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RESTORATION OF A CASELLA BROTHERS' ACOUSTICAL GUITAR AND CONSTRUCTION OF AN IDENTICAL COPY

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Abstract

Musical instruments consist a significant part of the global cultural heritage. Everywhere in the world such important artefacts can be traced and preserved for future generations as an important part of human heritage. A century old acoustical guitar was found in the Kefalonia Island, Greece, that was survived from time wear and earthquakes attacks. In this paper the procedure followed for the restoration of this guitar is presented. Old musical instruments, even the restored ones, should be treated carefully and stored appropriately, in order to be protected. Thus, the idea is to construct exact possible copies that could present publically their performance that is the sound they produce. Such a copy was designed and constructed for the above mentioned guitar and the two instruments were evaluated for their mechanical and acoustical characteristics.

Keywords: *Musical Instruments; Guitar restoration; Replica; Identical guitars.*
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Introduction

Restoration is a process aiming to recur a non-functional building or an object of historical significance in a functional situation. Restoration is one of the conservation works applied to monuments or artefacts so that its condition gets as good as it originally was [1].

Regarding the guitar history, there are two theories. The first reports that guitars appeared in Ancient Greece referring to a musical instruments named "kitharis" [2]. It was a string instrument, an optimization of lyre and better processed than the last, although for the Ancient Greeks lyre and guitar were synonymous as well as the phorminx. However, kitharis differed from lyre and phorminx with respect to the sound box, the size and the sound it produced. According to the second theory [3], guitar claims its origin from the medieval lutes, as they were transferred from Middle East to Europe during the Arabs conquests in Spain. This theory is most likely, since the modern guitar is closer to the ancient Greek "pandoura" or "pandouris", a lute family instrument, than to the ancient kitharis [4], with possible Mesopotamian origins [4]. In either case the origins of the guitar lies in the Eastern Mediterranean lands. Combining the above information, it is most likely that the nowadays guitar physical ancestors are the medieval lutes, while its name is traced back in the ancient Greek instrument.

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Ancient kitharis contained three to seven strings. The seven-string guitar was a *Terpandros* (7^{th} century BC) innovation. During the 6^{th} century BC an 8^{th} string was added and at the 5^{th} century BC guitars with nine, ten, eleven and twelve strings appeared [4]. Here ends the growth period for the kitharis and there is a large period of time without evidence for the instrument. It appears again, as the lute-family pear-shape guitar, during the 15^{th} century AD in Spain.

First guitars were small with four couples of strings. Spanish guitar (or the classical guitar) has a curved hollow body and uses the cavity of the body to amplify the sound (Helmholtz resonator). Initially, the strings were manufactured by cow intestines, later by animals' nerves and finally by nylon and steel that are used up to date. During the 16^{th} century guitars had five couples of strings. In the 17^{th}century Italy was the capital of guitars, while in France it was the instrument of aristocracy.

Spanish school of the classical guitar started flourishing after the end of 18^{th} century. The most important factor in the development of classical guitar was the addition of the sixth string at the middle of 18^{th} century. The social changes manifested in the 19^{th} century contributed to the further development and spread of the guitar. In Spain, *A. Torres* between 1850 and 1892 designed and shaped the modern guitar. Today, the six string classical guitar is probably the most popular musical instrument all around the world.

Nowadays, people show an increasing interest in playing or listening to historical musical instruments, which in many cases are not open to the public view, although some museums and private collectors provide special permission for experts in the field.

In most cases, the interaction with those artefacts is only by vision, without any permission to touch the artefact let alone work on it, in order to secure its conservation and restoration. Thus, the only way to interact with a historical musical instrument is to study it and to try to copy or reconstruct it by taking into account the physical characteristics (e.g. wood aging in the case of wooden musical instruments) affecting its acoustical performance. A first step towards the above mentioned direction is to study and document the artefact. Study and documentation could be analyzed into the following parts [5] (a guitar is given as an example): (a) architecture and geometry, (b) details of instrument manufacturing and (c) documentation. A very useful method for the survey of musical instruments architecture and geometry is thought to be photogrammetry [6]. After the instrument is identified, its repair can begin. In parallel, the creation of an identical `copy for public use can also be designed.

Restoration procedures depend on the material of the artefact. Metal instruments could be repaired using welding techniques such as laser welding [7]. A question arising during restoration is whether the restored instrument produces the original sound as the initial one. Information about strategies for the functional rehabilitation of wooden musical instruments are given in [1, 8].

In case of doubt on the authenticity of the musical instrument, various techniques, such as X-ray fluorescence analysis of the varnish [9], are used to authenticate it. X-ray radiography is also useful in characterization of the historical instruments mechanical status in order to better define restoration techniques. Similar information could be given using neutron radiography [10].

Another practice that assists in the protection of the artefacts is the application of computational modelling such as Finite Elements Modelling (FEM) [11] to study the instruments performance, their structural behavior, etc.

In the present, a century old acoustical guitar, manufactured in Italy at the late 19^{th} century is restored. The restoration processes are described in details. Additionally, a copy of the original instrument is designed and manufactured. Again, the decisions made during the copy processes are given in details. Finally, the two instruments are evaluated experimentally using the VIAS (Versatile Instruments Analysis System) system designed and constructed by the Vienna Institute of Musical Acoustics and the results are compared.

The guitar in restoration

The acoustical guitar that came into the lab for restoration was made in Catania, Italy by Casella brothers as is written in the label attached in the instrument (Fig. 1). Casella brothers were namely Mario and Gaetano. Mario Casella was a known Catanese luthier. Apparently, for a while he also worked with his brother Gaetano. Both Mario and Gaetano made quite a range of very good string instruments such as mandolins, violins and a few guitars of great sound quality. The label of the guitar that was found inside it, writes the following title referring to the Casella brothers workshop: "L' internazionale premiata fabbrica di strumenti musicali a corda et accessory", which means "The first global musical instruments and accessories factory", as can be seen in figure 1.

Fig. 1. Guitar Label

Their factory has been reported -as shown in the afore-mentioned label - to have won 6 awards for their quality of production. Remarkably, one of these awards was reported to be a French "Grand Prix" award for musical instruments at 1849, a piece of information which provides a terminus post quem for its creation.

The acoustical guitar was found in an extremely bad situation. The back-side, the soundboard and the fingerboard were dismantled in three different pieces. The sides of the guitar had serious cracks. It was observed that the old guitar had been constructed using animal glue (fish glue) so it was easy to separate all the guitar parts by applying heat.

Materials

Animal glue (fish glue)

An animal glue is an adhesive that is created by prolonged boiling of animal connective tissue. These protein colloid glues are formed through hydrolysis of the collagen from skins, bones, tendons, and other tissues, similar to gelatin. The word "collagen" itself derives from Greek "κόλλα", kolla, glue. These proteins form a molecular bond with the glued object.

Animal glue was the most common woodworking glue for thousands of years until the advent of synthetic glues such as polyvinyl acetate (PVA) and other resin glues in the 20th century. Nowadays, it is used primarily in special applications such as lutherie, pipe organ building, piano repairs, and antique restoration.

Animal glue displays several advantages -and disadvantages- compared to other glues. The glue is applied hot, typically with a brush or spatula. It is kept hot in a glue pot, which may be an electric unit built for the purpose, a double boiler, or simply a saucepan or crock pot to provide a warm water bath for the container of glue. Most animal glues are soluble in water, useful for joints which may at some time need to be separated. Alcohol is sometimes applied to such joints to dehydrate the glue, making it more brittle and easier to crack apart [12].

Animal glue joints are reversible and repairable. Recently glued joints can be released easily with the application of heat and steam. Glue sticks to itself, so the repairer can apply some new one to the joint and re-clamp it. In contrast, PVA glues do not adhere to them selves once they are cured, so a successful repair requires removal of the old glue first – which usually requires removing some of the material being glued [13].

Animal glue creates a somewhat brittle joint, so a strong shock will often cause a very clean break along the joint. In contrast, cleaving a joint glued with PVA will usually damage the surrounding material, creating an irregular break that is more difficult to repair. Instrument makers take advantage of the most of glue mechanic properties, brittleness being the most relevant for manufactory purposes. For example, instruments of the violin family require periodic disassembly for repairs and maintenance. The top of a violin is easily removed by prying a palette knife between the top and ribs, and running it all around the joint. Brittleness allows the top to be removed, often without significant damage to the wood. Re-gluing the top only requires applying new hot glue to the joint. If the violin top was glued on with PVA glue, removing the top would require heat and steam to disassemble the joint (causing damage to the varnish). Then wood would have to be removed from the joint to ensure no cured PVA glue had remained.

Animal glue is supplied in many different gram strengths, each suited to specific applications. Instrument and cabinet builders will use a range from 120 to 200 gram strength [14].

Gommalacca (Shellac)

Gommalacca - Shellac is a resin secreted by the female lac bug, on trees in the forests of India and Thailand. It is processed and sold as dry flakes and dissolved in ethanol to make liquid shellac, which is used as a brush-on colorant, food glaze and wood finish. Shellac functions as a tough natural primer, sanding sealant, tannin-blocker, odour-blocker, stain, and high-gloss varnish.

Shellac is a natural bio-adhesive polymer and is chemically similar to synthetic polymers, and thus can be considered a natural form of plastic. It can be turned into a moulding compound when mixed with wood flour and moulded under heat and pressure methods, so it can also be classified as a thermoplastic material. It scratches more easily than most lacquers and varnishes, and application is more labour-intensive, which is why it has been replaced by plastic in most areas. But damaged shellac can easily be touched-up with another coating of shellac (unlike polyurethane) because the new coating merges with and bonds to the existing coating(s). Shellac is much softer than Urushi lacquer for instance, which is far superior with regard to both chemical and mechanical resistance. Use of shellac was historically used as a protective coating on paintings and as a natural bio-adhesive to the top plate of classical guitars.

French polishing is a method of applying finish to wood by hand with a cotton pad. In the guitar world the term "French polish" is understood to be a shellac spirit varnish that has been applied by the French polishing method. Most of the fine old musical instruments made in Europe were French polished, as are a majority of fine classical guitars being hand made today. It is a most highly-prized and desired finish for both its visual and tone enhancing characteristics.

The luster, texture and color of the wood are all noticeably enhanced under an expertly applied French polish finish. The cured shellac film is also very thin and flexible and is believed to produce the clearest and most natural sound from the vibrating wood of the guitar, especially the top plate.

The advantages of using Gommalacca - Shellac by French polishing, as a guitar finishing are related to both the finishing and the process. The beauty of the wood under this finish is undisputed, and it is generally regarded as the best finish for tone. Even with these accolades for the finish, the actual process, French polishing, has benefits for the maker: It is very "organic", very personal and tactile. The finisher can watch the surface closely as he works and can minutely adjust material and method as the finish slowly builds and improves through multiple polishing sessions. This direct connection and the control of the results have certainly attracted many craftsmen. There is no equipment required, the materials are few and inexpensive, and the finishing can be done in a very limited space. The vapor and material are not hazardous or toxic and there is no need for air ventilation or face mask. Finish can easily be repaired or refreshed at any time. Additionally, shellac is used as a sealer or initial wash coat under any finish [15, 16].

Top-Plate Wood

A matter of great importance for an acoustical guitar is the top plate. The quality of the guitar sound depends on the quality of the spruce which is usually used to construct the top plate. A top plate made of high density spruce provides to the guitar clear tone and staccato low and high frequencies. The specific type of spruce usually luthiers uses, is the European Sitka Spruce, preferred for its strength and touch elasticity. Another reason for this selection is that the wood matures with time and, thus, matures the sound of the instrument.

Restauration by structural and polychrome reintegration

Disassembly

The first procedure in order to restore the guitar is the disassembly of the various parts that compose the instrument, in order to reach the damage points, to restore them and conserve them. The first part that was removed from the instrument was the neck. The neck was assembled on the body in a particular manner not common today for acoustical guitar. As it can be seen in figure 2a the joint was in the form of a wedge.

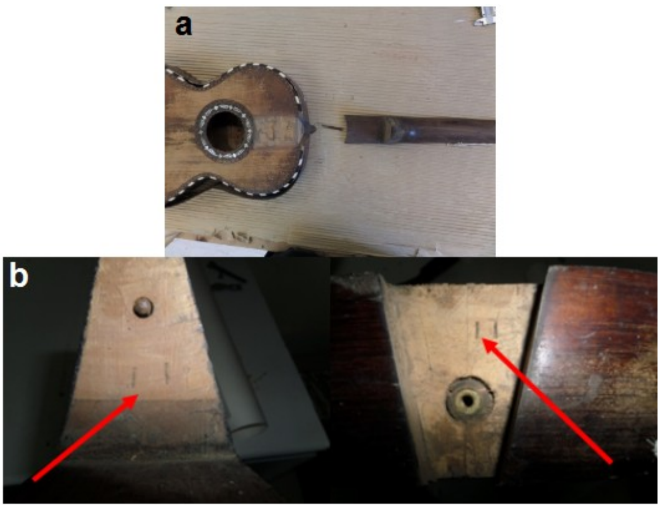

Fig. 2. (a) The guitar body and the neck removed; (b) The screw that stabilizes the neck on the body. The arrows point the marks made to note that this neck fits that nick

The neck was wedged in the guitar body, without any gluing between it and the body nor the top-plate (as is done today). In addition a screw was placed between the neck and the back chock of the guitar, in order to keep the neck stable at its right position (Fig. 2b). The constructors had marked the neck and the chock to remember that the specific neck fits perfectly in the specific nick (Fig. 2b).

In all the glue joints animal glue was applied. As mentioned before this type of adhesive is easily removed by heating and hot water. This process was followed here (Fig. 3). Thus, the top-plate, the back-plate, the bracing struts, the saddle and the bridge, and the sides of the guitar were unglued and separated from each other disassembled completely the instrument in its parts. When the bracing struts were unglued, their positions on the top-plate were marked in order to be put back in their original places after repair.

Fig. 3. The ungluing process

Soundboard (Top-Plate)

Since the instrument is in parts the restoration process was started. The first part to be repaired was the top-plate. The top-plate was made by a piece of picea excels (European Spruce). The top plate was cleaned from dirt and from glue using a piece of sandpaper. Next, small holes were drilled, filled with animal glue and pieces of spruce were added in the holes at the back side of the top-plate and near the bridge position in order to patch the cracks and to reinforce the position of the saddle and the bridge, where the strings exert mechanical loading (Fig. 4).

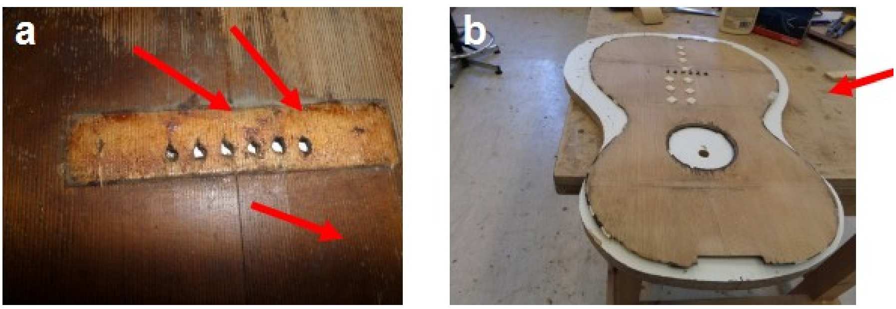

Fig. 4. (a) Arrows point the positions of cracks at the top-plate. (b) Small spruce patches added on the top-plate to repair cracks and reinforce the saddle/bridge position (arrow)

The next step was to clean the glue remaining around the patches and place back the bracing struts after cleaning them first. Thus, the top-plate is considered to be repaired and functional (Fig. 5). Some more work needed to be done for the top-plate to take its original picture will be completed during the assembly of the guitar.

Body sides (ribs) and assembly of top-plate

The guitar ribs were the most damaged parts of the instrument. They contained longitudinal cracks separated them into three pieces and portions of wood were missing (Fig. 6).

Fig. 5. The top-plate after finishing repair procedure

Fig. 6. The damaged ribs

In order to repair the ribs a mould was constructed by pine wood, which is tough and strong enough to withstand the pressure of clamps when the ribs will be putted inside. The ribs were then cleaned from dirt and glue. Following, the ribs were placed in the inner part of the mould and the broken parts were glued between them. A thick gauze filled with animal glue was used to stabilize the ribs. Pressure was applied using clamps and the ribs repair was completed.

After ribs were repaired, the top-plate was glued on them. To assembly the top-plate and since its edges were damaged an assisting jig was constructed. The damaged edges were manufactured by ebony and bone pieces as decoration but missing pieces complicated the assembly process. The assembly jig was manufactured by a plane plywood plate. The top-plate was placed on the jig and then the ribs were glued on the top-plate. This process was followed in order to be obvious where the ribs fit with the top-plate and where they don't. Initially the top-plate was stabilized on the jig and the front chock was glued on it because it was the only point on the ribs with obvious location on the top-plate. Next the ribs were forced to follow the top-plate face and were stabilized. At the locations where there were missing parts, special guides were applied pushing the ribs downwards and inwards (Fig. 7 – red arrows) to put them at their right position. In order to increase the gluing surface and to cover the missing decoration gaps, small pieces of plywood in a 3-d right triangle shape were added (Fig. 7 – green arrow).

Assembling the back-plate

The back-plate was constructed by rosewood (palisander). Its situation was not that serious like the ribs or the top-plate, yet some damage was obvious, namely, a piece of wood at the down left part of the plate was broken and missing. First, similarly to the top-plate, the bracing struts were unglued and all parts were cleaned. After cleaning, the struts were glued again and the back-plate was ready to be assembled on the ribs to close the guitar body. Special care was taken to put the struts at their original recesses on the ribs. The result is shown in figure 8, where the missing piece of wood is also presented (red arrow). The missing part was repaired by patching a rosewood piece at the damaged area. The patch was then treated in order to take the right shape following the guitar face.

Reintegration polychrome decoration of the instrument

As mentioned before, the instrument decoration was damaged and some parts of it were missing, especially at the top-plate perimeter. Decoration materials were mainly ebony, bone and linden. Generally, the decorative wood sequence from the inner part of the top-plate to the outer is: ebony-bone-ebony-bone, followed by a series of linden-ebony diamonds. Then there are again two consequent series of bone-ebony pieces and the decoration completes with bone-ebony diamonds. The most damaged place was the last series of bone-ebony diamonds. Pieces of bone and ebony were cut. Bone was treated appropriately in order to expel any oil and fat contained.

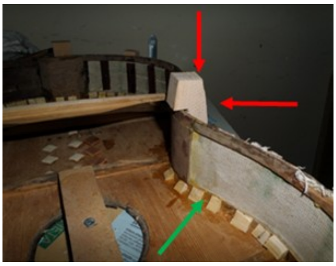

Fig. 7. Ribs – top-plate gluing process

Fig. 8. The back-plate assembled on the guitar body and the missing part of wood

Using a self-made jig, all diamonds were cut at the same size and the guitar decoration was replaced. In figure 9a the jig for diamonds cutting is presented, while in figure 9b the replaced decoration is shown.

Fig. 9. a. The self-made jig used to cut equal size diamonds for the guitar decoration; b. The restored part of the guitar restoration

Structural reintegration of the Neck – Fretboard

This part of the guitar appeared less problematic. Neck is manufactured by linden wood and painted black. Using sandpaper the old paint was removed and replaced with new one. The fretboard is constructed by rosewood. Again, cleaning was necessary, but the frets are different in size from the nowadays available, thus a really careful cleaning process was followed in order not to alter the frets shape.

Consolidation of the Bridge – Saddle

Examining the guitar bridge, the age of the instrument was verified for one more time from the way that the bridge is glued on the top-plate. Besides the adhesive (animal glue) it is stabilized at its right and left with small nails (Fig. 10a). This way of attachment is no longer present.

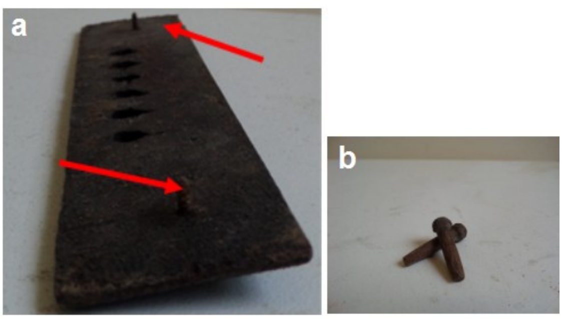

Fig. 10. a. Bridge attachment. Red arrows show the locations of nails; b. The pins that hold the strings on the bridge

After ungluing the bridge, it was cleaned and the rusty screws were removed. The bridge is manufactured by rosewood to withstand the strings applied stresses. Strings are hold on the bridge by wooden (rosewood) pins (Figure 10b). Then the bridge was attached back on the top-plate.

Cleaning of the keys

Guitar keys are made by bronze and at their present situation were oxidized. To remove oxidization hydrochloric acid was used.

Final finishing

Some more repair work that includes stucco encapsulation in the body cracks at its outer face and closing of top-plate cracks with spruce fillets, remained before the final finishing. The first was done using a mixture of rosewood powder and wood glue. The second repair work included the further opening of cracks using a thin fillet saw in order to put the spruce fillet. Fillets were glued using wood glue. The disadvantage of this process is that the fillets locations will be colored differently than the rest of the top-plate after varnishing, since the wood grains differ in the sense that the top-plate grain are vertical, while in the fillets are horizontal.

Finishing process includes three treatment steps: rubbing, varnishing and assemblage. Rubbing using sandpaper is necessary to remove any remaining dirt from the previous works. The first varnish layer was applied by paintbrush in order to close the wood pores faster. Following layers are applied by the so-called “ball varnish” process, using a gauze and cotton ball impregnated with varnish. The same process was followed in all guitar parts.

After varnishing, the last procedure in order to complete the guitar renovation, was the assemblage of guitar parts. The neck was attached on the guitar body in the way it was done by the manufacturers. The keys were screwed on the neck and the strings were put on the keys. The upper saddle, made by a piece of bone, was put at the beginning of the fretboard. The down saddle that is attached on the bridge is not made by bone, like in the contemporary instruments, it is just a piece of fret. Finally, strings were tied on the bridge pins and tuned with small correction in the neck slope, in order for the strings to touch only one fret at each time and not more. The final finished instrument is shown in figure 11.

Fig. 11. The guitar after restoration processes completed

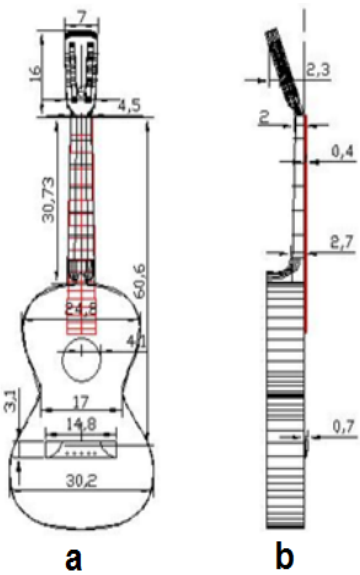

Fig. 12. Guitar drawings: a. Front view; b. Side view. All dimensions are in cm

Design – Copy Manufacturing

The concept of this project part was to construct a whole new guitar that would be identical to the original regarding its acoustical and structural characteristics. Thus, geometry, materials and manufacturing methods of the replica should be as close as possible to the original. Each part of the new guitar would be manufactured using the same materials with the original. Wood aging would be the main problem when comparing the new guitar to the old one, but it will be taken into account in the results discussion. In order to keep the same geometrical characteristics the commercially available 3D CAD software AutoCad provided by Autodesk was used to precisely design the instrument. The guitar drawings showing the instrument dimensions are presented in figure 12a and b.

The top-plate was made by spruce wood. For the body, back-plate, bridge and fretboard rosewood was used. Neck plays a special role in the instrument behaviour. Original neck was made by linden wood, which is light, tough and easy treated. The same wood was used in the replica, but with some changes in the manufacturing process.

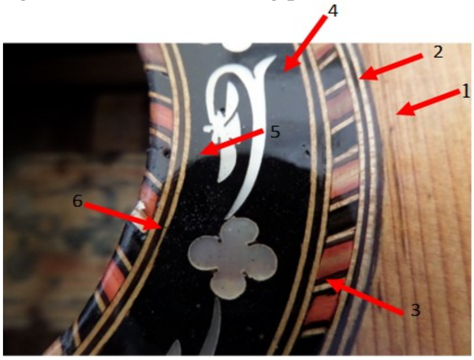

Fig. 13. The rosette six decoration levels

Top-plate – Rosette

To construct the top-plate of the guitar, two sheets of spruce wood are glued between them, taking care that no voids are left in the adhesion. Thus, the necessary plate is ready for further treatment. The next step is to draw on the plate the guitar dimensions and to locate the hole's position. For this work, the AutoCAD drawings were used.

Rosette and bracing struts are the most important details during the top-plate construction. Rosette should be constructed first and added on the top-plate before the struts because this is easier. Rosette is divided into six decoration levels as shown in figure 13. From outer to inner it can be observed the following decoration sequence: black-white-black-white fillets, white-black-red rhombuses repeating along the perimeter, white-black-white fillets, shells in two repeating along the perimeter shapes and embedded into ebony powder, white-black-white fillets and another set of white-black-red rhombuses repeating along the perimeter.

First the rosette center was located on the top-plate as a point of reference. Next, concentric circles were incised, using a Dremel cutting tool centered at the marked rosette center, to cut the decoration levels. Shell shapes were copied from the original and cut from a piece of shell. Then, they were glued on the top-plate and the space between them was filled with ebony powder similarly to the repair work done in the original. Finally, rosette was completed with the inner sequence of fillets and rhombuses. The result is very close to the original as can be seen in figure 14.

Since rosette was ready, the next step is to manufacture and glue the bracing struts. Spruce wood was chosen for the manufacturing, because it is light and withstands high pressure. Bracing struts are always cut along the wood grain. Struts were cut and fish glue was applied. Gluing was done using flexible wooden rods that pressed the bracing struts on the top-plate (see Fig. 15). Next they were formed in the usual shape that is thicker in the middle and thinner at the edges, with a quadrant between the thicker and the thinner part (Fig. 15). This shape is chosen in order to reinforce the top-plate without putting too much weight on it.

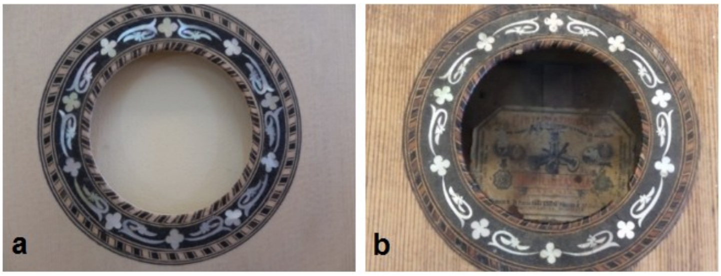

Fig. 14. Comparison of the replica rosette (a) to the original one (b)

Fig. 15. Bracing struts gluing and forming

Back-plate

Back-plate was constructed following the same process as for the top-plate. Two rosewood sheets were glued between them and bracing struts were placed on them. The difference in this case is that the bracing struts are not perpendicular to the back-plate but were added under a small angle. After gluing the struts were formed similarly to the top-plate struts.

Guitar body sides (ribs)

Replica ribs were constructed on the same mould used for the original guitar ribs. Two rosewood sheets, with 5mm thickness each, were bent after being embedded into a water bath on a heated metallic cylinder to take almost their final shape. Then they were putted into the mould and stabilized using clamps at close positions, in order to keep their shape when the water would be vaporized. Next, the upper and lower chocks were manufactured by linden wood according to the measurements made at the original guitar chocks and formed to apply correctly at the points they would be glued. Chocks were glued on the ribs while they were still into the mould.

Neck – Fretboard

Replica neck is made by linden wood as in the original, except that in this case it was cut in the middle along its length and a piece of maple wood, with its grains perpendicular to the linden grains, was placed between the two parts. This sandwich structure offers additional strength in the loading that the neck should bear from the strings and in the environmental conditions (temperature and humidity changes during instrument lifetime). The notch that will be set in the upper chock (as in the original) is also formed in this step. The neck head was cut in the original shape using the dimensions measured in the original guitar. Due to the sandwich structure of the neck, and since the head should bear high stresses from the strings, it was reinforced by gluing a piece of rosewood with the same dimension on it. Next, the holes for the keys and the two longitudinal holes along the head were cut following the original guitar drawing.

To manufacture the fretboard it is mandatory to calculate the effective length of the strings in order to mark the frets correctly. In this case the strings effective length was measured at 606mm from the upper to the lower saddle. Each fret location, f_n, is calculated from the following equation:

$$f_n = {f_{n-1}}/{k}$$

where: f_0 is the string effective length and k is given by: $k = \sqrt[12]{2} = 1{,}05946$. Thus, f_1 = 571.99mm, f_2 = 539.89mm, etc., all the way up to the 18th fret. 12th fret is at the middle of the distance between the two saddles (effective length) and is used as a guide to restore the lower saddle to its right position if it is moved. Frets positions after being calculated and marked on the fretboard were cut and then the fretboard was glued on the neck by animal glue and applying pressure.

The next step was to form the back of the neck at its usual curved shape using various rasps and sandpapers of different granulation. Finally, frets were set in the notches cut on the fretboard. The commercially available guitar frets differ from the frets of the original guitar. Thus, baglama (a Greek popular instrument) frets were used since are closer to the original.

Bridge – Lower Saddle

Measuring the original guitar bridge dimensions the replica was manufactured. The most important dimensions are the bridge height and the distance between the holes that the strings are tied.

Guitar Assembly

To assemble the replica guitar, all parts should be glued between them. Special care is taken in order not to remain voids between the parts. First the top-plate was attached using animal glue on the ribs and mechanical pressure was applied. Then a hole was drilled in the upper chock and in the neck, to pass the screw that will keep the neck attached on the body. The screw is not screwed in the wood, in order not to harm it and because that is how it was done in the original, but is screwed on a nut packed inside the chock. The next step was to glue the back-plate. First, a small angle was formed in the back side of the body in order to increase its strength. Then the back-plate was glued using animal glue and pressed taking care not to harm the wood.

Top-plate decoration

Since the guitar body is assembled, the top-plate decoration should be constructed. Decoration is copied from the original guitar and is consisted by the sequence: black-white-black-white fillets, a series of white and black rhombuses and white-black-white-black fillets. The black parts are made by ebony and the white parts are made by linden wood. Decoration is completed by a series of black and white rhombus alternately, made by ebony and bone. The top-plate was first carved at the places where the decoration will be putted. Then the decoration parts were glued at their predefined locations. Finally, all the decoration parts were grated to reach the top-plate level.

Reconstruction final stage–Finishing
(Assembly of the neck, placement of keys and strings)

Finishing stage includes grating, impregnation and varnishing. Grating was done using an electric sander, to remove any dirt and glues left on the outer sides of the guitar body and to open the wood pores to receive the impregnation glue. Impregnation role is to close the wood pores and homogenize the surfaces to receive the varnish. Impregnation is done using animal glue diluted into water that is used by luthiers as varnishing substrate. This process was not followed during the restoration of the original guitar because it was already impregnated and the pores were still closed even after grating. After impregnation the fish glue was grated using a fine sandpaper to become smooth. Finally, varnishing was applied following the same process as described during the restoration of the original guitar.

The last two steps include the assembly of the neck and the placement of the keys and strings. Keys were placed in the neck prior to assembly. Then the neck was wedged on the guitar body and screwed to be stabilized. Finally, the strings were placed and the final result can be seen in figure 16. In the same figure the original guitar is also presented for comparison.

Fig. 16. (a) The original repaired guitar;
(b) The reconstructed replica guitar

Evaluation

Wood is an anisotropic material so the structural characteristics varies. For the structural behavior of the guitar this variation of the characteristics isn't influential. But the acoustical characteristics of the two guitars the old one and its copy, must be as close as possible.

In order to be sure that the two guitars are acoustically identical, a set of measurements was fulfilled using a setup called VIAS (Versatile Instrument Analysis System) by Artim G.m.b.H. VIAS is used for admittance measurements and evaluation of bowed and string instruments such as violins, cellos, harps, guitars, pianos, and percussion instruments, with help of an impulse hammer and a sensitive accelerometer (Fig. 17).

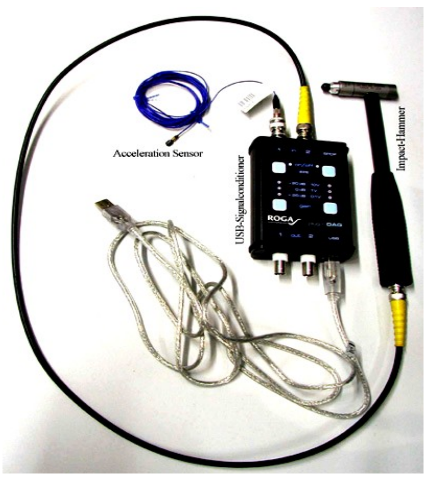

Fig. 17. Impulse hammer and sensitive accelerometer

It is also used for extended and more accurate impedance measurement and analysis, including audio tests of the measured instrument based on the measured or calculated impedance curve.

The VIAS setup which ARTIM have called as Components of the PCB System, is composed of a pulse hammer with integrated force sensor, a DAQ USB charge amplifier and a ceramic miniature accelerometer 0.2g (Fig. 17).

The working principle for the evaluation of bowed and string instruments, is that if the bridge of a violin gets excite at its upper edge by a stroke with a pulse hammer and if an accelerometer is mounted at the opposite edge of the bridge, you can obtain an admittance curve, which contains nearly all relevant information about the acoustical properties of this violin. The same working principle is used for our set of guitars. A sensitive accelerometer assigned on the guitar bridge, and with the impulse hammer we hit the opposite edge of the bridge, the same for the two guitars. Figure 18 shows a comparison between the two guitars using the setup described before.

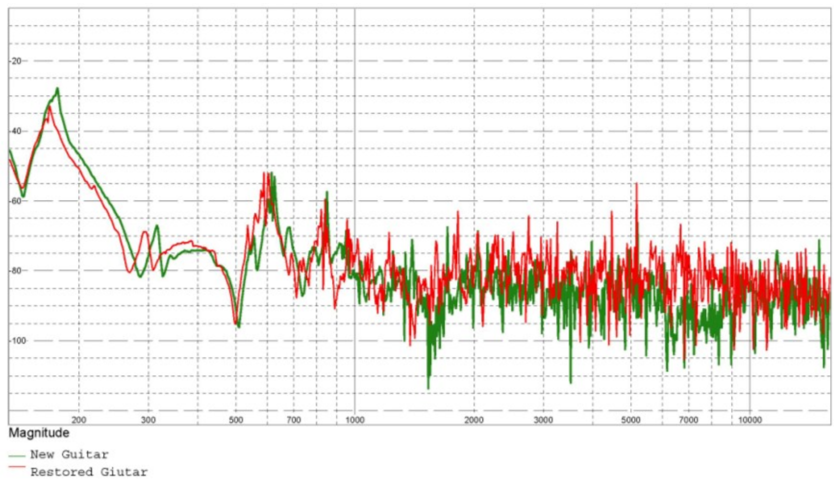

Fig. 18. Impedance curves of the two guitars. Red line represents the admittance curve of the restored original guitar, while green line represent the admittance curve of the replica

At the above picture we can see the admittance for both guitars. It seems that there is a very small difference between the two curves, which leads to the assumption that these two guitars have almost similar admittance curves at the range of 200 to 700Hz and the curve is too close in order to consider that the new guitar is a copy to the Casella’s restored guitar. However, this difference could be attributed to higher mass of the top-plate, which could be reflects either on wood mass or the finishing materials mass. Nevertheless, this difference could be considered negligible regarding the acoustical behavior of the two guitars.

Figures 19a and b show a type of spectrogram of the two guitars. At X-axis is the frequency in Hz (logarithmic) or musical note. Y-axis (left) shows partials (from bottom to top). First band is the First partial, second band is the second partial, etc. The right Y- axis shows frequency in Hz (logarithmic). The amplitude is color coded. Color grade step is 1.0dB, dark means low amplitude, bright means high amplitude.

The graphs show the amplitude of each harmonic at every frequency point, in other words, the contribution of each harmonic to the sound of a playable tone. As it can be seen, figures 19a and b are quite similar and, thus, can be assumed that the replica guitar is a nice copy of the Casella’s original [12].

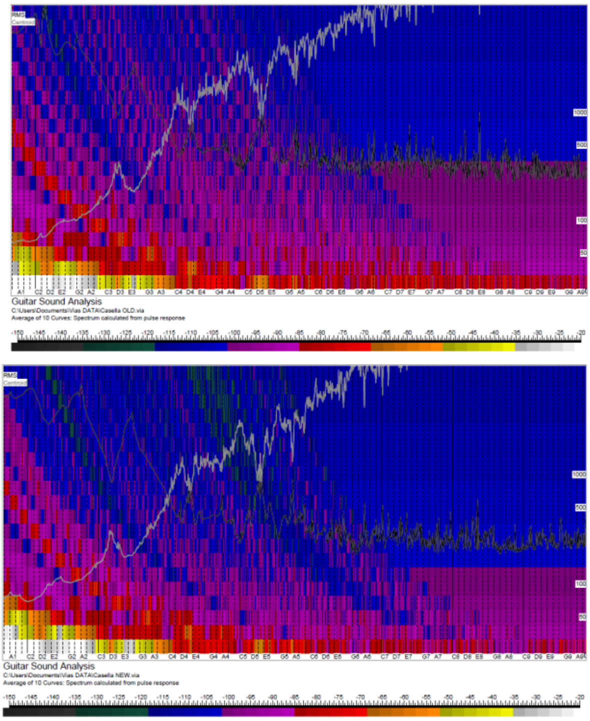

Fig. 19. The spectrogram of the restored original Casella's guitar (a)
and the spectrogram of the new identical with the restored Casella's guitar (b)

Conclusions

The idea to construct identical copies of an old damaged instrument using anisotropic materials such as wood could be regarded as utopic. Also the restoration of an old musical instrument changes the characteristics of the instrument, if even small pieces of new materials be merged with the old materials used many years ago. The admittance curve vs frequency for a musical instrument changes a lot after a small change at the mass of the top plate, for example. In the case presented here, it looks like that the restoration process of the old guitar using small pieces of wood fulfill with animal glue which modified the mass of the whole instrument and affected the admittance behavior of it, especially when the interventions took place at the top plate of the guitar. The results showed before prove that the two guitars are not exactly similar acoustically, but the producing sound is too close. Finally, it could be concluded that the process followed here and included restoration of the old artifact and design and manufacturing of a new replica, can solve the main problem of dealing with cultural heritage pieces that need special treatment and is exactly this, to retain the artifacts at their best possible situation. This problem can be solved if appropriate procedures are followed to repair them and special care is taken when designing and manufacturing a replica. Thus, contemporary audience could hear the old instruments sound, but produced by a modern replica.

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