitar produced by strings tension, using the electrical resistance tensometry. Because of different tension of strings tuned for playing, the values of micro strains differ. From this study, following remarks can be done:

• The wood subjected to the action of external forces deforms, the external force encountering a resistance, depending on the structure and elasticity of the wood material. After the forces action disappears, the deformation of the part can disappear completely if the stresses remained in the elastic domain, partially if it is in the elastic-plastic domain and to persist if it is in the plastic field.
• Experimental research has shown that elastic and plastic deformations are directly dependent on the wood species, on the density, humidity and temperature of the wood, on the position of the annual rings and on the fibre direction with respect to the force direction.
The variations in time of the recovery strains of wood from guitar structure are presented, after the successive tuned of the strings. Thus, the visco-elastic behaviour of the wood from the structure of the guitar can be observed by recovering the strain. Also, one can observe the effect of the relaxation of each string individually by the shape of the curve which shows a variation in steps. A similar behaviour is observed in the case of the neck, but the variation of the curve no longer has the same allure as the top plate, but there are numerous oscillations of the recovered deformation. An interesting phenomenon is the symmetry recorded by the two rosettes applied on the neck of the guitar (the upper part CS and the lower part CI).

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