This Engineer's perspective on the pole vault pole, is a brief yet in-depth look into the mechanics behind track and field's most technical event.

Included are critical thoughts on pole failure, pole bending, and column versus beam theory in relation to flex numbers and weight ratings. It is my intention to show that pole design and testing are not a series of lucky guesses, but is instead formulated, researched, and tested findings based in physics.

From an engineer's perspective, the pole is first and foremost a piece of equipment- a tool, to help the vaulter clear the bar. As with many other tasks, using the proper tool allows the user to perform the task more efficiently, which is especially important in the pole vault. A pole can't magically send the vaulter flying high over the cross bar: a pole cannot generate energy by itself. However, it has been stated by many people that a pole can store energy and then return it. How efficiently this is accomplished is mostly due to the skill and speed of the vaulter, but using a well designed, correctly chosen pole is many times the difference between a miss and a make.

There are several aspects to be considered when discussing what it means for the pole to be well designed and correctly chosen. A proper hand grip, weight rating, flex number, the weight of the pole, and the pole materials are just a few factors to think about. To illustrate this in the form of the equation for kinetic energy $E=\frac{1}{2}mv^2$; E is the energy put into the pole by the vaulter, m is the vaulter's size or mass, and v is the vaulter's speed or velocity. You'll notice speed is squared and has the largest influence in the formula. A lighter pole is easier to run with, which means the vaulter will be able to more effectively maximize their velocity, and if the pole has been selected properly, it will be able to give back that energy, helping the vaulter achieve the height. Consider this example, if a better tool or pole selection used properly has the potential to increase performance one-half of one percent (.5%), the vaulter would clear the bar by 1" on an 18' vault. If increased to one percent (1%), the potential would mean a clearance at the next height.

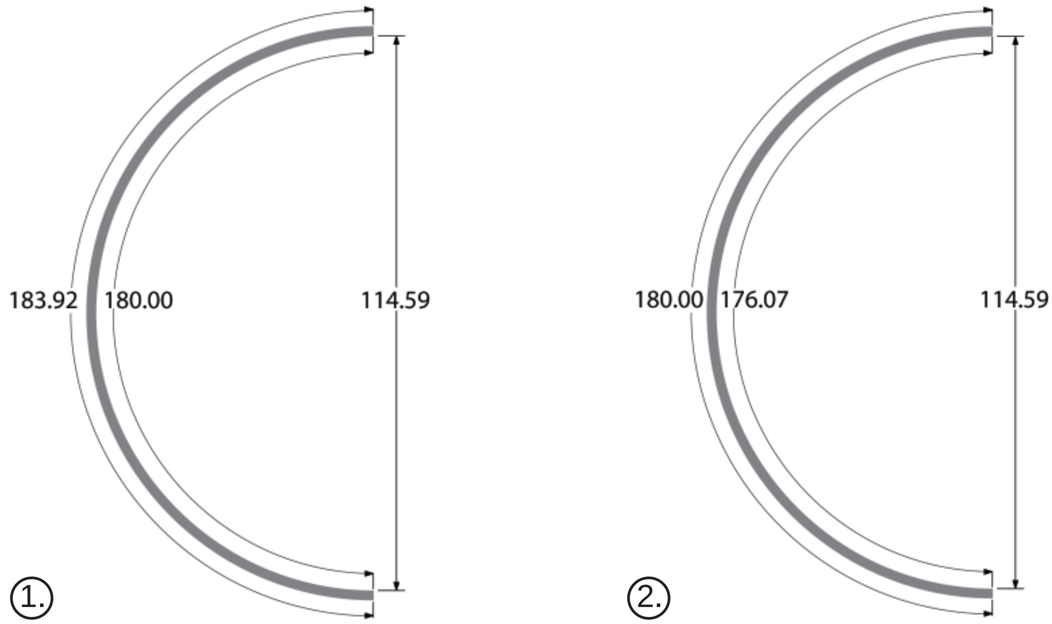
In the subsequent pages, what follows are my views as an engineer, sometimes coach, mediocre vaulter, and hard core track enthusiast.

The Basics

Let's start with some basic engineering concepts and realities. The pole is a hollow tube or column. Bending a pole can be basically broken down into three major reactions or things that may happen. Let's look at the pole bending in a mechanics of solids view. For the column to bend, at least one of these three things must happen, or a combination of some or all:

1. The material on the tension side must stretch.
2. The material on the compression side must compress.
3. The round tube or column must start to oval.

Figures 1 and 2 represent how much stretch or compression would be required on the outermost fibers of the pole if the opposite side remained a static length.



In this example, a 15' (180") pole with its chord length shortened to 63.7% (bent in a perfect semi-circle or 180 degrees). Again, this shows the stretching/compression if only one of the three reactions occurred.

1. Tension side must stretch: In fig. 1, the tension side stretches 3.92" or 2.18% while the compression side maintains the original 180" with no compression.

2. Compression must compress (shorten): In fig. 2, the compression side compresses to 3.93" or 97.8% of its original length.

3). Round tube or column ovals: The circle distorts to oval resulting in a 1.5% decrease in axis length in the tension/compression plane. Tension side would need to stretch approximately 2.15%. By ovaling, the tension side stretches .03% less.

-When the shape ovals, the strength is decreased: See moment of Inertia section.

Note: These number are based on a given diameter pole, with no taper. At Gill, we have data on various length and mandrel poles determine the most accurate information possible based on real world scenarios. In addition Gill work to maintain a certain maximum theoretical value for elongation, depending on how and what materials a pole is constructed from.

Some of the other engineering factors that contribute to pole strength and behavior- such as bend profile and response to load, are the same mechanical properties that any cylinder or tube has.

How the Pole Fails.

Poles commonly fail due to three reasons: hoop failure, compression side cracking, and/or fiber failure on the tension side.

Hoop Failure: Discussions about higher hoop strength and how a pole is constructed are common. A simple way to look at it is, as the pole bends and the load exceeds the capability of the pole to maintain its shape, as with pole or slender columns, the compression side has a tendency to collapse inward (buckle-Straw Failure). Since the geometry of the pole changes when it ovals, it also serves to decrease the Moment of Inertia in the primary bend direction.

Crack the resin/glass/fibers on the Compression Side: This cracking has been observed to happen when the pole bend is large (shortening of the chord length to under 65%) and the pole has very high hoop strength, high tensile loading capability, and the compression side loads cause a crack in the resin system on the compression side. This pole would then fail after the pole begins to recoil or unbend. This condition of compression side cracking has been duplicated in testing and in some cases cracks are formed without total failure.

Fiber Failure on the Tension Side: Fiber failure has been observed to happen in dynamic test conditions when the chord length was shortened well under what any vaulter would be expected to bend or shorten a pole. In some cases the fiber failure did not result in total failure. In fact, in some of the test cases the pole recoiled or unbent, but did show some internal failure of fibers. To quote from a *Materials Solution, Polymer Composite* article by AEA technology, "Failure of a single layer in a laminate will not always mean that the laminate as a whole cannot sustain a load." We have taken vaulting poles that have shown this tensile side failure of a layer and recoiled and then subjected them to loading to shorten the chord down to 60% and the pole maintained integrity. In basic terms, even after a white blister appeared showing a layer failure, the pole was able to withstand additionally loading or a vault. Even so, vaulting on a damaged pole is strongly discouraged.

5.00m pole shortened to 57% of original length.

The above pole (showing white blistered area) continues to be cycled to 65% of original length at set of ten.

Large Scale Overview of Pole Failure.

Overload: When the vaulter is able to apply more force than a pole can withstand (Maximum or ultimate stress load), the pole will fail. Determing which way the pole failed: hoop stregth failure, compression side cracking, tension side fiber failure or combination of the three is usually hard to determine since a failure due to overload can be a very dynamic event with other failures generated by the snap back effect.

With many good vaults, much of the force is applied down the axis of the pole and the goal is to move forward and up, not necessarily to bend the pole. An applied moment can generate a localized over-bend. If the bottom arm of the vaulter is locked out, mechanics dictate that a higher applied moment can result. If the vaulter also tends to pull down with the top hand you have the potential for a big bend or overload condition.

The old ‘warming up’ of the pole by flexing in the box or against a wall (not a good idea) is still practiced today by some vaulters, and is an example of a higher applied moment.

For vaulters and coaches alike phrases like ‘they really crushed than one” or “they really got into it” are common occurrences. Once a pole is bent or has its chord length shortened to 65-68% the pole is more that likely laying against the back and side of the box and may be contacting the pit. Once this contact occurs, the chance of the bend rolling up and getting a localized over-bend increases.

Fatigue Failure.

As stated by Robert M. Caddell in his book Deformation and Fracture of Solids, “there are two necessary conditions that must prevail if a fatigue failure is to occur. The first being the existence of a crack or an event must initiate the crack. The second prerequisite demands that the crack must propagate.” (Ref. 2). He goes on further to say, “ Although many parameters may accelerate crack propagation, some type of fluctuating or alternating stress is essential to bring about fatigue failure. Once a crack has propagated to some critical extent, the remaining sound section of the structure can no longer support the applied stresses and the catastrophic failure follows.”

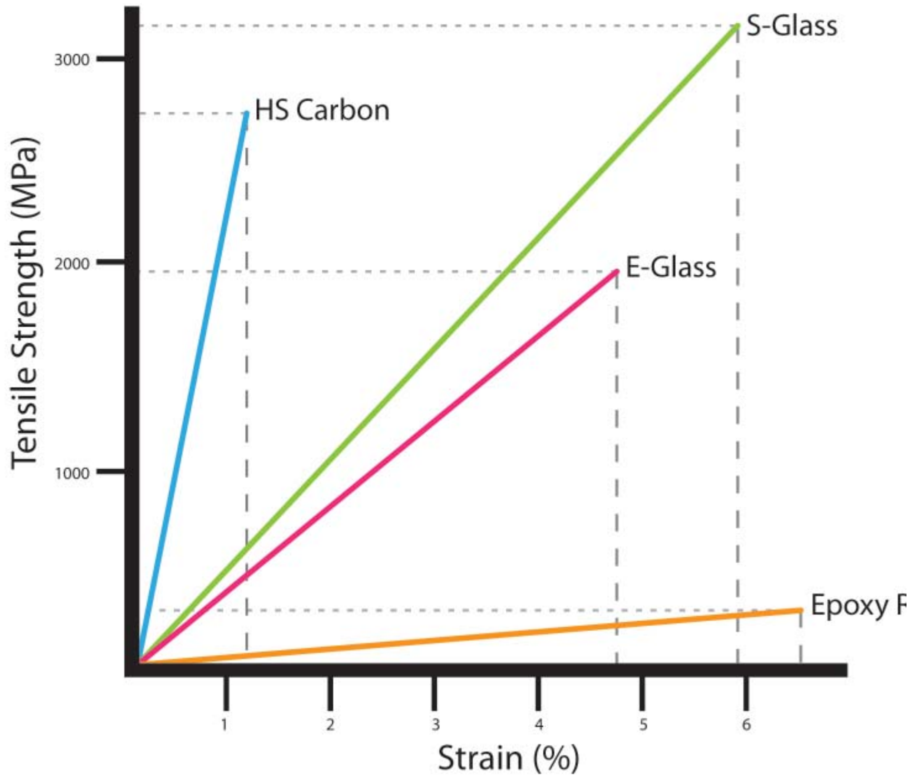
What this illustrates is that a pole being spiked, or impacting a standard, or a major over-bend could be the initiation of the process. The repeated bending (stressing) of the pole sets up the cycles. Where on an S-N curve (stress versus cycles to failure) this loading falls is what really dictates the life of the pole. Is a million cycles considered infinite for the life of a pole? That would be 50 years of about 55 jumps a day, everyday of the year. What this means is that major over bends, spiking the pole, standard impacts, and other such incidents tend to narrow this range or window of the poles fatigue life. The more often you load a pole to its maximum stress the shorter the life. Additionally, as fibers or resin are damaged, this maximum or ultimate stress required for failure get lower.

In a study done by the Oak Ridge National Library on Carbon Fiber Composite, glass fiber composites having a strain limit in the 0.3-0.4% range are discussed for design considerations. In this study, figures show S-N curves with cycles to failure ranging from 10-100,000,000. This illustrates that if consistently stressed to certain high levels or subjected to abuse, the fatigue failure process is initiated-and a drastically reduced life cycled can result.

Materials of the pole.

Understanding the material properties of vaulting materials is key in predicting failure and stress levels, as well as innovating the design and construction.

The resin and fiber properties and the orientation of the fibers contribute to overall composite behavior. The compression of the glass (cured resin) is a major contributor in fiber strain. Fibers are the primary contributors for tensile strength. When a composite is loaded in tension, for the full mechanical properties of the fiber component to be achieved, the resin must be able to deform/elongate to at least the same extent as the fiber. The diagram below gives a visual representation of the strain to failure for E-glass, S-glass, and high-strength grade carbon fibers in their pure form (not in a composite). The S-glass fiber, with an elongation to break of approximately 5.7% will require a resin with an elongation-to-break of at least this value to achieve maximum tensile properties.



One factor to note also is the steeper stress strain curve for carbon versus S-glass. While this steeper curve has some interesting and beneficial advantages when looked at in the context of use in a vaulting pole. However, the quantity, location, and orientation of the carbon must be considered to most fully utilize these properties.

The use of carbon fibers and more recently, woven carbon fibers, have allowed the design and production of some lighter poles (when compared to E and S glass designs) and also provided Gill Athletics an opportunity to work towards designs that can more fully take advantage of some of the afore mentioned properties.

Pole Design: It gets a litle complicated.

On the outside they look deceptively simple, a long hollow tube with a plug on one end and a fancy tape job, but that's not even scratching the surface.

There are many factors that go into the design of the pole: strength and rigidity, carry weight and mandrel size, stiffness and safety, just to name a few. The type of materials and how they're arranged around the madrel determines many of these characteristics. In a very simple overview to make a pole; a pattern is cut from fiberglass or carbon fiber and then wrapped around a metal mandrel. It is then baked in ovens with heat and pressure to melt and cure the resins in the glass. The pole cools and then is flexed to determine the weight rating for the length created.

Predicting how certain materials or designs will perform can be a difficult task, since the vast majority of poles are made on tapered mandrels, the Do (outside diameter) and Di (inside diameter) are constantly changing. To maintain a constant Moment of Inertia(I=Moment of Inertia$=\pi(D_0^4-D_I^4)/64$), wall thickness would have to be gradually added to offset the decreasing diameter. To gather accurate data for Pacer vaulting poles, poles are cut in sections and the Di and Do are measured at set intervals. This allows us to plot the various properties along the length. When a pole is made with various different materials, whose amount and location changes throughout the length, the straightforward determination of mechanical properties becomes extremely difficult. It is for these reasons also, that relying to heavily on modeling programs and FEA analysis, may not predicate actual behavior and strength characteristics as accurately as they would with other materials. This is also why testing of pole designs is important.

Engineers must also consider the many different sizes and shapes of poles needed to supply due to the wide variety of shapes and size of vaulters who use them. For instance, a smaller mandrel pole is stronger that a larger mandrel but is also much heavier. When the mandrel size increases the pole is lighter-a definite plus for vaulters-but the tension and compression sides is stressed more vigorously.

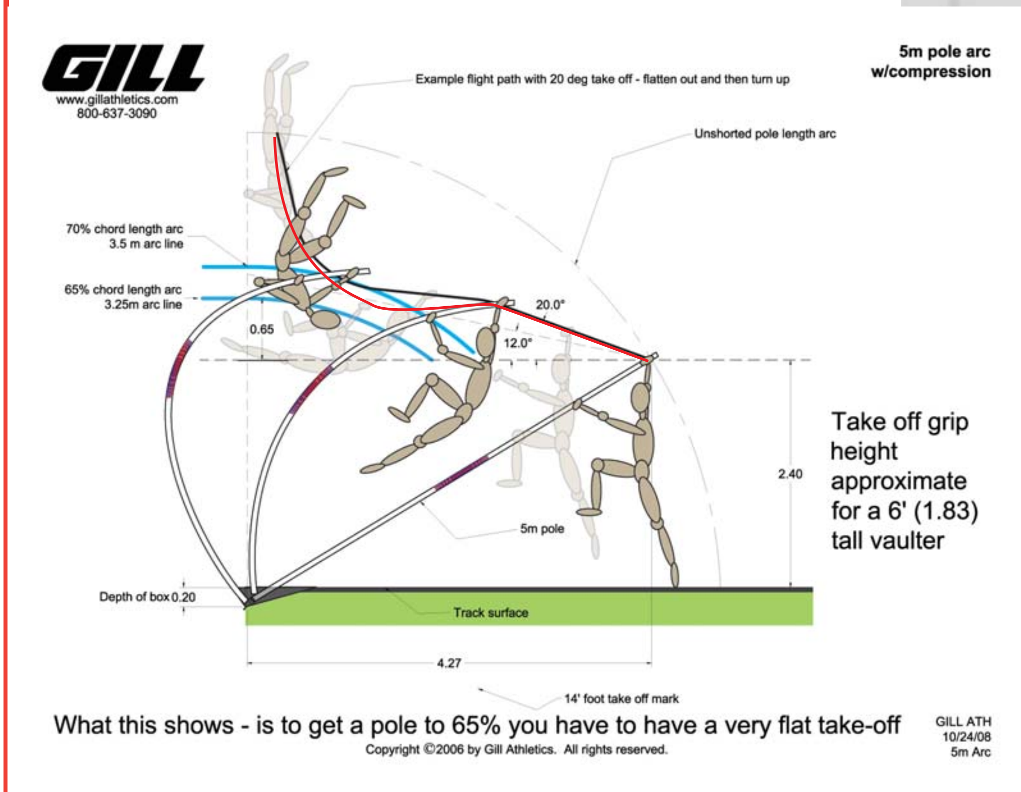
Loss of Moment of Inertia also comes into play in regards to the ovaling effect when designing and testing poles. If a pole ovals 1.5% it could lose about 2.5% of its Moment of Inertia. For Example, in a 200 Lb pole this would result in a loss of 5 lbs. The formula for the Moment of Inertia for an Oval differs from the formula of a circle: $I=\frac{1}{64}\pi(bd^3 - b_I d_I^3)$

Relating the Data to the Vault.

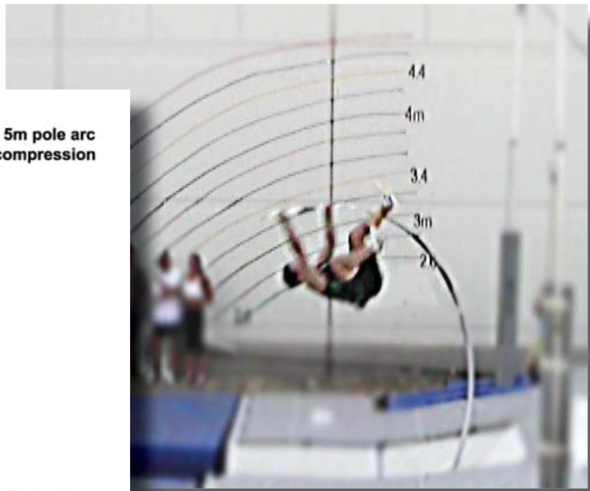
We’ve discussed the pole itself-how it’s made and what makes it fail, now let’s about some specific’s relating to the actual act of pole vaulting.

Pole Rolling Over:

One unofficial definition of “rolling over the pole” is the continued forward movement of the pole as it moves to the vertical position. One way to “see” the pole role over is by watching the path of the top end of the pole during the vault. As the pole bends to the point where it rolls over, the slope flattens out. This flatter slope section is followed by a drastic steepening of the slope as the pole uncoils/unbends.



In the above depiction, notice how flat the vaulter must project to achieve a 65% bend with a successful 12 degree take-off. At this point the pole is too small (not stiff enough) and the vaulter should move to a larger-stiffer pole.



Video analyzed in Dartfish video software: shows a vault with the pole shortened to 65% of original chord length. Notice the end of the pole angling down: a clear sign the pole is too soft.

The gray dashed line is the path of the unbent end if the pole rotating from horizontal to vertical. The black line follows the top hand path of the vaulter during the jump. The red line represents what happens when the vaulter drops, overloading the pole. Note the slope dips slightly negative during the journey upward. If the chord is shortened enough while in this phase, the chance of structural failure increases substantially. At this point, it is recommended that the vaulter move to a stiffer pole, or work to achieve a better take off.

End loads:

To an engineer, end loads are another way of describing how stiff or soft a pole is, similar to weight ratings or flex numbers for the vaulter. At Gill Athletics, end loads are measured during the production phase when a bend test to 65% of original chord length is performed on every pole produced. It can be said that end loads are an even more accurate way to predict how a pole will perform. As illustrated below, even poles with the same flex number may feel different to a vaulter-as well as produce different end load capabilites.

Jeff/David

Today we got a chance to jump on the test poles.

Time Thomas jumped from 14 steps indoors, so conditions where very constant. He did about 20 jumps total.

He really like the yellow/white (15.8) and blue/white poles (16.4). They did however appear to be about 0.3 softer than the same Fx pole.

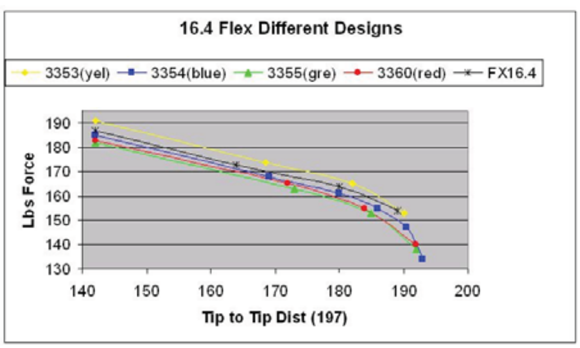
If you take Fx as the base line here is how the poles compare-

+0.3 Red/White/Blue (first batch of test poles)
0.0 Carbon Fx
-0.3 Blue/White
-0.5 Red/White
-0.7 Green/White

so Green/white was 0.7 softer than the carbon fx of the same flex.

Time really like the Blue/White-Yellow/white model.

Above is a picture of two elite vaulters with six new vaulting poles. All but the yellow striped pole have the same flex of 16.4cm. The poles were given to the vaulters to jump with and see how they felt while in use. As shown above, the vaulters *felt* that the blue, red, and green poles were softer than the silver Carbon Fx pole, even though the poles had the same length, flex, and weight rating. Unbeknownst to the vaulters, the poles had also been end load rated at several different chord lengths. Notice how the endloads correlate exactly to what the vaulters described.



End load testing results from flex tests.

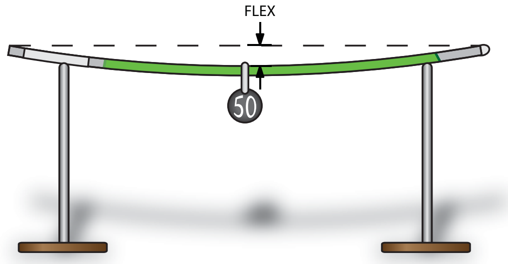
End load/flex testing of a vaulting pole.

While flex numbers do give a general indication of a given poles load bearing capability, they do not define the poles end load capabilities at various chord lengths. The design and construction of the pole has a significant impact on these end loads. The poles weight rating as used and mandated by NFHS does not correspond to measure end loads. In fact, there is a certain length and weight rating where the end loads at a 70% chord length cross the weight rating. By this I mean the pole weight rating may differ as much as 25lbs from the force the pole can produce: it has a lower end load than weight rating. From this point forward a pole of that length as moving upward in weight rating will continue to have the end loads exceed this rating.

Flex Numbers

To a vaulter, flex numbers help describe how flexible -stiff or soft- a pole is going to perform. To manufacturers flex numbers are a measure deflection when poles are suspended on two supports of a given span and a weight is hung in between the supports. The amount the pole bends or deflects, measured in centimeters (by most manufacturers), is the flex number.

If you were to compare it to a supported beam:



$$\text{Flex or } \Delta = W\ell^3/48\,E\,I$$

W=50lbs

ℓ = fulcrum spacing or span

E=Modulus of Elasticity

I=Moment of Inertia= $\pi(D_0^4 - D_I^4)/64$

From an engineering aspect, it is very dangerous to vary the length (fulcrum spacing or span) in the equation and then ratio the flex. Because pole mandrels are tapered, the Di and Do will always decrease from the tip end to the top end. Di will be a fairly linear decrease while the Do will decrease more slowly until it gets past the sail piece where it will then decrease at a faster rate. This means that the Moment of Inertia changes throughout at the length of the pole and can easily vary 15% from one end to the other. Modulus of elasticity is another factor that does not remain the same throughout the length of the pole. E is a material property that describes how it behaves with regards to stress and strain. To be the same throughout the length of the pole, there would have to be the exact same amount of resin, fiber density, and glass fiber orientation, etc.

For instance, an extreme example of this is a 16'5" 185 pound pole that was tested with a span of 169.5". The flex number was 17.5 (185lb rating). Flexing the same pole with a span of 108" at the top (Fig. 3) end then the tip end (Fig. 4), there was a 15lb difference between the two tests. The tip end was 2% heavier than the total pole rating and the top end was 17% lighter. This illustrates the variability of flex ratings without a consistent span placement due to the sail piece and design.

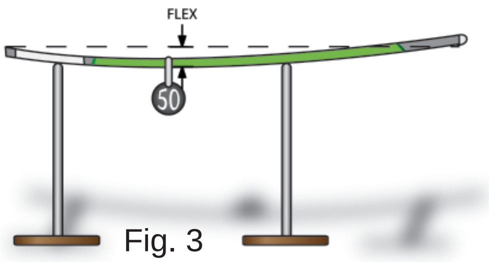


Fig. 3

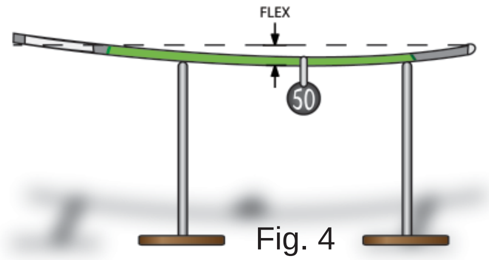


Fig. 4

Because the above equation is a beam theory equation, for it to hold true, a change in W should result in the same ratio change in flex. When this no longer holds true, the use of the equation becomes less reliable. Upon further testing, the results dictated that when the ratio of flex divided by span or as shown in the formula: Δ / ℓ is less than a certain ratio, the flex appears to follow the formula and you can ratio up and get the same flex number. When the ratio is above a certain value, the pole weight will change by about one increment. As the ratio increases, the change in pole weight class would also increase. Because not all poles are designed the same way, no specific test results for Pacer poles are listed here.

Column Theory:
How to predict the weight rating when changing grip height on a pole.

Euler's formula:

$$P_{cr} = E\,I\pi^2 / L^2$$

P_{cr} - stands for critical load (weight)

L_n - Load or weight rating of the pole

L_{lg} - Load or weight rating at a lower grip

$$P_{lg} = P_n * L_n^2 / L_{lg}^2$$

In layman's terms, the rule of thumb is that per six inches of grip change, there is a 10lb change in rating. If you use a 14' 150 lb pole- at 13'6" it would react more like a 161lb rated pole. This matches well with numerous published guides by Gill Athletics and also by UCS which indicated the same.

To illustrate this point, a 14' pole with an original weight of 160lb and 18.7 flex rating was cut-off to 13'6" and flexed to determine the new weight rating which was 170lbs and had a 16.3 flex. The pole was then cut again to 13' where it was now rated at 180lbs and a 13.9 flex.

Design and Testing today and in the future.

What does all this information mean? It means using basic engineering principles to help refine the development of a better, more efficient tool thus getting that extra 1%. Innovation in the sport means more research and testing. In particular, some areas yet to be investigated are non-linear stress/strain behavior of materials and how this could be utilized to build a better pole, as well as the possibility of a double taper mandrel concept similar to a patented concept for the original carbon javelins (by Gill Athletics). Built on a solid engineering foundation and with innovative designs, who knows what the next generation of poles and pole vaulters can achieve.

-Jeffrey P. Watry
Senior Engineer, Gill Athletics

Translated from Engineer's Nerd-Speak to English,
-Ashley Whittaker, Industrial Design

References:
1. David Nielsen, Athletics Outstanding Performer-The Vaulting Pole
2. Robert M. Caddell, Deformation and Fracture of Solids, Prentice-Hall, Inc.
3. J.M. Corum, R.L. Battiste, and M.B. Ruggles-Wrenn, Durability-Based Design Criteria for a Quasi-Isotropic Carbon Fiber Automotive Composite