INTERNATIONAL CONFERENCE ON ENGINEERING AND PRODUCT DESIGN EDUCATION
6 & 7 SEPTEMBER 2018, DYSON SCHOOL OF DESIGN ENGINEERING, IMPERIAL COLLEGE, LONDON, UNITED KINGDOM

DESIGNING A BETTER ARCHERY BOW

Colin LEDSOME
Chair, IED

ABSTRACT
Archery has existed for at least 64,000 years. The design of the bow has evolved slowly over that time, but developments in materials and manufacturing methods since the Second World War have allowed rapid changes in this ancient technology. Bows and arrows seem to be a simple concept, but the details are far more complex than they appear. Most of the historic development has been carried out by craftsmen bowyers and fletchers (bow and arrow makers) on a trial and error basis producing several basic bow types in different parts of the world for different reasons. Today we can apply modern engineering and research methods to investigate the subtle details of this technology and suggest a path to future design developments. PhD research has shown some potential for development but more is needed. Archery can be used to introduce a number of aspects of technology to students and can provide the basis for design and test projects. We still can learn from this ancient technology.

Keywords: Archery, sports equipment, dynamics, vibration, shock loading

1 HISTORIC DEVELOPMENT

Early bows and arrows were made from natural organic materials, which leave little in the archaeological record. Flint arrow heads some 64 000 years old are the earliest abundant trace. Before that, fire-hardened points would have been sufficient for bow use for many thousands of years earlier. Homo sapiens began to leave Africa perhaps 180 000 years ago, but earlier types of human may also have developed and used archery. The earliest surviving bows are the 8000-year-old “Holmegaard” bows made of elm wood found in a Danish bog in the 1940s. A Neolithic bow over 7000 years old was found near Girona in Catalonia, Spain.

1.1 String

String is one of the oldest human inventions. The simple action of twisting individual fibres, then letting them untwist as a bundle, curls the fibres round each other generating friction forces, which lock them together making a single yarn. Fibres may be added along the length allowing long yarns to be spun from short fibres. Further twisting allows yarns to be made into strands, (often known as string) then ropes, cables and finally hawsers, each with an opposite twist to the one before. “Cordage” is the collective English name for them. They can be used as structural connections, snares, nets, woven fabrics …. and bowstrings. Fragments of twisted threads have been found at Neanderthal sites more than 100 000 years old. Interestingly, the twisting action needed to produce cords, or tie knots, requires an opposed thumb, a major difference between humans and our simian ancestors. We have probably made more cordage than any other product in history. Even so, the analysis of how twisted fibres bind together to form rope has yet to be resolved. 200 years ago, some 10% of the weight of a British Navy fighting ship was rope, mainly as part of its structure.

1.2 Bow evolution

Tying a string across the ends of a bent length of wood produces a form of spring, which can be used to propel a pointed shaft. Hunting parties probably drove animals past an ambush position where short-range arrows could bring down animals more easily than spears. Early arrow shafts would have had fire-hardened points, which were eventually replaced by sharp flint heads. The heavier head would also have produced an arrow which flew better and further. Feather fletchings would have kept the arrow flight straighter as bows became more powerful, increasing range and accuracy. The woods used depended on what was available locally for both bows and arrow shafts.

The Mongols, amongst others, developed "horse bows", short stiff bows with a recurved extension to gain extra stored energy, which were possible to use on horseback. Other materials including horn and sinew were used in laminated bows. Yew was popular in Europe as it is made up of two types of wood forming a natural laminate or "self-bow". Yew has pale outer wood, good for tension, and darker heartwood, which better resists compression. In England and Wales in 1363 all men were ordered to practice archery on Sunday and holidays. No other form of sport was allowed so as to produce the numbers of archers needed in the long wars against France and others. The yew available in the British climate was large grained and usually twisted, so the English longbow supply depended on the availability of straight, tight-grained yew, growing in the high, sheltered Alpine valleys of Italy and Switzerland. From 1472, yew bow "staves" were the import-duty on goods brought into English ports at a rate of four staves for every ton of cargo.

2 MODERN BOWS

The development of personal firearms gradually retired the bow from military use beginning in the late 14th century and for many years archery remained a niche activity. It developed as a target sport early in the 19th century and was popular in Victorian England for both women and men. Archery was included in the modern Olympics in 1900 and occasionally until 1920. Longbows were used for several events. It has been included since 1972 with a specific type of Olympic recurve bow.

The development of the modern recurve began after 1945 when an aluminium bow was produced, which could be easily taken apart in two pieces. Then fibreglass laminates were developed which could be used for the limbs of a bow. This allowed the limbs to be detachable from the central handle or "riser" producing a "take-down" bow able to be packed into a smaller case. The modern riser has attachment points for a sight, an arrow rest, stabilizers, a hand grip and other equipment allowing bows to be modified to suit different archers. Aircraft grades of aluminium tubing became the preferred arrow shaft, with plastic fletchings replacing feathers. Today, high-performance bow limbs and risers, along with arrow shafts, are made from carbon fibre materials. Even the strings are made from the very stiff synthetic fibres originally developed for tyre reinforcement. Typical arrow speeds from a tournament level recurve bow reach 65 m/s with peak accelerations of 700 – 1000g.

In the early 1950s, the "compound" bow was invented in the USA as a hunting bow. By using cams and pulleys with a very stiff bow, they were able to store a higher level of energy by pulling through a peak load to drop back to a low pull when fully drawn. This allowed a hunter to draw the bow in anticipation and wait until a clear shot became possible. This has since become popular as a target bow and may be allowed in the Olympics in the near future. Arrow speeds from compounds can exceed 100 m/s with peak accelerations of 1500 – 1800g.

3 RESEARCH

Some 12 years ago, at Imperial College London, I supervised a PhD student, Leonora Lang (1), investigating ways to improve the design of the Olympic recurve bow. She researched the existing literature (2, 3, 4) and investigated the behaviour of several bows using high speed filming, tensile test machines, vibration sensors, strain gauges and more. The results extended our understanding and allowed her to suggest options for improving the performance of bows and arrows. I have continued to develop this thinking to design aids for adjusting bows and point to further research. The rest of this paper summarizes these findings.

One surprise, was the realization that as a bow is drawn the stress in the bow itself increases, but the tension in the string decreases. This is because the mechanical advantage of the string angles increases faster than the force component bending the bow. Since the string has a higher hysteresis than the bow, this can produce an apparent small negative hysteresis in the bow acting as a spring. When you load the bow, you are unloading the string. The pre-stressing, which occurs when the bow is strung, complicates the mechanical and structural behaviour of the bow when slowly loaded and unloaded in a tensile test. Add in the transfer of energy from the archer to the bow, and the bow to the arrow during the shot, then the shock loading and subsequent vibration in the bow after the string becomes straight, and theoretical modelling becomes very difficult.

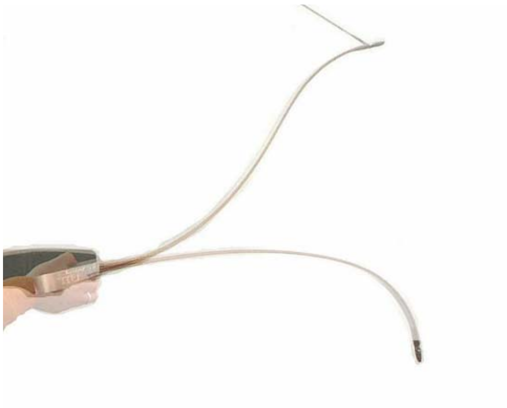

Figure 1. Limb flex from unstrung to full draw

A modern recurve bow of carbon-fibre materials can transfer over 70% of the strain energy put in by drawing the bow into kinetic energy in the arrow. The rest initially accelerates the limbs and string, then becomes vibration energy in the bow and replaces the strain energy in the string as its tension increases. The flexing of the limbs from unstrung to full draw is the highest deflection of any carbon fibre structure in service, Figure 1.

A recurve bow is not symmetrical. The “draw force line” is the line between the contact points in the two hands of the archer and is angled below the arrow line. If the two halves of the bow were equally stiff, the nocking point on the string would move downward relative to the arrow shaft during the shot giving the flight an initial upward tilt. In fact, the upper limb is less stiff than the lower one (known as “tiller”). This causes the riser to tilt downward slightly as the bow is drawn lifting the line of travel of the nocking point to coincide with the arrow shaft. Thus, the arrow is propelled from the rear directly along its axis, Figure 2. The tensions in the two parts of the string are different during the draw but become equal when the string is released.

Figure 2. Key force lines at full draw

The release of the string from the fingers gives it and the end of the arrow a sideways kick sufficient to bend the arrow shaft. The force from the string is now acting slightly sideways pushing the arrow against a sprung button mounted in the riser. This spring is adjusted, for position and pre-load, to absorb some of the lateral energy, giving a straighter flight. (This adjustment is known as “tuning” the bow.) At its maximum acceleration, the arrow is only in contact with the button for some 30mm of travel before aerodynamic lift and the vibration of the shaft moves it away. The stiffness of the arrow shaft must be chosen to allow it to remain clear as it vibrates and curls around the riser. An arrow is a lifting body and flies some 70 – 80% further than an equivalent ballistic mass at the same speed. Its aerodynamics as a long shaft, with a weighted point, initially vibrating in a horizontal plane, guided by rear vanes, has not been fully explored. The experimental difficulty of simulating that original sideways flip and recording the motion of the arrow in flight in a wind tunnel is challenging.

4 POTENTIAL IMPROVEMENTS

4.1 The riser

A major difference between a traditional bow and an Olympic recurve, is the provision of a “bow window”, where the riser bends out of the way, allowing the arrow to lie in the centre of the bow and allowing the use of an adjustable sight, Figure 3. The riser in this area has a rectangular cross-section. This inevitably introduces a slight twist, when the bow is drawn, because the flexural centre is out of line with the bow bending plane. As a result, when the arrow is released, there is a small torsional vibration affecting the lateral motion of the string. A little structural engineering expertise could change the rectangle to a shallow channel section, with its flexural centre lying on the bending plane, thus eliminating the tendency to twist. This has yet to be implemented.

Figure 3. Riser showing bow window

4.2 Bracing height

The “bracing height” of a bow is the distance between the undrawn string and a fixed point on the riser. This is critical to the efficiency of the bow. For any recurve bow, there is a specific bracing height where the bow imparts a maximum amount of energy to the arrow. Finding this state, even approximately by trial and error, can take many hours of shooting over several days. During the PhD research, we needed to know the tension in the undrawn string, so set up a string incorporating a strain gauge package and a screw adjustment to change its length. With this, we found that the tension peaked at the ideal bracing height. This could be found in 20 minutes. Trials showed that bows were indeed not only more efficient, quieter and had much less vibration after the shot. Simple equipment to do this is not in general use.

4.3 Tiller check

The difference between the stiffness’s of the two halves of the bow is adjustable, in a take-down bow, by screws on the joint-pockets between the limbs and the riser. These are usually pre-set by the manufacturer in a new bow. Ad-hoc methods for getting this tiller right; perhaps after changing the draw-weight of the bow, have been subject to interpretation. Observing that the aim is to produce a propelling force along the line of the arrow produced a potential solution. A simple pointer is attached to the riser to indicate the string nocking point when the bow has been strung. As the bow is drawn, and the riser tilts forward, this pointer should remain on the axis of the arrow shaft if the propelling force is to act along it. If not, the tiller should be adjusted. This method has not been adopted.

4.4 Fletchings

The traditional thinking is that fletchings need to be as far back as possible to maximise their stabilizing effect on arrow flight. For an arrow with no vibration in still air, this would be so.

However, for a realistic arrow flight, with a significant initial lateral vibration, this is not ideal (5). As the arrow leaves the bow, the fletchings are waved from side to side causing the arrow to weave in flight. By moving the fletchings forward, close to the vibration node point, the fletchings remain on the flight line and the arrow flies straighter. Since the vibration takes more than a second to die away, this effect lasts for most of the flight for normal target ranges up to 90m. There also seems to be a secondary effect. The lateral vibration of the string, as it initially propels the arrow, is dampened by the motion of the fletchings close to the nock, passing a slight sideways vibration to the bow. When they are moved forward, this is reduced making the bow feel steadier.

One line of research could be to investigate the replacement of arrow fletchings with a pattern of dimples or ribbing at the rear of the shaft. It may be possible to produce an equivalent stabilizing effect with less drag. This could result in faster, more consistent arrow flight, with less sensitivity to side-winds.

4.5 Spinning arrows

Traditional feather fletchings, from the wing feathers of a goose, have a lift effect by being rougher on one side. This introduces a tendency to spin the arrow. Spin is often given with plastic fletchings by setting them at a slight angle or by using shaped fletchings designed for spin. Many archers believe that spinning an arrow has a similar effect to rifling a bullet, giving gyroscopic stability to the arrow. Measurements show that an arrow can spin at up to 2000 rpm soon after leaving the bow. For such a long thin shaft, any gyroscopic effect would require a rotation speed of some 20 000 rpm to be effective. An historic reason to spin a wooden arrow is to even out the effects of grain direction and any imperfections in its construction, which is unnecessary with modern arrow shafts.

Spinning arrows are also subject to the effects of Coriolis aerodynamic forces. For a clockwise rotating arrow, a side wind from the left will give more lift, and one from the right will reduce the lift. Thus, an outdoor tournament with a variable cross-breeze will disrupt spinning arrows more. Side winds also have a greater effect on the fletched rear of the arrow, turning it into the wind and thus reducing the deflection at the target. Little research has been done on these effects.

4.6 Stabilization

The riser and limbs combination of a take-down bow has made it possible to add weighted rods to the riser. These have three effects: they help balance the bow in the hand putting the centre of mass just in front of the bow hand contact point; they impart “yaw” inertia to the bow making it steadier during the shot; and they absorb some of the vibration energy improving the archer’s experience of the shot. Their disadvantage is that they add weight to the bow. There are several design options, as well as where they are attached. Some are simple tubes with end weights. The tubes are often tapered and usually contain a powder as a damping medium to absorb vibration. Some have several parallel rods, usually of carbon-fibre arrow shafting, connected at various points along their length. The spacing of these connections varies to absorb different ranges of frequencies. The end connector may be weighted to provide balance. Some tube stabilizers carry an end weight on a rubber mount (often referred to as a “doinker”), which is very efficient at absorbing a range of vibration energy. Tests during the PhD showed the doinker type was slightly better than the multi-rod version at energy absorption, but no simple methods are available to tailor them for particular bows other than simple balance. Further research could refine these designs.

5 FURTHER RESEARCH AND DESIGN OPPORTUNITIES

Several design opportunities in recurve bows, arrows, and ancillary equipment, have been highlighted above. As more new materials and production methods, such as, perhaps, titanium for risers and additive manufacture for accessories, become available, further changes to bow design may become possible. More traditional bows, including longbows, flat-bows and recurve bows, as well as the further development of compound bows, bring a wide range of research and design possibilities.

An arrow is not a simple mass but vibrates in several modes on impact increasing its penetrating power. A modern recurve can give a target arrow sufficient energy to have a greater penetrating power than a 9mm bullet at shorter ranges. Hunting arrows shot from compound bows have been shown to pierce “bullet-proof” vests. Historic evidence shows that wooden arrows with “bodkin” heads could shatter chain-mail and penetrate light plate armour. Current work on the effects of different arrow-heads on gelatine blocks, to simulate flesh wounds, is being carried out in forensic science research at Abertay University in Dundee.

6 EDUCATIONAL OPPORTUNITIES

Although archery is a simple concept, it illustrates a number of technical principles. Examples of simple bending, pre-loading, springs and damping, vibration, hysteresis, shock loading, aerodynamics and more can be derived along with projects to research the effects of design changes. Arrows can be "customized" with number decals and colours of shafts, fletchings and nocks. These are used to distinguish between different archer's arrows in a target. Bows themselves come in different colours and are often chosen for their appearance. The product design aspects of archery equipment are rarely explored.

7 CONCLUSIONS

Archery uses the oldest craft manufactured products still in use today. Many of the details of the function of bows and arrows are poorly understood and have provided some design projects and research challenges for students at all levels. A simple model of the bow's action provides examples of a number of basic structural, mechanical and material behaviours for educational purposes. The interaction between a bow and an archer show a range of opportunities for research in product design, sports engineering (including disabled archery), engineering design and a number of other technical fields, which could have spin-off insights elsewhere, and continue to improve our oldest sport.

REFERENCES

[1] "An Investigation into the Material and Structural Design Parameters of the Archery Bow", Leonora Joyce Lang, PhD Thesis, Imperial College London, 2005.

[2] Ray Axford, "Archery Anatomy", Souvenir Press Ltd 1995 ISBN 978-0285632653.

[3] W. C. Marlow, "Bow and arrow dynamics," American Journal of Physics 49, 320–333 (1981).

[4] S. H. Joseph and S. Stewart, "Mechanics of the modern target archery bow and arrow," in Proceedings of the 1996 1st International Conference on the Engineering of Sport (Sheffield, 1996), p. 205.

[5] I. F. Zanevskyy, "Lateral deflection of archery arrows," Sports Engineering 4, 23–42 (2001).

FURTHER READING

"Longbow - A Social and Military History", Robert Hardy 1997. (ISBN 1-85260-412-3)

"The Great Warbow", Robert Hardy and Matthew Strickland 2005 (ISBN 10: 0750931671, ISBN 13: 9780750931670)

"The Medieval Archer" Bradbury, J. The Boydell Press 1985.

"The Ashley Book of Knots", Clifford W Ashley 1993 (first published 1944) Faber and Faber.

Wikipedia has a number of historic records on bows.