Functioning of ears and set-back at grip of Asiatic bows[1]

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1 Introduction

The outer sections of the limbs of the composite 'Asiatic' bows are stiff and bend backward. In figures and drawings shown in the literature with bows having these rigid ears, however, the angle between the free part of the string and the levers is small in braced condition. As an example I mention a drawing of the 'Omnogov' bow with sections in Atex and Menes[1, page 73], and the North Indian and Indo-Persian bows depicted in Latham and Paterson[2, page xxvi and xxix]. With some bows the string leaves even the tip of the limbs so that the string is free from the limb except at their nocks, see Boie and Bader[3, Fig. 2:'Inner Asian B'].

In the present paper I will investigate the influence of the shape of the ears and the reflex at the grip on the performance of the bow. An important question to consider is: why are the ears shaped so that the string leaves the nocks immediately or almost immediately when the bow is drawn? One would expect that the string must have contact with string bridges and leave these bridges somewhere before half draw. For, in that case, when the string touches the bridges the bow is effectively shorter than when free of these bridges close to full draw. This causes an sharper increase of the draw force in the first part of the draw than in the final part of the draw and the archer stores more energy in the bow. Moreover, just before arrow exit an effectively short bow could imply less kinetic energy in the limbs and hence a higher efficiency of the bow. This is presumably more important when the ears are heavy.

In order to be able to address this issue, the geometry of the ears has to be considered in detail. In simulation experiments on computer, the parameters which fix the functioning of the ears, such as the length of the ears, will be changed systematically in order to gain insight into their effect on the performance.

In Kooi[4] the performance of bows which resemble the Asiatic bows were compared with that of different type of bows such as the straight-end self bow, the composite angular bow and the modern working-recurve bow. I pointed out that the construction of the bow is more important than the mechanics of the bow. In this paper it is presupposed that the same construction materials are available to the bowyer for all bows studied. Consequently, the mechanics becomes again important for fine tuning in order to get the most out of the bow.

A reconstruction of the Ṭaybughā's bow is described in Ref.[2, page 170]. In this paper this bow will be analyzed also. It turns out that the mechanical performance is disappointing while experiments showed that it had 'a satisfactory performance by any standards'.

[1] *Journal of the Society of Archer-Antiquaries* **39**:73-77 (1996)

2 Description of the bow

We summarized all important quantities in the model which determine the mechanical action of the bow in Kooi[4]. The quantities are called design parameters. First I repeat the most important ones which describe the ears first.

length of the limbs
length of the grip
shape of unstrung working sections of the limbs
shape and mass of the ears

I recall that the classification of the bows I use is based on the geometrical shape and the elastic properties of the limbs.

- non-recurve: the limbs have contact with the string only at their tips.
- static-recurve: the outermost parts of the recurved limbs (the ears) are stiff. In the braced situation the string rests on string-bridges.
- working-recurve: the limbs are also curved in the 'opposite' direction in the unstrung situation, near the tips the limbs are elastic.

In this paper I will concentrate on the performance of the static-recurve bow and I will compare the results of computer simulations with data given in the literature where reconstruction trials for bows used by the 'Huns'[3] and a Mongolian bow, namely the 'Omnogov' bow[1], respectively are reported.

The definition of coefficients introduced in Kooi[4] are:

q: measures how much recoverable energy is stored in the drawn bow

η: the efficiency, that is the kinetic energy transferred to the arrow divided by the recoverable energy stored in the drawn bow

ν: the initial velocity of the arrow at exit

F: the weight

D: the draw

m_b: the mass of one limb of the bow

δ_{bv}: ultimate energy density

The first three coefficients are quality coefficients. They are defined for equal weight F, draw length D and mass of one limb m_b. This makes an honest comparison possible. The weight and draw depend on the strength and stature of the archer. The ultimate energy density δ_{bv} is a technological factor and represents the strength of the materials.

The dependency of the performance of the design can be explained as follows. One can think of the quality of a bow as defining a landscape where the position on the map is determined by the values of the design parameters and the altitude represents the performance which depends on the quality coefficients being functions of the design parameters. For example, with flight shooting the performance equates the velocity of the arrow. The landscape is, however, difficult to visualize. It has more than three dimensions unlike in our real world we live in. In our world a box has three dimensions, length, width and height and therefore the volume of the box is determined by exactly three numbers. In the case of the bow there are much more numbers needed for a complete description, namely all design parameters mentioned in Kooi[4]. As in reality, time plays its own role, it can not diminish and increases always. Generally, however, not all places on the map can be reaches because of constraints due to, for instance, shortage of good bow wood or materials for the string, lack of skill of bowyers, climate conditions and so on. Therefore, optimization is often local, in place on earth (area) as well as in time (era) and the improvements are relatively small. When new materials become available some constraints possibly become less severe and the feasible region in the design space is enlarged and consequently a higher top of a mountain, representing a higher performance, may become within sight. This process describes the development of the bow in different regions of the world though the ages.

When the static-recurve bow is the subject of discussion, all bows considered are relatively "close" to each other and form a cluster in the design space. This presupposes knowledge of a measure of distance in the design space, that is, the distance between two designs is defined. Suppose that two bows are exactly the same except the length of the working part of the limb. Then the difference in length can be used directly to define the distance between the bows. When several parameters with different dimensions differ a weighed sum of the differences can be chosen. Within such a cluster, in our case that of static-recurve bows, one bow is chosen to be the representative of this type of bow. The differences of all static-recurve bows to this bow are smaller than to bows of another type, for instance, a non-recurve bow or a working-recurve bow.

3 Description of a static-recurve bow

I show the unbraced, braced and fully drawn situation of the static-recurve bow in Figure 1. The ear is made up of two straight, rigid pieces each of length $1/2L_e$, where L_e is the length of the ear. The angle between those two pieces is denoted by θ_t. At the bend string-bridges are fitted in order to prevent the string from slipping past the limbs.

The ear starts in a direct line with the end of the working section of the limb. The mass distribution along the ear is chosen to be uniform and equal to the mass per unit of length at the connection point of the ear to the limb. The limb is set-back in the grip at an angle $-\theta_0(L_0)$ (the set-back is positive as $\theta_0(L_0) < 0$).

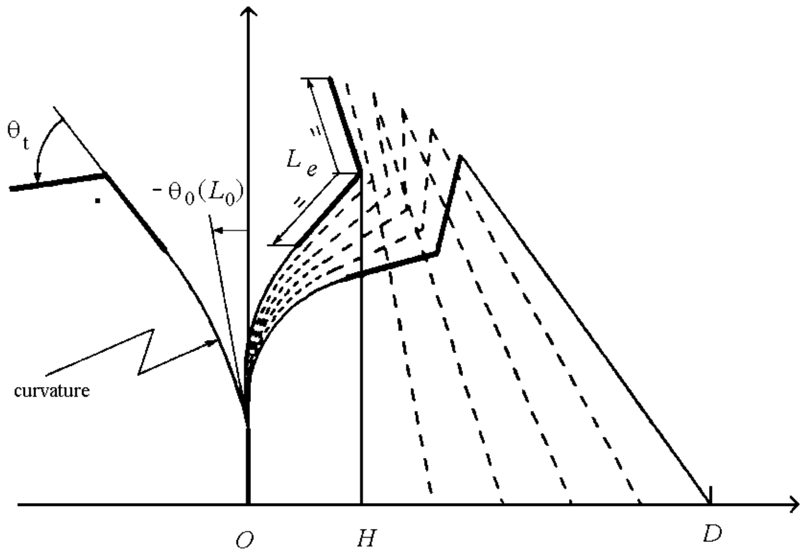

Figure 1: A static-recurve bow in various situations. In this paper I deal with the influence of the parameters, θ_t, L, $L_e/(L-L_0)$ and $\theta_0(L_0)$ on the performance of the bow.

3.1 Analysis of the PE- and TU-bow

I showed the static deformations at various draw lengths for two static-recurve bows, one called the PE-bow from China, India and Persia, and one called the TU-bow which resembles a Turkish flight bow in Kooi[4, Figure 2, page 24]. These two bows are also described in that reference. The working sections of the limbs of the TU bow are recurved backward while those of the PE-bow are straight, but otherwise the bows are exactly the same. Table 1 provides the quality coefficients of both bows.

Figure 2 shows the calculated Static Force Draw (SFD) curve and the Dynamic Force Draw (DFD) curves for these two static-recurve bows. The draw force is plotted as a function of the draw length. The area below this curve equals the amount of energy supplied by the archer in drawing from braced condition to full draw. Both, force and length, are scaled so that the weight and draw length both become 1 and therefore the area below the curve equals the static quality coefficient q by definition.

There is a bend in the SFD curve when the string looses contact with the bridges. In this way the ears provide leverage for the bowstring allowing more energy to be stored in the drawn bow (large q).

The DFD-curve gives the acceleration force acting upon the arrow during it discharge as a function of the draw length. The arrow leaves the string when this force becomes zero. Observe that this happens when the middle of the string has passed already its position in the braced condition. This is due to some elasticity of the working part of the limbs and the string. The area below this curve equals the amount of kinetic energy transferred to the arrow. This area is proportional to the velocity of the arrow squared, ν^2, for the kinetic energy of the arrow is half times mass of the arrow times the velocity squared. The ratio between the areas below the DFD-curve and the SFD-curve is the efficiency η.

Just after release there is an oscillatory behaviour of the acceleration force. The am-

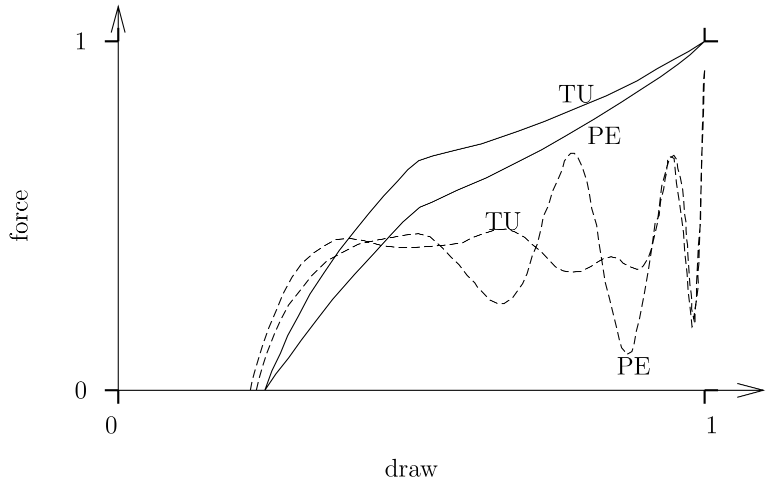

Figure 2: Static (solid line) and dynamic (dashed line) force-draw curves for the static-recurve PE-bow and TU-bow.

Table 1: The calculated quality coefficients for the PE- and TU-bow.

	PE	TU
q	0.432	0.491
η	0.668	0.619
ν	1.94	1.99

plitude depends strongly on the mass of the ears and on the stiffness of the string. During the final part just before departure from the string, the acceleration force is rather large. The force in the string decelerates the outer sections of the limb including the relatively heavy ears, and in that way it gives the arrow a final snap as it leaves the bow, see Ref.[5].

3.2 Sensitivity analysis

The PE-bow will be used as a starting point for changing design parameter values. In the previous section the curvature of the working sections of the limbs of the unstrung bow for the TU bow was already subject of analysis. In what follows I change the parameters θ_t, L the half length of the bow, the length of the ears relative to the effective length of the limb (is length of the bow L minus the length of the grip L_0), thus $L_e/(L - L_0)$ (see also Figure 3) and finally the set-back of the limb in the grip, $\theta_0(L_0)$. In all following tables the default parameter values for the PE-bow are underlined. For the PE-bow the parameter values are: $\theta_t = 60°$, $L = 1.000$, $L_e/(L - L_0) = 1/2$ and $\theta_0(L_0) = 0$. With $L = 1.000$ the bow length is twice the draw length and $L_e/(L - L_0) = 1/2$ means that half the length of each limb is stiff and this part forms the ear.

Angle, θ_t, and length, L: First I change the angle θ_t and the length L simultaneously, while all other design parameters are kept the same. Table 2 gives the calculated quality coefficients. In Figure 4 the SFD curves of bows with $\theta_t = 0°$, $\theta_t = 30°$ and $\theta_t = 60°$ are

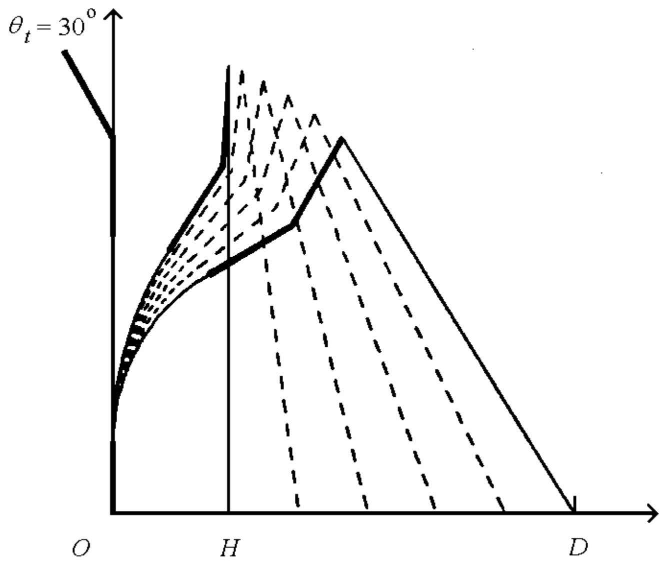

Figure 3: PE-bow with $\theta_t = 30°$ in various situations.

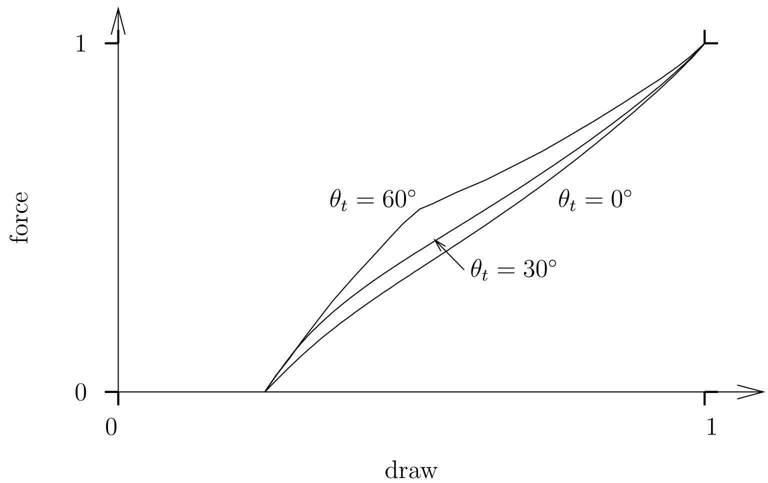

Figure 4: SFD curves for PE-bow with $\theta_t = 0°$, $\theta_t = 30°$ and $\theta_t = 60°$ (see also Table 2).

shown. For $\theta_t = 0°$ the bow is straight and the string has never contact with the string bridge. For the bow with $\theta_t = 30°$ this is also the case, as can be seen in Figure 3, in which I show the shape of this bow in various situations. Therefore the SFD curves in Figure 4 of these two bows with $\theta_t = 0°$ and $\theta_t = 30°$ increase without a bend. Calculations showed that the maximum q value was obtained for $\theta_t \sim 60°$.

The maximum velocity ν is obtained for $\theta_t \sim 30°$ and this holds true for all the three lengths. Hence, the largest velocity is obtained for a bow where the string does not lean against string bridges, see Figure 3. These profiles are often depicted in the literature, see Refs.[1,3]. Notice that when the bow is shorter, the length of the ears L_e is short too, for the length of the ears is taken proportional to the length of the limb ($L_e = 1/2(L - L_0)$). Longer static-recurve bows have a better static performance and also the greatest speed is obtained with the longest bow (the first three columns of Table 2), but the difference with the shorter PE-bow is rather small.

Table 2: Influence of length L and angle θ_t simultaneously, on the performance of the PE-bow.

L	1.286			<u>1.000</u>			0.7857		
θ_t	0°	30°	60°	0°	30°	<u>60°</u>	0°	30°	60°
q	0.400	0.441	0.470	0.373	0.397	0.432	0.301	0.314	0.314
η	0.770	0.740	0.765	0.782	0.788	0.668	0.796	0.809	0.723
ν	2.00	2.06	2.01	1.95	2.02	1.94	1.77	1.82	1.72

Table 3: Influence of the quotient $L_e/(L - L_0)$ on the performance of the PE-bow.

$L_e/(L - L_0)$	<u>1/2</u>	1/3
q	0.432	0.408
η	0.668	0.753
ν	1.94	2.00

Length of ear, $L_e/(L - L_0)$: I shorten now the relative length of the ear with respect to the length of the limb $(L - L_0)$. In Table 3 the results are given. As expected, the static quality coefficient is smaller when ears are shorter. However, the efficiency is much better and this produces a somewhat higher velocity with shorter ears. Comparison of the DFD curves with that of the PE-bow reveals that the amplitude of the oscillations is smaller for shorter and hence lighter ears. I conclude from these results that it is advantageous to use long but also light ears. Technical limitations determine of course what is realizable. With respect to this a statement made in Ref.[1] is very important. I quote from[1, page 75]

> The long tapering and forward curving tips were made of wood only, being stiffened by becoming thicker as they got narrower, and taking a ridged shape in their cross section. This modification of the old Hunnic design, eliminated the need for the heavier bone stiffening plates of the earlier bows. Doing away with the mass [$\cdots$] of the bone tips would have added a considerable amount of speed to the bow and would explain why the Mongols of the 13th Century were said to have used both light and heavy shafts. Horn, bone sinew and glue, is roughly twice the weight of an equivalent amount of hardwood and the elimination of these materials on more than a third of the outer portion of the limb would allow a much higher recovery speed of the tips, greatly increasing arrow speed, especially with light arrows.

Set-back of grip, $\theta_0(L_0)$: Attention is now directed to the influence of the parameter $\theta_0(L_0)$, namely the set-back. Bows with a straight working part of the limb, which are set-back in the grip at an angle $-\theta_0(L_0)$ are discussed. The quality coefficients are given in Table 4. A small negative angle $\theta_0(L_0)$, thus a positive set-back, appears to be

Table 4: Influence of the angle $\theta_0(L_0)$ on the performance of the PE bow.

$\theta_0(L_0)$	$-5°$	$\underline{0}°$	$5°$
q	0.437	0.432	0.421
η	0.684	0.668	0.648
ν	1.97	1.94	1.89

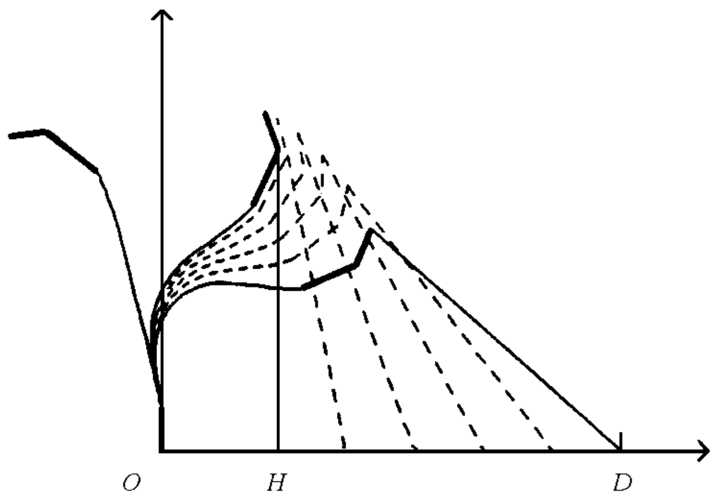

Figure 5: Deformation curves of the "Asiatic bow".

advantageous, both for static and dynamic performance.

Especially the Scytian bow[6, Fig. 5e] with the well known 'Cupido' shape had the set-back grip. The Ih Uul Sum archer's bow shown in Ref.[?, Plate 13] has also a heavily set-back handle section.

4 An Asiatic bow

In this section the Ṭaybughā's bow described by Latham and Paterson[2] is analysed. Photos of the reconstruction by E. McEwen are shown in Ref.[2, plate 18]. In Figure 5 the calculated shape of the bow in various situations are given. The flexural rigidity of the limbs was determined by trail and error. It was tuned so that the profile of the bow matched those depicted in unstrung, strung and full draw. In[2] unfortunately the mass of the bow and arrow are not reported and nothing is said about the distribution of the mass along the limb. I assumed this mass distribution to be uniform. The mass of the arrow, and mass and strain stiffness of the string are taken the same as those in the case of the PE-bow.

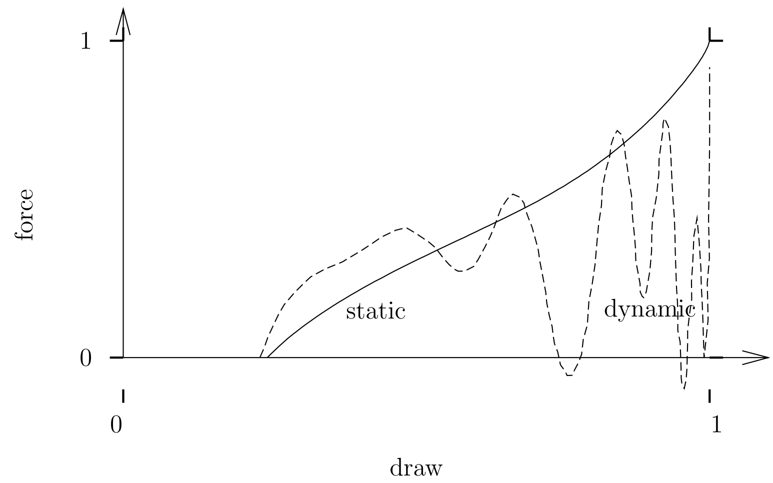

Figure 6: SFD and DFD curves of the "Asiatic bow".

The calculated SFD and DFD curves are provided in Figure 6. The bow stacks because the draw-force increases rapidly toward the end of the draw. The static quality coefficient is rather low $q = 0.332$. Because of the heavy ears the acceleration force acting on the arrow oscillates heavily. The force becomes even shortly slightly negative. The dynamics quality coefficients are $\eta = 0.726$ and $\nu = 1.77$. I conclude that the calculated performance of the bow is rather bad. Despite the disappointing quality coefficients, according to Latham and Paterson[2, page 170] the bow was of an efficient design and well suited to hunting or warfare as they had proved in field trails. The weight was 50 lb. at full draw and it shot a 30 inch arrow over a distance of 285 yards.

In discussing the reconstruction of this static-recurve bow Latham and Paterson[2, page 170] state that

> One unknown factor proved to be the amount of reflex allowed in the grip. An interesting point which emerged from the reconstruction was that when a string of the specified length was fitted, the resulting bracing height was $7\frac{1}{4}$ in. It was found, however, that the reflex could be reduced, as also the angle of the siyah in relation to the working part of the limb, to achieve the same result. Which form was the original, we cannot say, and it is doubtful whether the problem like that of the grip, will ever be resolved with any certainty.

The static quality coefficient is about the same as that for the short static recurve bow with $L = 0.7857$, see Table 2. Hence, a similar situation as with the performance of the Turkish bow holds true, namely that probably the strength of the materials of this composite Asiatic bow is responsible for the efficient design and not the mechanical performance itself.

5 Conclusions

The string of Asiatic bows in many pictures in the literature is free from the bend in the ear. I investigated the influence of the shape of the ear on the performance of the bow. I started with one static recurve bow, the so-called PE-bow, and I changed parameters one by one. The calculated results suggest that bows with the string in braced situation free, are better than bows with functioning ears. In bows with longer ears more recoverable energy can be stored in the fully drawn bow. For a good dynamic performance it is essential that the ears are light.

If the shape of the ears is such that the string does not lean again the bridges two hypotheses can be brought forward: first, this is done intentionally and second, it is a remnant characteristic of a 'real' static-recurve bow? When the string is free from the limb, the shape of the rigid section of the limb is unimportant. The gap between the outer points of the flexible limb, where the ears starts, and the nock, has to be bridged by a stiff and preferably light section. One would expect just a straight piece of material; without a bend and without string-bridges. Hence, when the outer rigid parts are shaped like ears which are non-functioning, this suggests that the second hypothesis holds true.

On many paintings recurved bows look like the Cupido bow with a set-back grip. The mathematical model predicts that the set-back has a positive influence on the mechanical performance.

I stress that the calculated sensitivity coefficients hold true for the PE-bow. For other bows the influences of the parameters differ. This makes the construction of the bow complex. The results of the sensitivity analysis are used when parameters are changed simultaneously. The total effect is found by superposition of the effects of each single parameter alone. This explains why it was found with the reconstruction of the Ṭaybughā's bow, that the reflex could be reduced, as also the angle of the siyah in relation to the working part of the limb, to achieve the same result. The 'recurve' for these bows is a composition of the set-back, curvature of the working part of the limb and the angle of the ear at the position of the bend.

There is an interplay between the shape of the bow and the materials used. By assuming that for all bows the maximum amount of energy stored per unit of mass is the same, I decoupled the construction from the mechanics and only the latter becomes important.

The calculated quality coefficients of the Asiatic bow were rather bad while experiments with the reconstruction of the Ṭaybughā's bow showed that it had 'a satisfactory performance by any standards' stated in Latham and Paterson[2, page 170]. I hypothesize that this is due to the use of good materials of this composite bow.

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