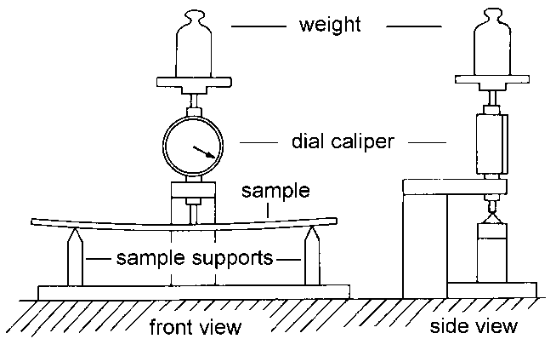
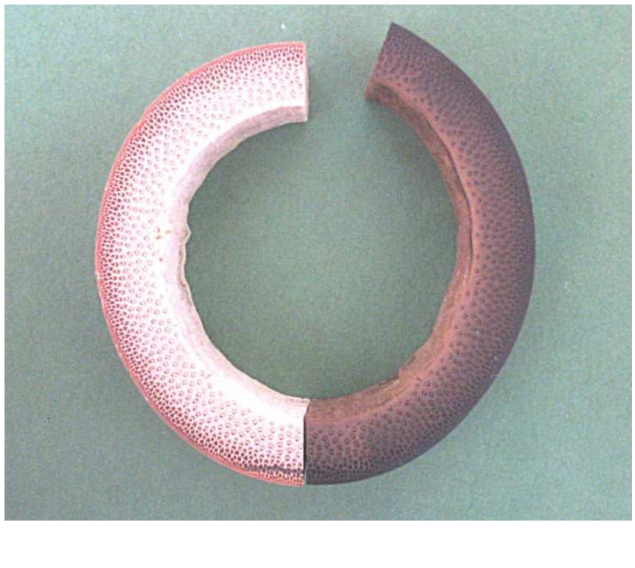
Bamboo
in the Laboratory

By Wolfram Schott
2006





FOREWORD : by Bob Milward.

I am delighted to be able to introduce this report to rod-builders. It is the first full investigation of the subject. It reviews history, theory and for the first time presents accurate test data on nearly every aspect of heat treatment relating to rod-building.

This report is important to all rod-builders :- For the "Artistic" : look at the graphs and go straight to the conclusions. For the technical, there is enough meat here to chew on for weeks.

Wolfram Schott is a doctor of mineralogy who built his first bamboo rod in 1981. All the research work and most of the laboratory work is his, with some items provided by Stephan Pauly. I am happy to have played a small part in helping with the presentation of this report and its conclusions.

We should all be thankful for Wolfram's intellect, hard work and access to laboratory equipment most of us can only dream of.

Bob Milward Nov. 2006

FOREWORD

After having published my paper "Bamboo under the Microscope" in 2005, I have had a number of queries as to the temperatures used for some of the photos presented there, and to heat treating of bamboo for rod making purposes in general. After contemplating this for some time, I finally started to write down some of my thoughts, experiences and test results.

It has been a long way to compile the treatise below, as many details and test results, made during the past 20 years or so (and most notes only written on paper), had to be considered and put together. New drawings had to be made to present everything properly. I wanted to keep it limited in space, and not do another thesis. My goal was 20 pages. The material I have gathered would be enough for a whole book, which no one would either buy or read.

My sincere thanks go to Bob Milward, who was kind and patient enough to read through a number of preliminary casts, and also for in-depth discussions on a number of topics. I also appreciate very much his corrections. English is not my mother tongue.

Wolfram Schott Nov. 2006

Bamboo in the Laboratory

Some observations on heat-treating of bamboo for rod making purposes

Wolfram Schott, 2006

Almost every bamboo rod maker is heat treating his bamboo some way or another: indirectly in an oven, or a heat pipe, or directly with open flame, both from the outside or the inside. As whole culm, split into strips, and planed into triangular parallel splices. A number of new rod making books contain chapters on this procedure, and more observations have been published in rod making magazines and in the internet.

Why would one want to "cook" bamboo in the first place, and how? And what are the expectations the rod maker has from such a treatment? Much "Voodoo" has been made around heating. I will try to share some of my personal observations and procedures in this treatise.

Studying older literature, there is little to be found: Thaddeus Norris (1864), James A. Henshall (1881), Henry P. Wells (1885), John H. Keene (1886), Perry Frazer (1908), George L. Herter (1949) never say a word about it. George P. Holden (1920, page 62) and Letcher Lambuth (1979, pages 82/87) mention straightening of strips, or splines, using heat. Holden even remarks: "Professional rodmakers place strips in a steam-box". The first one to "cook" bamboo sections with a torch in an iron pipe, is Claude Kreider (1951, page 74 ff). He uses ammonium carbonate in his galvanized iron pipe, "...employing a little secret process, ..." and heats the sections until "... one of these often desired shades..." (tan, straw or light brown) are produced. But he warns of "...continuing too long and ending up with bamboo of a brown tone, for then it will have reached the dangerous, brittle stage".

Ammonium carbonate $(NH_4)_2CO3$, also known as "baker's ammonia", was a forerunner to the more modern leavening agents baking soda ($NHCO_3$) and baking powder. When this is subjected to high temperatures, the chemical reaction is: $(NH_4)_2CO_3$ --> $2NH_3 + CO_2 + H_2O$. It decomposes into ammonia and carbondioxid, both gases, and water. Ammonia is known to react with tannic acid (a polyphenol), which is present in most woods (and also in tea, where it adds to the taste and wine, where it prevents oxidation), producing a brownish stain. Ammonia is (or rather was) much used to stain e.g. oak furniture dark. Whether it has an effect on bamboo other than cosmetic I do not know. A watery solution of Potassium permanganate ($KMnO_4$) is also used to stain bamboo brown, usually applied to the finished blank.

George W. Barnes (1977) uses much the same procedure, but without ammonium carbonate.

In British literature, Richard Walker (1952) advocates: "Before the halved poles are split down into narrow strips they should be thoroughly heated until the outside just – and only just – shows signs of scorching by changing colour. The amateur can do this easily in front of an electric fire, or over a red-hot plate on a gas-ring or a fire". Peter Stone (1961) tells us the same: "...hold the cane in front of an electric fire or failing that a gas ring...until the cane shows signs of just changing colour by scorching", while G. Lawton Moss (1969) flames his poles: "To bake, hold the pole at one end and place the other in the naked flame turning it between your fingers all the time and moving it backwards and forwards about 10 in. in order that the heat is evenly distributed". Also Harry Brotherton (1960) says that the amateur can "... achieve similar results by passing the halv-canes to and fro over the flame of a gas-jet until they begin to show traces of scorching".

Danish authors, too, have some information. Poul Suder (1955) deals with heat treating of both whole culms and splits, without going into details as to temperature and time, though. Henrik Bech (1964) mentions to have heard that "...others treat tonkin with infrared light, the heat of which penetrates into the depth". Poul B. Jensen (1976) puts whole culms, diaphragms pierced, into an iron pipe which is heated with a gas torch.

In Germany, Haager & Lorenz (1958) recommend to "bake bamboo ... somewhere between 140 and 180°C ... raising the heat for half an hour, maintaining the maximum temperature for one hour, and cooling off for at least half an hour... The colour of old gold is our utmost limit as to a colour change".

The process of heat treating is described in some detail in Garrison/Carmichael (1975, page 61 ff), and in a score of post-Garrison books, with most of them repeating Garrison's numbers.

But before heat treating, one should know WHAT to treat, and something about the properties of the material, and how it will eventually react to elevated temperatures, both chemically and mechanically. I am no botanist. So much of the information related below is gathered from numerous sources, both in print and from the internet.

Too many, in fact, to list them all. I have tried to condense the interesting and important facts to a few, and, I think, necessary sentences. I know, all the layman wants to be told is: "Cook at x degrees for y minutes". Period. But some background information about this cooking can't be wrong. R.E. Milward, in his book: "Bamboo. Fact, Fiction and Flyrods", details on this subject, too.

Bamboo, although no wood botanically, is built up of the very same chemical substances as wood, and in approximately the same proportions. Much information can be found in sources dealing with wood. One such publication, for example, is: "The Chemistry of Wood Strength", by J.E. Winandy and R.M. Rowell, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, published 1984 by the American Chemical Society. Here is an excerpt from the foreword.

> "The source of strength in solid wood is the wood fiber. Generally, cellulose is responsible for strength in the wood fiber because of its high degree of polymerization and linear orientation. Hemi cellulose acts as a matrix for the cellulose and increases the packing density of the cell wall. ... Lignin not only holds fibers together, but also holds cellulose molecules together within the fiber wall... Changes in temperature, pressure, humidity, pH, chemical adsorption from the environment, UV radiation, fire, or biological degradation can have significant effects on the strength of wood".

Average proportions of the constituents of spruce and bamboo:

Dry material in weight percent	**Spruce**	**Bamboo**
Total carbohydrates	65.8	67.8
Lignin	28.0	25.2
Acetyl	1.4	2.8
Miscellaneous	4.8	4.2

(The acetyl radical is a component of many organic compounds)

Bamboo is built up of 50-70 % cellulose, 20-30% hemicellulose and 20-30% lignin, depending on the species.

Cellulose $(C_6H_{10}O_5)_n$ is a long-chain, linear polymeric polysaccharide carbohydrate, of beta-glucose (a long chain of linked sugar molecules), and with lengths of 1 000 to 14 000 units. It is extremely resistant to tensile stress because of the covalent bonding between the individual units.

Hemicellulose can be any of several heteropolymers (matrix polysaccharides), present in almost all cell walls along with cellulose. Hemicellulose is similar to cellulose but is less complex. The molecular weights are usually lower than that of cellulose.

Lignin is a chemical compound that is an integral part of the cell walls of plants. It fills the spaces in the cell wall between cellulose, hemicellulose and pectin components and confers mechanical strength to the cell wall and therefore the entire plant. It is the second most abundant organic compound on earth after cellulose. Lignin is a large macromolecule with a molecular mass in excess of 10 000 atomic mass units. It is the most hydrophobic (water-repelling) component of the cell and often considered nature's adhesive.

Pectin is a heterosaccharide derived from the cell wall of plants. Pectins vary in their chain lengths, complexity and the order of each of the monosaccharide units. Under acidic conditions, pectin forms a gel, and it can be used as an edible thickening agent in processed foods, like jam.

And of course, and this concerns the rod maker perhaps most, water is present in all plants. Green bamboo has a moisture content of from 50 to 150% of kiln-dry weight, depending on species, season, position in culm (tip, base), and age of culm. One year old stems have twice as much as 10 year old ones. Drying bamboo thoroughly is an important step prior to putting it to use. The culms, as it is, have been dried to some extent in their home land, and we can not do much about it. In fact, most of the drying has taken place there. About 30% weight is lost during air-drying following felling. But we can store them out of rain, preferably indoors, once we have them at home, for some additional time.

And here comes the first but. Bamboo is a hygroscopic material, which gains or looses moisture to reach equilibrium with its immediate environment. The equilibrium moisture content is the steady-state level it achieves when subjected to a particular relative humidity and temperature. Relative humidity is strongly dependent on temperature. One cubic meter of air at 0°C (32°F) contains 4.8 grams of water at saturation point = 100% rel. hum. At 20°C (68°F) 17.2 grams, at 40°C (104°F) 51.1 grams, at 60°C (140°F) 129.6 grams. Thus, in winter, 50% rel. hum. means much less water in the air than 50% rel. hum. in summer. The moisture content in your bamboo will change accordingly.

Therefore the culms will not become any drier than the relative humidity and temperature of the storing area will permit. If you live in, say, a climate with 50% rel. hum. on average, the bamboo will dry to maybe 6-8% moisture content, until its equilibrium with the surrounding atmosphereric moisture is reached. Of course it will "swing" somewhat up and down, with humidity and temperatures changing. But 50 years of storing it under these conditions will not make it any drier. You take a culm to the Sahara Desert, and it will become drier, possibly as low as 0% moisture. You take it to some Rain Forest with 95% rel. hum. and it will seek equilibrium there, possibly resulting in 15-20%, or even more, moisture content (temperatures being equal). And back to the Sahara Desert it will loose all of its moisture again. It is "breathing", how I like to call it. So, don't be overly concerned with seasoning. Keep it out of extreme moist conditions, like rain or fog, though, or else you run the risk of fungi attacking it (but by all means soak the split strips in water prior to planing, if that is your fancy).

Running a split down the full length of a culm is a good idea. One deliberate check split will prevent multiple unwanted splitting caused by stresses from drying due to changes in temperature or humidity. Also, air can get to the inside of the culm, helping in the process.

Strength is related to the amount of water in the fiber cell wall. At moisture contents from oven-dry to the fiber-saturation point, water accumulates in the cell wall (bound water). Above the fiber-saturation point, water accumulates in the cell cavity (free water), and there are no tangible strength effects associated with changing moisture content. However, at moisture contents between oven-dry and the fiber-saturation point, water does affect strength. Increased amounts of bound water interfere with and reduce hydrogen bonding between the organic polymers of the cell wall which decreases the strength.

Now, strength is a somewhat cloudy term. Numerous mechanical properties have to be considered, and most of them are dependent on moisture content. From the above mentioned paper "The Chemistry of Wood Strength", page 219, please see the following table (excerpt):

"Table III: Approximate Change in the Mechanical Properties of Clear Wood when Subjected to Change in Moisture Content"

Property	Change per 1% change in Moisture Content (%)
Static bending	
Fiber stress at proportional limit	5
Modulus of rupture	4
Modulus of elasticity	2
Work to proportional limit	8
Work to maximum load	0.5
Shear parallel to grain	
Maximum shearing strength	3

Fiber Stress at Proportional Limit is the maximum bending stress a material can sustain under static conditions and still exhibit no permanent set or distortion.

Modulus of rupture is the ultimate bending strength of a material. It describes the load required to cause a beam to fail and can be thought of the ultimate resistance or strength that can be expected.

Modulus of Elasticity (MOE) quantifies a material's resistance to deformation under load. It is solely a material property and has nothing directly to do with stiffness (large and small beams would have similar MOEs but different stiffnesses).

Work to Proportional Limit is the measure of work performed in going from an unloaded state to the elastic or proportional limit of a material.

Work to Maximum Load is the amount of work needed to cause material failure or fracture.

Shear parallel to the grain measures the ability to resist the slipping or sliding of one plane past another parallel to the grain.

Not all mechanical properties change with moisture content. The performance under dynamic loading conditions is a dual function of the strength of the material, which is decreased with increased moisture contents, and the pliability of the material, which is increased with increased moisture contents.

The above table refers to clear wood. But bamboo really is not so "far off". It is built up of the same chemical substances as wood, after all. And it is these substances which react to heat. Only the geometric arrangement, size and distribution of cells is different. So, a certain amount of comparison is legitimate, I believe.

Strength is also dependent on specific gravity, or weight (the ratio of the weight of a given volume of bamboo to that of an equal volume of water). As specific gravity increases, strength properties increase because internal stresses are distributed among more molecular material. Hence: heavy material is stronger. The dense outermost powerfibers are heaviest in a culm.

The most abundant constituent in bamboo, and hence the one that is most important for the mechanical properties, is cellulose. It reacts to thermal treatment with **Thermal Degradation**. A number of different thermal degradation reactions are known to occur with cellulose at different temperatures. Degradation at lower temperatures (as in aging of cellulosic materials) is often predominantly thermo-oxidative and/or hydrolytic. As expected, aging of cellulose is, thus, usually a function of humidity, light, oxygen availability, etc., in addition to temperature. At higher temperatures (>200°C = 392°F) water is lost, first from that absorbed by the cellulose and then by elimination from the cellulose hydroxyls. At still higher temperatures (>250°C = 482°F), several competing pyrolytic reactions begin to take over. These reactions can be grouped into three basic classifications: the first group occurs at lower temperatures and is similar to the aging reactions. Products are water, CO, CO_2 and a carbonaceous char. At higher temperatures, another reaction begins to take over which results in depolymerization of the cellulose chain and formation of anhydroglucose derivatives, volatile organic materials and tars. At still higher temperatures, more-or-less random bond cleavage of cellulose and intermediate decomposition products results in formation of a variety of low molecular weight compounds.

Now, in other words, we have to deal with different ways water is present in organic matter like bamboo.

1. Water from moisture in the air, which is freely moving in and out. It is deposited at/on the inner surfaces of the bamboo, the cell cavities.

2. Water that is absorbed by the cellulose molecules (cell walls), and which needs much more energy (higher temperatures) to be removed.

3. Water that is/was part of the molecule and is produced, together with other matter, by destruction of the cellulose chain by still more energy (higher temperature). Test runs using DTA (Differential Thermo Analysis) have indicated an endothermic (energy consuming) reaction, starting slowly at 180°C, and two exothermic (energy producing) reactions with maxima at 240°C = 464°F and 280°C = 536°F, respectively.

It is the first two "types" of water we want to, or have to, deal with as rod makers.

But at which temperatures and times? To find out I have conducted a number of tests. Not really scientific, with systematic sampling at butt, mid, and top of culm, or thick- and thin-walled culms, or from different sides of culms, or culms of different vintage, etc. I just wanted to know what was happening at large.

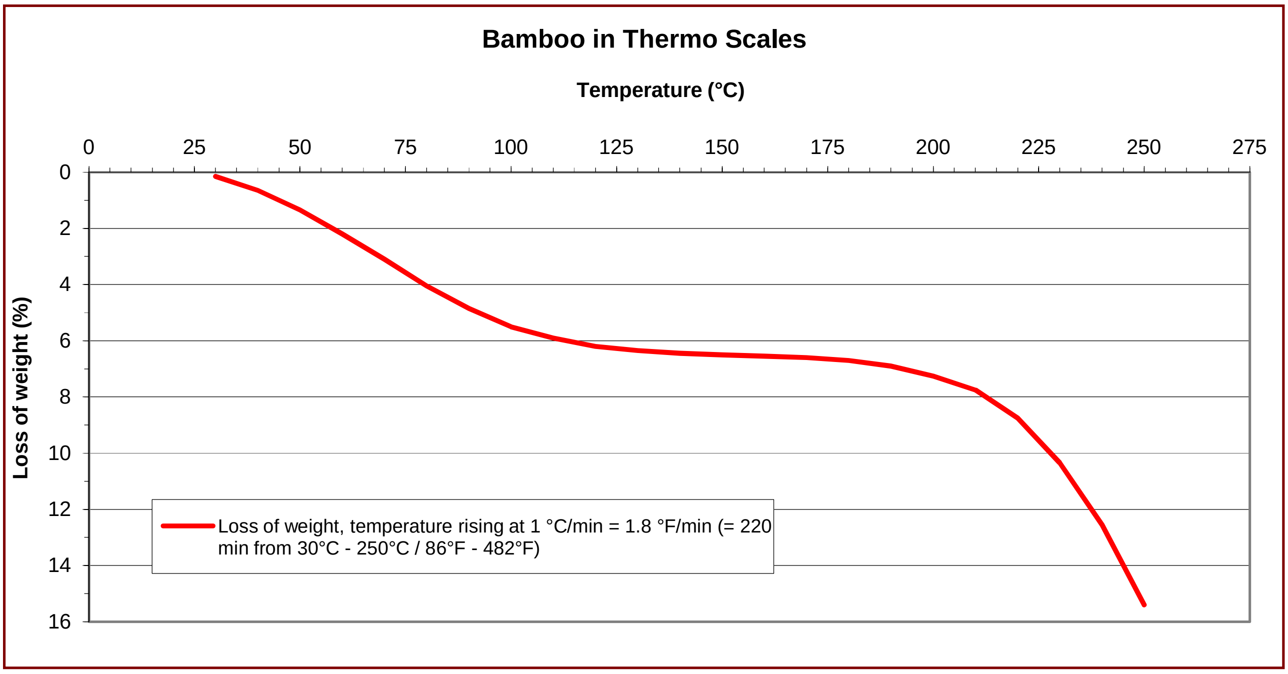
My first guess was that water must primarily accumulate in the rather spongy "pith"-material. But this is not the case. Measurements, conducted by a rodmaking friend[1], showed almost no difference between the skin-near parts of a culm and the inner parts. An 8 mm (0.315 in) thick wall contained 7.2% in the outermost millimeter, 7.5% for the next 3 mm and 7.3% for the rest of the wall, 4 mm.

[1] With kind permission of Stephan Pauly more of his results are included in this treatise. His tests were made in the chemical/physical laboratories of a chemical company in Germany.

Following are some of my test results:
<u>THERMO SCALES TEST</u> (Thermogravimetric Analysis, TGA)

A bamboo sample (80 milligrams = 1.234 grains) from the outside of the wall was continuously heated in Thermo Scales, under a protective argon atmosphere. Thermo Scales provide a continuous weight reading while the sample is heated at a predetermined rate (in this case by 1 degree Celsius = 1.8 degree Fahrenheit per minute). The weight, or rather weight-loss, was continuously recorded. Below is a graph with the test result.

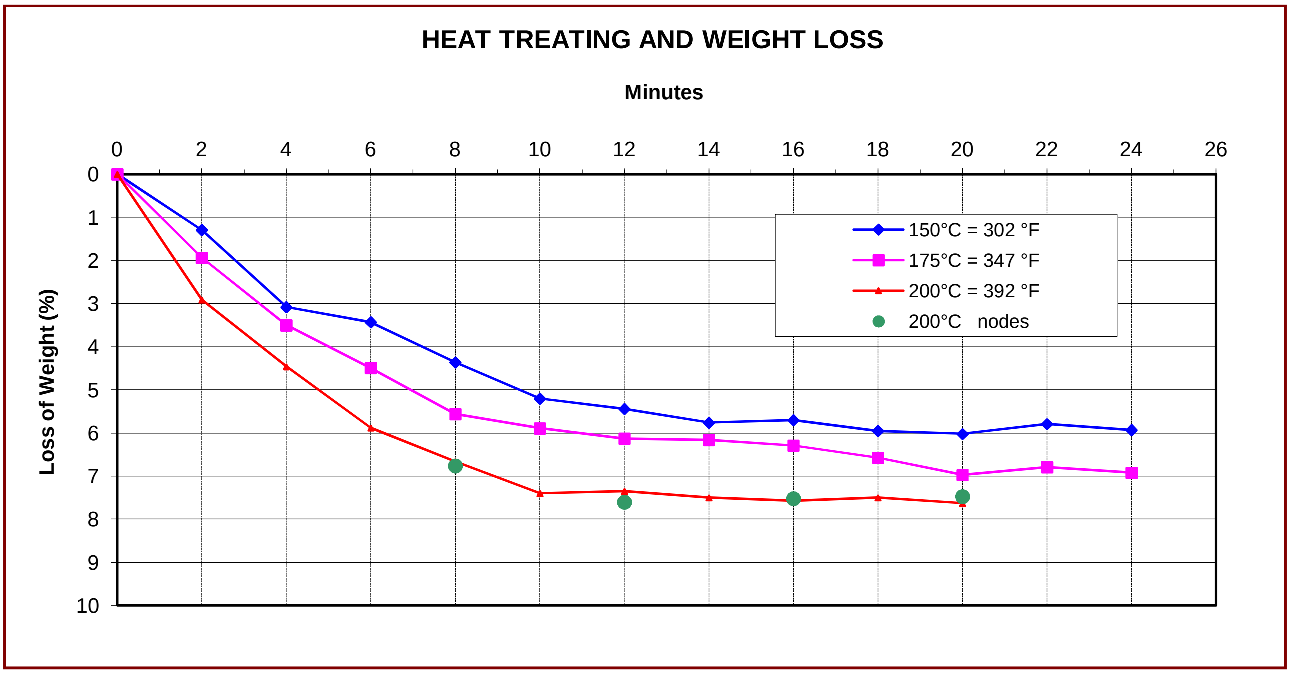
Fig. 1



This small volume of bamboo and the very slow heating rate was chosen to make sure that the heat-insulating properties would not cause any "delay" in the results (loss of weight). So what can we see? Starting at about room temperature (30°C = 86°F) the bamboo first looses free water (from the moisture in the air), deposited in the cell cavities. Slightly above the boiling point (100°C = 212 °F), at approximately 130°C (266°F), this water is completely driven out of the bamboo. It is dry. In this case the bamboo had had a (free) moisture content of approx. 6.5%. Nothing much happens for a while then until, slowly starting at 180°C (356°F) and growing speed at 220°C (428 °F), the sample starts to loose more weight. This is when the temperature (energy) is high enough to free the water that is absorbed by the cell walls. This second "loosing of weight", here stopped at 250°C (428°F) and 15.4% loss of weight, continues until the sample is reduced to charcoal. I have made tests up to 300°C = 572°F, also with other heating rates, where the samples had ultimately lost 29% of weight. It is a continuous curve, and it is not detectable where thermal degradation starts, that is elimination of water from the cellulose hydroxyls, pyrolytic reactions or depolymerisation of the cellulose chain.

Next, I prepared a number of parallel planed triangular strips of 6 mm (0.236 in) height, each about two inches long. All were numbered and weighed on precision laboratory scales. They were placed into a large laboratory oven with 6 kW installed power and internal air-circulation, preheated to a predetermined temperature. One sample was kept, without heating, for zero-reference. After 2, 4, 6, 8, etc. minutes of heating one after one was removed and after a few minutes cooling time weighed again. In addition some samples containing a node each were heated. These were removed after 8, 12, 16, 20 minutes. No drop of temperature was observed introducing the relatively cool samples, or during/after the repeated opening of the door for removal of samples. The test results for three temperature runs are presented in the following graph.

Fig. 2



The 150–degree strips required 18 minutes to dry out completely, and no more weight (water) was lost until the end at 24 minutes. They had contained around 6% (free) water. The strips heated to 175 degrees had lost a little more than 6% after approximately 12 to 14 minutes, and started losing more weight (another percent) from 16 to 18 minutes onwards. This seems to represent the beginning of the above described freeing of water absorbed by cell walls. About 7% weight was lost after 20 to 24 minutes. Possibly all of the "free" water plus some of the "cell-bound" water. The last strips, heated to 200 degrees, loose more weight and much quicker. About 7.5% was removed after 10 minutes, and that seems to be all that can be driven out at that temperature, as nothing more happens until 20 minutes exposure time. Obviously both free water and cell-bound water was removed simultaneously. The samples containing nodes show much the same weight loss. No noticeable difference between those and the "straight grain" samples can be observed.

Test runs with other samples, from other culms and with other moisture contents, and heated at other temperatures, showed no great difference in terms of minutes required to dry the strips.

To remove both free water and some cell-bound water, at the temperatures tried above, needs in any case from 10 to 18 minutes, provided the heat capacity of the oven is large enough to provide for the required energy fast enough. A home made heat treating oven may be dimensioned somewhat smaller than the laboratory oven which was used here. Inserting, say, three bundles of 6 strips each, 50 inches long, and of room temperature, which is actually rather cold compared with the target temperature of perhaps 200°C, into such an oven is drawing much energy from it. Vaporizing the free water needs much energy, and the samples are cooled during the process. Much like sweat on your forehead, which, vaporizing in a breeze, cools your head. The oven temperature will drop sharply by maybe 40°C (= from 392 to 320°F) or more, and additional time, very possibly several minutes or even a quarter of an hour, is required to reach the intended heat treating temperature again. This time has to be taken into consideration and, at least in parts, added to the actual heating time at target temperature.

> Just a little estimation: 3 bundles of parallel planed bamboo, weighing 300 grams (10.58 oz.) at 7% moisture, contain 3 x 7 grams = 21 grams = 0.74 oz. of water. Even pouring this on a red-hot plate would take some time to boil off.

The timings shared in "Garrison", page 63, from 6:30 to 8:30 minutes, seem to be somewhat on the short side. But it is a good idea to "overheat" your oven prior to inserting the strips, like Garrison did. How much is a matter of your oven, its size, electric or other power, insulating properties, number of strips (bundles) to be treated, and others. You have to find out yourself.

VISUAL LIMITS OF HEAT TREATMENT

The above mentioned thermal degradation is evidenced to the naked eye by a changing of color. The long chains of cellulose molecules are broken down into shorter units of inferior strength properties, sugar molecules are caramelized. The bamboo takes on a brownish hue first, which becomes progressively darker with increasing temperature and time, until it is all but black.

It is easy enough to prepare a dozen or so short samples, insert them into your oven and take them out successively after 2, 4, 6, 8, etc. minutes. At some time they start changing color (become darker), and this is a good basis to try further with full length sections, and/or whole sixpacks, which might yield yet other results.

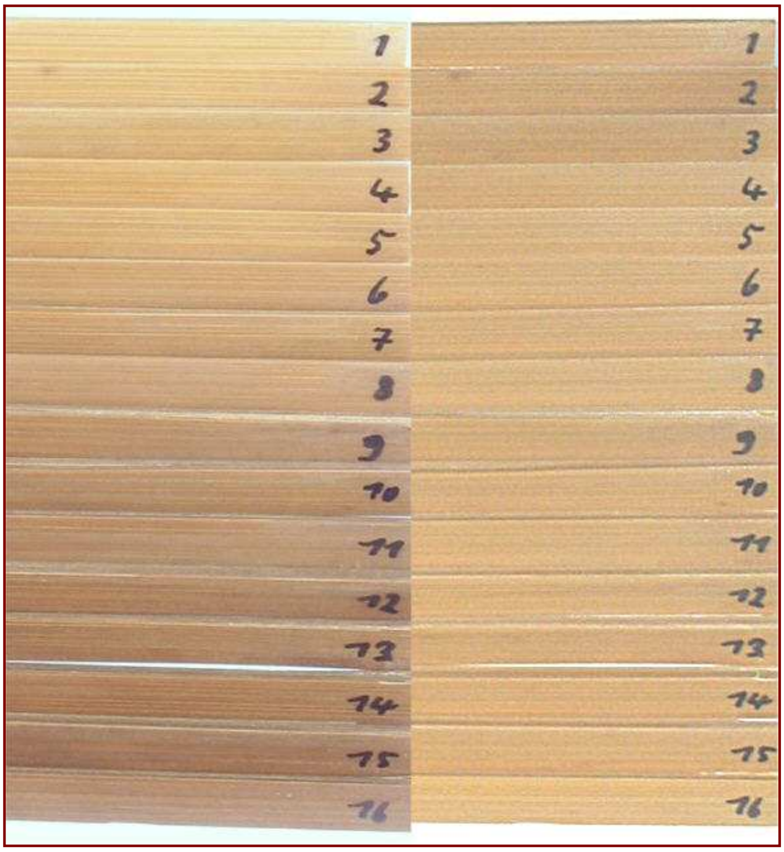


Fig. 3

Shown here are 16 short (2 inches) triangular samples, enamel skin removed. The right side photo before heat treating, the left side after heating at 200°C = 392°F. All were put into the oven at the same time. After 2 minutes nr. 1 was removed, after 4 minutes nr. 2, after 6 minutes nr, 3, etc. Starting ever so slightly, the nr. 6 sample (= 12 minutes) begins to show signs of coloration, which indicates the beginning of thermal degradation. The last sample, nr. 16, was heated for 32 minutes.

The darker hue of the nrs. 1-3 of the untreated samples (right side photo) is due to a mistake on my side. They were tilted somewhat, resulting in a shadow in the photo. All samples were from one piece of bamboo, with the same color.

The same tests were made at other, both lower and higher temperatures, and with triangular strips of different thicknesses (triangle height).

Fig. 4

Thirteen samples of 5 mm = 0.197 in. height (triangle), heated at 175°C = 347°F, from 2 minutes = sample nr. 175-1 to 26 minutes = sample nr. 175-13. No brown toning can be observed, just a slight "deepening" of the color.
Sample nr. 175-14 was heated for one hour.

Others samples, with only half that height, 2.5 mm = 0.098 in, did not show any change in color, either.

Samples heated at 225°C = 437°F started turning brown after 6 minutes. Samples heated at 250°C = 482°F became brown after 4 minutes and turned black after 8-10 minutes, smoking.
For more information on this topic, see photos in my paper: "Bamboo under the Microscope".

Now, as we have some clue about the required temperatures and times: what happens after we remove the bamboo from the oven? I have outlined above, that moisture from the air is absorbed by the bamboo, until equilibrium with the surrounding atmosphereric moisture is reached. Also heat treated bamboo will do this. It absorbs moisture from the air. The above (Fig. 2) samples were stored under controlled conditions, 50% rel. hum and 25°C. After one day and three days, respectively, they were weighed again. The results are presented in Figs. 5, 6, 7. The ones heated for some longer time had reabsorbed approximately 1 % after the first day, and another 0.8 % after 2 more days.

Fig. 5

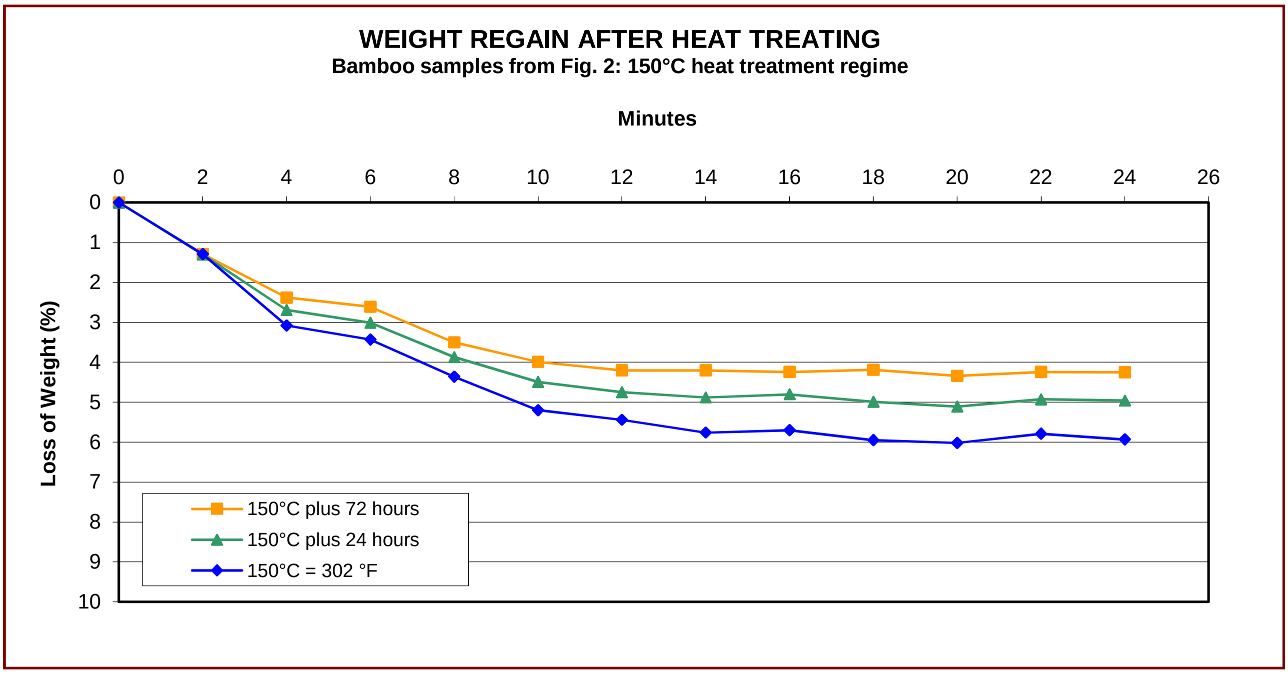


Fig. 6

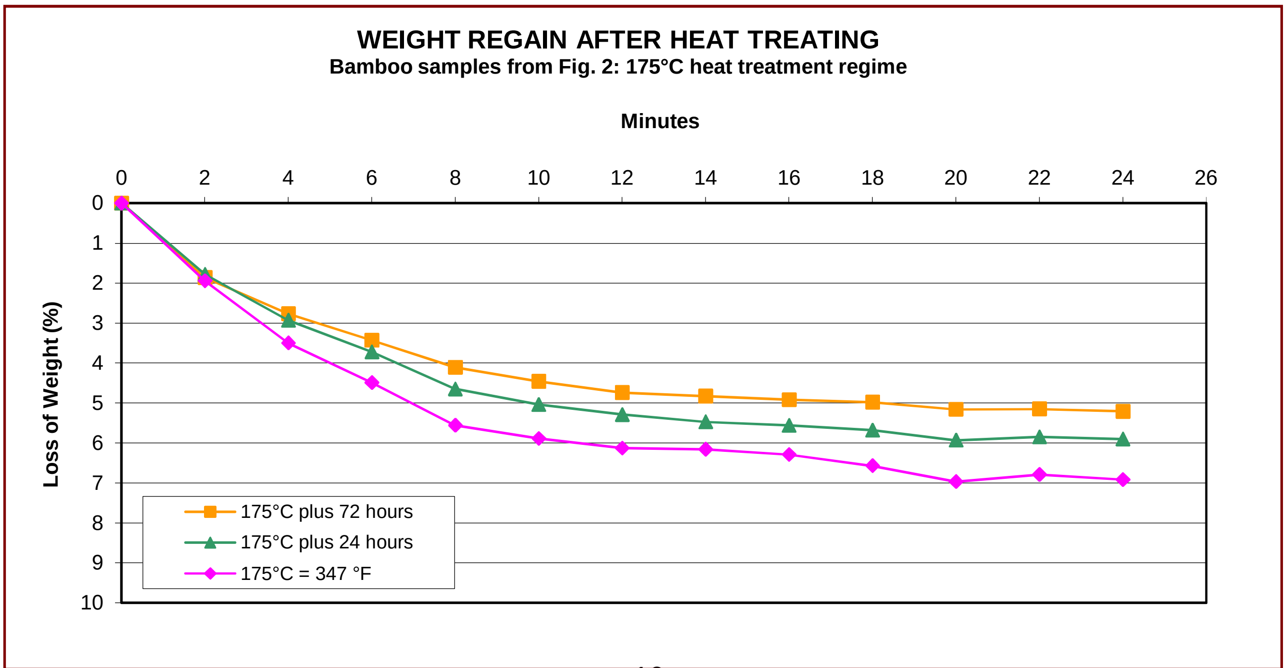
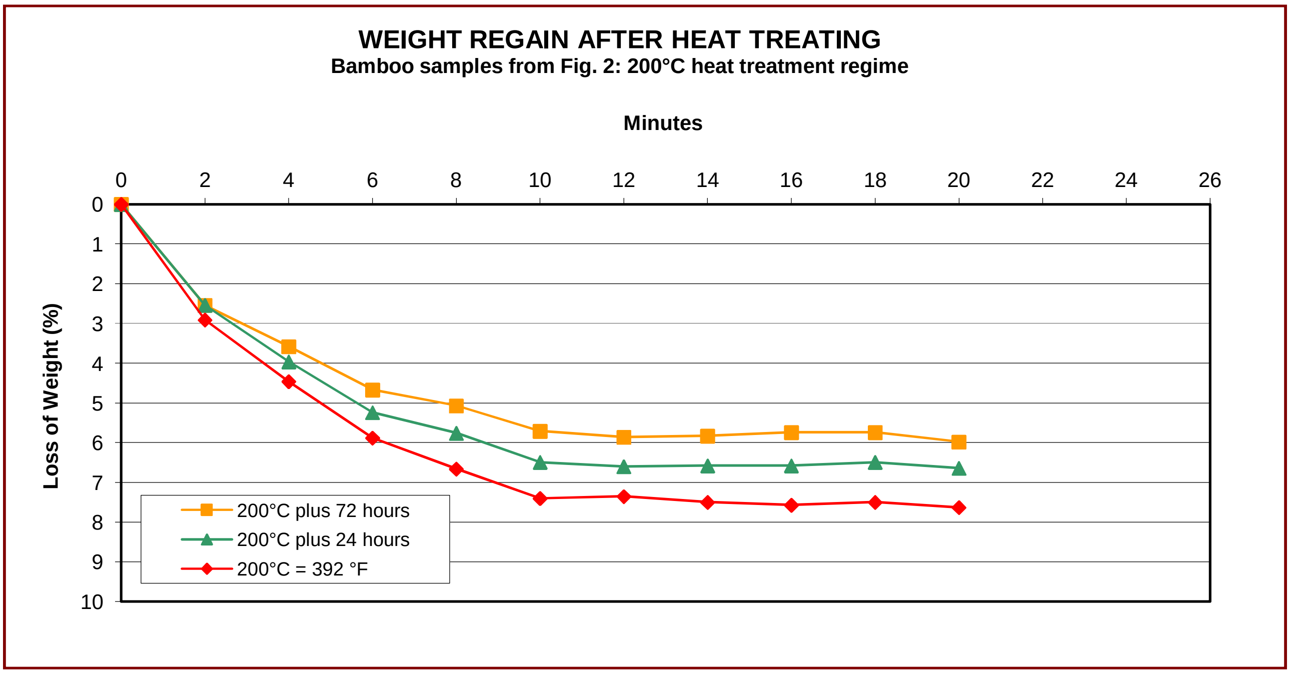


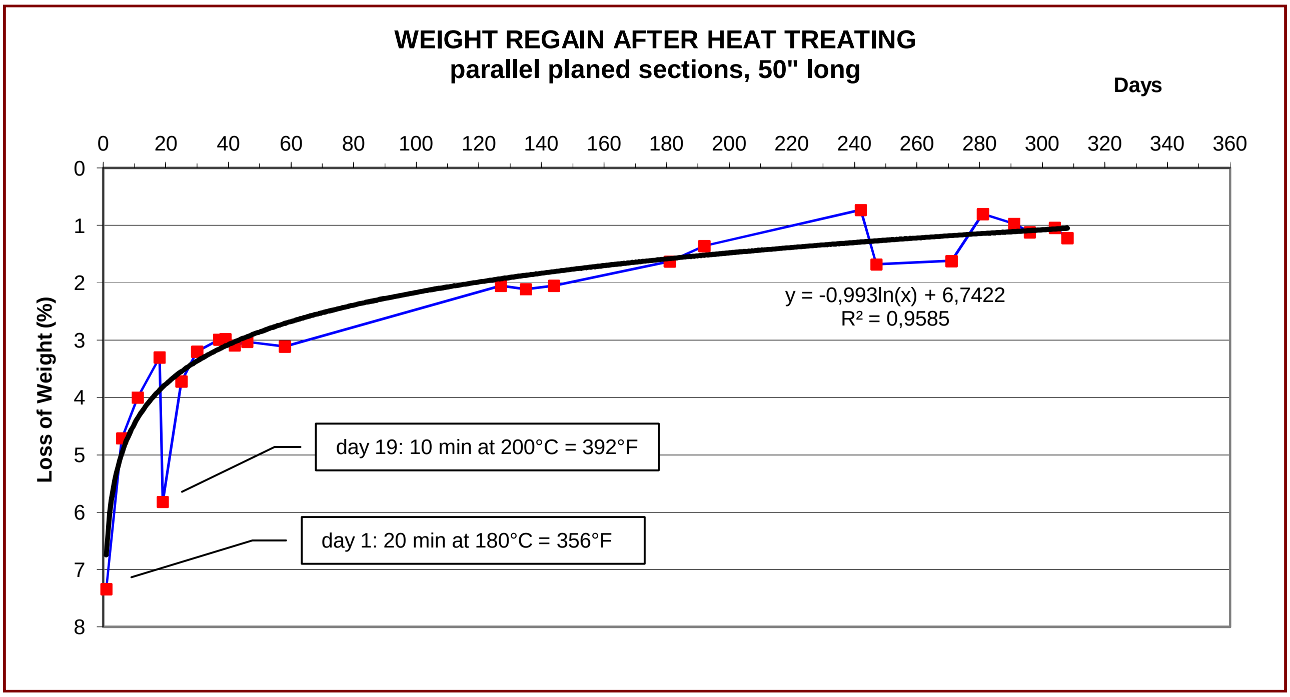
Fig. 7



LONG TERM EFFECTS OF HEAT TREATMENT

How does this continue? Will bamboo, heated to the above temperatures, in time reabsorb all the water we have just removed? Only a long-time test will answer this question. Below, in Fig. 8 the combined (average) result of 6 "sixpacks", of 10 mm diameter (2 sets of butt strips) and 8 mm (4 sets of tip strips), and of 50 inches length, heated in my oven, in 2 runs, 1 butt and 2 tips at a time, at 180°C (356°F) for 20 minutes each. Start was in January, which is a dry and cold month here where I live. Included in the graph is a logarithmic trend curve.

Fig. 8

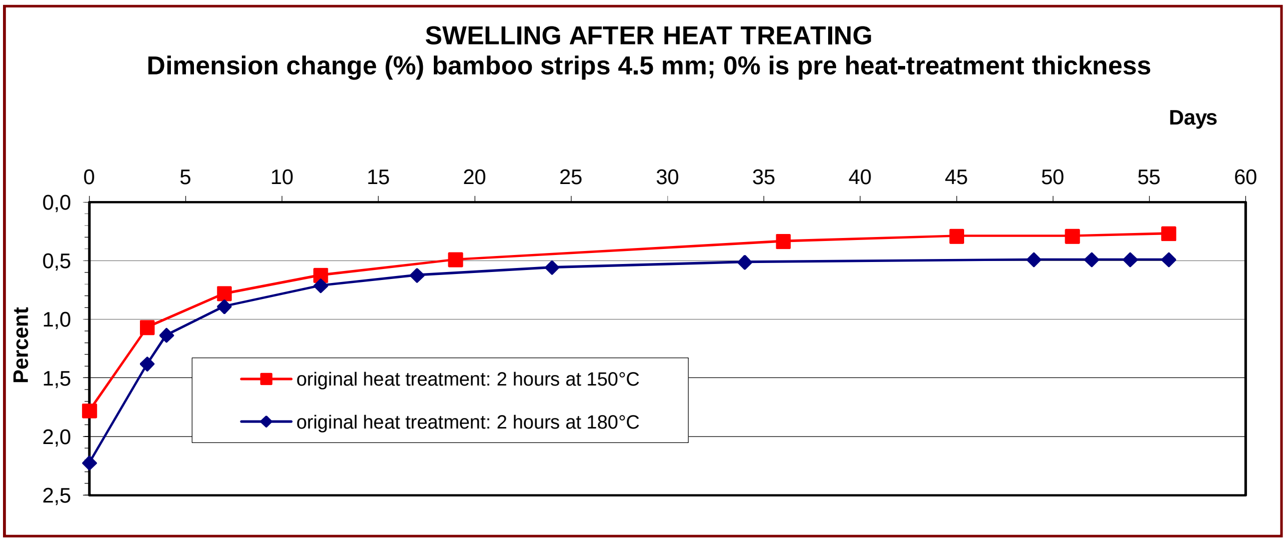


The initial weight-loss of all 6 bundles combined was 7.34%. A similar weight loss result as with the 2" long sections in Fig. 2. After 18 days 3.72% of water were reabsorbed by the bamboo, and I decided to reheat my sections for 10 minutes at 200°C = 392°F. This set me back to 5.82% weight-loss (I should have heated for 12-14 minutes, according to my own test results, see fig. 7, which would have resulted in a larger weight loss). But rather quickly, after 39 days, my 36 strips had, again, absorbed so much moisture, that net loss was only 3%, and they stayed at this level for some time. Then both ambient temperature and relative humidity started rising, and after 127 days a net loss of approx. 2% was measured. This reabsorbing continued until only one percent (plus/minus) net weight loss remained. Especially in late fall, with much rain and fog, (days 240–280) much "up and down" was observed. The sad truth is, that heat treated bamboo will in time (a year or so) reabsorb all water that was deposited at/on the inner surfaces (nr. 1, page 5). Only water which was absorbed by the cellulose molecules (cell walls, nr. 2, page 5), and which needed much higher temperatures to be removed, will contribute to a permanent weight-loss. And water which was part of the molecule, nr. 3 page 5.

> I have made a number of such tests in the course of years, and still do so occasionally, with different time-temperature regimes, and I strongly encourage rod makers to do so as well. All lasting as long as a year or even two, and with several sections (bundles) heat-treated differently. Sixpacks heated 15 min. at 175°C (347°F) e.g. resulted in only approx. 0.5 percent permanent weight-loss after one year. Parallel tests with heated and glued-up sections, varnished immediately, can also be made.

A similar behavior was observed by Stephan Pauly in his research. He had heated strips for 2 hours at 150°C and 180°C, respectively. The initial loss of weight was 7.3% and 7.9%. In addition he had measured the dimensional change (shrinking/swelling) of the triangular strips of 4.5 mm (0.177 in) height. See Fig. 9 (the initial dimensional change of length is in the order of 0.1% or less).

Fig. 9



A very similar curve to that of Fig. 8 is observed: within 20 days or so, when most of the (free) water is rather quickly reabsorbed, also most of the initial shrinking is reversed. The bamboo swells. After a month or so only little of the initial dimensional change (shrinking) remains.

> This swelling, also, has consequences for the taper of a rod, if you plane right after heating. Two percent difference (swell after planing) is something like one fourth to one third in terms of line-weight. And maybe this is the reason, why sometimes male ferrules seem to "grow" a little after the rod is a few months old, and need refitting.

Does this loosing/absorbing of water and accordingly shrinking/swelling of bamboo affect strength? And how?

One major parameter for the performance of a fly rod is Modulus of Elasticity, or Young's Modulus. This material property can be measured quite easily by the rod maker, using the following set up and formulas. In fact, your depth gauge comes in handy for this. It is best to use it upside-down, and mount a little "platform" instead of the 60°-point. On this you can put your weight (load). But it is very important to prepare the samples accurately, and measure them very precisely. Both length (L) and height (h) enter the formulas in 3rd or even 4th power.

MODULUS OF ELASTICITY

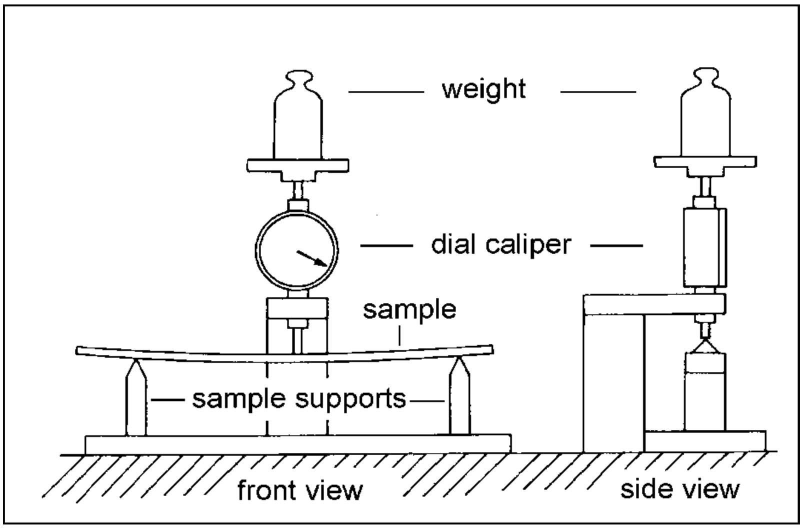


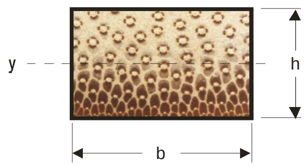
Fig. 10

E = modulus of elasticity (N/mm^2)
F = load = weight (grams)
b = sample width (mm)
h = sample height (mm)
f = deflection of sample (mm)
I = moment of inertia (mm^4)
L = distance of sample supports (mm) (approx. 40 times h)

Conversions:
1 N/mm^2 = 2320.7241 oz/in^2
1 N/mm^2 = 145.04525 lb/in^2
1 oz/in^2 = 0.000430922 N/mm^2
1 lb/in^2 = 0.00689475 N/mm^2

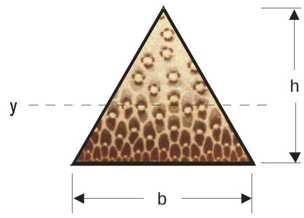
Modulus of Elasticity:

$$E = \frac{L^3 \times F}{48 \times I \times f} \quad \frac{N}{mm^2}$$



Moment of Inertia:

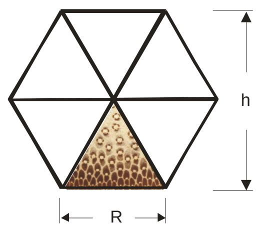
Rectangular sample: $I_y = \frac{b \times h^3}{12}$



Triangular sample: $I_y = \frac{b \times h^3}{36}$ $\quad b = \frac{2 \times h}{\sqrt{3}}$

Hexagonal sample: $I = \frac{5 \times \sqrt{3}}{16} \times R^4 = 0.5412659 \times R^4$

$$I = \frac{5 \times \sqrt{3}}{144} \times h^4 = 0.0601407 \times h^4$$



Testing triangular sections is not the best possibility. Any cellular variation at the apex i.e. solid power fiber or sclerenchyma fiber (pith) would make a big difference in the effective height of the triangle – a rectangular section would be much better. However, you are measuring the deflection (f) only, and once the apex is crushed at the contact point first time load on you simply reset your calliper to zero, and measure again. The magnitude of the variation is clear even allowing for being picky about the testing method.

NATURAL BAMBOO VARIATION

When measuring MOE at different positions around the circumference of a culm (Fig. 11), and at different levels below the surface (enamel, skin), quite some latitude is found. The table below presents some measurements from 0 - 0.5 mm (pos. 1) and from 0.8 - 1.5 mm (pos. 2). The tests were conducted by Stephan Pauly.

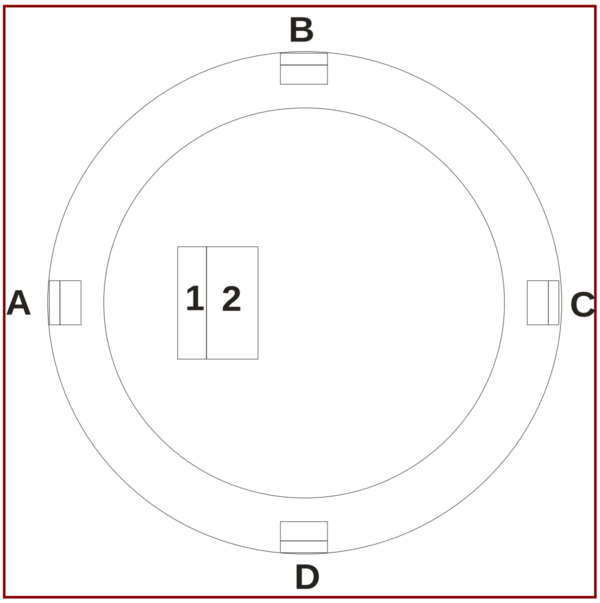


Fig. 11

Position	**MOE (N/mm^2)**	**MOE (mp/in^2)**	**MOE (%)** difference from maximum
A1	39 400	5.71	84.4
B1	46 700	6.77	100.0
C1	46 500	6.74	99.6
D1	42 700	6.19	91.4
A2	25 700	3.73	56.2
B2	32 000	4.64	70.0
C2	45 700	6.63	100.0
D2	32 900	4.77	72.0

Drop from position 1 to position 2 in % :

A1	→	A2	100	→	65.2
B1	→	B2	100	→	68.5
C1	→	C2	100	→	98.3
D1	→	D2	100	→	77.1

This was just one randomly selected piece of a culm. 15.6% difference was found in this sample, between pos. B1 and pos. A1, which represent the outer and most dense "powerfibers", and an even larger difference is observed in positions 2, like 43.8% between C2 and A2. The measured depth, reaching only as deep as 1.5 mm (0.06 in) is well within the useful range for rod making and far from the inner "pith". Positions C1 and C2 show almost no difference. These figures are presented to demonstrate the quite large difference a rod maker may have to deal with, unknowingly. It might be one reason for stiff or weak splices, resulting in a stiff or weak side in the finished rod.

The rod maker, having planed his strips to equilateral parallel triangles of equal size, can easily detect at least very strong or very weak ones with the set up shown above. The reasons for the differences are unknown, but growth-factors certainly play a role. It is after all a natural material.

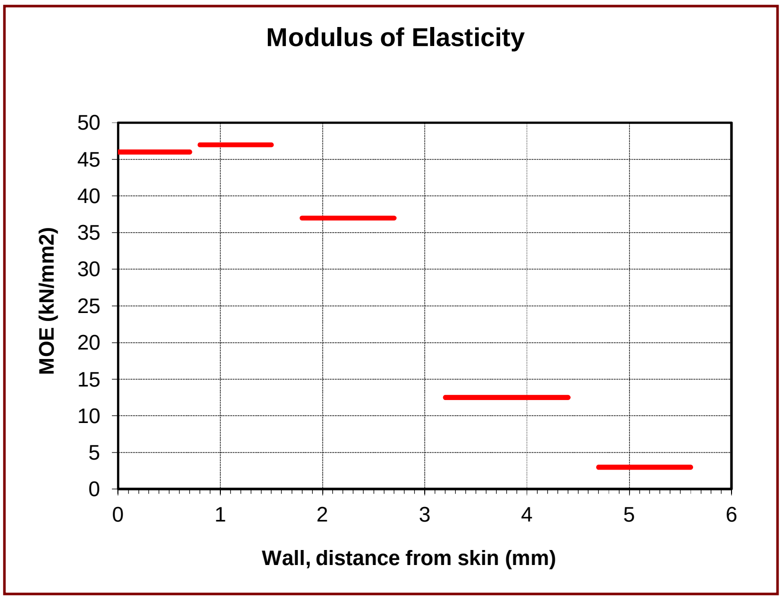


Fig. 12

On a more general basis, MOE is decreasing from the skin of a culm and towards the inner side of the wall. The outer 2 or 3 millimeters (0.08–0.12 in) of the culm are very much suited for rod making, whereas the inner half or so has rather low values, only about a third or a fourth, or less, of the skin-near ones. A point in favor of hollow-building. Likewise, MOE is decreasing from tips of culms to butts.

The samples for the graph at left were prepared as rectangular strips from indicated levels beneath skin.

Systematic investigations, e.g. from top, mid and butt of culms, and of different "brands" of culms can be studied in Bob Milward's book, Chapter 1: Bamboo strength tests.

To collect some more data on MOE after heat treating, I very carefully prepared 10 parallel planed triangular splices from one internode-section with a height of 2.5 mm (0.098 in). Each one was numbered and measured in 1 inch increments the whole length of the splices. An average value for h (height) was calculated and the MOE of every splice was determined. The table below shows the results.

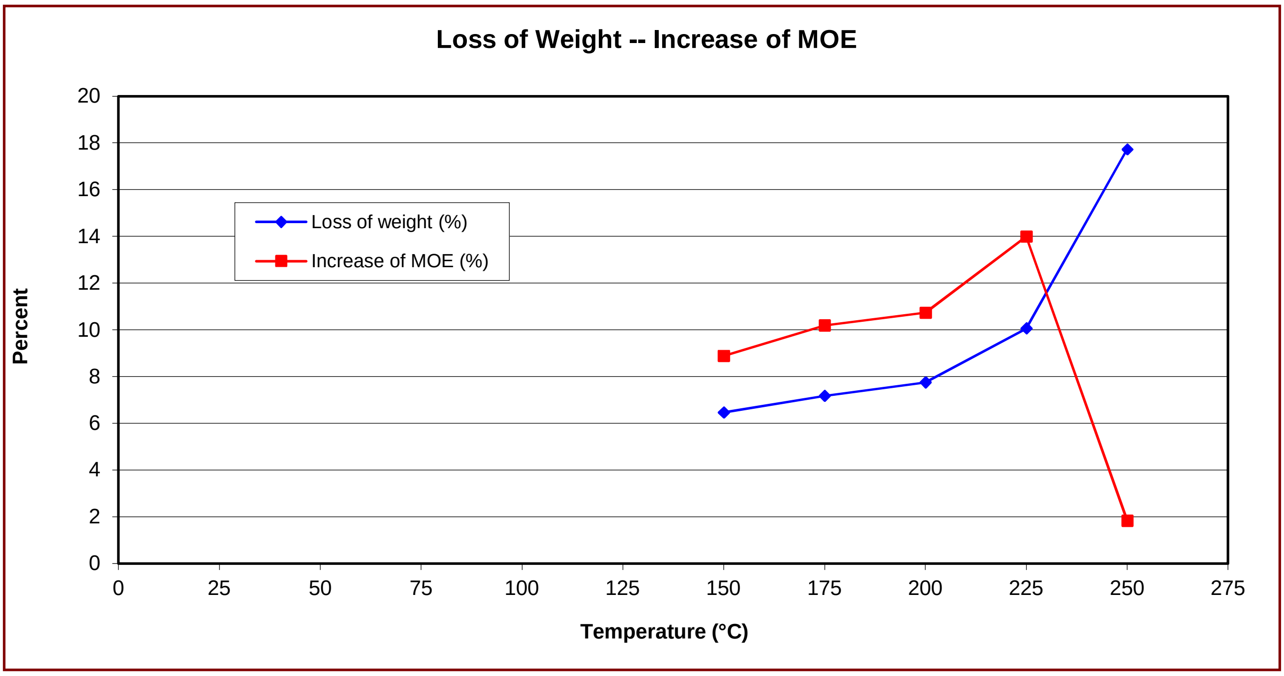
Fig. 13.

Splice Nr.	MOE (N/mm^2)	MOE (mp/in^2)	MOE (% of nr. 10)	MOE (% difference)
1	32 290	4.683	85.2	14.8
2	36 930	5.356	97.4	2.6
3	29 730	4.312	78.4	21.6
4	29 750	4.315	78.5	21.5
5	34 420	4.992	90.8	9.2
6	32 380	4.696	85.4	14.6
7	28 750	4.170	75.8	24.2
8	34 660	5.027	91.4	8.6
9	35 350	5.127	93.2	6.8
10	37 920	5.500	100.0	0.0

As it happened, splice nr. 10 had the highest value of MOE. It was set to 100%. Splice nr. 7 was the one with the lowest value, 24.2% lower than nr. 10. The average of all 10 splices was 33 218 N/mm^2, plus-minus 12.4 %. This confirms pretty much the test results presented in Fig. 11 with its variations around the circumference of a culm.

Next, two strips each (nrs. 1+2, 3+4, 5+6, ...) were weighed, heat-treated for 10 minutes at 150, 175, 200, 225 and 250°C, respectively, in the large laboratory oven, and weighed again. After one day they were measured again, as described above, and MOE determined again. The average values of the two strips, both before and after heat-treating were determined and the results are presented in Fig. 14 as Percent Weight-Loss versus Percent MOE-Gain.

Fig. 14



As we can see, heat treating at higher temperatures in fact does increase modulus of elasticity. This is mainly due to the dimensional change (shrinking) of the material. As outlined above, h = height of the strips enters the formula in third power. So, a small amount of shrinking results in a large gain of MOE. Even at 225°C an increase of MOE is achieved. But here the bamboo is dark brown and very brittle; unfit for rod making. Interesting to note is the sharp drop from 225°C to 250°C. At this high temperature thermal degradation had virtually destroyed the bamboo. Of course, I could have chosen different (optimum) exposure times for the different temperatures, see fig. 2, and would have achieved larger gains in MOE, but introducing too many variables at one time does not make things clearer. The point is made. And again, a big "but". These results were obtained one day after heat treating. What is left after a month or ten (see Fig. 8)? The reabsorbing of most of the dried-out water, and accordingly the swelling of the bamboo very possibly leaves but little of the initial 9 to 14% gain of MOE. Assuming that 200°C is about the highest temperature to be used with respect to thermal degradation (see Fig. 3), an initial increase of approximately 11% will be reduced to maybe half of that after a month or two, or less (no, I did not repeat the measuring after 1, 2, 3, etc. months).

What we have achieved is a **permanent** loss of weight (water) of 1-2 percent (or roughly one fourth of initial weight-loss) after some long time (see Fig. 8), depending on heating temperature, and correspondingly a **permanent** increase of MOE of maybe 4 percent. The question is: is it noticeable in the finished rod? (Remember: the difference from AFTM line-weight 3 to 4 shall be from 100 grains to 120 grains, or plus 20%, from 4 to 5 = 120 grains to 140 grains, or plus 16%, from 5 to 6 140 to 160 grains, or plus 14%, etc., per 30 feet of line).

Modulus of Elasticity is solely a material property. But our material, as used in rod making, is far from being homogeneous. The outermost two millimeters (~0.08 in) are rather homogeneous, with a high specific weight and a high MOE. But thicker splices, as for mids and butts of rods, usually include some of the more "pithy", inner parts of a wall. This inferior material will introduce its low MOE (see Fig. 12) to the overall performance of the splice. It seems to be a good idea to select the best possible culms, rather than trying to improve mediocre material by a few percent. MOE (the skin-near two mm) can vary from as low as 25 000 N/mm^2 (3.6 mp/in^2) to 60 000 N/mm^2 (8.7 mp/in^2).

There are other parameters to consider. Breaking Strength of bamboo and Bending to Break Point, for example. Stephan Pauly had made some tests on these items, and the following graphs are from his work.

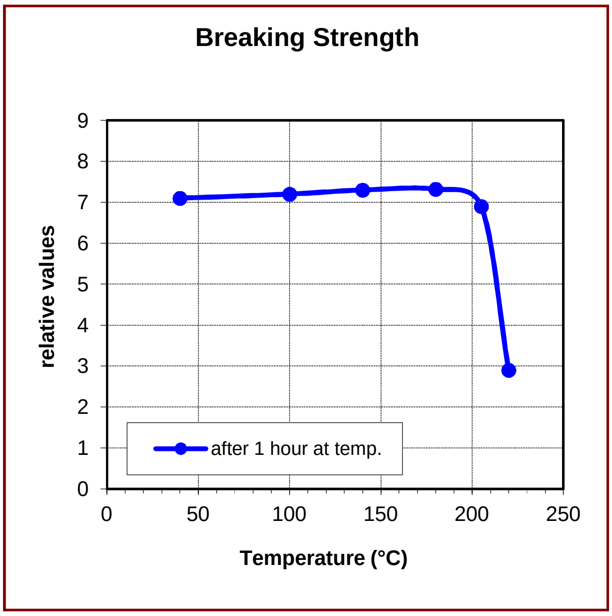


Fig. 15

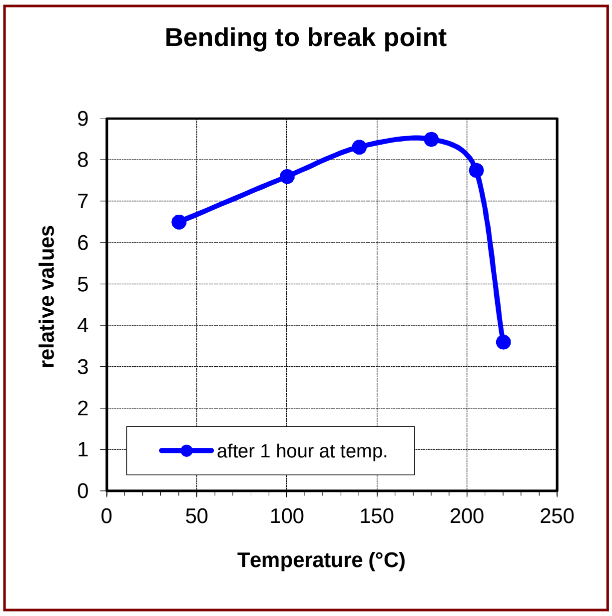


Fig. 16

Breaking strength: A slight increase is observed, with temperatures rising to 180°C (356°F), where it starts dropping. A maximum temperature of 200°C (392°F) is maybe the limit and still tolerable, but any higher temperature dramatically reduces breaking strength to a level way below (less than half of) the one before heating. The samples were heated at the indicated temperatures of 40, 100, 140, 180, 205, and 220°C, and for one hour each.

Bending to break point: again a maximum at approx. 180°C was found. Bamboo heated at higher temperatures (200°C and beyond) required less bending to break. At 220°C it was much more brittle than before heating. These tests were made with the samples heated for one full hour each. The above described thermal degradation might have done some of its job during this time, especially at temperatures of 180°C and above. Possibly shorter exposure-times, like 12 to 18 minutes (c.f. Figs. 3 ff) would have resulted in other (better?) results. And the tests were not repeated after some months, with the same samples. Reabsorbing of water certainly would have influenced later tests (c.f. Fig 8). Some more systematic tests should be made, some time and by someone (any volunteers ?).

The point is, that both of the above parameters can be improved with heat treating. And likewise others, which are tabulated in Table III. It is the combined improving of all important strength-parameters by drying bamboo at high temperatures, and forcing out not only "free water" but also some or all of the "cell-bound water", which improves the mechanical properties and, ultimately, the finished rod. And the bamboo becomes hydrophobic (water-repelling) to some degree.

Any heating beyond approximately 200-210°C decreases the strength properties dramatically. Both MOE, which can be measured by the rod maker himself, and bending/breaking strength and other parameters, which require sophisticated "pulling"-machinery only physics laboratories have, are reduced at higher temperatures.

There is yet another point, and a rather important one for me. Heating the preplaned (parallel) strips, wrapped tightly together, turns out perfectly straight strips. The lignin becomes soft/plastic and the cells are rearranged to some degree, retaining the new position after cooling. All internal stress resulting from splitting is relieved.

OTHER MISCELLANEOUS TESTS

Two strips were chosen from one culm, side-by-side, and planed parallel to a triangle of 5 mm height. One was heat treated, the other not. Both were weighed and immersed in (under) water for 48 hours. Number one had absorbed 23,4% water, number two only 19,0%. The permanent shrinking of number two, due to heat treating, had prevented more water re-entering the bamboo.

Two heat treated and glued-up, parallel planed hexagonal sections of 4 mm (0.157 in) and 10 mm (0.393 in) respectively ("tip" and "butt"), and of about one foot length, were immersed in water for 48 hours. They had absorbed 11.9% and 15.9% water. Much less than the "open" strips. This indicates that water penetration through/into the densely packed powerfibers near the outside of the culm wall is slower. After heating them at 100°C (212°F) for 5 hours they had returned to their original weight prior to immersing. The ends were not sealed, but I don't believe that water (or water vapor) only leaves/enters bamboo following the length of the split sections, as Bob Milward suggests in his book on page 13 (Bob is revising this in the next edition because the results of fig. 2 and 8 clearly show that the waterproof nature of living bamboo cells is destroyed by drying and/or heat treating). After all, people succeed in impregnating finished blanks, also with non-water-soluble "sauces".

> About 15 years ago, one of my rods was fished in northern Norway (Finnmark), for three weeks. The party of three men had camped in a tent, and the rods, rigged up, were leaning against a bush beside the tent for all that time, in rain. The reelseat (birchwood burl, varnished but not stabilised) had swollen so much, that the nickel-silver sliding band had cracked (split) over the reel foot with the reel in place. I received the rod a few days after their return, to put on a new sliding band. Though dip-varnished three times in a polyurethane-containing alkyd varnish, it surely felt limp and lifeless. Slowly drying it indoors returned the rod to its original condition. I do stabilize my reel seats now.

Varnish (any varnish !) will allow water vapor to pass through. A brand of PU-containing alkyd-varnish was measured to 20 g/m^2 per day, at a thickness of 0.1 mm, a temperature of 23°C, and a difference of humidity from 0 to 85%. A calculation (surface area, volume) will tell you, that e.g. the tip section of a rod will reabsorb all the water it possibly can (after heat treating and the resultant permanent shrinking, that is) within approximately 150 days. It reaches equilibrium. Varnish is no barrier. It will prevent bamboo soaking up water instantly though, when exposed to rain or a dipping for a short time (just take your newly finished rod and weigh it, say, once a week, for one year or more, and record the rel. humidity and ambient temperature every time). If and how impregnated rods react to changes in humidity, I don't know.

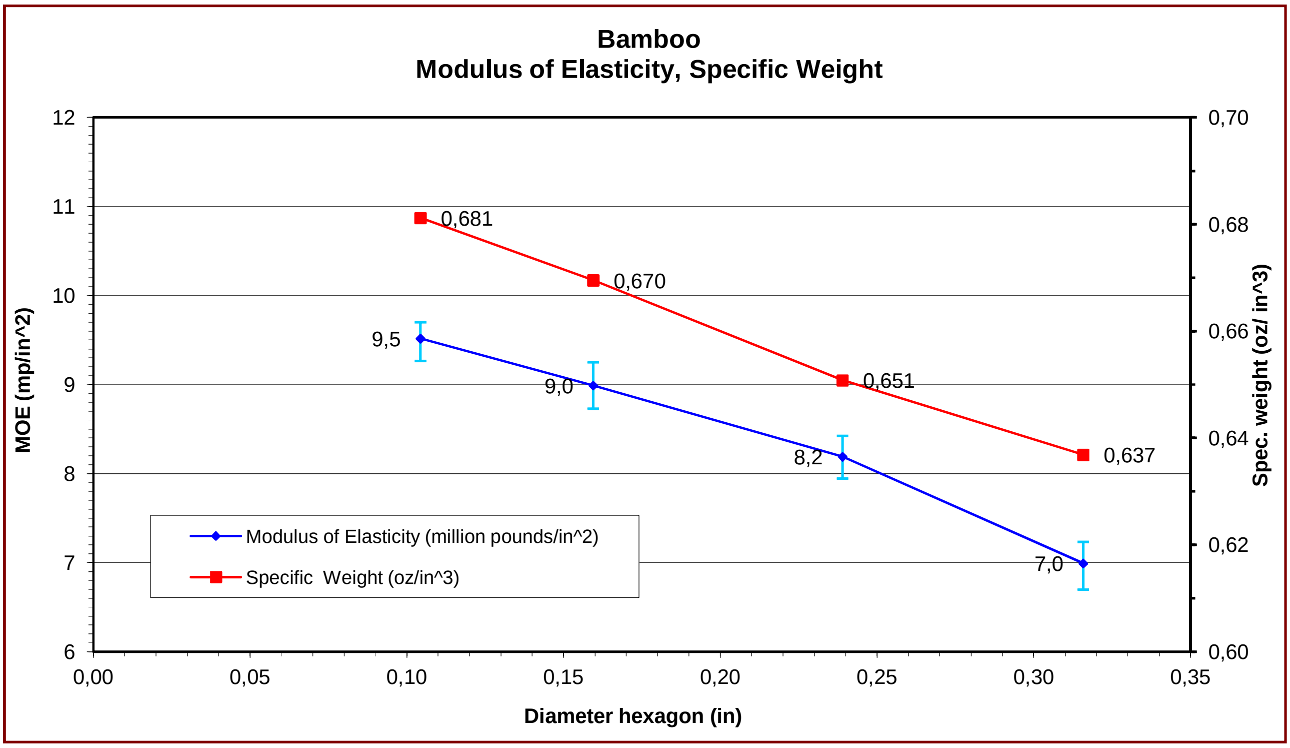
Back in 1988 I needed workable numbers of Specific Weight and MOE, to use in a rod calculation program. Garrison, on page 256, talkes of "... between 12 million and 15 million pounds per square inch" for MOE. And of 15

million to 5 million lbs./in^2 on page 17. This was not really satisfactory for me, and other values were not available, then.
I very carefully selected, from one of my best culms, of 1973 vintage, one internodal section and prepared four parallel hexagonal sections of different diameters (2.65, 4.05, 6.07 and 8.02 mm, like tip to butt). The bamboo was heat treated as much as I dared (very light brown), the sections glued up with resorcinol glue. The pieces, each approximately one foot long, were sent to a friend in Denmark, who conducted the measurements in the physical laboratory at the University of Lyngby. His results are presented in Fig. 17.

The values of specific weight, or gravity, are highest at tip calibrations. This is to be expected, as there are only very dense powerfibers in the splices. Towards the "butt" section some of the inner, or "pith"-material reduces the over all specific weight considerably. The values are a little lower than the ones given in "Garrison", page 248. Although Garrison relates the "Unit weight" (oz./cu.in.) to Rod Length, it is quite easy to relate them approximately to rod diameter. Just take any of the given rod tapers on pages 279/280.

The values of MOE seem to be extraordinarily high, as compared to the above values (Figs 11, 12, 13) and to the numbers presented by Bob Milward. Much lower, though, than Garrison's. I cannot say anything about their reliability, and just pass them on. The straight forward relationship between Specific Weight (density of material) and MOE is very clear, though. Selecting the best possible culms with tightly packed outer powerfibers certainly is an advantage.

Fig. 17



Finally, a few words on temperatures and times.
First, repeating a few observations from the above mentioned work "The Chemistry of Wood Strength":

> "... the initial effect of heating wood is dehydration. As temperatures approach 55-65°C for extended periods (2-3 months), hemicellolose and cellulose depolymerisation begins... Heating Douglas-fir in an oven at 102°C for 335 days reduced MOE by 17%. The same loss might be observed in 1 week at 160°C".

If we draw parallels to bamboo, and I believe this is allowed to some extent, then time of exposure, both at low and especially at high temperatures has an effect on the strength of bamboo which is not yet fully understood or, to my knowledge, examined. Maybe someone will conduct systematic tests some time, like short-time (minutes) versus long-time (hours) heating. And, thinking about it, maybe years of storage under a hot roof (at high summer-temperatures) actually starts depolymerisation? And maybe really old bamboo (e.g. pre-embargo), which has acquired a dark color (caramelized sugar?), is not so supreme any longer? A heretical question, I am afraid; but no one, to my knowledge, has made any systematic tests "old" versus "new" bamboo.

I am aware of the fact that many vintage rods, heat treated or not, still do their job splendidly. I own several 15' and 16' Salmon Rods from 1900 to 1935, and some Trout Rods from 1930 to 1970 vintage, and I have fished them all. I wonder how they performed when new, though.

My personal conclusions derived from the tests described in this paper are:

I heat treat my bamboo to a maximum of 200°C, for no more than 12 to 14 minutes at target temperature. Time is of importance at such high temperatures. No significant browntoning must occur.

You should know the water-content of your bamboo, dependent on the relative humidity where you live. My bamboo contains about 6-7% free water. If your's is dryer to begin with, your heating time will be shorter. And it will take more time to cook off e.g. 10 or 12% water.

You have to know your oven and its heat capacity and temperature along its length. I have installed 1760 Watts in my oven, and the temperature difference is plus/minus 2°C (~ 4°F) from end to end. Its heating is regulated to plus/minus 1°C.

And make notes, plenty of notes, e.g. on temperature-drop when inserting one or three or six bundles of bamboo, of different lengths and diameters, and returning-time to target temperature (this may be somewhat different with hot-air-gun types of "ovens"). Check your themostat against a thermometer.

What I am trying to say: calibrate your heat treating, with your oven and your bamboo.

Going as high as 200°C is the limit for me. I went as far as sample 8 or 9 in Fig. 3 (light brown, which means 14 to 16 minutes in my oven) a couple of times, and up to 210°C (410°F). But the bamboo was no joy to plane: short and brittle curls. The rods are still alive, but I have mixed feelings. It is to tickle out the utmost, balancing on the knife edge of maximum stiffness versus brittleness. With parabolic rods, where most of the work is confined to the lower third or so and I want a bit more pliability, I stay below this temperature; something like 180°C. I even treat tips and butts at different temperatures/times sometimes, to "help" the taper. At this lower temperature-level heating-time is not so critical, either. Thermal degradation, as visualized by brown-toning (see Figs. 3 and 4) does not seem to have started to any degree. Heating time is from 15 to 20 minutes at this temperature level, to heat the sections all the way through and drive out all the water (see Fig. 2).

Immediately after heating (and cooling), I remove the string (and the layer of enamel) and rewrap the bundles tightly (they have shrunk). Then I store them for a couple of months "in the string", before I turn them into rods. Plenty of time to equilibrate and swell.

The temperatures indicated in "Garrison" are not so bad, after all. His time-regime seems to be on the short side, though. But obviously his gas-powered oven did the job for him? And maybe his hot iron pipe produced infrared radiation from underneath (the gas-flame side) which helped in the process? Or why would he rotate the bundles?

I have never treated bamboo with an open flame. The temperature of perhaps 1000°C ~ 1800°F or more will destroy the outermost layers of powerfibers in a short time, leaving the inner ones largely unaffected (which results in unnecessary stress, at minimum). Bamboo, like wood, is a very good heat insulator. To heat a 6 mm (0.24 in) thick wall all the way through requires holding the flame a long time, possibly a couple of minutes on every part. After a minute or so it would ignite, and very likely one would produce charcoal.

Thermal conductivity, k, is the property of a material that indicates its ability to conduct heat. It is defined as the quantity of heat, Q, transmitted in time t through a thickness L, in a direction normal to a surface of area A, due to a temperature difference ΔT.

A few (rounded) k- values from literature, in units of ($W \times m^{-1} \times K^{-1}$):

copper	380	wood	0.15
aluminum	230	bamboo	0.1
iron	80	cork	0.06
water	0.6	air	0.025

Simplyfied, heat travels 3800 times faster in copper than in bamboo.

CONCLUSIONS AND RECOMMENDATIONS FOR ROD MAKERS

1. Heat treating can remove large quantities of moisture from bamboo including some of the water bonded within cell walls. Not all water bonded to the cellular structure can be removed because thermal degradation of the bamboo accompanies the loss of the final few percent of water.

2. A minimum threshold temperature of about 130°C (266°F) is necessary to remove the free water. (Fig. 1)

3. Recommended heat treatment for bamboo is at180°C (356°F), or better 200°C (392°F). It is essential that a rod maker runs test samples to establish the time taken to achieve a "just-detectable" colour change. This then becomes the cooking time. The time will vary considerably according to moisture content of the bamboo. At these temperatures, leaving samples in for a few minutes too long will not cause too much damage. As an example, bamboo with 6 to 8% free moisture content will take 18 minutes at 180°C or 12 to 14 minutes at 200°C. Because of several variations test strips should be made in summer and winter. Also the heat treating times may have to be revised because of the heat capacity of your oven and its insulating properties (see pages 3/4).

4. When free water and cellular water is removed to a minimum level without impairing material strength, weight loss and an increase in MOE results. After heat treating, moisture is re-absorbed over weeks and months, but a permanent loss in weight (Fig. 8) remains and there is a permanent MOE increase of perhaps 2-4%, or more (depending on the starting moisture content).

5. Heat treating within the limits recommended raises breaking strength and bending to break point values (Figs. 15 and 16). Exact details for the recommended heat treatment regime are not available.

6. Resistance to set: The fibre stress where a permanent set begins is raised considerably more than the MOE is raised and the work done before permanent set starts is raised by even more (see page 4 table III).
   This is a quotation not tested by the author of this discourse, but clearly this effect is of much greater importance to rod building than the minor gain in MOE. Bamboo, due to the geometrical arrangement and size of the fibers, possibly yields even larger improvements than wood.

7. For those who heat treat finished strips with fine tips, heat treatment times may need to be reduced. Very thin strips have not been tested and measuring small percentage-changes of tiny weights poses technical difficulties. For now you must rely on "just discernible" colour change as your guide. Tapered sections (bundles), thicker in one end than the other, might need adjusted temperature-time regimes. I have no suggestion to this problem, since I plane my strips parallel prior to heating.

8. For those who impregnate their blanks with non-water-based potions: do this as quickly as possible after heat treating, and before water (vapour) has had a chance to re-enter the bamboo. Keep the glued-up sections in a dry environment, and/or reheat them mildly, like 100 - 130°C = 212 - 266°F, for some time (depending somewhat on the glue used), immediately before impregnating.

9. Very few rod maker's ovens are accurate. Ovens may be approximately checked by recording the settings which produce the start of visible discolouration at the times listed above, or, better, "trial runs" can be made (see Fig. 3 and 4), preferably with full-length strips/bundles. However, there is no real substitute for lots of digital thermometer probes. Any type of heat browntoning weakens bamboo.

10. Heat treating by naked flame will destroy surface bamboo with no guarantee of heat tempering interior layers of bamboo at all, or to which degree. There is no control of the results, only guesswork at best. Heat treating in an oven to remove moisture, followed by scorching the surface with a flame for cosmetic reasons, or vice versa, is a method employed by some. Another maker I know uses a modified bread-toaster to browntone his strips. De gustibus non est disputandum. Bob Milward calls it Wanton Vandalism.

11. (Not related to heat treating). Variation of MOE in strips from a single level cut from one culm showed a surface-near MOE variation of approximately 15% and a sub-surface variation of more than 40%. The cause: moisture content variation? fibre density variation? – possibly due to climatic reasons like sun/shade, prevailing wind direction?, or others, was not established. Possible implications as to strip-placement in a finished rod are discussed below.

Possible fields of research are to heat treat under a protective atmosphere of an inert gas, like argon, or under a vacuum. Thermal degradation is, amongst other factors, dependent on oxygen from the air. Possibly higher heating temperatures could be employed, resulting in more permanent weight loss. Vacuum would certainly speed up the process of moisture removing. Or with infrared radiation (no, stay away from the microwave, it is too dangerous). Another idea is an adaptation of the good old Steam Box. I have made a few such experiments: Water vapor was conducted through a coil of copper piping (0.4 in diam), heated red-hot by a gas torch. The superheated water vapor was further conducted through a glass tube (2.5 cm = 1 in diameter), containing my full length bamboo bundles. After some time brown juices were trickling out. The bamboo turned out very dry, "springy", straight, and no colour change was observed. I did not make any systematic measurings of MOE etc., though. And yes, the rods were superb.

Heat treating has always been subject of diverse opinion among various rod makers. Some hold that a short, intense cycle with high temperatures should be applied (several minutes), others adhere to a policy of less temperature for a long time (several hours). A. J. McClane (1951) e.g. advocates that "Temperatures for the first hour should not exceed 225°F." and continues "Temperatures above 375°F, if maintained for an appreciable length of time, will deteriorate bamboo strength rapidly. One hour at any temperature from 300°F to 350°F will change color of bamboo very slightly, while a considerable effect will be noticed after three hours". Such long times are not necessary and in fact detrimental. Thermal Degradation, as described above, is not only dependent on temperature, but also on time.

I wonder, if someone will make a "brace of rods" some time, from one carefully selected culm. One rod heat treated, the other not. Or one flamed, the other heat treated in an oven. Or even all three. With identical taper, hardware and all. Painted black and blind-tested with identical reels and lines. After a year, that is! What would the difference be? I did a similar experiment once, with two rods from one culm. One twisted à la Letcher Lambuth, the other straight. Very interesting indeed. But this is another story.

Selected Literature:

Milward, Robert Eaton.: "Bamboo. Fact, Fiction and Flyrods"
Privately printed, copyrighted 2001, ISBN 0-9688829-0-0
Second edition copyrighted 2010, ISBN 978-0-9688829-1-7

Pauly, Stephan: "Auswahl und Wärmebehandlung von Bambus für den Bau von gespließten Angelruten".
Fly Only, 1/1987, pp. 50 – 57 (in German).

Schott, Wolfram: "Bamboo under the Microscope" (2006)

Winandy, J.E. and Rowell, R.M.: "The Chemistry of Wood Strength"
U.S. Department of Agriculture, Forest Service, Forest Products Laboratory,
published 1984 by the American Chemical Society

Title photo: Cross section of a culm, split in half. Diameter 55 mm = 2.17 in. Wall 8.5 mm = 0.335 in. The right side half has been heated for 10 minutes at 250°C (= 482°F). A considerable shrinking has deformed the section.

Some thoughts on the variation of Modulus of Elasticity and strip-placement in a finished rod.

It was my rod making friend Atle Venn, from Trondheim, Norway, who brougth up the following, perhaps somewhat academic, question, related to the variation of MOE in strips from a single level cut from one culm, see figures 11 and 13. I have redrawn his sketches, added a few more, and put some words to it.

The dictum states, that you shall distribute the strips in your finished rod in such a manner, that they occupy the same relative positions which they had in the unsplit culm. Garrison, on pages 12 – 25 explains this in detail (and also the distribution of the nodes). The culm is first split into 6 pieces, numbered 1 to 6, and those are further split into thirds, which makes 18 strips. 6 each for the butt (numbers 1/1, 2/1, 3/1, 4/1, 5/1, 6/1) and the two tips of a rod (numbers 1/2, 2/2, 3/2, etc and 1/3, 2/3, 3/3, etc).

But is this really the best manner to arrange the strips?

As we can see from the above figures 11 and 13, the variation of MOE within/around the culm varies from 15.6% to 43.8 % in Stephan Pauly's samples, and as much as 24.2% in my splices. If we calculate the average of Stephan Pauly's outer (1) and inner (2) samples (= 1.5 mm = 0.059 in. total depth), we arrive at the following numbers:

	MOE (N/mm^2)	MOE
A	32 550	70,61
B	39 350	85,36
C	46 100	100,00
D	37 800	82,00

.
The difference of MOE between opposite samples C (100%) and A (70.6%) is in the same magnitude as in my samples

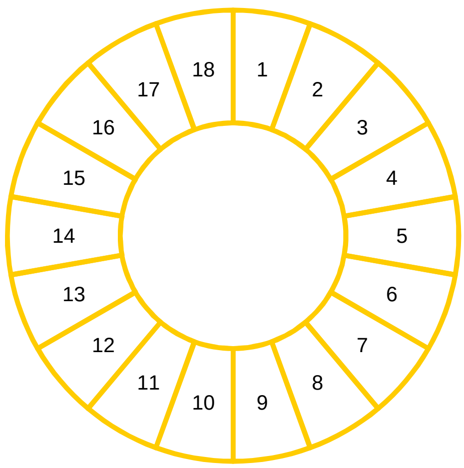
A weak strip on one side might be one reason for a weak side in the finished rod. Garrison, on page 139, remarks: "It is a phenomenon of most hexagonal bamboo sections that one of the triangular strips will be somewhat weaker than the others due to the inherent characteristics of the fibers in that strip, the way they were cut (less bamboo in one strip), or simply the relative juxtaposition of one strip to the other five pieces."

Let us have a closer look at the relative juxtapositions.

The drawing below (Fig. 18) represents a cross section through a culm, split into 18 splices. The highest value of MOE shall be on the right side (at 3 o'clock, splice nr. 5), the lowest on the left side (at 9 o'clock, splice nr. 14). I will assume that the variation in MOE from the "high" side to the "low" side is evenly around the circumference of the culm. Further, a difference of 25% from high to low shall be considered, from 100% to 75%.

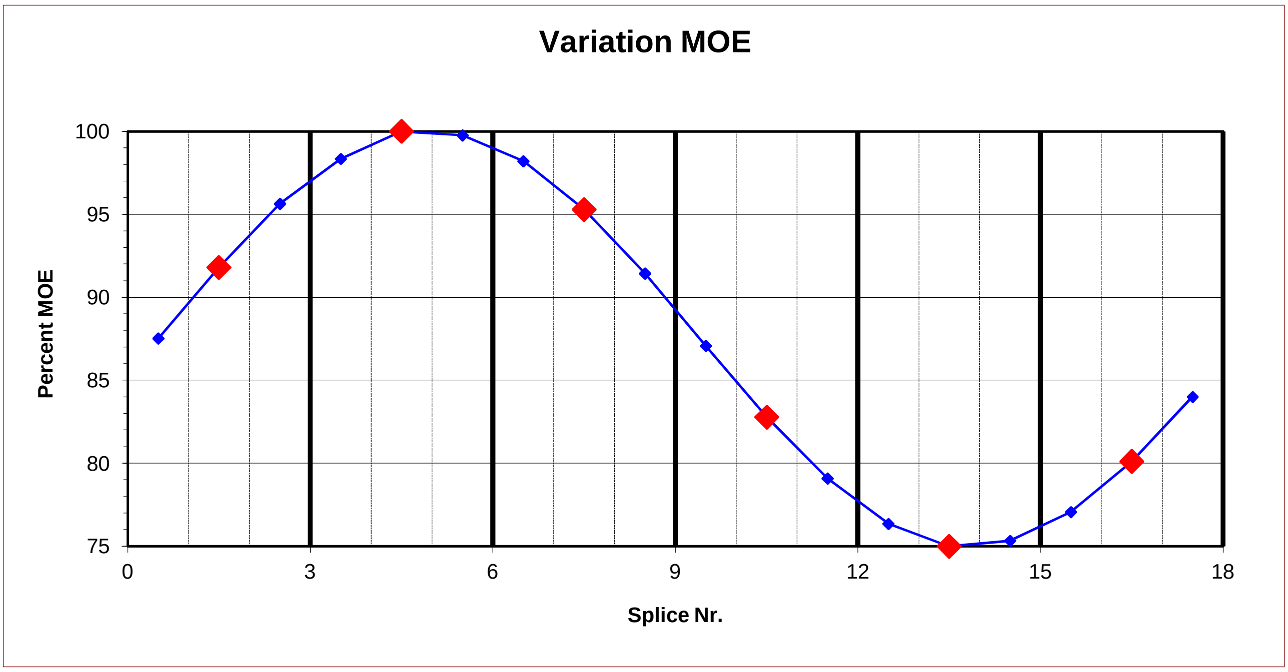
Fig. 18

Cross Section Bamboo
18 Splices
Variation in MOE: 25 %



If we "unroll" the culm, with the 18 splits in groups of 6 sections, and starting with splice nr. 1, the percentages of MOE will follow the curve of a sine-function (think of it like a diagonal cut through the culm), provided the culm is round and not oval. Splice nr. 5 representing 100%, splice nr. 14 representing 75%.

Fig. 19



The percent-values from the above curve are tabulated below (Tab. 1). The maximum difference between any two neighbouring strips is 4.36% (between 9 and 10), the minimum difference is 0.23% (between 5 and 6).

Tab. 1

Splice Nr.	Percent MOE
1	87,53
2	91,80
3	95,64
4	98,35
5	100,00
6	99,77
7	98,21
8	95,28
9	91,44
10	87,08
11	82,77
12	79,09
13	76,36
14	75,00
15	75,34
16	77,07
17	80,11
18	84,01

If we choose every third strip for one rod section, like Garrison advocates, we have the following options (Tab. 2):

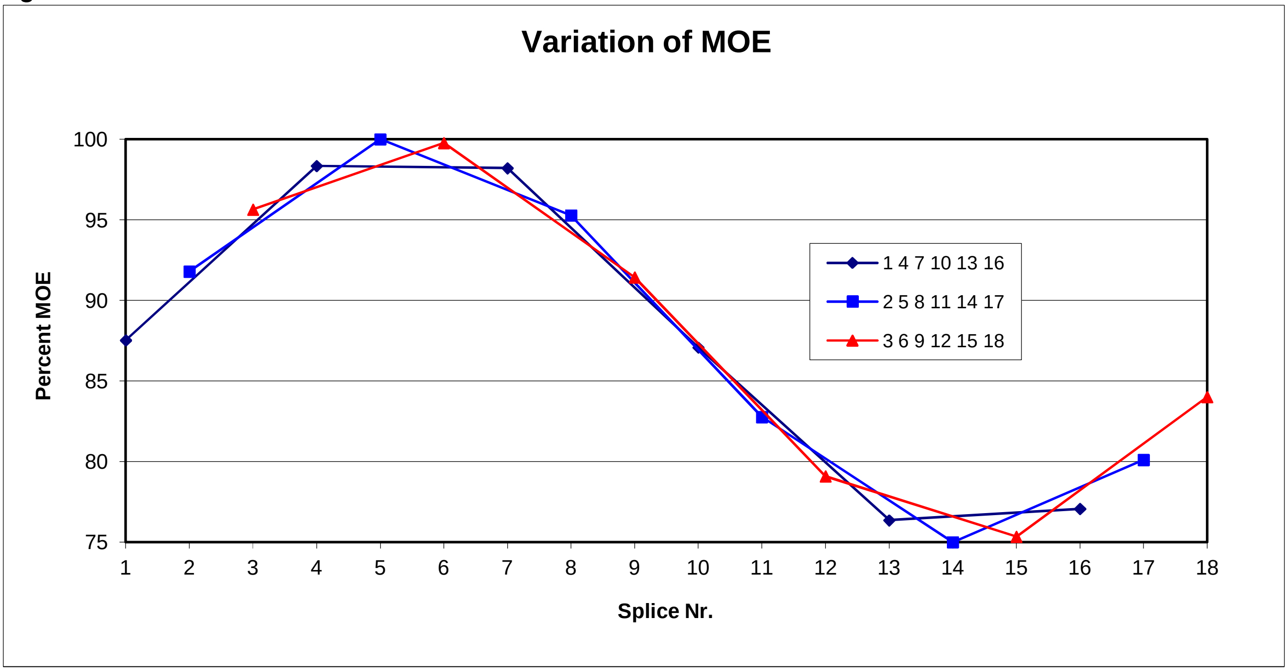
Tab. 2

Splice nr.	% MOE	Splice nr.	% MOE	Splice nr.	% MOE
1	87,53	2	91,80	3	95,64
4	98,35	5	100,00	6	99,77
7	98,21	8	95,28	9	91,44
10	87,08	11	82,77	12	79,09
13	76,36	14	75,00	15	75,34
16	77,07	17	80,11	18	84,01
Diff. %	**21,99**		**25,00**		**24,43**

The first option, using strips nr. 1+4+7+10+13+16 will give us a maximal difference of 21.99%, between strip nr. 4 (98.35%) and strip nr. 13 (76.36%).
The second option, starting with strip nr. 2, and marked in red in the above drawing, yields the largest possible difference, 25% (strip nr. 5 minus strip nr. 14).
The third option, starting with strip nr. 3, shows a maximal difference of 24.43% (strip 6 minus strip 15).

These three options are visualized in the drawing below (Fig. 20).

Fig. 20



Now, if we use for our rod making not every third strip around the culm, but six successive strips for a section, we will arrive at the following possible distribution of MOE –values. In red the maximum difference between any two strips (Tab. 3):

Tab. 3

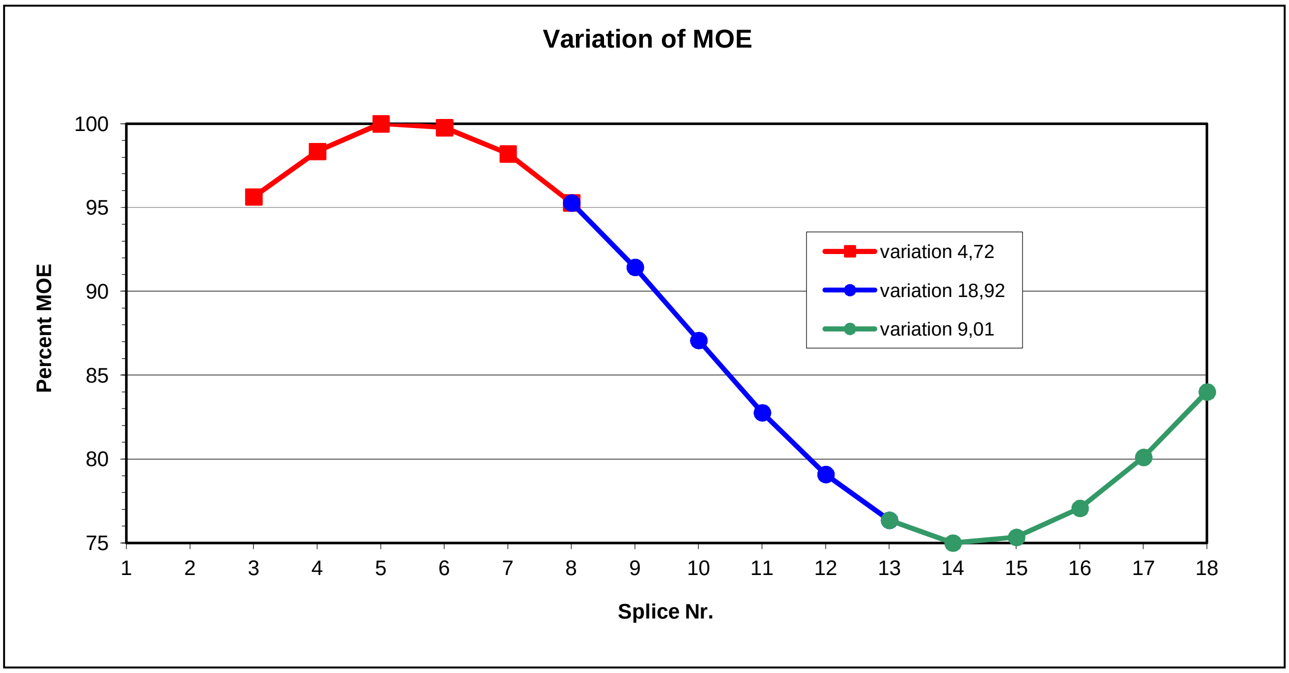
Splice Nr.	MOE %	variations of all possible combinations of 6 successive splices, numbers rounded to 1 decimal digit																	
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
1	87,53	87,5																	
2	91,80	91,8	91,8																
3	95,64	95,6	95,6	95,6															
4	98,35	98,4	98,4	98,4	98,4														
5	100,00	100,0	100,0	100,0	100,0	100,0													
6	99,77	99,8	99,8	99,8	99,8	99,8	99,8												
7	98,21	12,5	98,2	98,2	98,2	98,2	98,2	98,2											
8	95,28		8,2	95,3	95,3	95,3	95,3	95,3	95,3										
9	91,44			4,7	91,4	91,4	91,4	91,4	91,4	91,4									
10	87,08				8,6	87,1	87,1	87,1	87,1	87,1	87,1								
11	82,77					12,9	82,8	82,8	82,8	82,8	82,8	82,8							
12	79,09						17,0	79,1	79,1	79,1	79,1	79,1	79,1						
13	76,36							19,1	76,4	76,4	76,4	76,4	76,4	76,4					
14	75,00								18,9	75,0	75,0	75,0	75,0	75,0	75,0				
15	75,34									16,4	75,3	75,3	75,3	75,3	75,3	75,3			
16	77,07										12,1	77,1	77,1	77,1	77,1	77,1	77,1		
17	80,11											7,8	80,1	80,1	80,1	80,1	80,1	80,1	
18	84,01												5,1	84,0	84,0	84,0	84,0	84,0	84,0
1	87,53													9,0	87,5	87,5	87,5	87,5	87,5
2	91,80														12,5	91,8	91,8	91,8	91,8
3	95,64															16,5	95,6	95,6	95,6
4	98,35																18,6	98,4	98,4
5	100,00																	18,2	100,0
																			16,0

The largest difference in Percent Modulus of Elasticity occurs in combination nr. 8, with 18.92% difference between splice nr. 8 (95.28%) and splice nr. 13 (76.36%).
The smallest difference is realized in combination nr. 3, with 4.72% difference between splice nr. 5 (100%) and splice nr. 8 (95.28%).

ALL of the 18 above combinations of possible successive 6 splices (Tab. 3) have a considerably lower variation (difference) of Percent MOE than the three possible options shown in Tab. 2.

Below, in Fig. 21, I have selected, from Table 3 above, the best (nr. 3), the worst (nr. 8), and one in-between (nr. 13) possibility.

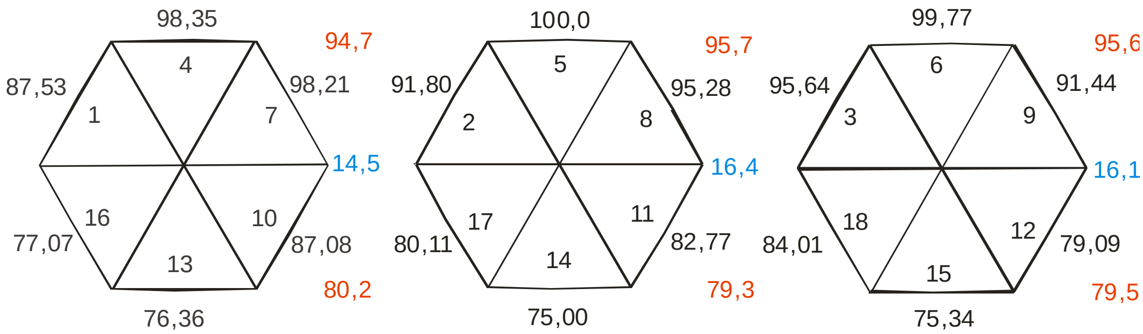
Fig. 21



Each of the 18 combinations (Tab. 3) above offers a number of different ways to arrange the 6 strips, like: 1-2-3-4-5-6, 1-3-5-2-4-6, etc. Let us look at a few of the forty-'leven possibilities.

In Fig. 22 below I have arranged the strips from Figs. 18 and 19, as listed in Tab. 2, in the order Garrison explains in his book. The hexagon shall be a cross section through a rod, with the guides mounted on the lower side. In red the average of the "upper" three values (percentages), e.g. strips 1 + 4 + 7 = 87.53 + 98.35 + 98.21 = 284.09 divided by 3 = 94.69 (rounded to 94.7), and also for the "lower" three values, and so forth. The difference, in blue, between upper and lower half is considerable in each of the three versions: 14.5%, 16.4%, and 16.1%, respectively. Each of the three possibilities, and hence bundles of strips, like one butt and two tips, will have a "weak" side, in this arrangement the "lower half" side. The one with the largest difference, 16.4%, will be the one Garrison would have found rolling his sections as described on pages 139/140. The guides would be mounted on strip nr. 14. If you continue this arrangement of strips and make the same calculations for the rest of the 6 possibilities, the weak side(s) will shift to the "upper" half in the drawing.

Fig. 22: Garrison – strip arrangement, see Fig. 19 and Tab. 2



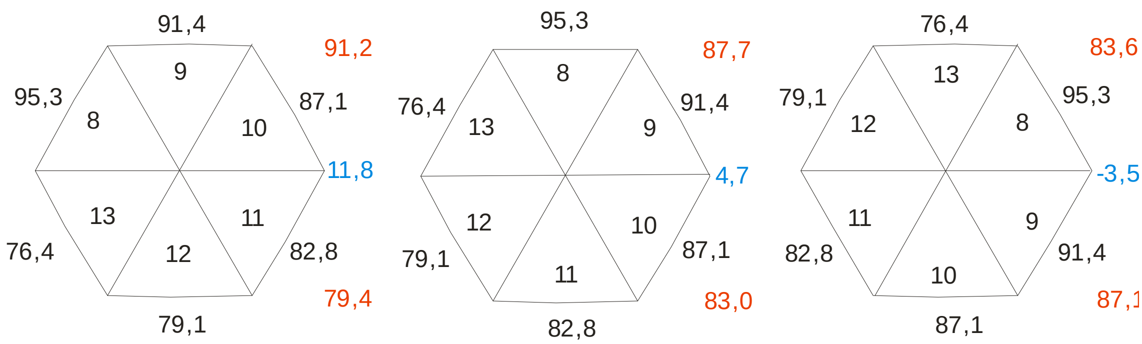
Average strips 1+4+7 ("upper half") = 94.7%
Difference upper minus lower half = 14.5%
Average strips 10+13+16 ("lower half") = 80.2%

Average strips 2+5+8 ("upper half") = 95.7%
Difference upper minus lower half = 16.4%
Average strips 11+14+17 ("lower half") = 79.3%

Average strips 3+6+9 ("upper half") = 95.6%
Difference upper minus lower half = 16.1%
Average strips 12+15+18 ("lower half") = 79.5%

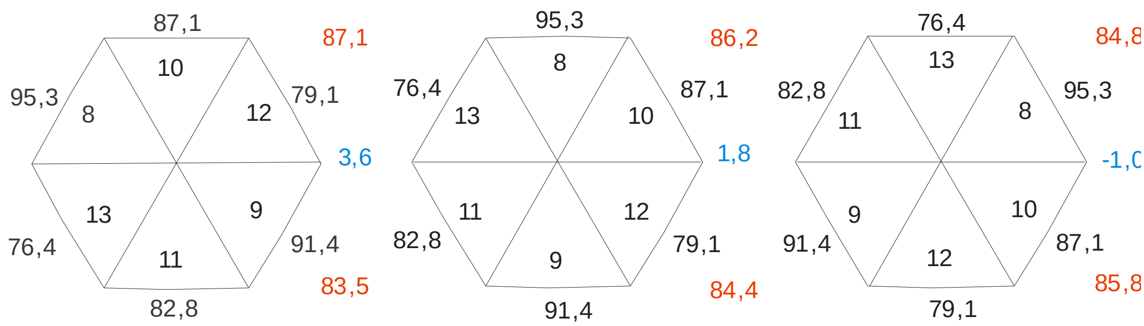
In Fig. 23 I have chosen six successive strips from Tab. 3, (nrs. 8,9,10,11,12,13), which have the **largest** difference between any two strips, of 18.92% (see Figs. 18 and 19). They are arranged in three (of 6) possible positions, following one another clockwise. The largest difference between "upper" and "lower" half occurs in the first drawing, with 11.8%. In the third drawing the upper half is the weakest, 3.5% weaker than the lower half.

Fig. 23: Strip arrangement from Tab. 3, nr. 8. Max difference = 18.92%. See. Fig. 21, blue section ("worst case scenario"). Successive strips



In Fig. 24 below I have rearranged the 6 strips from Fig. 23, so that every other strip is positioned **opposite** the first one, not next to it: 9 opposite 8, 11 opposite 10, 13 opposite 12. The largest difference is found in drawing 1, with 3.6%, the smallest difference in drawing 3, with only 1.0% (the upper half being weaker).

Fig. 24: Strip arrangement from Tab. 3, nr. 8. Max difference = 18.92%. See. Fig. 21, blue section ("worst case scenario"). Alternating strips



In Fig. 25 I have chosen the strips with the **smallest** difference between any two strips (4.72%) from Tab. 3, numbers 3,4,5,6,7,8. See Fig. 21, red section. The strips are again arranged successively, clockwise. The largest difference is 3.0%, with the weak side on top. Fig. 26 again the same strips, but every other one arranged opposite one another (alternating).

Fig. 25: Strip arrangement from Tab. 3, nr. 3. Max difference = 4.72%. See. Fig. 21, red section ("best case scenario"). Successive strips

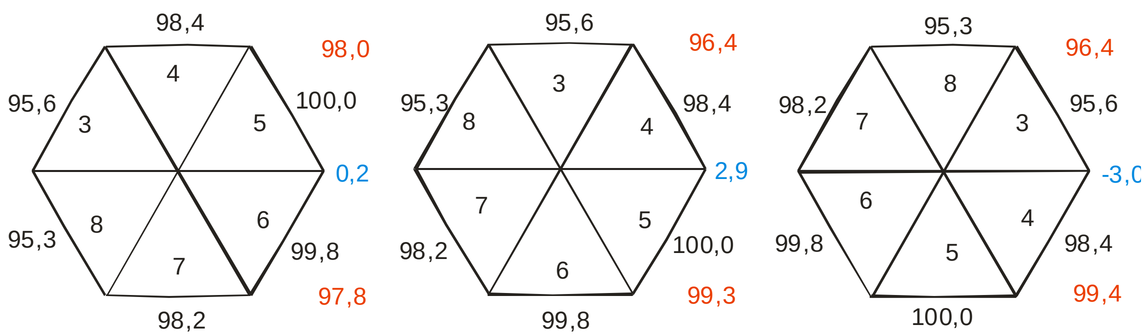
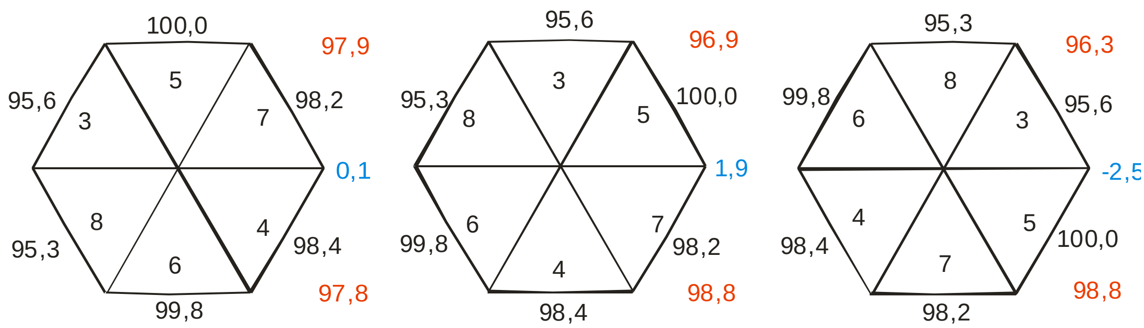


Fig. 26: Strip arrangement from Tab. 3, nr. 3. Max difference = 4.72%. See. Fig. 21, red section ("best case scenario"). Alternating strips



In Figs. 25 and 26 the differences between "upper halves" and "lower halves" are smallest. The maximum differences being 3.0% and 2.5%, respectively, the minimum differences, 0.2% and 0.1%, which is next to zero.

This "arranging of splices" can, of course, be continued with all possible configurations. But the point is made.

What have we learned from all this fuss and juggling with numbers?

1. Provided there is a noticeable variation of Modulus of Elasticity (and possibly other mechanical parameters) around the circumference of a bamboo culm, the "Garrison" – arrangement of splices in a rod section, as explained in his book, clearly has the largest differences between "upper" and "lower" half and thus is most liable to have a pronounced "weak" side, as described on pages 139/140 in his book.

2. Any one of 18 possible **successive** arrangements of six splices in a rod section will have much smaller differences, and hence a much less pronounced "weak" side.

3. Any one of 18 possible **alternating** arrangements of six splices in a rod, with neighbouring splices arranged opposite one another, produces the smallest differences of all possibilities. There might not be a noticeable "weak" side at all.

The best suggestion for the arrangement of strips, if you want to avoid any "weak" side, is:

> "Take any six successive strips from the culm (1-2-3-4-5-6) and arrange them in the order 1-3-5-2-4-6".

There is a back-side of the coin, though: If you happen, by chance, to use six strips from the "high" side of the culm for one tip section (numbers 3,4,5,6,7,8 in the above example, average 97.88%), and six other strips from the "low" side (numbers 12,13,14,15,16,17, average 77.16%), your two tips will have a difference in MOE by 20.72%. This might well be noticeable and the two might perform differently.

So, the choice is your's: either you want two (almost) identical tips, but with a "weak" side each to put your guides on (if there are any weak strips at all). Or, better yet, synchronise your rod like Letcher Lambuth advocates in his book on page 72 ff. This means to follow Garrison's way of placing strips.

Or you want two tips with no "weak" side, but which might or might not perform a bit differently. Then the above outlined method of selecting/placing your six strips is to be preferred. The last option is possibly the better one when making "mirror" tips. The odds are 1 in 18 (or better, if you get more than 18 usable strips out of a culm).

Sadly, it is not written on the culm if it has a "high" and a "low" side, where it is, and how large the difference is.

Bob Milward had the following observations on this topic:

"**We now know** that bamboo MOE (and very likely other parameters) varies around the culm, so there is often a weak side and a strong side. Any system designed to keep the strips in the finished rod section in the same relative position as in the culm has to produce a rod section with a strong and a weak side. No graphs required, simple logic tells us it must be the worst distribution pattern.

If as seems likely, the weaker side of a culm is continuous up the same side, you could build two rods: one from the stiff side and one from the weak side. Each rod would be perfect within itself, but one would be stiffer and heavier throughout its length (due to fibre density). I am not sure that either rod would feel "better" than the other. In practice it may be hard to tell the difference, particularly in a blind test with 5 minutes between changing rods.

The aim of the builder is to make rod sections which flex evenly from all sides. The logic is to take adjacent strips from the culm and place them at symmetrical points round the rod section. So, culm strips1,2,3 should be interleaved with any other three adjacent strips to give, for example 1,10,2,11,3,12 positions in a rod section.

The perfect solution is to do a few test strips first and establish the strong side and the weak side and discard the weak side. At the moment we do not know for certain that the "weak" side of the culm stays the same all the way up, unless we start testing every internode around and all the way up the culm - a daunting prospect.

And we do not really know if the weak side of a culm stops and starts at different heights above ground or even dodges from side to side of the culm. Any volunteers for lots of waste bamboo and lots and lots of testing?

Garrison's bamboo culms were only 8 ft. long, so butt and tip had to come from the same piece. His method of splitting was very inefficient too. We now have the luxury of 12 ft. culms, and we know to build butts and tips from the best locations (see "Bamboo. Fact, Fiction and Flyrods"). When splitting for tips, you may get as many as 30 to 40 strips out of one good large diameter culm, and maybe 25 to 30 butt strips. You can make at least two rods with double tips from one culm, with enough spare for mistakes, accidents and spare tips for repair work, and you can pick cosmetically perfect strips".