Steam Bending of Wood; Embellishments to an Ancient Technique

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Bending wood dates back to antiquity in the form of baskets from willow branches. Fresh growth willow twigs are readily bent into practically any shape. When wood has been separated from the tree and dried it is more rigid, difficult to bend, and breakable. Bending drier wood with the help of heat and water is centuries old. Fishing hooks, barrel staves, and planks turned into boat hulls are examples. Steamed wood is less rigid, since adding moisture and heat to wood results in plasticization. Steaming at atmospheric pressure is common, wherein diffusion prevails as the predominant mechanism governing moisture movement. Applications using conventional atmospheric steaming can be time consuming, non-uniform, and can result in failures. Vacuum steam technology offers a promising method that utilizes pressure differentials to accelerate the addition of steam to wood due to water vapor bulk flow and subsequently an accelerated temperature rise. More uniform plasticization results in less breakage of the wood.

Keywords: Steam bending; Wood; Plasticization; Vacuum steam technology (VST); Diffusion; Water vapor bulk flow; Luthier

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Why Change Now?

The essential characteristics describing the application of atmospheric pressure steam to wood for the purpose of softening it sufficiently to bend it, into quite small radii if desired or necessary, is a state of the art that is at least 60 years old, and more generously to the earlier researchers, 84 years old. In the United States, the recorded history of wood bending that we have found begins around 1929 in the form of a presentation at the annual meeting of the American Society of Mechanical Engineers in Rockford, IL. It was presented by T. R. C. Wilson, an engineer from the Forest Products

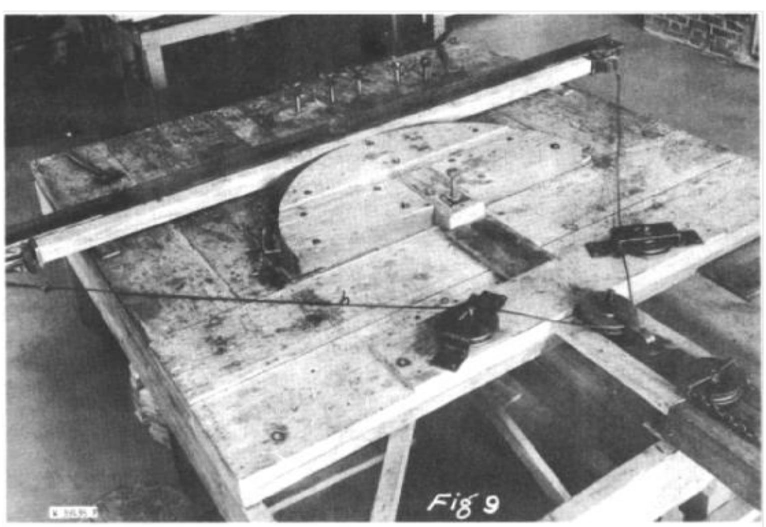

Fig. 1. Apparatus to aid in bending thick-section wood. Photo: Forest Products Laboratory, Madison, WI

Laboratory (Madison, WI). He later added an appendix in 1941 to describe an apparatus developed to aid in bending boat ribs. This apparatus (Fig. 1) includes a metal strap on the convex side of the piece of wood to support that surface, minimizing undo strain during bending. The metal strap concept had been originally described and the engineering derived in the 1929 presentation. A 64-page technical report called "Bending Solid Wood to Form" carries a revision date of 1955, prepared by Edward Peck, again of the Forest Products Laboratory. This document contains essentially every key element pertaining to steam bending wood that can be found in all current literature on the subject. Figures, photographs, and drawings have been brought to current publication standards, but the state of the art remains effectively unchanged.

So why change now? Well, we wanted to help a friend, a luthier, who makes banjos for a living. As a maker of stringed instruments, he was talking about troubles in his wood bending for the hoops on his banjos.

What About the Old Way? Why Even Bend Wood?

Addressing the second question first, just imagine sitting on the porch on a pleasant evening with a pleasant drink, and how much nicer that experience might be in a wooden rocking chair. Or fancy holding your first baby or grandchild, and not being able to rock. Certainly there are engineering reasons, such as maintaining integrity of the strongest axis of the wood; but I think the rocking chair addresses the 'why' just fine.

The 'old way' can take a long time, about 30 minutes of steaming per centimeter of wood thickness for 'drier' wood (or if you prefer, about 75 minutes per inch of thickness). The set-up that our friend, the banjo builder was using required about 45 minutes for pieces 3/16" (4.76 mm) thick, x 2 ½" wide (63.5 mm), x 45" (1.14 m) long. He uses three concentric rings, laminated with staggered joints, to make the hoop. He also uses kiln-dried material, as did other luthiers we have talked to. The use of kiln-dried wood is preferred because only a minimal amount of moisture is added back for bending, minimizing the risk of splits, checks, warps, *etc*. Obviously the kiln-dried material can require more time to steam.

The reason that more time for atmospheric steaming is required is due to the fact that the primary driver of moisture through wood, after it has been removed from the tree, is diffusion. Diffusion is a process by which a high density of molecules in some area has an opportunity to move to another area through whatever molecular pathways happen to exist. The process is always rate-limited by the complex molecular pathways in wood, both longitudinally (along the grain of the wood) and radially (from the center of the original tree toward the outside where bark would be). Different tree species develop a variety of cell types to transport water and nutrient-rich fluids, as well as to inhibit fluid transport in the older 'non-living' portions of the tree. The latter cell types are structured so as to protect against pathogen introduction in the tree center region.

In the living tree there is a pressure differential from the root system at higher pressure to the leaves at a lower pressure. The pressure differential, which has been found to be in the range of 2.5 to 3.0 MPa (25 to 30 atmospheres or 365 to 440 psig) in taller trees (80 to 100 m or 280 to 330 ft) accounts for the movement of water and nutrients from root to crown. For perspective, automobile tires are pressurized to about 32 psig. If the tree figured out how to move moisture via pressure differential, why not the wood scientist?

Fig. 2. Greg Galbreath, luthier and "Buckeye Banjos" owner bends steamed curly maple around hoop mold. Cooling forms stacked on left, which formed hoops are clamped to. The drink is ice tea! Photo by author 2008

In fact they have. An example dates back several decades when the “full cell” method of introducing preservative into the center of timbers was developed. A single vacuum stage, in which wood is evacuated, is followed by a high pressure stage in which preservative solution is applied to fill the cells. Another vacuum stage is used to remove free preservative from within the cell. Vacuum dry kilns operate in a similar fashion, with differential pressure serving to ‘pull’ water from wood.

A friend and colleague at Virginia Tech, co-author Zhangjing Chen, had been working for a number of years in an effort to develop the best combinations of cycles of vacuum and steam to effect many interesting issues associated with gaining heat deep within cellulosic materials for the purpose of phytosanitation; bailed cotton, fire wood, pallets veneer logs, *etc*. As we discussed these applications with him and also the issues of banjo hoop steaming, it occurred to us that cycles of vacuum and steam might also add moisture quickly to dry wood, reducing the required time and perhaps enabling easier bending.

A Project is Born

Thus began an unfunded, but nonetheless interesting (for us) project. Fortunately, our work at Virginia Tech had centered on steam vessels, steam and vacuum utilization, as well as boilers too, for quite some time. A mechanical engineering background helped. Our mental inventory of available hardware (*i.e.* stuff no one else wanted) readily identified key pieces. Over a period of about three months we had assembled, repaired, modified, insulated, installed, and tested a system to apply cycles of vacuum and steam to wood with the intent of adding moisture to perfectly good, kiln-dried maple. In this way, “Vacuum Steam Technology” was about to be developed for preparing wood for bending.

Moisture and heat applied to wood enables a plasticization of all constituents of wood; lignin, hemicellulose, and the cellulose. Each constituent is affected to varying degrees depending upon moisture content and temperature, and the balance of these variables with the desired final goal of wood bending accounts for much of the art and crafting skill associated with this technique. Different woods behave differently, thickness has a pronounced effect, and even the same piece of wood at different locations might behave differently depending on what the wood grain does. These are a few reasons why steam-bending wood can also break wood. If a person is bending a very special piece of wood, such as from the storm-damaged tree your great, great, great grandfather planted, not breaking it is preferred. A process enabling uniform moisture and heat addition might diminish the likelihood of breakage.

Vacuum Steam Technology roughly behaves according to the following brief description. When a vacuum is initially applied to wood, there is a lowering of the internal pressure and temperature due to the resident gas (air) expanding and exiting under reduced pressure. A subsequent steam cycle would rapidly move steam to the interior of the wood due to Water Vapor Bulk Flow. Upon condensation of the steam within the wood, brought about because the wood is cooler than the steam, maximum heat transfer and maximum moisture addition to the interior of the wood takes place. At low moisture contents, such as when using kiln-dried wood, this initial moisture addition would quickly become bound water within the cell wall. By introducing a low pressure state again (vacuum) there would be a repeat of internal wood temperature depression, and that would be followed by another subsequent higher pressure steam cycle and the fast heat gain / moisture gain repeats. A sequence of these stages would result in rapid, uniform moisture re-gain up to the fiber saturation point if desired and rapid internal heat gains due to the latent heat of vaporization from steam condensing inside the wood, yielding uniformly plasticized wood in reduced time relative to the state of the art atmospheric steaming.

How Did It Work?

For equivalent times (35 minutes), beginning with kiln-dried maple at 9% moisture content, vacuum steam technology increased the moisture content to 26% versus 14% for atmospheric steaming. In addition, vacuum steam technology produced zero failed bends compared to 39% failed bends with atmospheric bending. The work required to bend the wood was significantly less for vacuum steam technology compared to atmospheric steamed wood.

However…. Our luthier friend Greg felt that the system was too complex and that it could not fit into his banjo shop anyway. If it did fit, getting the electricity necessary for the boiler was going to cost the equivalent of about 100 completed banjos, representing maybe three or four years of his skilled craftsmanship. *Moral – always find out what the customer wants.* Other luthiers making thin sectioned bends, such as guitar sides or fiddle sides, are able to spritz the wood with water from a hand-held bottle, place it under a high wattage light bulb or silicone heating blankets and wait a short time before bending. Meanwhile, the vacuum steam technology hardware system at Virginia Tech has been moved to a completely new location where continued experimentation is being conducted with thicker section wood, suitable for furniture applications and rocking chair rockers.

For the complete write-up of this endeavor (200+ pages), the reader is referred to the following link: http://scholar.lib.vt.edu/theses/available/etd-07112011-172216/
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