Fundamentals of the Design of Olympic Recurve Bows

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Abstract

Modern materials and fabrication methods offer new opportunities to redesign competition recurve bows. Through improved bow geometry and proper construction methods, designs can be created which propel arrows with greater energy and efficiency, smoothness on the draw, and stability than before. This paper outlines the physics of bow behavior, and how desirable performance characteristics can be quantified. Also examined is how changing the bow geometry, new materials, and construction techniques can lead to improve bow performance. Recommendations are forwarded on how target bows can be redesigned for better performance in the future.

Introduction

The performance of Olympic recurve bows has advanced dramatically over the past two decades as a result of new materials and fabrication methods that take advantage of these materials. However the basic geometry of these bows, which is typified in Figure 1, has remained relatively unchanged, except for a few isolated models, during this same period. In order to realize the full potential performance improvement offered by new materials and manufacturing methods, the geometry of the bow must be optimized. In this paper, the fundamentals of Olympic recurve bow performance and design are reviewed. These fundamentals can be used to guide future improvements in bow design.

Figure 1. Olympic recurve bow.

The most basic representation of a bow is as a spring. As any spring is pulled back, the resistance force increases with the deflection to create a deflection-force curve (DFC). The energy stored in the spring is the area under the DFC. For the familiar coil spring, the DFC is linear, as shown in Figure 2. For a cantilever spring, however, the DFC is non-linear, as both the force and the differential force both increase as the deflection increases. As the deflection increases, the cantilever deforms in the direction of the force, such that the force becomes one that is applied axially to the cantilever instead of transverse to it. A bow can be treated as a two-sided cantilever that is held in the middle by the bow hand. When a bow is drawn back by an archer, the distance that the string can be drawn back to the anchor point on the archers face, and the force that the archer can hold at that point, are two limits that restrict the deformation and stiffness of the bow. For an archer, the maximum draw length and the maximum holding force are constant, no matter what bow design is used.

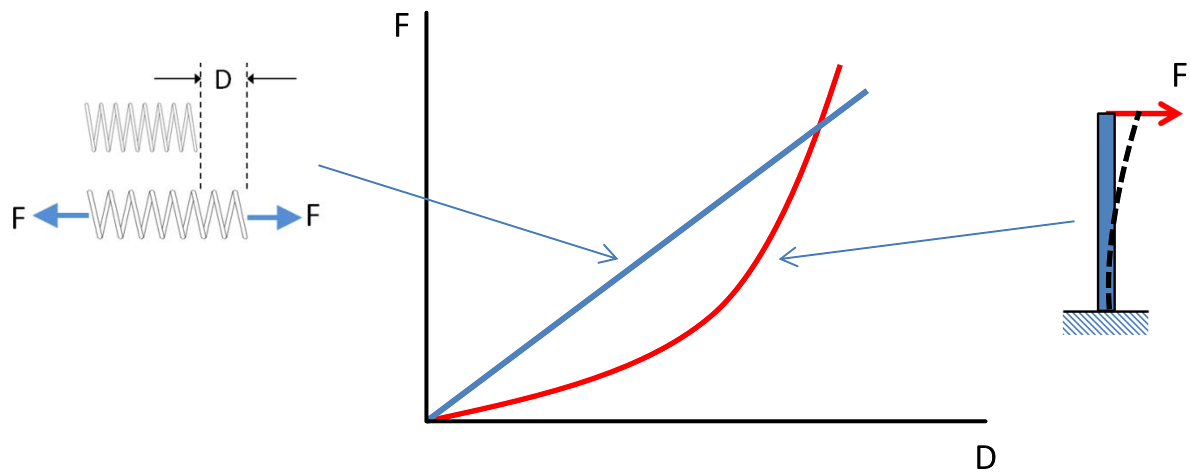

Figure 2. Draw Force Curve (DFC) for coil spring vs. cantilever spring.

The performance criteria for bow design have been identified by Park [2008] as speed, smoothness, and stability. For a given draw length and holding force, speed is the initial speed of an arrow when it is launched from the bow. Smoothness is the uniformity of the draw force, especially near the maximum draw length. Stability is the tolerance of an arrow trajectory to errors made by the archer. While better speed, smoothness, and stability are generally accepted in the archery community as desirable features for a bow, the methods by which these qualities can be improved by bow design have remained elusive. The fundamental problem in bow design, therefore, is to identify how these qualities are produced, and what variables should be changed to modify them.

Improving Speed

The resultant speed of an arrow when it leaves the bow is dependent on two quantities: the energy that is stored in the bow, and the efficiency with which this energy can be transferred to the arrow. Park [2008] quantified the approximate effect of changing selected variables on the launch speed of an arrow, as shown in Table 1. While the maximum draw length and the maximum holding force are fixed, the shape to the DFC below these limits is variable. Part of bow design therefore turns to ways in which the DFC can be modified to increase the area under the DFC, which is the energy stored in the bow.

Variable		Speed Increase
bow weight	1 pound increased	about 2 f/s
draw length	1 inch longer	about 3 f/s
brace height	1cm lower	about 1 f/s
string strands	2 strands less	about 1 f/s
bow length	2 inch shorter	about 3 f/s
arrow	X7(2114) to X10(410)	about 6 f/s

Table 1. Effect of changing selected variables on arrow speed, from Park [2008].

In a primitive bow, shown in Figure 3, which has simple deflected cantilever geometry and relatively short length when compared to more advanced designs, the cantilever deforms rather quickly into the direction of the draw force as the bow is drawn. This deformation causes the draw force and the force rate to monotonically rise as the bow is drawn. In the archery community, this effect is known as "stacking". Since the maximum force at full draw is fixed, the initial force rate must be kept low in order not to exceed this force. The result is a DFC that falls below that of a linear spring, and where both the force and the differential force monotonically increase with draw length. One method of reducing the stacking effect is to simply make the bow longer, as shown in Figure 4, so the relative transverse deformation of the bow compared to its length is reduced. Long bows thus store more energy for the same draw force and draw length than primitive bows.

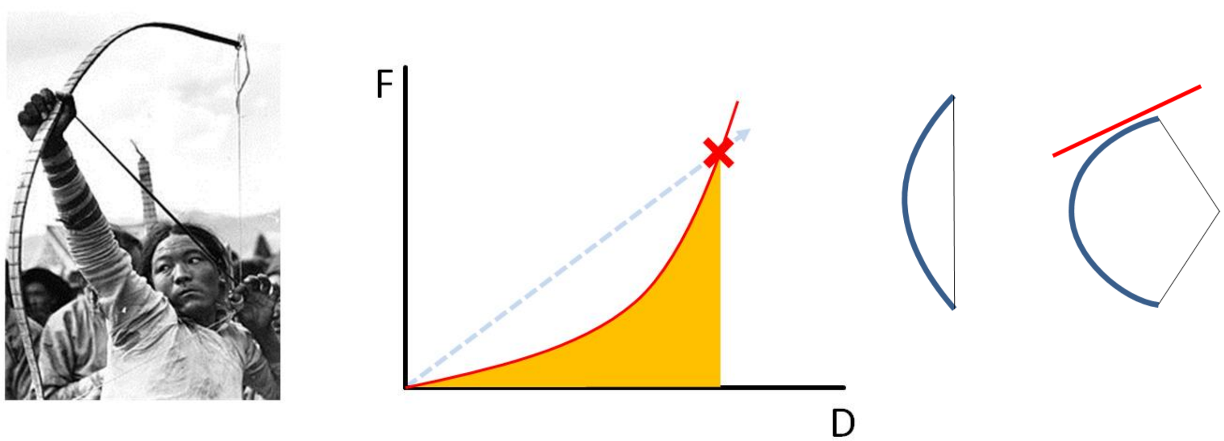

Figure 3. Idealized DFC for linear spring and primitive bow, with maximum limit for draw length and draw force.

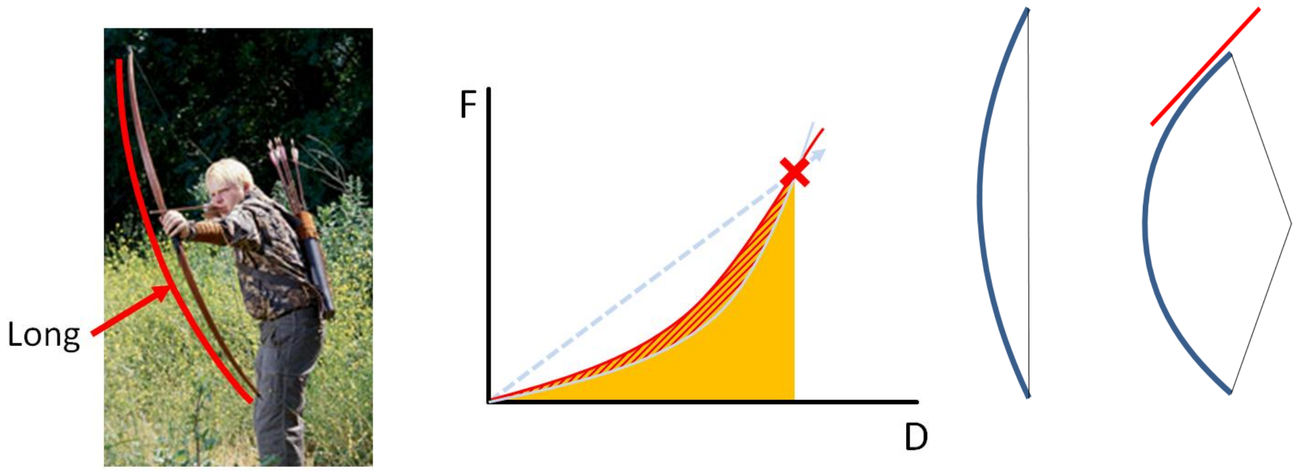

Figure 4. Idealized DFC for a primitive bow compared to a long bow, with maximum limit for draw length and draw force.

The geometry of a recurve bow includes a portion at the tip that is preformed to initially point in the opposite direction of the draw force (i.e away from the archer). As a recurve is initially drawn, the pre-deformed tip is in the opposite direction of the draw force. As the bow is further draw, the tip begins to straighten. As the maximum draw length is approached, the tip once more is deformed in the direction of the draw force. The resulting DFC is rather unique, as shown in Figure 5, rising above the DFC for a linear spring, and then falling again. The energy stored in a recurve bow is a significant improvement over the energy stored in a long bow for the same draw length and draw weight.

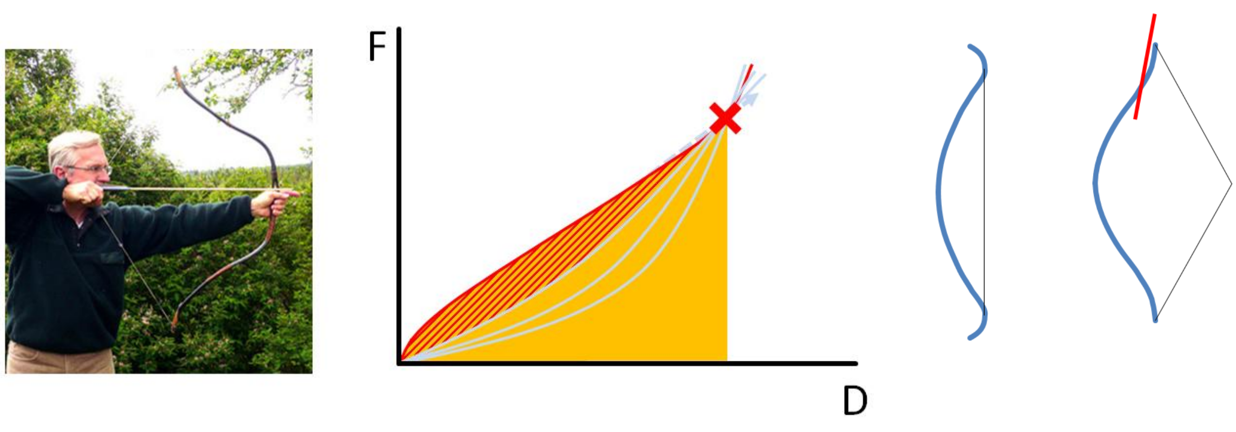

Figure 5. Idealized DFC for a recurve bow compared to a long bows and primitive bows.

A recurve bow has the added advantage that the improved energy content can be gained without the need to make the bow longer, thus reducing its size (and improving its portability) and mass when compared to a long bow. The reduction in mass, in particular, leads to better efficiency and thus to further improvements in arrow speed.

Olympic recurve bows appear to be a hybrid between a long bow and a traditional recurve bow. While the tips of an Olympic recurve bow retains the general shape of a recurve bow, it is also longer that a traditional recurve bow, but not quite as long as a traditional long bow. The rather unique geometry allow the Olympic recurve bow to exploit some of advantages of energy content and efficiency of traditional recurve bows, while maintaining some of the advantages of stability of traditional long bows. Bow stability is discussed later below.

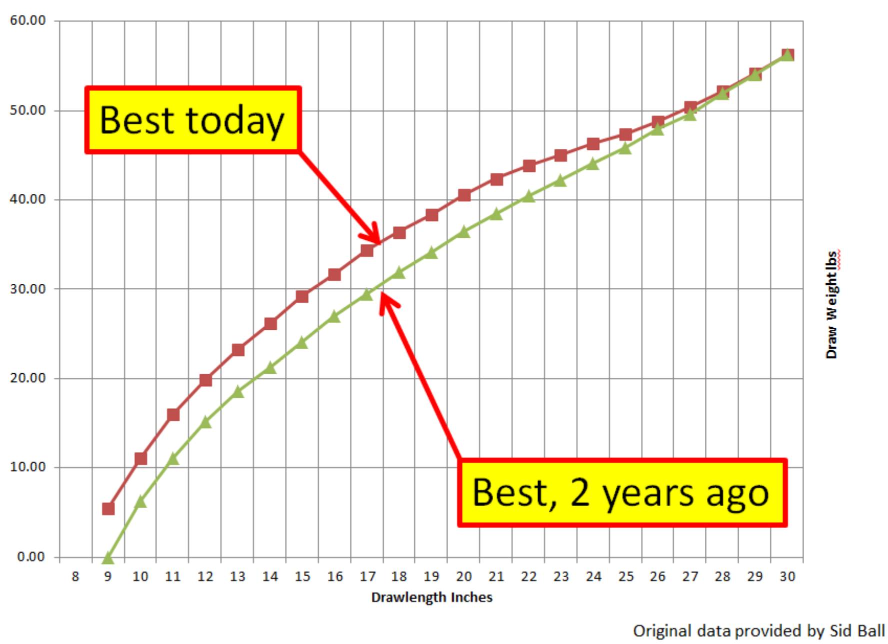

Figure 6. Actual measured DFC from Olympic recurve bows.

The measured DFCs from the best (for energy content) Olympic recurve bow at present, compared to the best that was available two years previously, show a significant improvement in energy content, as seen in Figure 6. The improvement was due mostly to more aggressive recurve geometry, shown idealized in Figure 7, used by a small manufacturer, instead of the typical recurve geometry used by most manufacturers.

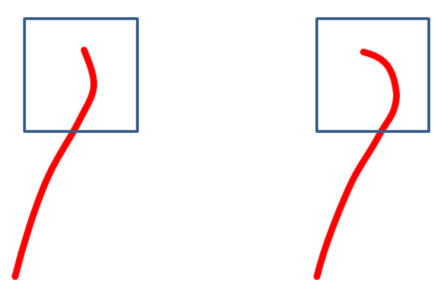

Figure 7. Typical (left) recurve geometry compared to more aggressive recurve geometry.

Recurve geometry can be crudely defined in terms of the length and the depth of the recurve, as shown in Figure 8. While the depth of the recurve can be easily defined as the distance that the tip of the bow curves away from the archer, the length of the recurve is not obvious. The length of the recurve can be defined by the location of the inflection point where the rate of slope of the bow geometry changes direction. Mathematically, this location is where the second derivative of the limb geometry is zero.

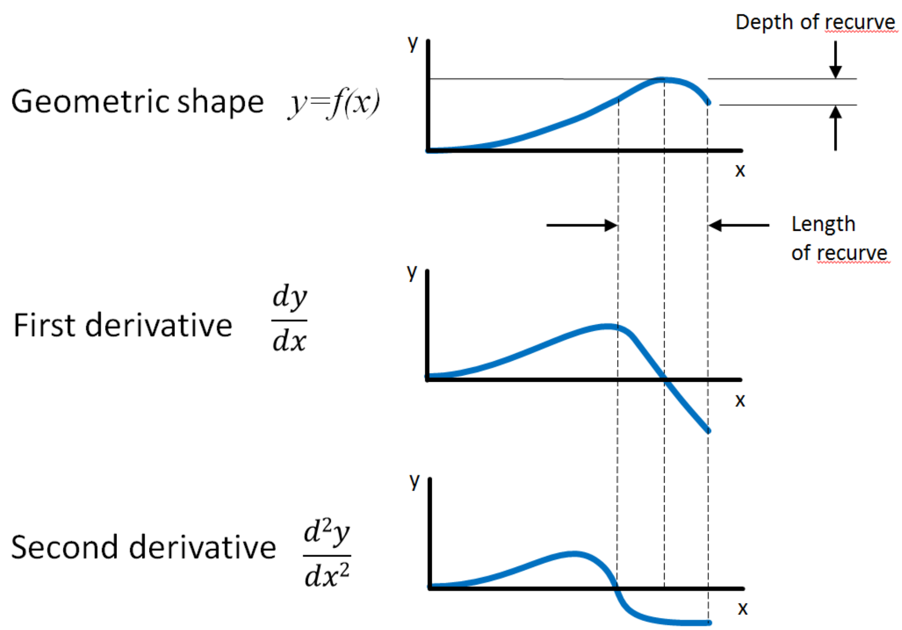

Figure 8. Recurve depth and length. Limb shape, and its first and second derivatives.

Since stacking is caused by the alignment of portions of the bow in the direction of the draw force, increasing the depth of the recurve increases the draw force at the beginning of the draw cycle for the same final holding force and draw length. As the recurve straightens, the differential force drops. As the original recurve bends backward in the direction of the draw force, the differential force increases again, and the bow begins to stack. Increasing the length of the recurve causes the bow that is proximal to its center to align to the draw force, which also increases the draw force at the beginning of the draw cycle for the same final holding force and draw length. The increased draw force at the beginning of the DFC allows more energy to be stored in the bow for the same final draw weight at the maximum draw length.

Improving the efficiency of a bow (for the same arrow) is straightforward. The efficiency of the bow will be dependent almost entirely on its mass. The lighter the moving parts of the bow are, the more efficient the entire bow will be. Upon releasing the string at full draw, part of the energy that was stored in the bow will be converted into the kinetic energy of the moving arrow, with the remainder converted into kinetic energy that remains in the moving parts of the bow. The lighter the moving parts of the bow, the less kinetic energy that will remain in the bow, since kinetic energy is directly proportional to the moving mass.

Improving Smoothness

The smoothness of a bow can be described as the lack of abrupt changes in the draw force as the bow is drawn. This quality is particularly desirable in the portion of the draw near the maximum draw length. In the target archery community, it is generally considered desirable to have a low differential draw force near the maximum draw length. Smoothness can be qunatified by examining the slope of the DFC, as shown in Figure 9. A high differential force would be seen as a higher slope of the curve and thus less smooth. A lower differential force would be seen as a lower slope and thus more smooth.

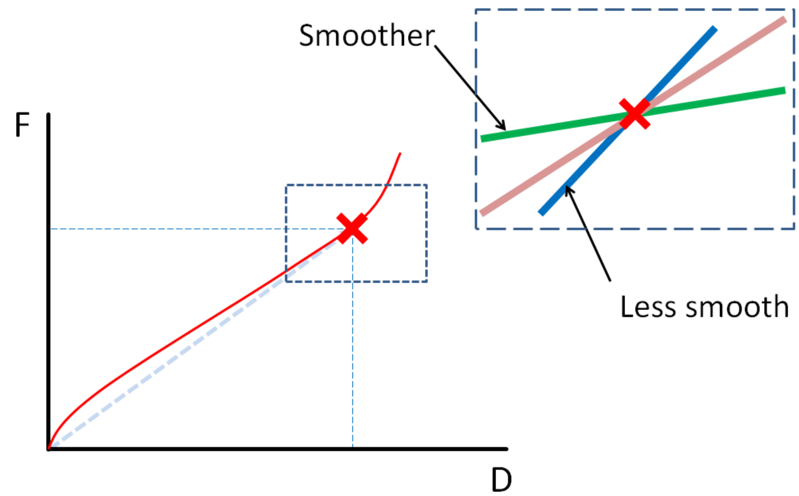

Figure 9. Smoothness, as seen on a DFC, near the maximum draw length.

If the first derivative of the DFC is plotted against draw length, as shown in Figure 10, a lower value of the first derivative would be interpreted as being smoother. The smoothest location along the draw length would be seen as the location of the lowest part of the first derivative curve of the DFC.

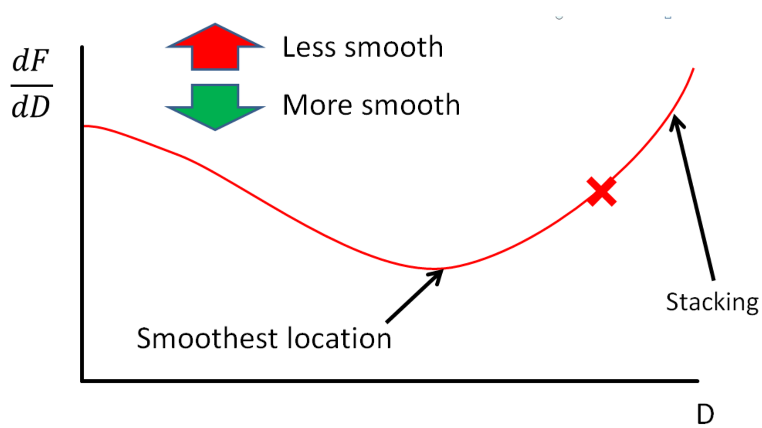

Figure 10. The first derivative of the DFC shows the differential draw force and reveals the location and value of the smoothest part of the draw cycle.

A plot of first derivative curve of the DFC for existing limbs, shown in Figure 11, shows that the smoothest part of a typical recurve limb geometry today is not necessarily in the region of typical maximum draw lengths (26" – 31"). However, the best measured first derivative curve on an existing limb shows that it is possible to design a bow that has the smoothest part of the draw cycle in the region of typical maximum draw lengths.

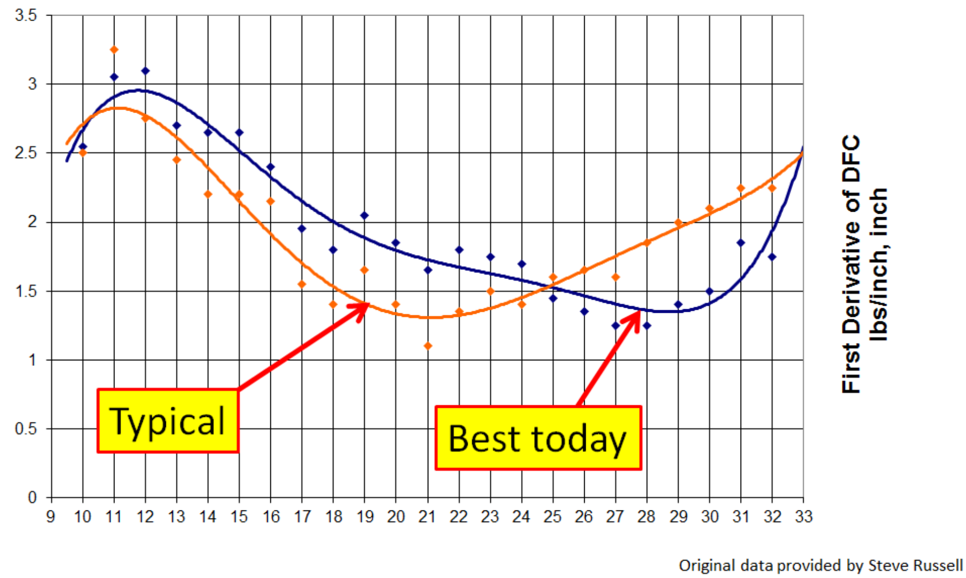

Figure 11. Actual first derivative curves from existing limbs, showing typical and best measured smoothness and its location.

Within the target archery community, stacking is often considered to be the primary cause of a bow to be less smooth near the maximum draw length. Since stacking is caused by the limbs of the bow becoming oriented in the direction of the draw force, stacking can be reduced by shaping the limbs such that they remain more transverse to the draw force at the maximum draw length. Using this design approach, the smoothest part of the DFC can be moved further back in the draw cycle by making the recurve part of the limbs deeper. Under crude observation, the smoothest part of the DFC will likely appear in the part of the draw cycle when the tips of the limbs are nearly vertical. Beyond this location, the limbs tips will begin to orient themselves in the direction of draw force, and stacking will begin.

Improving Stability

Caution must be exercised when designing a bow with recurve, because bows with greater recurve can also be less stable unless the proper provisions are made to improve the stability. The stability of a bow is its ability to minimize errors induced by the archer upon release of the string, and still have the arrow assume its desired trajectory. This quality is known in the target archery community as "forgiveness". Since the string must move around the fingers upon release, the predominant error is inconsistent side-to-side movement of the string while the arrow is still attached to the string.

The ability to resist the side-to-side motion of the string (and thus the perturbations caused by release errors) is often associated with the torsional stiffness of the bow; however this resistance is also strongly associated with the shape of the bow. In a bow with no recurve, such as a long bow, all parts of the bow are oriented toward the archer when moving along the limbs from the center of the bow to the tip. As the bow is drawn, a top view of a long bow in Figure 12 shows that the draw force tends to return the bow to its original in-line orientation when that orientation is perturbed slightly to one side. Upon release, the bow limbs drag the mass of the arrow (through the string) such that the return force tends to rotate the bow to its in-line orientation when that orientation is deformed slightly to one side, as would be induced by a release error. This behavior makes the long bow inherently stable at all draw length.

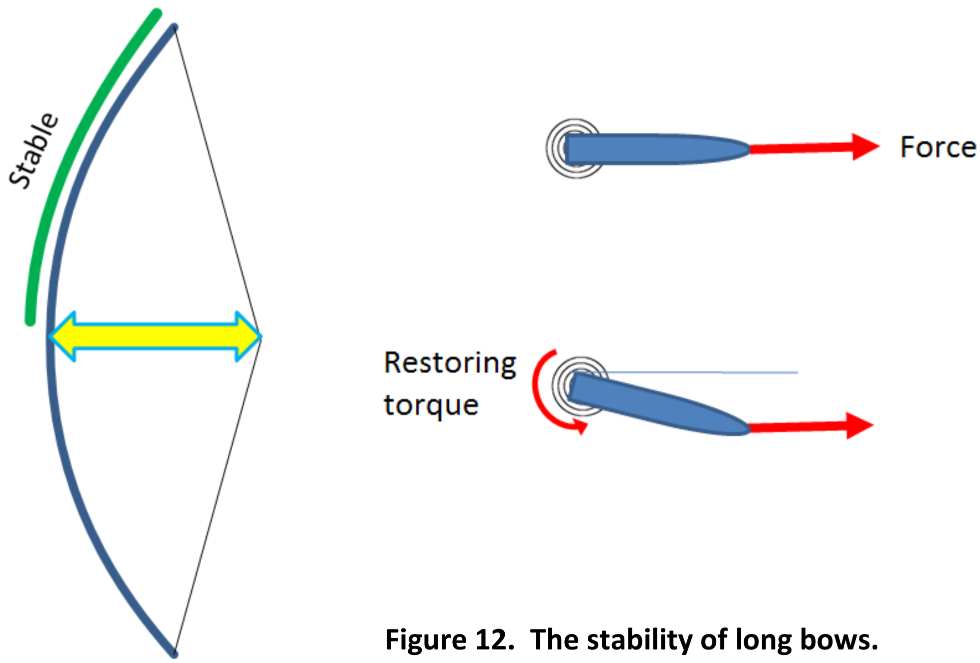

Figure 12. The stability of long bows.

In recurve bows, as the bow is drawn, a top view of the recurve portion of the limbs shown in Figure 13 shows that the draw force tends to force the bow even further out-of-line from its original in-line orientation when that orientation is deformed slightly to one side. Upon release, the bow limbs drag the mass of the arrow such that the return force tends to deform the bow even further out-of-line from its original in-line orientation when that orientation is perturbed slightly to one side, as would be induced by a release error. This behavior makes any bow with recurve inherently unstable for the parts of the draw or release cycle where any recurve exists. It is important to note, however, that as a recurve bow is draw further back, the recurve begins straighten, such that the entire bow is usually stable at the maximum draw length, as shown in Figure 14.

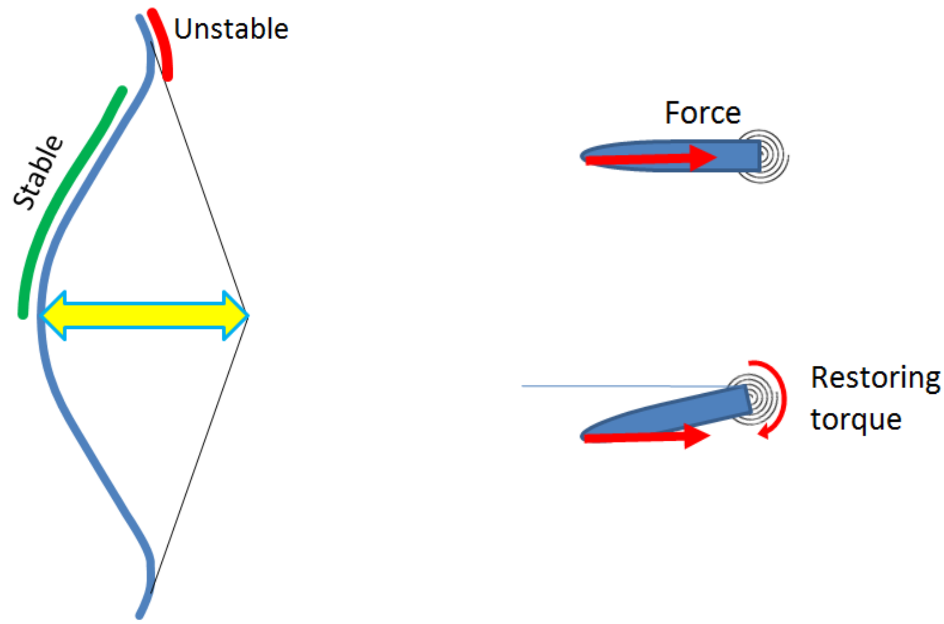

Figure 13. The instability of recurve bows.

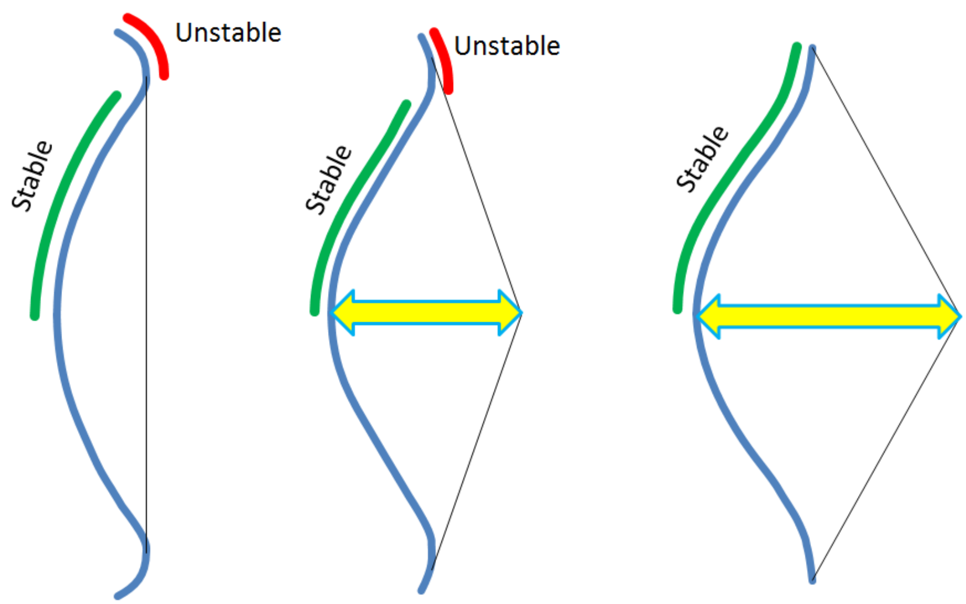

Figure 14. Stable and unstable parts of the draw cycle for a recurve bow.

Currently, the torsional stiffness of Olympics recurve bows vary widely among different manufacturers and models, as high as 50% even among bow limbs that are considered to be the best quality. Yet, all these bows have been proven successful in high-level competition. Since the shape of the recurve for these bows is nearly identical (and essentially unchanged for the past two decades), it is likely that that only a minimal torsional stiffness is required for this geometry, and additional torsional stiffness beyond this minimum yields little additional benefit. However, as the recurve geometry become more aggressive, it is likely that the minimum required torsional stiffness will increase, otherwise the stability of the bow may be compromised. Thus it would be prudent to increase the torsional stiffness of the bow as the recurve becomes more aggressive, as would be done to increase the energy content and smoothness of the bow at the maximum draw length.

Since enhancing the torsional stiffness of a recurve bow is likely necessary for reducing its instability as the recurve geometry becomes more aggressive, it is prudent to pursue methods for improving torsional stiffness of the bow. A cross-section of a modern Olympic recurve bow limb in Figure 15 shows that it is built in multiple layers. The outer layers are usually a fiberglass or carbon fiber epoxy matrix to produce strength and stiffness with low mass. Fiberglass is less expensive than carbon fiber, but has higher mass, less stiffness, and less strength than carbon fiber. Thus, more expensive bows typically use carbon fiber rather than fiberglass to reduce weight, and thereby improve efficiency. The core is usually carbon or synthetic foam, or wood, for low mass. Carbon foam typically is lighter than wood, and thus creates a slightly more efficient bow, but wood typically has better damping properties, creating a bow that vibrates less after string is released. Since the outer layers are typically a much stronger and stiffer material than the core, nearly all the stress during deformation of the bow is carried in the outer layers. When the bow is deformed during the draw, the stresses in the outer layers are primarily normal stresses, with principal directions that are oriented at 0° along the length of the limbs and 90° from the length along the width of the limb, as shown in Figure 16.

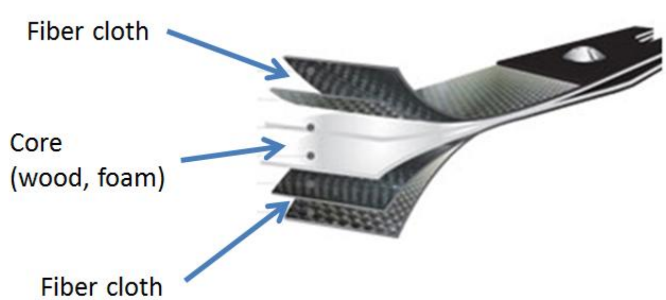

Figure 15. The layered construction of modern Olympic recurve bows.

When a limb is deformed by torsion, the stresses produced in the outer layer are primarily shear, as shown in Figure 17, which has principal stress directions that are 45° and -45° from the length of the limb on the flat face of the limb. In fiber composite materials, the stiffest direction of the material is along the length of the fibers. Since most fiber material is a woven in two directions that are 90° from each other, laying the weave such that the fibers are along the length and width at the outer layers produce a limb that is very good at resisting bending deformation.

To produce a limb that is good at resisting torsion, however, requires that the directions of the fiber be oriented at 45° and -45° to the length of the limb.

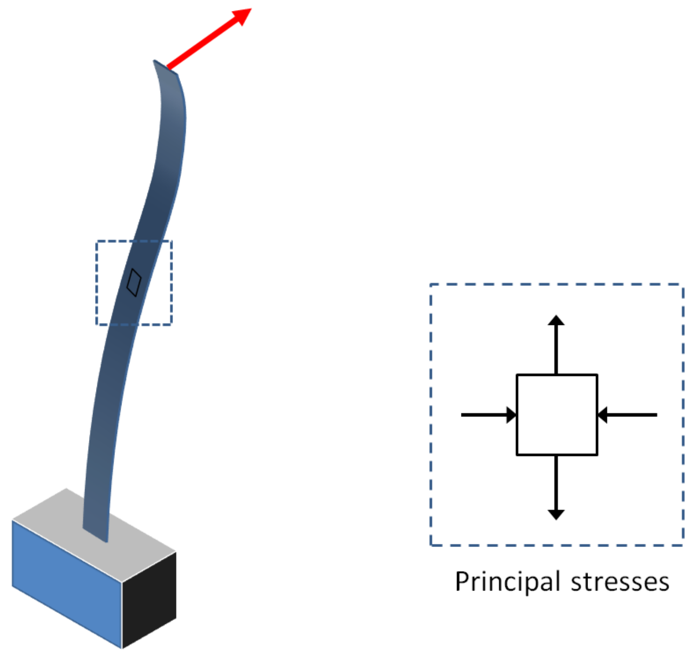

Figure 16. Principal stresses in a limb due to bending.

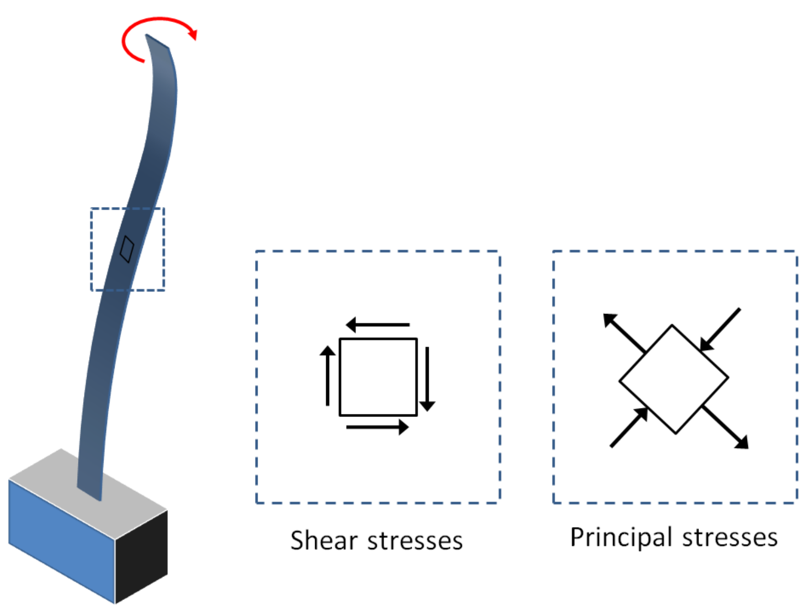

Figure 17. Principal stresses in a limb due to torsion

Figure 18. Orientation of the woven fiber in the outer layer, optimized for bending at 0° and 90° (left) and for torsion at 45° and -45° (right).

Since 0°-90° bi-directional fabrics are common, and also because these fabrics are often processed into long strips where the fibers are alight with the length and width of the strips, limbs are often manufactured with the fibers oriented along the length and width of the limbs because the fabric is easiest to process in this manner. Installing the fabric with the fiber directions turned by 45°, as shown in Figure 18, makes processing more difficult, thus increasing production costs. In addition to the common bi-directional weave, materials also exist with tri-axial weaves. Tri-axial materials, such as that shown in Figure 19, afford stiffness in three primary directions instead of only two. Although such materials are more expensive, a layer can be constructed to resist bending and torsional deformations simultaneously, without requiring a separate layer to resist each type of deformation.

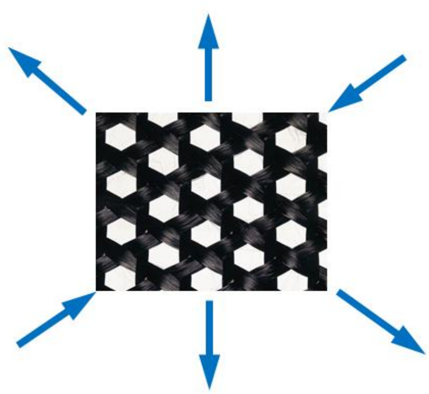

Figure 19. Tri-axial carbon fiber weave.

The primary advantage of any woven material is its ease in handling and processing during the manufacturing process. Any woven material is, however, inherently more elastic in any of its principal directions than the same volume of uni-directional in that direction. This is because the weaving processes naturally bends the fibers in a direction normal to the face of the fabric with each weave. The resultant zigzagging of the fibers in the principal directions increase their elasticity in those directions. The stiffest fiber material that can be produced for a single direction is uni-directional fiber, shown in Figure 20. In uni-directional materials, the fibers are oriented in a single direction only, without zigzagging. By using two independent layers, at 45° and at -45° and relative to length of the limbs, the torsional stiffness would be superior to either a bi-directional woven material (oriented at 45° and -45°) or a tri-axial woven material (oriented at 0°, 45°, and -45°). Uni-directional materials however are expensive to create, handle, and process, so they increase the cost of bow fabrication.

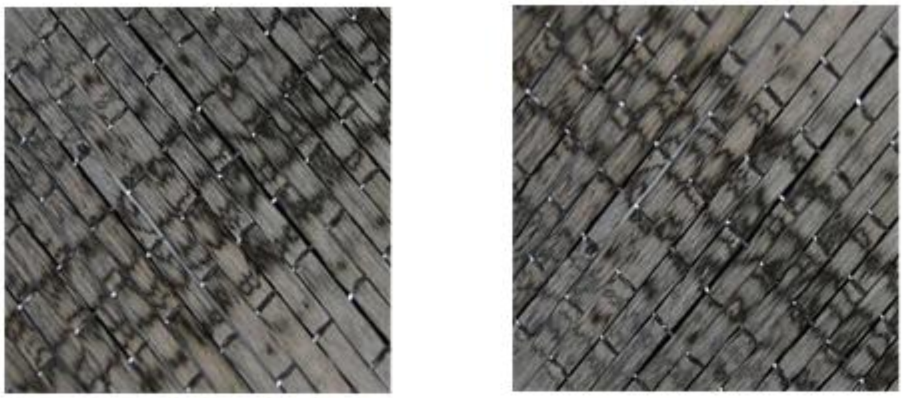

Figure 20. Uni-axial carbon fiber at 45° and -45°.

Conclusions

The appearance of new materials such a as carbon fiber composites, which are both lighter and stronger than previous materials, have improved the performance of Olympic recurve bows over the past two decades. Most of these improvements, however, came in the form of reduced mass in the moving parts of the bow, which generally led to improved bow efficiency. The overall geometry of Olympic recurve bows has remained basically unchanged, except for a few isolated designs, over this same time period. With a deeper understanding of how the geometry and deformation of a bow stores energy, generates smoothness, and affects stability, the geometry of the bow can be altered to take advantage of new materials to further improve bow performance. In particular, it appears that the recurve of the Olympic bow can be made more aggressive to increase energy storage and improve smoothness near the maximum draw length. However, doing so will likely require the improvement of the torsional stiffness of the bow to maintain, or perhaps even enhance, the stability of the bow. The use of uni-direction materials such as unidirectional carbon fiber, in the correct orientation to increase torsional stiffness, shows great promise as a means for enabling the design of bows with enhanced overall performance.

References

Park Kyung Rae, "What Function is Required for Bow?" Proceedings of the ISBS Conference, July 14-18, 2008, Seoul, Korea.