Laminated bamboo ya

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I. Stability and uniformity from traditional materials

In his book, "The Essence and Practice of Japanese Archery," Onuma sensei writes: "In recent years, aluminum or carbon fiber shafts have come into use. But even though they, too, are fitted with real feathers, they cannot compare with the natural beauty and feel of bamboo arrows." The "beauty and feel" come with practical costs: Bamboo stalks are very prone to longitudinal splitting as they dry out from the initial green state. It's as if they want to shrink their circumference at a given diameter. Even if the splitting is suppressed by sufficiently slow drying, it is highly likely that strong circumferential stresses remain. As elastic properties vary with changing temperature and humidity, warping away from straightness is almost certain. Long time take-ya users are very familiar with splitting and/or warping. There are also the idiosyncrasies of a biological structure. By craftsmanship, a yamishi can produce a beautifully uniform cylindrical outer surface of the ya. If you cut a yadake stalk lengthwise into two, and you will see that the interior void is not at all a uniform cylinder between nodes. Hence, a uniform outer cylindrical outer surface does not imply uniform material properties along the length of the ya. The aluminum and carbon ya are one material science answer of the issues of splitting, warping and natural variability. There is another, but working with the traditional bamboo.

Unlike take-ya, take-yumi are advanced far beyond single staves. Thin bamboo back and belly laminations are laid up about a core with multiple strips of bamboo and hardwood. What is possible for ya, laminated from multiple strips? Something like this already happens when fly-fishing rods are laminated from six strips with triangular cross sections to form a pole with hexagonal cross section.

II. Stable layups of laminated ya

Figure 1a depicts the cross section of a laminated fly rod. The dense, high strength layers of the individual bamboo strips are adjacent to the outer surface of the rod. There, they make the best contribution to stiffness. The material near the center axis of the rod contributes little to the stiffness, since bamboo filaments near the axis undergo little stretch or compression. In figure 1b, the cross sections of individual strips are truncated from triangles into quadrilaterals, so the rod is hollow, much like an individual bamboo stalk. Nice, if it can be done. During the layup, how do you compel the cross section to retain the configuration in figure 1b, with the uncured glue "lubricating" the surfaces where the strips join?

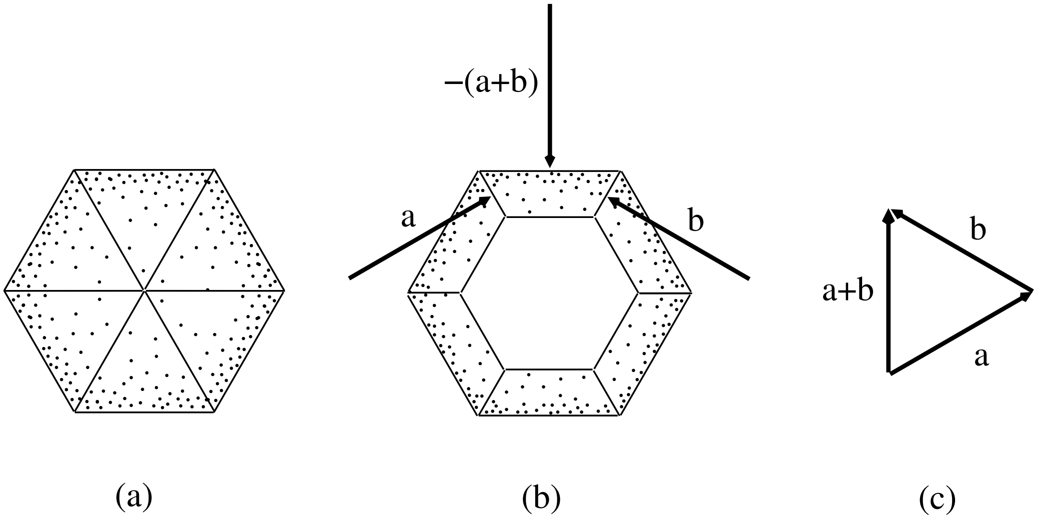

Figure 1: Hexagonal laminated rods and forces that act on their layup

Some practical physics is at the heart of why such a layup can be done at all. The layup is to be secured by a thin but strong chord which wraps tightly around the outer surface in a helix. Look at the forces acting on one of the strips with its trapezoidal cross section, say the top strip in figure 1b. **a** and **b** represent compression forces acting on the top strip across the joints between itself and its neighbors. With these joints lubricated by uncured glue, there is slippage between strips unless the forces **a**, **b** are perpendicular to the joints across which they are applied. If **a** and **b** were the only forces acting on the top strip, the *net* force on the top strip would be the *vector sum* $\mathbf{a}+\mathbf{b}$, visually explained in figure 1c. The top strip would be pushed upwards. But remember: The chord wrapping around the ya which induces the compression forces **a** and **b** in the first place is an obstacle to this upward movement. In fact, it supplies the opposite and equal force $-(\mathbf{a}+\mathbf{b})$ on the top surface, as depicted in figure 1b.

Once the layup is done, the system of forces acting on each strip of the lamination stably maintains the cross section of figure 1b while the glue cures. Starting from a cured hexagonal rod, the final cylindrical surface of the ya is produced by removing the vertices. Figure 2 depicts the final cross section of ya that results.

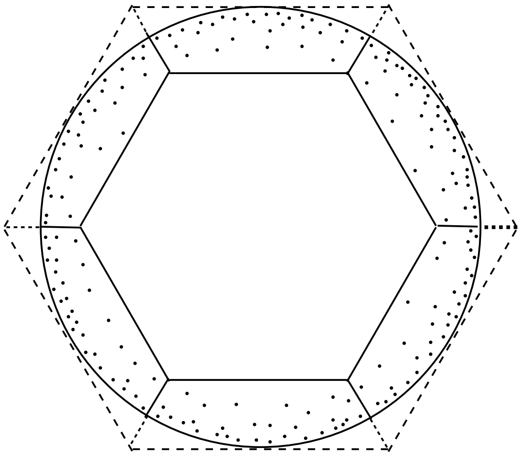

Figure 2: "Rounding" the hexagon

A simple geometry exercise shows that the radius of the completed ya equals the "outer width" of the original quadrilateral strips. If we have more strips, the polygon perimeter of the cross section before rounding is closer to a circle. Figure 3 depicts a cross section with twelve quadrilateral strips. Another slightly longer geometry exercise shows that the final outer radius r of ya is related to the width l of the quadrilateral strips by

$$r = (1+\sqrt{3}/2)l \approx 1.866l. \tag{1}$$

A twelve sided layup secured by a helically wrapped cord is stabilized by the induced circumferential and radial forces much as before. With more sides, the stability is more delicate. Nevertheless, quite achievable, as we shall demonstrate.

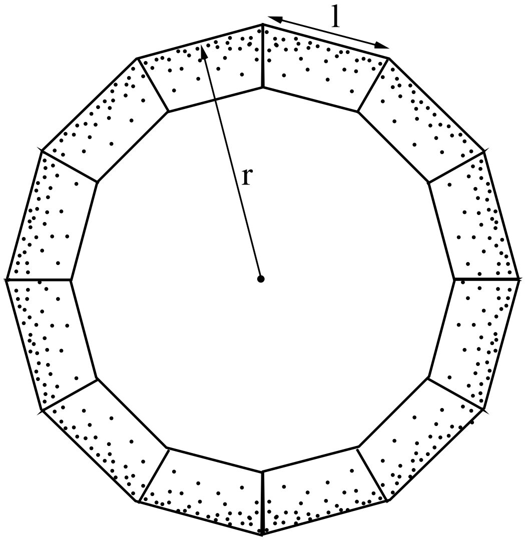

Figure 3: Twelve sided lamination

III. Workshop practicalities

The process from intact bamboo stalks to the layup of a twelve-strip laminated cylinder has practical steps: How do we produce the individual strips, each thinner than a matchstick, with sufficient precision? How do we arrange the twelve strips lubricated with glue into the cylindrical configuration, to be tightly wrapped with the chord?

Strips from bamboo stalks

Figure 4 focuses on the cross section of the individual bamboo strips that make up the 12 strip lamination with the cross section depicted in figure 3. l denotes the outer width as in figure 3 and τ denotes the thickness. Some typical values: To fabricate a ya with an outer diameter of $9.1mm$, we need

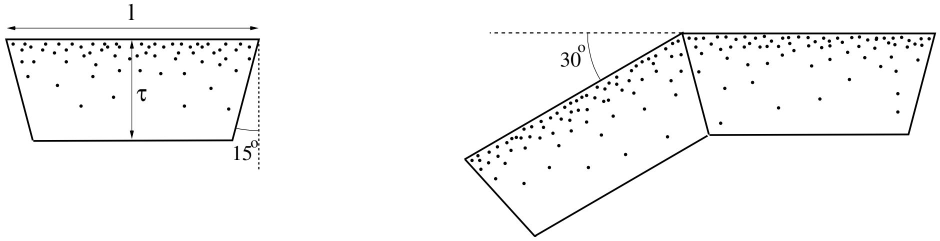

Figure 4: Trapezoidal cross section of strips in the twelve sided lamination

$l \approx 2.44mm$, consistent with the geometry formula (1). A thicknesses τ close to $.8mm$ produces laminated ya whose weight is close to a traditional take-ya (but stiffer, as it turns out). The angle of the sides with respect to the vertical is 15°. This means that the rotation angle from one strip to the next is 30°, as depicted in figure 4. The net rotation as we pass through all twelve strips is $12 \times 30° = 360°$.

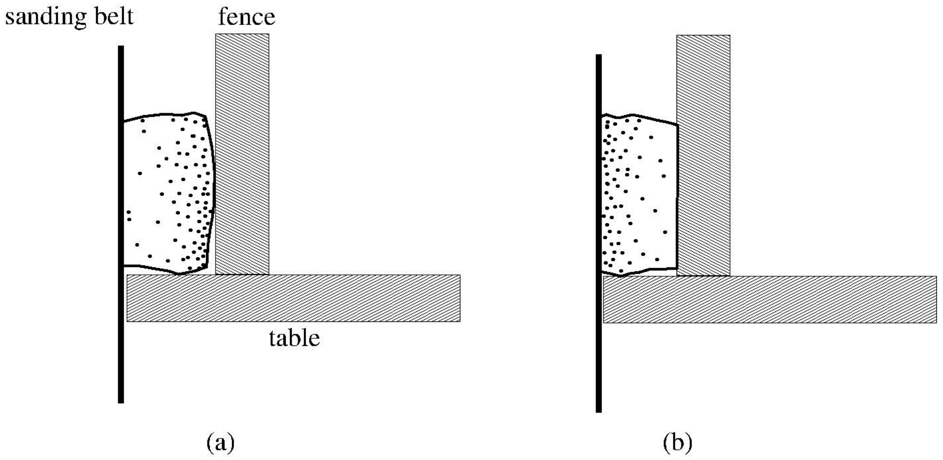

Figure 5: Preliminary thickness by sanding

The strips may be produced from almost any bamboo stalk with outer diameter greater than a centimeter. By use of a bandsaw and a spindle sander, even large stalks suitable for yumi can be effectively processed into thin strips. In practice, the large stalks are preferred: The layer of strong fibers just beneath the surface has thickness on the order of $2mm$ and there are no leaf pockets to avoid. Let's say we've band-sawed a large stalk into strips roughly $2cm$ wide and $130cm$ long (ya are typically shorter than $110cm$). Raised nodal bumps on the outer surface are sanded flat. The inner surface is sanded flat by passing the strip through the spindle sander jig depicted schematically in figure 5a. This preliminary work uses the flat belt sander with a course 60 grit. The strip can now be laid flush on the bandsaw table and it is easily cut into narrower strips, each roughly half a centimeter wide. The rectangular cross sections of the narrow strips are refined by further passes through the spindle sander jig. In particular, thickness is reduced to about one millimeter by a pass as depicted in figure 5a and the backs are lightly flattened as figure 5b.

The fine work begins. The flat sanding belt in figure 5a is replaced by a 3" drum with a fine 120 grit sleeve. The inside surfaces of the strips are sanded to produce the design thickness, say $\tau \approx .8mm$. Figure 6 schematically depicts the spindle sander jig for producing the final trapezoidal cross section of strips. The photograph in figure 7 shows what this jig looks like. It is simple and crude, and there is trial and error to set it up for the design width, say $l \approx 2.44mm$.

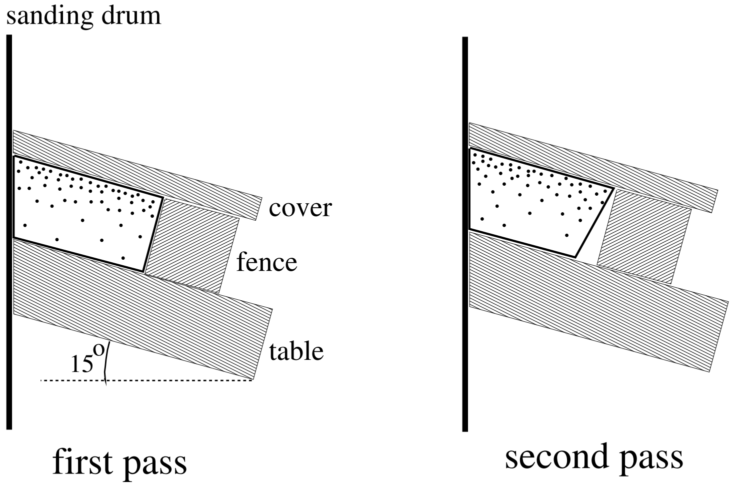

Figure 6: Sanding the trapezoidal cross section

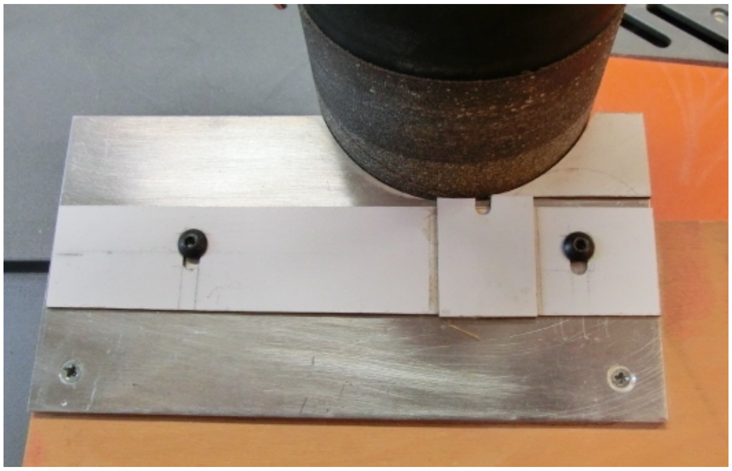

Figure 7: The physical jig

Layup

We have argued for the stability of the twelve sided layup, once it is achieved. How is it assembled in the first place? Figure 8 is a photograph of the twelve bamboo strips laid up around a dowel whose diameter is slightly greater than the inner diameter of the finished ya. Initially, they are lightly secured by low tack masking tape at about $10cm$ intervals (the blue strips). These blue tape wrappings are replaced one at a time by paper strips secured to the bamboo by carpenter glue. The paper strips don't "close" the cylindrical raft, so we can pry it open open spread epoxy on the inner surface. The epoxy should have low viscosity so that excess "gobs" are easily removed, and overall, less glue is used. The pot life should be on the order of an hour. The reason for paper strips secured to the bamboo by carpenter glue becomes clear: Masking tape cannot withstand the permeating character of epoxy. The final layup is secured by the helical wrapping of a thin but strong chord, as discussed before.

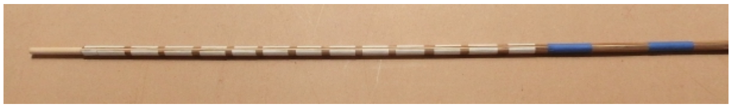

Figure 8: Securing the bamboo strips into a "raft"

The initial layup with uncured glue is not likely to be straight. In fact, the layup is initially malleable like a copper wire due to slippage along uncured glue lines. Rolling the proto-ya on a flat surface like a breadstick induces a rough, preliminary straightening. Finally the layup is lightly secured to a straight aluminum L-bracket as depicted in figure 9. There is stays until the epoxy cures. Many of the earlier laminated ya were produced in this manner. A recent upgrade has these additional features: Cylindrical chords of ethafoam are used as insulation to caulk points in masonry construction. The foam chords are very light. For instance, a chord with diameter close to

Figure 9: Layup "clamped" to straight L-bracket

a centimeter and a length of 110cm weighs about a gram. The idea is to lay up the ”raft” of bamboo strips around an ethafoam core. The small pressure from the foam core allows another helpful modification: A thin fiberglass veil (.003” thick) with its filaments criss-crossing in all directions is pressed against the inner diameter of the ya, to prevent splitting when the ya is shot into the harder backstops as are typically found in venues for Western archers.

Rounding the cylinder

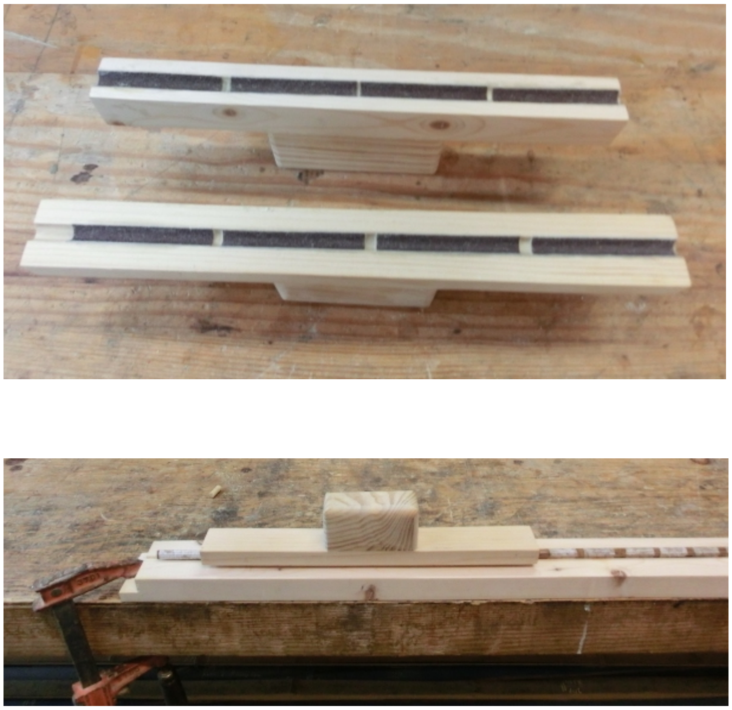

Figure 10: Planing the ya into roundness

The remaining job is to remove the vertices of the twelve-sided polygon cross section, to produce a circular cross section. The first panel of figure 10 is the photograph of improvised ”planes:” Strips of sanding belt are secured to a semi-cylindrical channel cut into a pine board by a router. The proto-ya is placed in a slot of a long board to secure it as the ”plane” is passed over it, as depicted in the second panel of figure 10. Figure 11 depicts a section of the finished cylindrical lamination left over when the ya are cut to length.

Figure 11: A section of the final cylinder

IV. Comparison between laminated ya and take-ya

Figure 11 depicts the tail end of a laminated bamboo ya with fletch and hazu. The specifications of the laminated ya (averaged over a set of four) are: length $111cm$, diameter $9.1mm$, weight $32.1g$, and stiffness 1.11 $kg\ m^2$. Three sets of long, stiff take-ya have similar specifications, listed in table 3 of the article "Arrow Selection East and West." Recall that the weights and stiffnesses of these take-ya are close to 2015 aluminum proxies. The $32.1g$ weight of the laminated ya compares well with the take-ya. The three sets of take-ya have weights (estimates adjusted to the $111cm$ length) of $33.6g$, $31.5g$ and $35.8g$. The laminated ya have wall thickness $.8mm$. Earlier laminated ya with wall thickness $1.3mm$ are about $4g$ heavier. The 1.11 $kg\ m^2$ stiffness of the laminated ya is within the range covered by the three sets of take-ya: 1.04 $kg\ m^2$, .97 $kg\ m^2$ and 1.31 $kg\ m^2$. Only the third set of take-ya, the

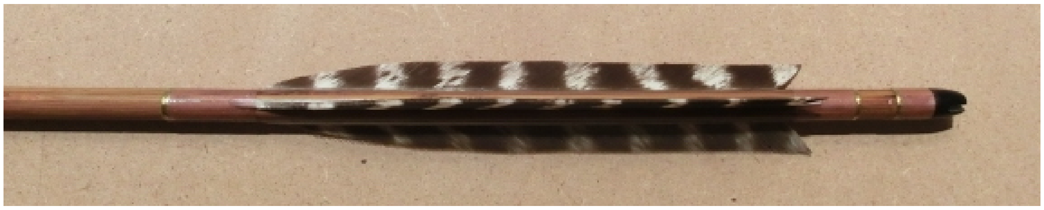

Figure 12: Tail end of laminated ya

widest and heaviest ($9.2mm$ diameter and adjusted weight $35.8g$) is stiffer than the laminated ya. As noted in the article on arrow selection, their relatively high stiffness (1.31 $kg\ m^2$, 40% greater than 2015) is probably an upper bound on what is achievable for take-ya.

To achieve higher stiffnesses for Kyudoka with the longest yazuka shooting the strongest yumi, the author has constructed ya with a layer of bamboo wrapped around carbon tubes. That is another story.