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Pole Vault and the Pole

An Engineers perspective on the pole vaults main piece of equipment, the pole. First and foremost the pole is a piece of equipment, a tool, used in the event to help you clear the bar. Just with many other tasks, the proper tool allows you to perform a task more efficiently.

A pole will not generate energy or magically throw you over the bar. It has been stated by many people that a pole can store energy and then return energy. How efficiently this is accomplished is dictated in a great majority by the pole vaulter. The proper pole choice is important and the design of that given tool does play a part in that equation.

Why the discussion of the pole then? If a better tool, or pole selection, when used properly, has the potential for a performance increase of only $\frac{1}{2}$ of one percent what would that mean? That would be just over 1" extra clearance or height on an 18' vault. A 2% potential would be the next height.

Energy stored or put into the pole is the result of the vaulters size (mass) and speed (velocity). Speed being the squared term in the equation has the biggest influence in that formula. This is not to take away from how important the vaulters technique is. All things equal, technique and weight, an increase in speed is a major contributor.

Where is this leading? To the pole, the piece of equipment you run down the runway with. The lighter and easier it is to carry, the faster you can run. So pole weight and carry weight are important. How important is a separate discussion.

The other important part of the pole besides how much it weighs is how it bends (We prefer to discuss it as a shortening of the chord length) and unbends. This chord length and relative bend was described very clearly by one of the top pole vault coaches, Dave Nielsen, in his article "Athletics Outstanding Performer – The Vaulting Pole", (Reference 1). It is highly recommended that this article be read. What follows is my view as an engineer, sometimes coach, mediocre vaulter, and hard core track enthusiast.

This gets into some real basic engineering concepts and realities. The pole is a hollow tube or column. Bending a pole can be basically be broken down into three major groups of things that can happen. Looking at this bending in more of the 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 give you a graphic representation off how much stretch or compression would be required on these outer most fibers if the other side remained a static length.

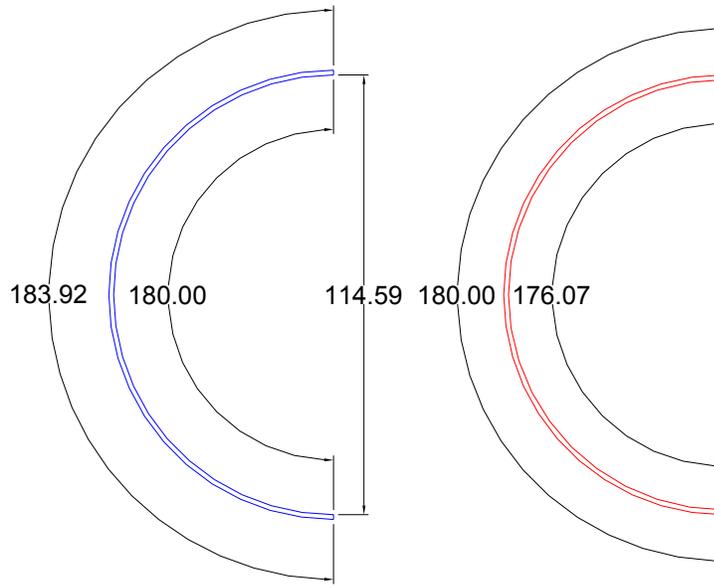


Figure 1

Figure 2

As an example: A 15' pole with its chord length shortened to 63.7% (bent in a perfect semi-circle or 180 degrees).

1. Tension side stretch – no compression or shortening of the compression side. The material on the tension side would need to stretch 2.18%
2. Compression side shortens – no elongation on tension side. The material on the compression side would compress to 97.8% of its original length (again a change of about 2.2%)
3. Oval resulting in a 1.5% decrease in axis length in tension/compression plane. Tension side would need to stretch approximately 2.15%. This means that by the pole ovaling by 1.5% the tension side would have to stretch 0.03% less.
 - a. Loss in Moment of Inertia – if a pole ovals 1.5% it could lose about 2.5% of its Moment of Inertia. For oval: $I = \frac{1}{64} \pi (bd^3 - b_1d_1^3)$ for circle: $I = \frac{1}{64} \pi (d_o^4 - d_i^4)$

Note: These numbers are based on a given diameter of the pole, with no taper. We have spread sheets that have the various length poles and mandrel sizes on them and we try to maintain a maximum theoretical value for elongation, depending upon how and with what materials the pole is constructed off.

In reality the mechanics of the bending pole combine all three areas. The design of the pole dictates how these factors combine in the overall behavior of the pole.

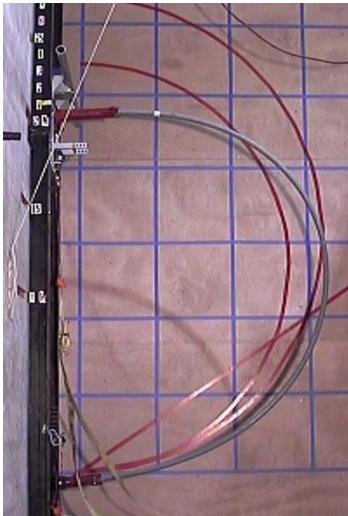
Some of the other engineering factors that contribute to pole strength and behavior (bend profile, response to load) are the same mechanical properties that any cylinder or tube has.

How does the pole fail?

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 loading is such that the pole starts to take an oval shape, you reach a point where the loading exceeds the capability of the pole to maintain its integrity, and with poles or slender columns, the compression side has a tendency to collapse inward (buckle). 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 compression side – This 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 formed without experiencing total failure.

Fiber failure on tension side – This 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 complete structural 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 “Material Solutions, Polymer Composites article by AEA Technology, “Failure of a single layer in a laminate will not always mean that the laminate as a whole cannot continue to sustain 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 its integrity. In basic terms, even after the white blister look layer failure, the pole was able to withstand additional loading or a vault. Note: Would not recommend a damaged pole be used for vaulting.



4.15m pole shortened to about 2.05m – Fiber failure (941566W)

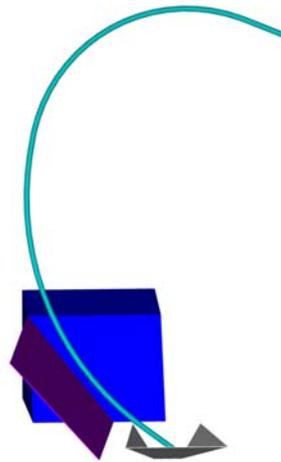
The above pole continues to be cycled – shortening chord to 65% - cycled in sets of 10 cycles

Larger Scale overview of pole failure

Overload – When the vaulter is able to apply more force than pole can withstand (Maximum or ultimate stress load), the pole will fail. Which of the three discussed above, or combination of the three occur 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 to necessarily bend the pole. An applied moment can generate a localized over bend. If the bottom arm is locked out, the mechanics dictate that a higher applied moment can result. If the vaulter in turn also tends to pull down with the top hand you have a potential for a big bend/overload condition. The old warming up the pole in the box that is still practiced by some today is an example of a higher applied moment.

How often have you heard “he really crushed that one” or “really got into it”? Once a pole is bent or has its chord length shortened to a 65-68% the pole is more than 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 in reference (2), “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 a crack. The “second prerequisite demands that the crack must propagate.” If the following excerpt does not describe pole vaulting and certain type failures, then a lot of engineers are misguided. “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 a pole. Is a million cycles considered infinite life for a pole? That would be 50 years of about 55 jumps a day, every day of the year. What this means is that major over bends, spiking the pole, standard impacts and other such incidents do tend to narrow this range or window of the poles fatigue life. The more often you load a pole closer

to its maximum stress the shorter the life. Additionally, as fibers or resin are damaged, this maximum or ultimate stress required for failure gets lower. Reference (3) is a study done by the Oak Ridge National Laboratory on Carbon Fiber Composites. It discusses glass-fiber composites having a strain limit in the 0.3 to 0.4% range for design considerations. Figures 10 and 11 of this reference shows S-N curves with cycles to failure ranging from 10 cycles to 100,000,000.

What these do illustrate, that if consistently stressed to certain high levels or subjected to abuse, the fatigue failure process is initiated and a drastically shortened life cycle can result.

Moment of Inertia and Section Modulus:

Since all competition poles that I know of are made on tapered mandrels, the D_o (outside diameter) and D_i (inside diameter) are constantly changing. To maintain a constant Moment of Inertia you would gradually have to add wall thickness to offset the decreasing diameter. We actually do cut poles in sections and measure D_i and D_o at set intervals. This also allows you to plot the various properties. When a pole is made with various different materials, whose amount and location changes throughout the length, the straight forward determination of mechanical properties becomes extremely difficult. It is for these reasons also, that relying to heavily on modeling programs such as FEA, 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.

$$I = \text{Moment of Inertia} = \pi(D_o^4 - D_i^4)/64$$

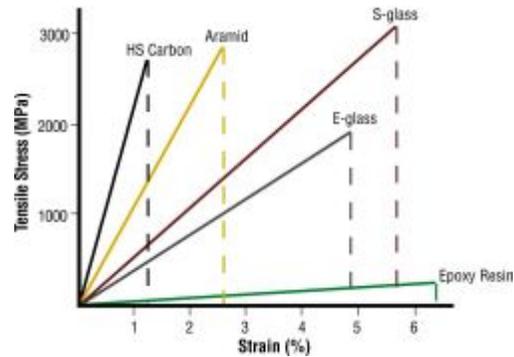
Moment of Inertia and its use will be discussed in greater detail later.

The materials that make a pole:

The resin properties, fiber properties and orientation of the fibers all contribute to overall composite behavior.

The glass (cured resin) is a major contributor for compression. Fibers are primary contributors for tensile loading.

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/elongated to at least the same extent as the fiber.



The above figure (footnote) gives a representation of the strain to failure for E-glass, S-glass, aramid and high-strength grade carbon fibers on their own (i.e. not in a composite form). The S-glass fiber, with an elongation to break of approximately 5.7%, and will require a resin with an elongation to break of at least this value to achieve maximum tensile properties.

One factor to also note 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, it also presents careful consideration on how much, location and orientation so you can most fully utilize these properties. It is in this area that some of our current testing and prototyping is focused.

The use of carbon fibers and 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 material properties.

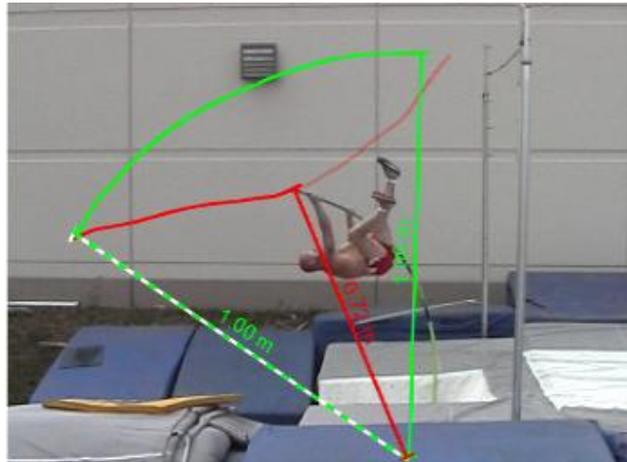
(description of end loads on carbon poles versus E and S glass poles – plus carbon weave – this section still under development)

We are currently doing tests and recording end loads at various chord lengths. This along with dynamic tests may allow use to determine at what point the changes in pole geometry start to have a pronounced effect.

Pole rolling over:

The continued forward movement of the pole as it moves to the vertical position. Ask various people what rolling a pole over means and you will get various views. If you focus on the top end of the pole and follow its path from the moment of takeoff to the moment the vaulter leaves the pole at its vertical position, some of the following can be observed.

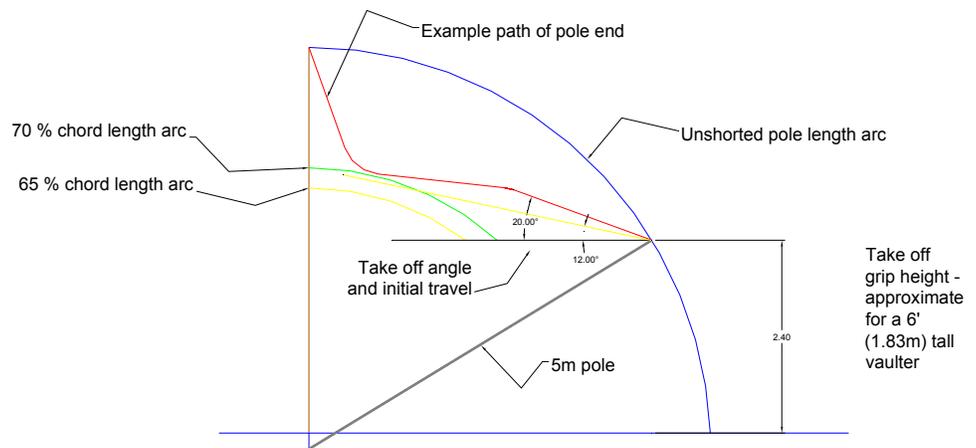
The end of the pole travels towards the pit, or forward and upward at a certain slope. As the pole bends to the point it starts to “roll over” the slope flattens out. This flatter slope section is followed by a drastic steeping of the slope as the pole uncoils or unbends.



Above video was analyzed using Dartfish and shows a vault with pole shortened to a 72% chord length

The green arc was made by walking the pole up from the plant position to vertical. The red arc is the path the top of the pole traversed. This example shows a pole shortened to about 72% chord length when compared to its straightened length. Video camera was stationary.

If this middle or flatter slope section actually takes on a negative slope you are in fact dropping and overloading the pole. If the chord is shortened enough while in this phase the chance of structural failure increases substantially. My opinion is you either need to work on a better take-off or get on a stiffer pole.



The above depicts a vaulter using a 5 meter long pole:
 As long as the distance between the pole end path and the unshortened length arc is increasing, the pole is continuing to bend or shorten. At the point that the distance to the "straight pole" arc starts to decrease, the pole is unbending.

Note: In above depiction even at a 12 degree take-off – unless the slope flattens appreciably it is extremely difficult to get to a 65% chord length unless the pole is in my opinion, is too small.

End loads:

Describe how poles of the same or similar flex number can and do have different end loads at larger bends or shortening of the chord length.

This is where the steeper stress strain curve of the carbon fiber will avail some of its advantages

While flex numbers do give a general indication of a given poles load bearing capability, they do no define the poles end load capabilities at various chord lengths. The design and construction of the pole does have a significant impact on these end loads. Flex numbers are discussed in the following sections. A comparison of a series of poles with the same flex numbers but varying end loads can be found in a PowerPoint presentation at www.gillathletics.com/pvnews

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 endloads at a 70% chord length cross the weight rating. By this I mean the pole has a lower end load than weight rating until this point. From this point forward a pole of that length as they go up in weight rating will continue to have the end loads exceed this rating.

Flex numbers – only a part of the puzzle - and weight ratings:

Flex numbers are a measured 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 cm by most pole manufacturers) is the flex number.

If you were to compare it to a simply supported beam:

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

$$W = 50\text{lbs} \quad l = \text{fulcrum spacing or span} \quad E = \text{Modulus of Elasticity}$$

$$I = \text{Moment of Inertia} = \pi(D_o^4 - D_i^4) / 64$$

The following information pertains to various flex tests performed at Gill Athletics, Inc.

- Moment of Inertia changes throughout the length of the pole. Since the mandrels are all tapered, the D_i and D_o will always decrease from the tip end to the top end. D_i will be a fairly linear decrease. D_o will decrease at a slower rate until it gets past the center of the sail and then decrease at a faster rate. What this means is the Moment of Inertia is changing throughout the length of the pole and can easily be 15% different from one end to the other.
- Modulus of Elasticity is a material property and describes how it behaves with regards to stress and strain. What we can say is that E is not exactly the same throughout the length of the pole. To be the same we would have to have the exact amount of resin, orientation of glass fibers, density of fibers, and such the same throughout the span length.
- What do the above two points mean? From an engineering aspect, it is very dangerous to vary the length in the equation and then ratio back up the flex. An extreme example is illustrated below:
 - We took a 850084 – a 16'5" 185 pound pole that was tested with a span of 169.5". This pole had a flex number of 17.5 (i.e. – 185 rating)
 - We flexed the pole using a 108" span and did this starting at the tip end and then again at the top end of the pole. There was a 15lb rating difference between these two flex tests. The tip end was 2% heavier than the total pole and the top end was 17% lighter than the total pole.
 - What this also points out is that sail piece placement and design will have a major impact on flex if you start varying the span placement.
- Since 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. The testing done to this point has shown the following:

- When the ratio of flex divided by span or as shown above in the formula: $\Delta \div l \leq$ 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 you will move about one pole weight. As the ratio increases the change in pole wgt class would also increase. Since not all poles are designed the same, we have not listed the values that our testing have found for our poles.

Column Theory is a good predictor of weight rating when changing your grip height on a pole:

$$P_{cr} = EI \pi^2 / L^2$$

Above equation is usually called **Euler's formula:**

P_{cr} is critical load – or in our case weight

P_n = Load or weight rating of the pole

P_{lg} = Load or weight rating at a lower grip

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

If you use a 14' 150 lb pole – at 13'6" would give a 161 lb. This matches well with numerous published guides including Gill Athletics, Inc. and UCS which indicate about 10 lbs for a six inch change. Again, this is a fair “rule of thumb” since I and E are not or may not be constant throughout the length of the pole.

What does all this mean? It means you can use some basic engineering principles to help refine the development of a better tool. It would be arrogant to think that the perfect pole has been developed.

Design and Testing for today and the future.

Some of the key areas that are and we feel will be investigated are as follows:

- Non-linear stress strain behavior of materials and how this could be utilized for a better pole.
- Double taper mandrel concept similar to what Gill Athletics, Inc. has patented for its original carbon javelins.

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