Stress Analysis in the Design of Split Cane Flyrods

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This document is a nontechnical introduction to stress analysis and its uses within the Hexrod program. For a slightly more advanced intro, with sample calculations, look at the *Hexrod Explained* document by Wayne Cattanach:
http://www.canerod.com/rodmakers/tips/hexexp.html

1 History

The concept of **stress** is fundamental in the field of mechanical engineering. It was developed over two centuries ago to quantify how external forces exert "stress" on an object. Stress can be calculated at each point in the object; it depends on the magnitude of the forces and the size and shape of the object, but does not depend on the material the object is made of. Units of stress are mass (weight) per cross sectional area (the same as pressure). Rod stress units traditionally are ounces per square inch (osi).

The related concept of **strain** quantifies how an object is deformed when subjected to stress. Strain of course depends on the material.

The application of stress analysis to the evaluation of tapers for split cane rods was developed by Everett Garrison and explained in Chapter 14 of *A Master's Guide to Building a Split Cane Fly Rod* by Garrison and Hoagy Carmichael, first published in 1977. It was as a mechanical engineering student in 1913 that Garrison encountered the engineering concepts that he realized could be applied to understanding a fly rod, but it wasn't until until the period from 1927 to 1933 that he developed his method of stress analysis. Garrison's rod design goals were twofold: to develop tapers that would optimally transmit energy from the caster's arm to the fly line (what he called *progressive tapers*), while also keeping the stress to the cane rod itself within safe levels.

In order to apply the method of stress analysis, Garrison needed to determine several quantities:

1. The weight of all the separate components of the rod:
   (a) The line extending from the rod tip
   (b) The line within the guides
   (c) The varnish, guides, and wrappings (V&G)
   (d) The ferrules
   (e) The cane itself
2. The location of all these components along the length of the rod
3. The multiplying effect the component weights caused by casting the rod
4. The maximum safe level of stress a bamboo rod can handle

Some of these are quite easy to determine, such as weight of the line and ferrules. Garrison determined the weight of cane to be 0.668 ounces per cubic inch, and the weight of the varnish, guides and wrappings for a typical rod by ten inch intervals. The multiplier ("tip impact factor") he set at 4, and the maximum safe stress at 220,000 osi. Garrison did not arrive at these values casually, and subsequent implementations of his method follow his conclusions closely.

Let's illustrate this pictorially. Imagine you are standing on a high bridge, holding your rod out horizontally with a given amount of line (say 40 feet) hanging from the tip. In engineer speak, this rod is a cantilever beam: a horizontal structure fixed at one end with the other free to move under load.

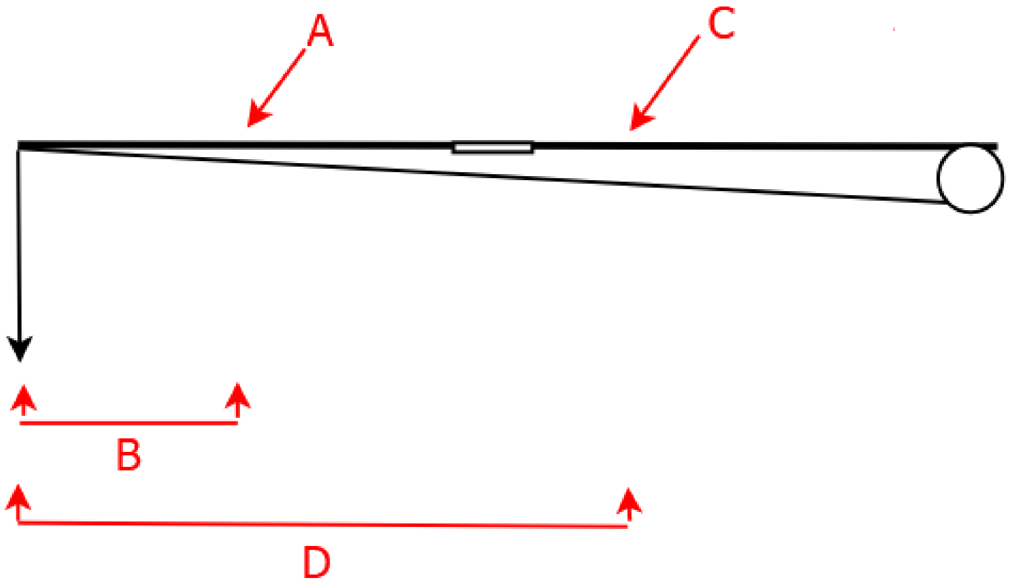

Figure 1: Horizontal Rod

The stress at any point along the rod depends on gravity, the pull exerted by the mass (weight) of the components involved. The stress at point **A** depends on the weight of all the components in region **B**: the line hanging off the rod tip, the weight of the line in the guides, the weight of the cane itself and of the guides varnish and wraps. The stress at point **C** depends on the weight of everything in region **D**, which now includes the ferrule, nore cane, V&G, and line within the guides.

Besides the weight of all components, stress at a point depends on where the weights are. The stress created by the weight the 40 feet of line hanging from the rod tip is greater at point **C** than at **A** because it is multiplied by the distance over which it is applied, length **D** being greater than length **B**. These weight-times-distance components are called *moments*.

Of course, we don't fish by standing on a bridge and letting our fly line hand straight down to the water (unless that's the only way to get a drag free float). We have to cast the whole affair. Overcoming air resistance and the inertia of the line, rod etc. effectively increases the weight of the components. Garrison arrived at the tip impact factor of 4: during the action of casting, the weight of all components is effectively increased by a multiplier of 4.

Let's carry the thought experiment a little further. Suppose we over-lined the rod, say by putting a 6 weight line on a 4 weight rod. That would logically increase the stress throughout the length of the rod. Suppose you removed the nickel silver ferrule and replaced it with something lighter, perhaps a composite ferrule or even just a truncated N-S ferrule. The stresses on the tip section would stay the same, but the stresses in the butt section would be reduced. Similarly, if we add a ferrule to the middle of the tip section, stresses would increase starting at that new ferrule location and continuing to the butt. Basically, anything that changes the weight of the components of a fly rod or its line will change the stress numbers, from the point it is located to the rod butt.

Garrison did his stress calculations with pencil, paper and a slide rule, computing stress values at five inch intervals along the rod. By the time his book was published in 1977, two years after his passing, calculators were common and it was feasible to talk about doing stress calculations at one inch intervals. With the advent of computers in the 1980's it finally became practical to calculate stress values for large numbers of actual and conceptual rod tapers, expanding our understanding of what stress analysis can and cannot do.

There have been many implementations of Garrison's method over the past 30+ years. The online version of Hexrod (written in Perl and MySQL) was based on Wayne Cattanach's original Hexrod program, written in BASIC and distributed (as a compiled executable) with his 1992 book *Handcrafting Bamboo Fly Rods*. After online discussions about stress calculations and his Hexrod program on the Rodmakers listserv, Wayne shared the BASIC source code with some of us. At the time I was working at the University of Wisconsin-Milwaukee and was charged with learning enough HTML and CGI scripting to turn a lot of technical documentation from paper and flat files into hypertext. It seemed like making an online version of Wayne's program could be justified as an educational experience, so I tackled it. The first online version of Hexrod was announced to the Rodmakers listserv in December of 1996, and after feedback from users and as I myself learned more about the interpretation of the stress numbers, more features were added. Hexrod, as well as all other U.S. implementations of the method, compute stresses at one-inch intervals.

2 The Stress Curve

Computed stress numbers can be displayed in a table, showing a value every inch, but they are more easily interpreted when displayed as a graph. Figure 2 is the stress curve for a Garrison 209E taper, casting 40 feet of DT5 line:

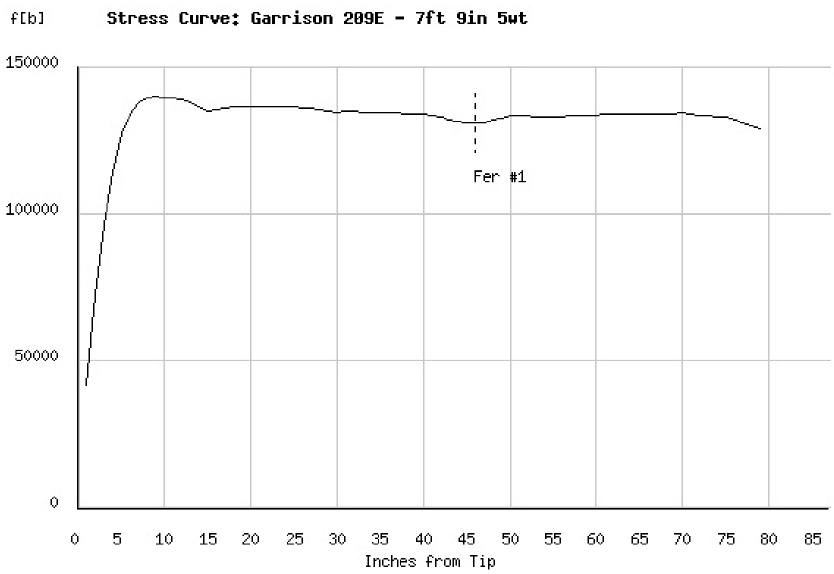

Figure 2: Garrison 209E Stress Curve

The horizontal axis displays location along the rod, in inches from the tip. The vertical axis displays stress values (abbreviated $f(b)$) in units of ounces per square inch.

Three features of this graph are important to note. First, the general shape of the graph is flat. Garrison thought the ideal rod was one where the energy delivered by the caster moved smoothly through the rod from butt to tip, and he believed that was achieved when the stress curve is relatively uniform:

> If a rod feels like a single unit, the rod is well built for the purposes of casting a line. A rod should act in unison, to pass the energy you wish to impart to your line at an equal speed from one end of the rod to the other.

There are no peaks or valleys in the stress curve of Garrison's rod tapers.

Second, from the tip to about 10 inches, stresses start low and increase rapidly to the plateau. Garrison found that designing a rod with equal stresses all the way to the tip resulted in a rod with impractically tiny tip dimensions. For construction, durability and casting efficiency, the tip size must be increased to reasonable levels.

Finally, the peak stress value of approximately 140,000 osi is comfortably under the safe design limit of 220,000.

Some of these points will become more clear when we compare Garrison's taper to a Pezon et Michel Ritz PPP Colorado, a 7 foot 7 inch casting 40 feet of DT5 (Figure 3). Garrison was critical of

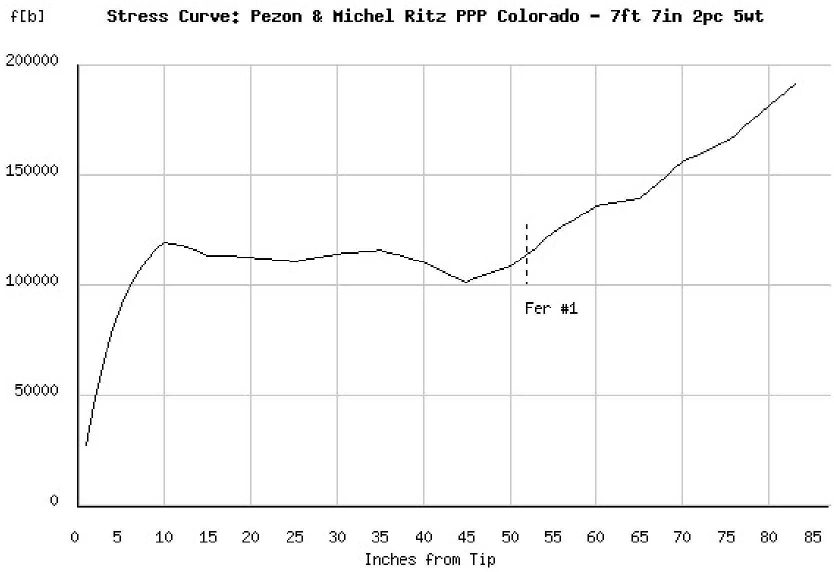

Figure 3: Ritz Parabolic Stress Curve

Ritz-type tapers; while they were able to cast a heavy line a long distance he did not consider them good fishing tools. He described these tapers as "parabolic" because the shape of the stress curve is (roughly) that of the right half of a parabola: relatively flat toward the tip and increasing rapidly as you approach the butt. The term parabolic generally refers to a rod with a flexible butt section.

On Page 6 are stress curves for a few other well-known tapers, and how they can be interpreted.

First Wayne Cattanach's 7 foot 2 piece casting 40 feet of DT4 line (Figure 4). This is the stress curve of a fast action rod (almost the reflection of a parabolic stress curve). The peak stress is at the 10-inch point and is above 200,000 osi from about 5 to 20 inches, while the entire butt section is around 100,000 osi. The maximum stress is approximately 220,000 osi, which is Garrison's limit for safety. During the cast the butt section is relatively stiff, flexing little, while the flexing is concentrated just below the tip. At 55 inch point (middle of the butt section) there is a little blip in the stress curve, a relative weak spot in the taper. This is the roll casting hinge, a point where the rod flexes a little to assist in roll casting and lifting line off the water.

Next is a Young Para 15, and 8 foot two piece rod casting 40 feet of DT5 (Figure 5). There are many slightly different Para 15 tapers in circulation, this one comes from Wayne Cattanach and is known as the "K. T. Keller version" with the light tip. It is obviously a parabolic rod with a stress curve increasing in the butt section but also a flexible section in the tip from about the 5 to 25 inch region, and a relatively stiff middle around the ferrule. The stress values overall are quite low (between 100,000 and 150,000 psi); this rod might be under-lined as a 5 weight.

Finally, here is another somewhat more complex stress curve: A Cross rod (tentatively identified as a Sylph taper), 7.5 feet 2 piece casting 40 feet of DT5 (Figure 6). (This taper is one I have adapted for several personal rods): This stress curve has two distinct peaks: one in the tip in the 10 to 20 inch region, and another in the butt below the ferrule. It is somewhat like the Cattanach 7024 with a much more prominent hinge in the butt. The stress values are quite low overall; this rod can easily handle a 6 weight line.

3 Limitations of Stress Analysis

In the half century since the Garrison and Carmichael book was published, numerous problems and criticisms of stress analysis have been brought up. I will list some of these here. It is important to

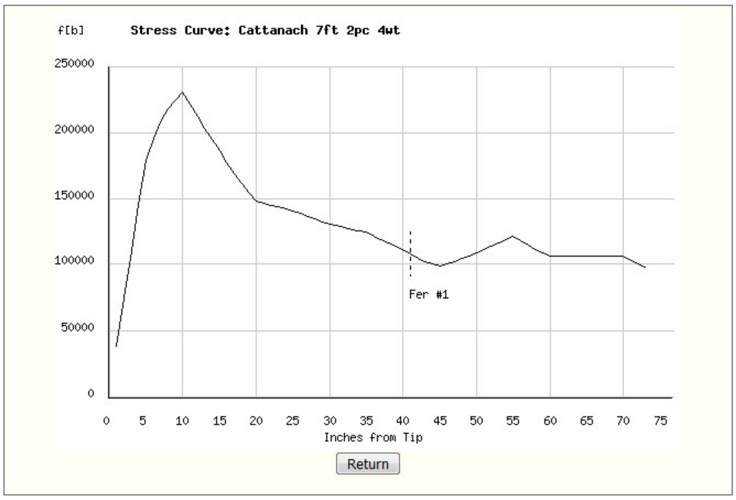

Figure 4: Cattanach 7024

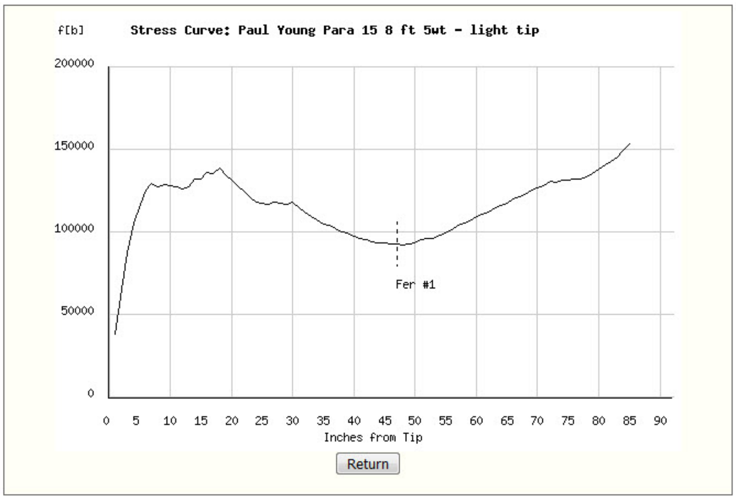

Figure 5: Young Para 15

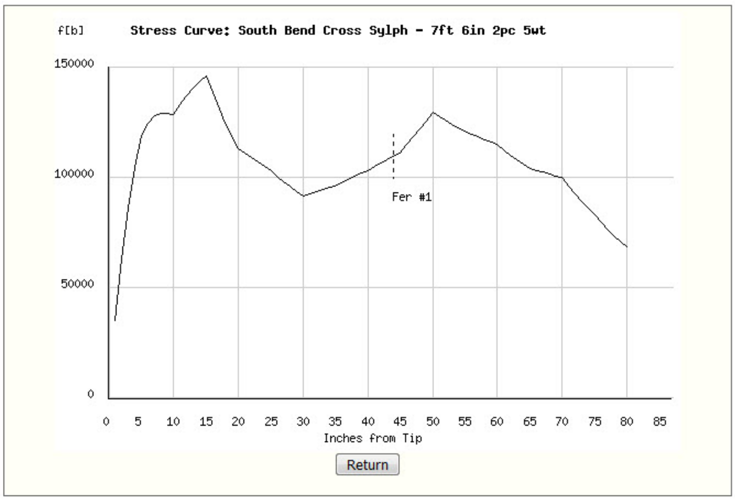

Figure 6: Cross 7.5 foot 2 piece 5 weight

distinguish between limitations on the general application of the engineering concept of stress and limitations on Garrison's particular goals and assumptions.

1. **Unnecessary.** One argument is simply that an experienced builder can evaluate a rod taper with a simple graph of the taper. Stress numbers tell you nothing that the taper numbers cannot.

2. **Garrison's constants.** Garrison's calculation of the density of cane at 0.668 ounces per cubic inch has been replicated within reasonable limits. Varnish and guide moments are relatively inconsequential in the final stress numbers and Garrison's values are accepted without much controversy. His tip impact factor of 4 has sometimes been questioned, but it is easy to change in the calculations if one desires. His safety limit of 220,000 osi is often regarded as too conservative; there are many tapers with stress values exceeding this, especially near the tip, that are widely used and do not seem especially prone to damage.

3. **Garrison's design criteria.** Rods designed with Garrison's criteria of uniform stress throughout continue to be popular. Whether they are the best way to design an efficient casting and fishing rod is an open question. Certainly there are rods with very different stress curves which equally please their users and are ideal for particular casting styles or fishing situations. Most users of stress analysis in rod design do not adhere to Garrison's design goals.

4. **Tip design.** As noted, stress analysis by itself does not help us design the top 10 inches of a cane rod. This seems to be a problem without a consensus solution.

5. **Inadequate static analysis.** The most general criticism of stress analysis is that it is a static engineering analysis of a very dynamic process. Standing on a bridge with line hanging straight down does not capture what happens when we cast a rod, even if we multiply the moments by a factor of 4. In the pre-computer era of Garrison's engineering training and practice this was the state-of-the-art, but those days are past. Much more sophisticated dynamic modeling tools are now available and simple stress analysis should be abandoned.

   One vocal critic of stress analysis is R. E. (Robert) Milward in his book *Bamboo: Fact, Fiction and Fly Rods*. Milward utilizes high speed photography of a rod being cast, and from the bend in the rod calculates the actual stress during the cast. These stress curves look nothing like the one derived from Garrison's math. This result is enough for Milward to declare static stress analysis worse than useless in rod design.

4 The Case for Stress Analysis

In brief, the case for stress analysis is that many builders have found it useful for several problems in taper design[1]. The case rests on the result that, within limits, rods with similar stress curves feel and perform similarly during the cast. And changes to the stress curve result in fairly predictable changes to rod action.

Of course rodmakers are an inventive bunch and some with contemporary engineering skills are experimenting with alternative tools, but there is no consensus as to which approach will prove most useful, or even what the goals are.

Acknowledgment of its usefulness does not mean stress analysis can be used without a circumspect and experienced eye. The more experience and sensitivity a rodmaker has with casting different tapers, the more he (or she) is likely to use it wisely.

Here are some of the specific problems that can be addressed with stress analysis. All of these are implemented in the online version of the Hexrod program.

1. **Deriving a taper from stresses.** The stress values can be derived from basic measurements of the rod and the constants discussed above. The process can be reversed, and a rod taper can be derived from a set of stress values and these same assumptions.

[1]There are many examples of similar oversimplified but useful tools. For example the calculation of BMI in medicine. It is often criticized as a measure of healthy weight, especially by those of us somewhat above a BMI of 25, but it continues to be used because it is simple and comparable, at least for an individual over time.

This reciprocal relationship is the key to many applications of stress analysis: if we know a stress curve we can work backward to find a taper. A few people start by specifying a stress curve entirely from scratch and derive the taper. For example, it would be straightforward to extend Garrison's taper family to other rod lengths and line weights with the same relatively flat stress curve. More common however is to start with the stress curve of an existing rod and modify it or the constants to derive a new rod taper.

2. **Modifying rod fundamentals.** Changing one or more "fundamentals" of a rod without changing the taper will change the stress values, or conversely, fundamentals can be changed while preserving the stress values which will change the taper. In Hexrod this is accomplished by choosing the "Modify Fundamentals" option, changing the item, then choosing either "Hold Constant Dimensions" (for new stresses) or "Hold Constant Stresses" (for a new taper.)

   When calculating a new taper for a changed rod by holding constant stresses, be aware that the sizes of the ferrules may change. In Hexrod, be sure to click the checkbox under Ferrule sizes Unknown.

   (a) **Ferrules.** A common modification is to change the number of pieces in a rod by adding or removing ferrules from the taper. Adding a ferrule (say from a 2 to 3 piece) adds considerable weight at certain points, which increases moments and increases stress. Adding a ferrule will add stress from that location back toward the butt. If we want a new rod with the same stress characteristics, we will have to increase the taper dimensions from that point backward to support the additional weight without increasing the stress.

   Changing the number of ferrules will involve computing not only the locations but the sizes of the ferrules.

   Naturally, adding ferrules does more than add weight. It also introduces a flat spot to the taper. Not all tapers will respond well to changing ferrule locations. In general, ferrules are least objectionable in a fairly low stress part of the taper. Many classic tapers used step down ferrules; the taper was designed for a ferrule at that particular location and moving it will alter the feel of the rod.

   Besides the number of ferrules, it is possible to change ferrule types, from standard to truncated or the opposite. This will change the weight, which will change the stress, or change the taper to achieve the same stresses. To use a ferrule other than nickel silver, see the Hexrod documentation for tips.

   (b) **Line weight.** Changing the weight of the line, or the type of the line (weight forward, double taper, or spey), or the length of the line cast will alter the stresses. Conversely you can hold constant stresses and derive a new taper that will give the same stresses with the new weight. Logically, adding line weight will increase moments which will increase stresses; to achieve the same stresses the taper will have to be beefed up.

   (c) **Geometry.** Stress analysis provides a method to convert tapers between hex, penta and quad geometries. The formula for stress takes into account both the weight of the cane (which varies by shape) and the shape itself. In Hexrod, choose the new geometry and Hold Constant Stresses to convert by equal stress.

   A paper by Claude Freaner on the Hexrod website provides the math for computing stresses for different geometries.
   http://www.hexrod.net/Documentation/Modified_Garrison3_.pdf

   (d) **Rod Length.** Following Garrison, stress values are calculated starting at the tip and ending at the top of the grip. This is called the "action length". For a typical trout rod, it is about 10 inches shorter than the entire rod.

   Action and rod lengths can be changed in Hexrod. If dimensions are held constant, a shorter rod just means ending the taper earlier, and a longer rod extends the taper near the grip a little longer. If stresses are held constant, then the stress curve is compressed to shorten the rod or stretched to lengthen it. The new taper is computed from this altered stress curve.

3. **Editing the stress curve.** Hexrod has a tool for hand-editing the stress curve. It is a little kludgy. The stress curve is displayed graphically as a set of individual points at one-inch intervals. With your mouse you may individually reposition each point. With this editor and a little patience you can perform operations such as increasing or reducing the stresses in a certain region, or adding a roll casting hinge.

   When you are done editing, the new taper is created. See Figure 7.

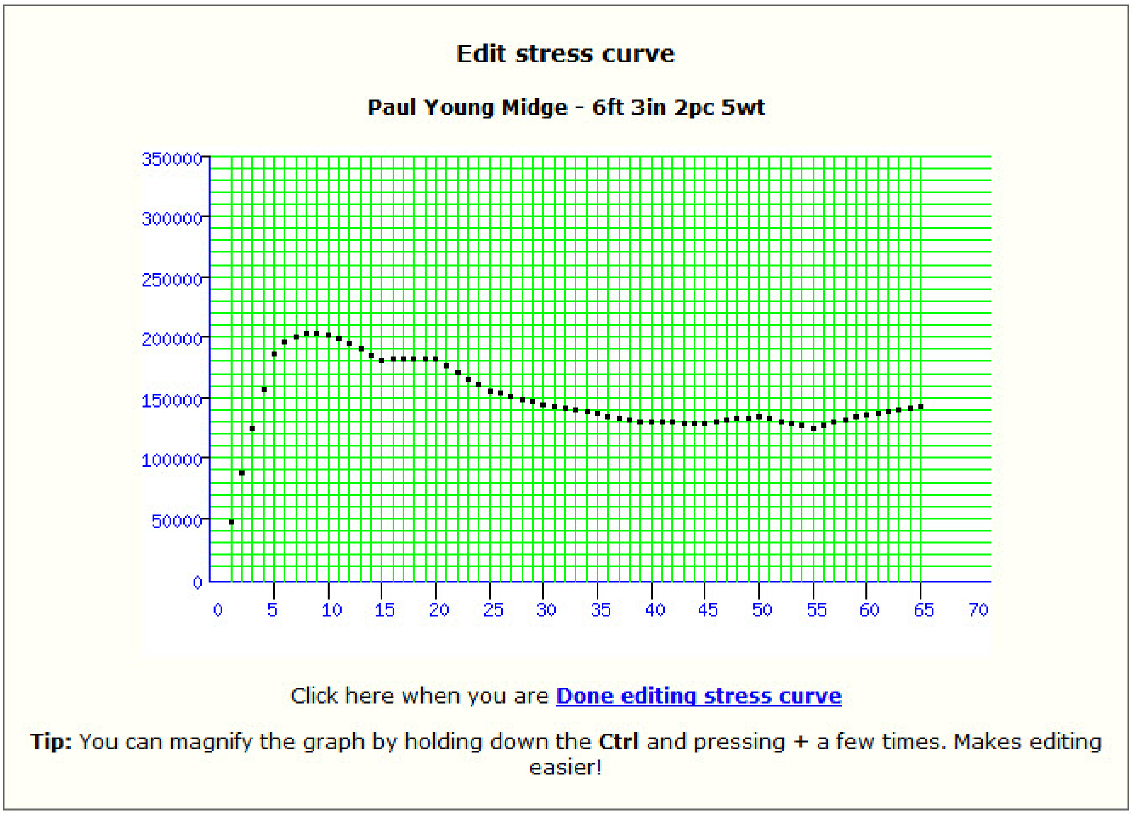

Figure 7: Stress curve ready to edit

4. **Hollow Building.** Hollowing affects stress in two ways: it reduces weight, thereby reducing the bamboo moments and reducing stress, and it changes the structure of the beam (rod), raising stress in the remaining cane. It is difficult to predict in advance which of these will dominate a particular problem.

   There are several methods of hollowing, the most common being scallops and dams and fluting. Hexrod allows for a simple scallop and dam hollowing. You have the choice of either computing stresses for the hollow rod, or computing a new taper to match the original stresses. The paper by Claude Freaner gives some of the math involved. See also Mike McGuire: *Dimension compensation for hollowing bamboo rods.*
   http://mmcgr.users.sonic.net/HollowComp/HollowCompensation.html

5 Caveats

Examining the stress curves of many "classic" rods, you will see a lot of jaggedness. These rod tapers were designed empirically over many years, and may have been modified after glue up by sanding or scraping. Often stress curves from different examples of the same rod model will bear only a general resemblance. If you want to understand stress curves a little better, I recommend you start with series of tapers by a few modern makers, such as Garrison, Wayne Cattanach and A. J. Thramer, which are in wide circulation.

When creating a new taper from the stress curve of an existing taper, do not make too large a leap. If you have a 7 foot 3 weight you like, and want to create a 7.5 foot 4 weight with the same feel, maintaining (stretching) the same stress curve gives you a reasonable chance of success. If you want to recreate the feel in a 9 foot 8 weight, it will probably fail. You are better off looking at stress curves of other long, heavy rods and see what they have in common, in terms of general shapes and actual stress values, and not deviating too far from these.

If you go back and forth between tapers and stresses, the math often causes the tip dimensions to become very small. When you have finalized the rod from the 10 inch point on, take a look at the tip numbers and make sure they are reasonable. If not, there is a “Modify Dimensions” option in Hexrod to change them. Tip design seems to be an under-researched area of cane rod building.

Stress analysis does not capture every aspect of taper design. Step down ferrules and swelled butts are design features not illuminated by stress analysis.

6 Stress of a Deflected Rod

The engineering theory and methods available to Garrison assumed that the actual deflection of the rod (cantilever beam) was very small compared to the length of the rod. Of course rods actually deflect by large amounts, and computer algorithms are available to find the deflection of rods under a variety of assumptions. In the Hexrod program, what is termed “casting deflection” uses the same inputs that Garrison used in his stress analysis: the weight of the rod components, the line in the guides, and the line being cast, all multiplied by an impact factor to effectively increase the weight of components to capture the effect of swinging the rod through the air. Besides finding the deflection, Hexrod finds the stress curve of the deflected rod.

Compared to the undeflected rod in Figure 1, the deflected rod involves identical weights and impact factor, but the distances of the weights have changed. The stress at point **A** is reduced in the deflected rod because the leverage of the weights in region **B** on point **A** (the moments) is reduced. In general, in a deflected rod the stress values are reduced toward the tip, relative to the stresses in the butt area.

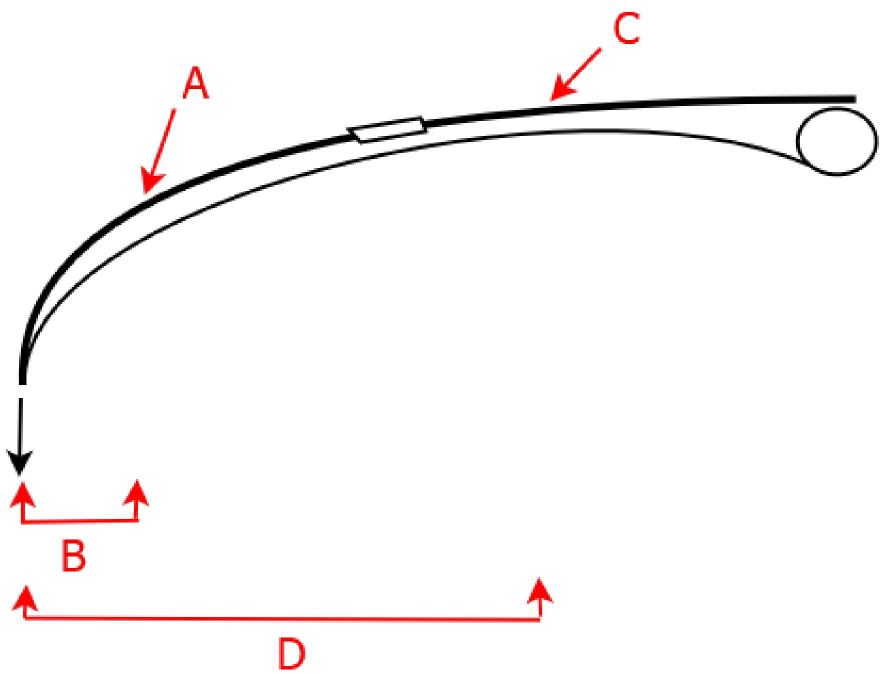

Figure 8: Deflectedl Rod

Here are two stress curves from Hexrod of a two piece eight foot five weight rod, for the undeflected and deflected rod:

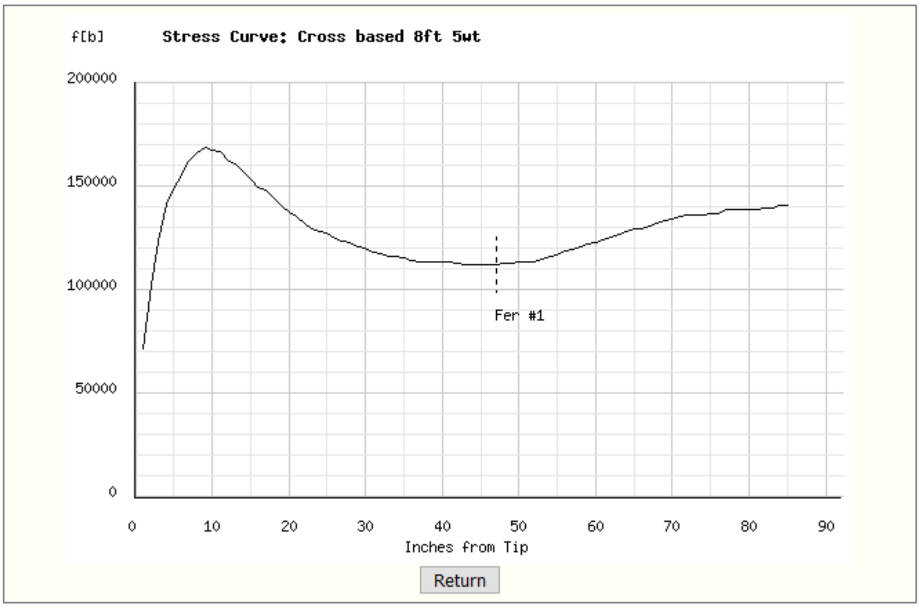

Figure 9: Stress Curve Undeflected Rod

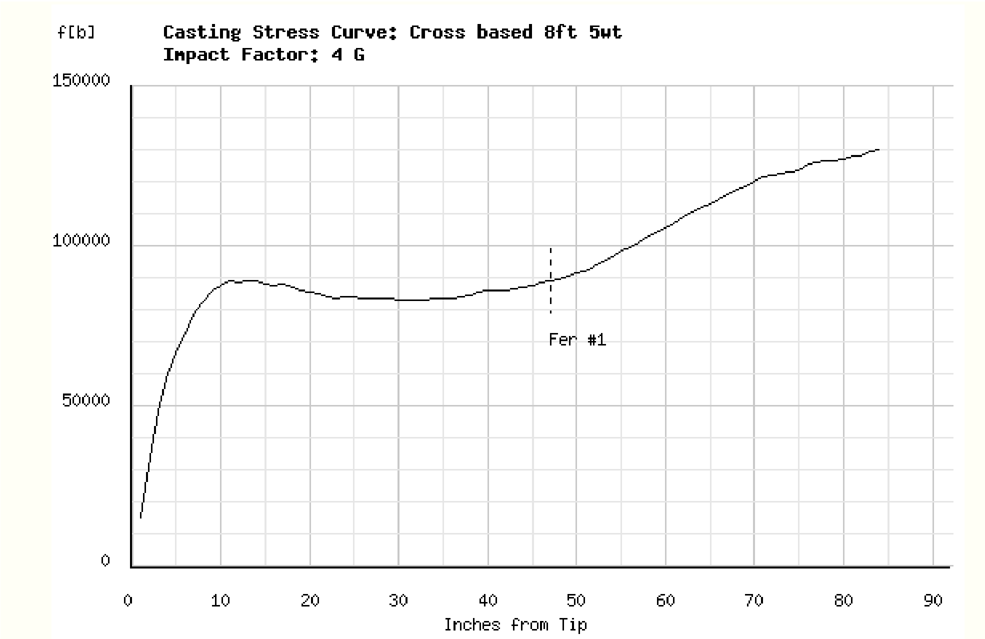

Figure 10: Stress Curve Deflected Rod

Mathematically, the stress values in the deflected rod do not need to be calculated directly from the weights and locations. Once the deflection curve is calculated, the stress is calculated just from the curvature of the deflection curve (which is its second derivative) and the dimensions of the rod at each point. Similar to the Garrison stress curve, the deflected stress curve can be used to make modest modifications to the rod. In Hexrod, modifying a rod by holding constant the deflection curve is equivalent to holding constant the deflected stress curve.

7 References and Resources

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