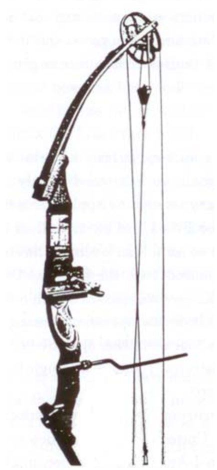
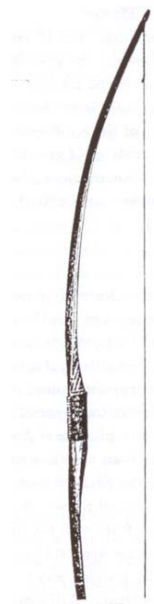
EN 4: Dynamics and Vibrations
Brown University, Division of Engineering

LABORATORY 1: DYNAMICS OF THE BOW AND ARROW



Compound Bow

Recurve Bow



Long Bow

SAFETY

You will be testing three very powerful, full sized bows. The bows release a lot of energy very quickly, and can cause serious injury if they are used improperly.

- **Do not place any part of your body between the string and the bow at any time;**
- **Stand behind the loading stage while the arrow is being released;**
- **Do not pull and release the string without an arrow in place. If you do so, you will break not only the bow, but also yourself and those around you!**

1. Introduction

In Engineering we often use physical principles and mathematical analyses to achieve our goals of innovation. In this laboratory we will use simple physical principles of dynamics, work and energy, and simple analyses of calculus, differentiation and integration, to study engineering aspects of a projectile launching system, the bow and arrow.

A bow is an engineering system of storing elastic energy effectively and exerting force on the mass of an arrow efficiently, to convert stored elastic energy of the bow into kinetic energy of the arrow. Engineering design of the bow and arrow system has three major objectives; (1) to store the elastic energy in the bow effectively within the capacity of the archer to draw and hold the bow comfortably while aiming, (2) to maximize the conversion of the elastic energy of the bow into the kinetic energy of the arrow, and (3) to keep the operation simple and within the strength of the bow and arrow materials system. In addition, the bow should be cheap and easy to manufacture. There are many different designs for bows: some meet these objectives better than others. In this laboratory you will compare the features and performance of three different bow designs: a European long bow; an Asiatic recurve bow; and a modern compound bow.

When engineers compare physical system characteristics, they often use non-dimensional characteristic numbers. In this laboratory we will use three characteristic numbers; (i) the amplification factor of the elastic energy storage of a bow; $\eta = W/\left(F_D s_D / 2\right)$; (ii) the launching efficiency of a bow and arrow system; $\xi = \left(mv_f^2 / 2\right)/W$; (iii) the relative maximum axial force on the arrow with respect to the static buckling load; $\zeta = ma_{max}/\left(\pi^2 EI / L^2\right)$.

Regarding the storage of elastic energy, it is stored by drawing the bow slowly with a static equilibrium force $F_s(s)$, as a function of draw distance s, to the release draw distance s_D. The storage is made up to the amount of the draw work, $W = \int_0^{s_D} F_s(s)ds$. If it were a linear spring, then the stored energy would be $F_D s_D / 2$, where F_D is the final draw force at the release point, i.e. $F_D = F_s(s_D)$. Then the amplification factor of the energy storage in the bow compared to that of the linear spring can be defined as $\eta = W/\left(F_D s_D / 2\right)$.

When the arrow is launched, a part of the stored energy (W), is converted to the final kinetic energy of the arrow $mv_f^2 / 2$, where m is the mass of the arrow and v_f the final speed of the arrow as it leaves the bow. Then, the fraction of the kinetic energy within the available stored energy, $\xi = \left(mv_f^2 / 2\right)/W$, is the launching efficiency. The efficiency is always smaller than one.

While the bow string pushes the arrow from behind, the maximum force of the push is ma_{max}, where a_{max} is the maximum acceleration of the arrow during the launching process. When you process the data that you have collected in this lab, you will notice that the recurve bow pushes the arrow twice, while the long bow or the compound bow pushes the arrow just once during the launching process. (The recurve bow is a double kick bow.) Since the arrow is a slender and long rod, it would buckle if it is pushed beyond the buckling limit. The dynamic buckling limit load is somewhat larger than the static limit; however, for simplicity, the maximum push force is compared with the static buckling load $\pi^2 EI / L^2$. Here E is the elastic modulus of the arrow material (70 GPa for our aluminum arrows), $I\left(= \pi\left(r_o^4 - r_i^4\right)/2\right)$ is a cross sectional geometric property of the arrow with r_o the outer radius and r_i the inner radius of a hollow cylindrical arrow. The length of the arrow is L. (You can learn this formula in EN31; but here you just take it.) Then, the relative maximum axial force is $\zeta = ma_{max}/\left(\pi^2 EI / L^2\right)$.

You can use these nondimensional numbers to make engineering decisions in selecting different bows for different purposes.

In this laboratory, you study principles of work and energy, applied to a system in static equilibrium, by integrating the force – distance relationship, and the Newton's laws of motion and the principles of work and energy, applied to a dynamical system, by differentiating the (velocity square over 2 or kinetic energy) – distance relationship. You will also learn how to perform scientific experiments and data processing including how to differentiate and integrate a discrete numerical data set that contains measurement errors or noise. In particular, this lab is designed to study spatial, not temporal, description of motion, which leads to the principles of Work and Energy.

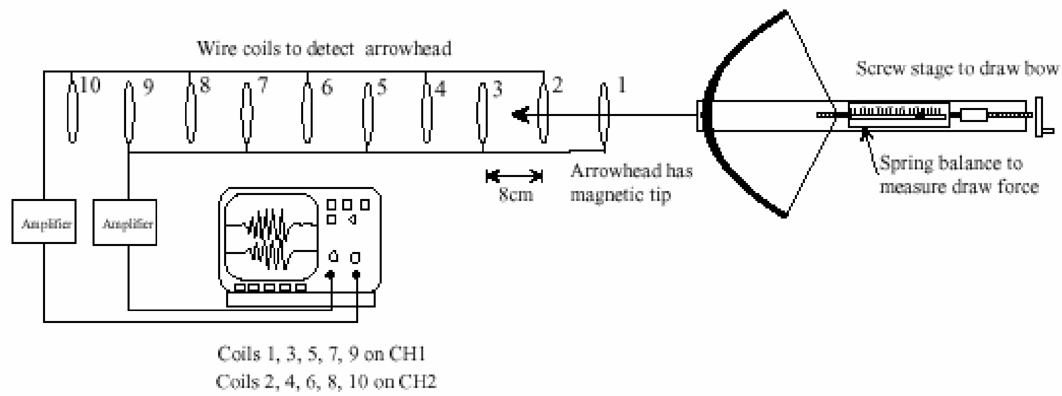


Fig 1. Experimental Apparatus

2. General Instructions (Recommend to read http://www.imechanica.org/node/598)

- Form lab groups of five students by signing in the form. See instructions and due dates for signing in at http://www.engin.brown.edu/courses/en4/labs.htm .
- The experimental measurements will be done by groups. Three groups may do the experiment at one time.
- The lab will be run in the Giancarlo Laboratories Rm. 096.
- Labs should be done in groups, and collaboration is permitted on the calculations.
- Each student should submit his or her own report. It is not acceptable for students to submit identical copies of the same report.
- See the website for the relevant due dates and scheduled lab times.
- Every student must bring in a pre-lab report to get a signature of a TA before the experiment is carried out. The pre-report form is provided in appendix A.
- Every student must attach the signed pre-report to the final report to get full credit.
- The data processing procedure is provided in Appendix B and an Excel template of data processing is provided in Appendix C.

3. Experimental Measurements

There are two sets of measurements. First, you will measure the force required to draw the bow (the static test); then, you will measure the velocity of the arrow as a function of position while it is being fired (the dynamic test). The velocity is measured by detecting the travel time of the arrow for a fixed distance between detectors. From the velocity – position data, you will derive the acceleration, exerted force and kinetic energy of the arrow.

You should conduct static tests on one of the 3 bows and dynamic tests on all three bows. You can obtain static test results for the other two bows from the other lab groups.

The apparatus is sketched in Fig. 1. Each bow is attached to a screw stage, which can be used to draw the bow. The draw force can be measured by attaching a spring balance to the bowstring and draw stage; the draw distance can be measured using the ruler attached to the draw stage.

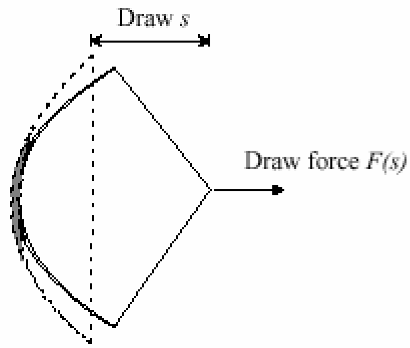


Fig 2: Draw length of a bow

The arrow's speed is measured by shooting it through a set of 10 wire coils, 8cm apart. A magnet is attached to the tip of the arrow, and as this passes through each coil, it induces an electric current in the conducting wire coil. This current is amplified and a voltage proportional to the electric current is displayed on two channels of a storage oscilloscope. The signal on the oscilloscope can be used to measure the time at which the arrow passes through each coil; these data may then be used to compute the velocity of the arrow.

3.1 Static Test

The purpose of this test is to construct the force versus draw curve of a bow to study principles of work and energy, applied to a system in static equilibrium, by integrating the force – distance relationship. You will also learn how to integrate a discrete numerical data set with noise.

You are only required to do the static test for one of the bows. To accomplish this goal, you will attach the bowstring to a scale, and slowly draw the string back to the firing position using a hand crank. As the string is drawn, measure the force using the scale and record it in Table 1. Use the following procedure.

(i) Rotate the screw wheel until the mounting block is about 20-30 cm away from the relaxed bowstring.

(ii) Attach the scale to the mounting block.

(iii) Attach the scale hook to the bowstring below the brass snap ring in the middle of the string. The scale is now in a position to measure the force as a function of draw distance. The starting point is the undrawn, relaxed bow/string position. The draw force is zero when the draw distance is zero.

(iv) Draw the bow, and record the force on the scale every 4 cm from the starting point, the undrawn bow/string position. Don't forget to record both the force and the displacement measurements. You should measure the actual displacement of the bowstring, Fig 2, not the displacement of the mounting stage. It is best to have one group member work the crank, a second supporting the balance, and a third recording the force and displacement measurements.

(v) After reaching the maximum pull distance of approximately 50 cm, relax the string by unscrewing the crank.

3.2 Dynamic release test

The purpose of this test is to determine the velocity of the arrow as a function of position while it is being fired to study the Newton's laws of motion and principles of work and energy, applied to a dynamical system, by differentiating the (velocity square over 2 or kinetic energy) – distance relationship. You will also learn how to differentiate a discrete numerical data set with noise.

You will do this test for all three bows. To do this, shoot the arrow down a long tube. A set of 10 copper coils, 8cm apart between them, has been wound around the circumference of the tube, and a magnet is attached to the tip of the arrow, as shown in Fig. 1. As the magnet passes through each coil, it induces an electrical signal in the coil. The signals from all 10 coils are recorded on 2 channels of an oscilloscope.

During the dynamic test, make certain that all group members are behind the bowstring, well away from the drawn string.

Record the data in table 2. Use the following procedure:

(i) Measure and record the mass, diameters, length of the arrow you are using. Also measure and record the distance between the bowstring and the first wire coil.

(ii) Place the arrow on the bow. Engage the arrow tail (called the nock) on the string. The nock should snap onto the string above the brass snap ring. To avoid damaging the feathers when the arrow is fired, make sure that the odd colored feather is facing away from the bow.

(iii) The TA will demonstrate the trigger and its use. Engage the trigger directly below the snap ring. Attach the other end of the trigger to the screw stage.

(iv) Make sure the oscilloscope is on. Make sure the power supply is on and set to no more than 7 V. Make sure the cables are connected (ask a TA if you are unsure).

(v) The triggering for the signal on the oscilloscope should already be set, but here is how it is done. Hit the "edge" button. Turn the "level" knob. A green square should light up in the upper right-hand corner. Move this knob until ~ "-80 mV" is selected in that square. Look at the bottom of the screen---there are gray buttons for changing menu options. Make sure that on the "edge trigger" option, the downward slope (curve with arrow pointing down) is checked.

(vi) Prior to *each* run, hit the run/stop button. Make sure the color of the button is red. If it is green, hit it again so it is red.

(vii) You can control the time scale with the thick knob in the "horizontal" area at top left of oscilloscope. Turn the knob so that the green box in the top middle of the screen reads 5 or 10 ms.

(viii) Draw the bow. You must use the screw stage to draw the Long bow and the Recurve bow, but you may draw the compound bow by hand if you wish. Adjust the screw stage until the arrowhead is level with the end of the tube. At this point, the arrowhead is nominally 4cm away from the first wire coil.

(ix) Record the draw distance. It should be within the range you measured in the static test.

(x) Press the "Single" button. It should turn orange, and the run/stop button should turn off. A green square around "trig'd" should light up in the upper right-hand corner.

(xi) Aim the arrow down the firing tube (ask the TA how to properly aim the bow and arrow). One of you should observe the flight of the arrow **<u>from behind the loading stage</u>** to make sure that the arrow tip does not hit the tube walls during the test.

(xii) Fire!

(xiii) The "Run/stop" button should turn on, red, and you should see two signals. This makes sure that the oscilloscope won't be triggered again, which would cause your data to vanish.

(xiv) Examine the trace on the oscilloscope screen. You should see a display similar to Fig. 3. One trace of the oscilloscope shows the electrical signals from coils 0,2,4,6 and 8. The second trace shows signals from coils 1,3,5,7 and 9; the peaks from the two traces should alternate. Each time the signal changes sign from positive voltage to negative voltage, the magnetic tip of the arrow is just passing through one of the coils. Thus, the tip is passing through coil 1 at time t_0 in Fig. 3; it is passing through coil 2 at time t_1, and so on. We will assume time $t_0 = 0$. You need to measure the times t_1; t_2 …t_9, as follows:

- You may find it helpful to expand the time scale on the trace using the thick knob in the "horizontal" area of the oscilloscope.
- Press the small oval `Cursors' button. A green light will appear with a counterclockwise arrow above the knob that controls cursor position. Align the vertical line with the first zero crossing. (A warning - the first zero crossing can be quite hard to find. Make sure you can find 10 zero crossings. If one appears to be missing, ask the TAs for help).
- To read the zero crossing, you may want to use the vertical AC knobs to align the zero of the signal with a horizontal grid line.
- Use the cursor buttons to align the vertical line with each of the zero crossings, and record the time of each zero crossing. The times are displayed, in milliseconds, on the bottom left hand corner of the screen. You may find it helpful to display one trace at a time to see the zero crossings more clearly---use the "1" and the "2" buttons.

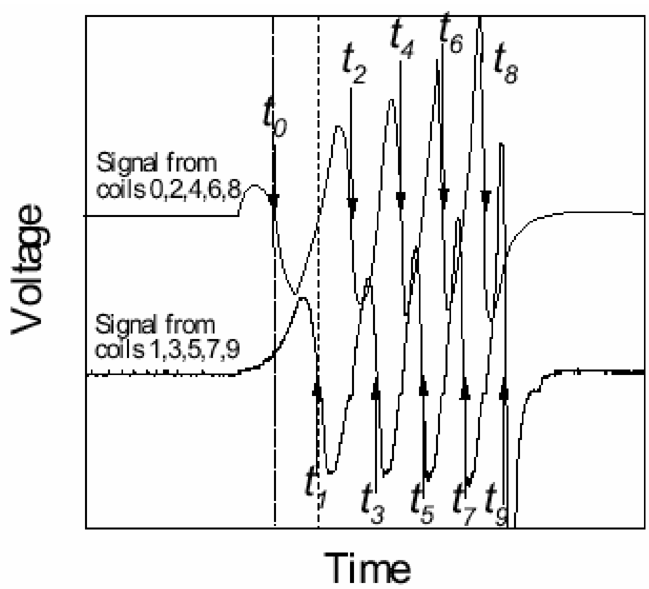


Fig 3: A typical time display on the oscilloscope

General Remarks
To get good results, you must shoot straight, and release the arrow smoothly. If you pull the bowstring sideways, the arrow buckles while it is being fired. This produces very strange looking velocity and acceleration curves, even though the shot might look fine to the naked eye. **We recommend that you obtain several sets of data for each bow** (shoot each bow at least twice, preferably three times) to increase your chances of obtaining at least one good set of data.

4. Calculations and Graph Plotting (The steps you should follow for each graph and calculation are described in Appendix B.)

You should do the following calculations using the data obtained from the **static tests:**

(i) Plot the draw force vs. draw distance s curves, $F_s(s)$, for all three bows.

(ii) Calculate the draw work W and the amplification factor of the elastic energy storage of the bow, $\eta = W/\left(F_D s_D / 2\right)$, for each bow.

You should do the following calculations using data obtained during the **dynamic tests**:

(iii) Calculate the velocity, v, of the arrow at every midpoint between two adjacent coils, and plot a graph of arrow $v^2/2$ versus the arrowhead position x for each bow. Then, calculate the launching efficiency of the bow and arrow system, $\xi = \left(mv_f^2/2\right)/W$ for each bow.

(iv) Interpolate $v^2/2$ as a function of the arrowhead position x with 5th order polynomial, and take a derivative to get the acceleration as a function of x in 4th order polynomial. Then, plot the force $F_d(x) = ma\left(x\right)$ as a function of x, and calculate the relative maximum axial force on the arrow with respect to the static buckling load, $\zeta = ma_{max}/\left(\pi^2 EI/L^2\right)$.

(v) Plot $F_s(s)$ and $F_d(s_0 - s + x_0) = ma\left(s_0 - s + x_0\right)$ on the same graph, and compare the dynamic and static force characteristics of the bow, for each arrow.

5. Report

Your report should compare the characteristics of the three bow designs, and discuss the suitability of each bow for target shooting, hunting, and as a weapon of war.
You could use the links to Archery web sites on the EN4 web page to find out more about the desirable characteristics of bows for these applications. You should also discuss the factors that influence the dynamic efficiency of the bow. The report should contain the following sections

(i) **Cover sheet:** The cover sheet should show a title; your name; the names of the other members of your lab group, and the date the experiment was performed.

(ii) **Introduction:** The introduction should summarize the objective of the report; give any background information that you think is relevant (e.g. history; general issues in bow design; description of the various bow types); outline the results that will be presented in the report and summarize the conclusions. It should be as short as possible (300 words).

(iii) **Experimental Method:** Describe the experimental method and apparatus briefly. You can take most of this from the lab sheet but use your own precise wording so that the description is clear to another experimenter. Describe how you compute the work done in drawing the bow and how you determine the arrow's velocity and acceleration from your measurements. Again, make your description as short as possible but be complete and precise.

(iv) **Results and Discussion:** Show the graphs listed in the preceding section (Don't list your actual experimental measurements. They should go in an appendix). Comment on the general features of the results and on any remarkable differences between the three bows. Prepare a table comparing the characteristics of the three bows: list the maximum draw force; the energy stored in the bow and its three non-dimensional numbers discussed in Introduction. You could add to the table other features that distinguish the bows: reliability; complexity; cost; weight, etc. Decide what characteristics are desirable in a bow and discuss which bow best meets your criteria. Also, in a separate subsection, discuss the factors that you think determine the dynamic efficiency of a bow. For example, why is the dynamic efficiency less than 1? Where did the extra energy go? Is air resistance important? Why is the force acting on the arrow while it is being fired different from the static draw force? What are the variables that might determine the efficiency of a bow? (e.g. the mass of the bowstring; the bow material…) What experiments or calculations would you do to determine the influence of these variables on dynamic efficiency?

(v) **Conclusions:** No more than 50-100 words. The conclusion is a concise summary of your findings pertaining to the specific stated purpose of the experiments.

(vi) **References:** Cite any books or web sites that you have used in preparing your report.

(vii) **Appendix:** Attach your tables of experimental measurements and any calculations in an Appendix.

General instructions on report: Presentation is important. Your report should be prepared using a word processor and printed using a good quality printer. All graphs should be clearly labeled; axes should be labeled with the variables and their units. Make sure your report is well-organized and present topics in a systematic way. Written style is important too: make sure your sentences are well structured; don't switch between tenses in a paragraph; avoid using the same word too many times in successive sentences. It is considered bad form to excessively use the first person ("I" and "we") in technical reports. Try reading your report aloud. If it doesn't sound right, it's badly written. Above all, be brief. Your report will be judged by the quality and number of ideas in it, not by its length. A significant proportion of the grade for your report will also be awarded for presentation and written English. If you find writing difficult, you are welcome to ask the graduate TAs and professors for help.

6. Useful References

[1] The Encyclopedia of Archery, Paul C. Hougham, A.S. Barnes and Company INC.,1958. (Library of Congress Catalog Card Number: 57-9910).

[2] Archers Digest; Encyclopedia for All Archers, edited by J. Lewis, Digest Books, INC., 1975. (ISBN 0-695-80218-6, LCCCN 77-148772).

[3] Archery, Pszczola, L. and Mussett, L. J., third edition, Sauders College Publishing, 1984.

[4] The Traditional Bowyer's Bible, (Vol. 1; Steve Alley, et. al.), (vol. 2; G. Fred Asbell et. al.), (Vol. 3; Tim Baker, et. al.), Bois d'Arc Press, 1993. (ISBN 1-55821-207-8).

APPENDIX A: Pre-report with a lab note to perform the experiment

EN 4: Dynamics and Vibrations

Brown University, Division of Engineering

LABORATORY 1: DYNAMICS OF THE BOW AND ARROW

Date and Time ____

Team Name: ____

Your Name: ____

Other Members 1)____

2)____

3)____

4)____

Teaching Assistant Initials ____

* Every student must bring in this two-page pre-report before the experiment is carry out and the pre-report signed by a TA must be attached to the final report to get full credit.

Page 1

Objectives and Preliminary Introduction (less than half page with font 12)

Brief Description of Experimental Procedure (less than half page with font 12)

* This page must be filled in before the experiment is carried out.

Laboratory Note

Team Name: ____________________ Date: ____________________

TA signature ____________________

Record on-site observations and calculations on this page

* Each team must bring in one set of this four-page Laboratory Note printed, and the note filled in during the experiment must be signed by a TA when the experiment is completed. Copies of the filled-in note must be distributed among the team members, to be used for individual data processing. The copies must be attached to the final report.

Table 1: Static Pull Test Results (Each group measures one bow) Page 2

Long Bow		Compound Bow		Recurve Bow	
Draw distance (m)	Balance reading (lbs)	Draw distance (m)	Balance reading (lbs)	Draw distance (m)	Balance reading (lbs)
Remarks:		Remarks:		Remarks:	

Table 2A: Dynamic Test Results (Each group fires all 3 bows)

		Long Bow		Compound Bow		Recurve Bow	
		Shot 1	**Shot 2**	**Shot 1**	**Shot 2**	**Shot 1**	**Shot 2**
Arrow Mass (g)							
Arrow Length (cm)							
Max draw (cm)							
Coil	Pos-ition (cm)	Time (msec)	Time (msec)	Time (msec)	Time (msec)	Time (msec)	Time (msec)
0	4.0						
1	12.0						
2	20.0						
3	28.0						
4	36.0						
5	44.0						
6	52.0						
7	60.0						
8	68.0						
9	76.0						
Remarks							

Table 2B: Dynamic Test Results (Each group fires all 3 bows) Page 4

		Long Bow		Compound Bow		Recurve Bow	
		Shot 3	**Shot 4**	**Shot 3**	**Shot 4**	**Shot 3**	**Shot 4**
Arrow Mass (g)							
Arrow Length (cm)							
Max draw (cm)							
Coil	Pos-ition (cm)	Time (msec)	Time (msec)	Time (msec)	Time (msec)	Time (msec)	Time (msec)
0	4.0						
1	12.0						
2	20.0						
3	28.0						
4	36.0						
5	44.0						
6	52.0						
7	60.0						
8	68.0						
9	76.0						
Remarks							

APPENDIX B: GRAPHS AND CALCULATIONS

Important Note: This laboratory is designed to study principles of work and energy. The principles of work and energy in dynamics are based on spatial descriptions of motion. Forces are measured in terms of draw distances and the velocities of the arrow are detected at different arrow tip positions. (The momentum principles are based on temporal descriptions of motion in dynamics, and they will be handled in Laboratory 2.) In Laboratory 1, you encounter interesting issues of temporal description versus spatial description. The expressions of acceleration, $a = \frac{d^2x}{dt^2}$ (temporal description) and $a = \frac{d}{dx}\left(\frac{v^2}{2}\right)$ (spatial description) are simply different descriptions of the same quantity in theory. However, different choices of the expressions make huge differences in data processing for its easiness and accuracy. For example, the red curve in Fig. B-1 shows the double peak force (proportional to the acceleration) exerted on the arrow during the launching process of a recurve bow. If we fit the data with polynomials to take differentiations, we have to use at least 4^{th} order polynomials to capture the double kick acceleration. Then, the arrow tip position with respect to time, $x(t)$, must be expressed in a 6^{th} order polynomial in the temporal description. Since we have only seven or eight data points for the acceleration process in our experiment, the fitting curve will pass all or most of the data points that contain measurement errors. The second derivative of a data with such errors amplifies the errors in acceleration so much that we cannot resolve the actual acceleration of the arrow, if we use the temporal description. As a matter of fact, control of errors or noise in data or signal processing is a significant part of science and engineering work. [You will waste a lot of time and get nothing in preparing for your lab report, if you use the temporal description for data processing for our Bow and Arrow Dynamics Laboratory.]

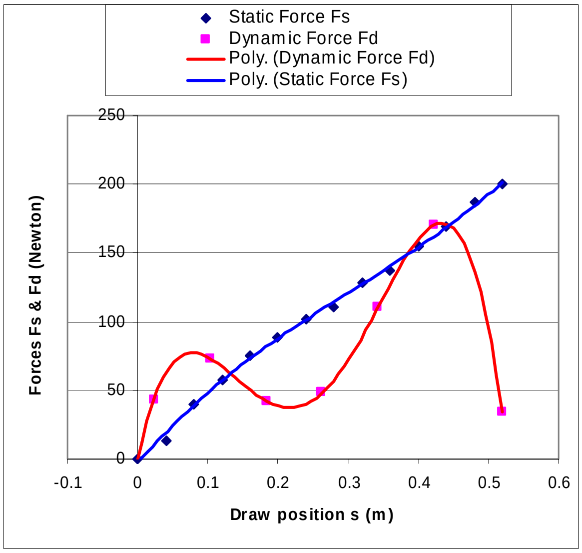


Fig. B-2. Static draw forces as a function of draw position, in a blue curve; dynamic forces exerted on the arrow during the launching process in a red curve, for a recurve bow.

The sections below describe in detail how to do the calculations and plot the graphs for this laboratory.

1. Force-Draw Curve

Plot a graph of the data you recorded in the static pull test, showing the draw force $F_s(s)$ in Newton on the y axis and draw distance *s* in meters on the x axis, as shown in Fig. B-1 in blue tic marks. Then, interpolate (or best fit) the data in with a 4th order polynomial. All forces and accelerations must be interpolated with 4th order polynomials, while all velocity square, work and energy with 5th order polynomials.

2. Work done in drawing the bow and the amplification factor of energy storage

By definition, the work *W* done in drawing the bow to the release draw distance s_D is $W = \int_0^{s_D} F_s(s)ds$. Once the static force $F_s(s)$ is interpolated in a 4th order polynomial, the integration can be carried out analytically. In the Excel template in Appendix C, the integration is carried out in terms of *x* variable instead of *s* variable, in convenience for over all data processing, $W = \int_0^{s_D} F_s(s_D - x)dx$, since $s = s_D - x$. Then, the amplification factor of the energy storage in the bow compared to that of the linear spring, $\eta = W/\left(F_D s_D / 2\right)$, can be evaluated.

3. Arrow velocity and acceleration

In the laboratory we record the passing time $\{t_i,\ i = 0,1,\cdots,9\}$ of the arrow-tip, at each nominal coil location $\{xn_i,\ i = 0,1,\cdots,9\}$. With the data set, carry out the data processing in following steps. See examples of the processing in the Excel template in Appendix C.

(i) Evaluate the velocity $v_i = (xn_i - xn_{i-1})/(t_i - t_{i-1})$ at each midpoint $xm_i = (xn_{i-1} + xn_i)/2$ between two adjacent measurement coils, for $i = 1,2,\cdots,9$.

(ii) Re-evaluate the arrow tip location of the release point for the nominal release position of $xm_0 = 0$, making linear fit of $(0,0)$, (xm_1, v_1), (xm_2, v_2) with a form of $y = Ax + B$. (See yellow cells in Appendix C.) Here, the re-evaluated location of release point is $x_0^* = -B/A$ where the *y* value, velocity, vanishes. Then, we reset the arrow tip position coordinate with respect to the re-evaluated release point as $x_0 = 0$ and $x_i = xm_i - x_0^*$, for $i = 1,2,\cdots,9$. (This step is required, since the release position of the arrow tip is not accurately known initially. In addition, we get another data point of velocity measurement, $v_0 = 0$ at $x_0 = 0$, with this step.)

(iii) Fit the data $\left\{\left(v_i^2/2,\ x_i\right),\ i = 0,1,\cdots,7\right\}$ of 8 points with a 5th order polynomial of six unknown coefficients to get $v_i^2/2 = A_0 + A_1x + A_2x^2 + A_3x^3 + A_4x^4 + A_5x^5$, and then to get the acceleration, $a(x) = \dfrac{d}{dx}\left(v^2/2\right) = A_1 + 2A_2x + 3A_3x^2 + 4A_4x^3 + 5A_5x^4$. (See green cells in Appendix C.) In this way, the measurement errors in the data set can be regulated with the polynomial fitting. (Tricks of carrying out analytic differentiation, integration and plotting of the functions with Excel program are given in Appendix C. You can contact lab TAs if you wish to get more details.)

4. Resultant force acting on the arrow during firing

Once you get the acceleration $a(x)$, the dynamic force acting on the arrow is $F_d(x) = ma(x)$. The dynamic force $F_d(s_D - s)$, shown as a red curve in Fig. B-1, can be compared with the static force $, F_s(s)$ shown as a blue curve in Fig. B-1, in terms of the draw distance, *s*. Then, the relative maximum axial force, $\zeta = ma_{max} / \left(\pi^2 EI / L^2\right)$, can be evaluated.

5. Kinetic Energy of the Arrow and the Dynamic Efficiency

By definition, the kinetic energy of an arrow of mass *m*, which travels with velocity *v*, is $T = m|v|^2 / 2$. The kinetic energy of the arrow during the launching process of a recurve bow is calculated in dark-green-box cells in Appendix C and shown as a dark green curve in Fig. B-2. The kinetic energy is compared with the static energy released by the bow, shown in a red curve in Fig. B-2. The static energy released by the bow is given by $E_s(x) = \int_0^x F_s(s_D - x')dx'$. (See purple cells in Appendix C.) Evidently, $E_s(s_D) = W$. Then the dynamic efficiency $\xi(x) = m\{v(x)\}^2 / \{2E_s(x)\}$ during the launching process can be computed and displayed as shown as a red dash line in Fig. B-2.

As shown in Fig. B-2, the energy is transferred to the arrow in variable rates during the launching process. In the beginning of the launching process, the elastic energy release is shared between the motions of the bow and arrow more or less equally for a well designed bow, i.e. $\xi(0) = 0.5$. Then, the efficiency $\xi(x)$ climbs up to high values as it accelerates to the final velocity. In theory, $\xi(s_D)$ is the dynamic efficiency of the bow and arrow system. However, the arrow can lose energy in nock friction as it leaves the string of the bow. Therefore, we calculate the dynamic efficiency of the bow and arrow system as $\xi = \left(mv_f^2 / 2\right) / W$ for which v_f is evaluated as the average value of v_7, v_8 and v_9. The three velocity values v_7, v_8 and v_9 are measured for free flights of the arrow right after it leaves the bow string.

All the non-dimensional numbers, ξ, η and ζ are calculated in red cells in Appendix C.

Now, the non-dimensional numbers can be used to choose different bows for different purposes.

In this laboratory you have seen engineering experiments to create multiple solutions for a problem of engineering decision making to make the best bow design for various uses of the bow and arrow system.

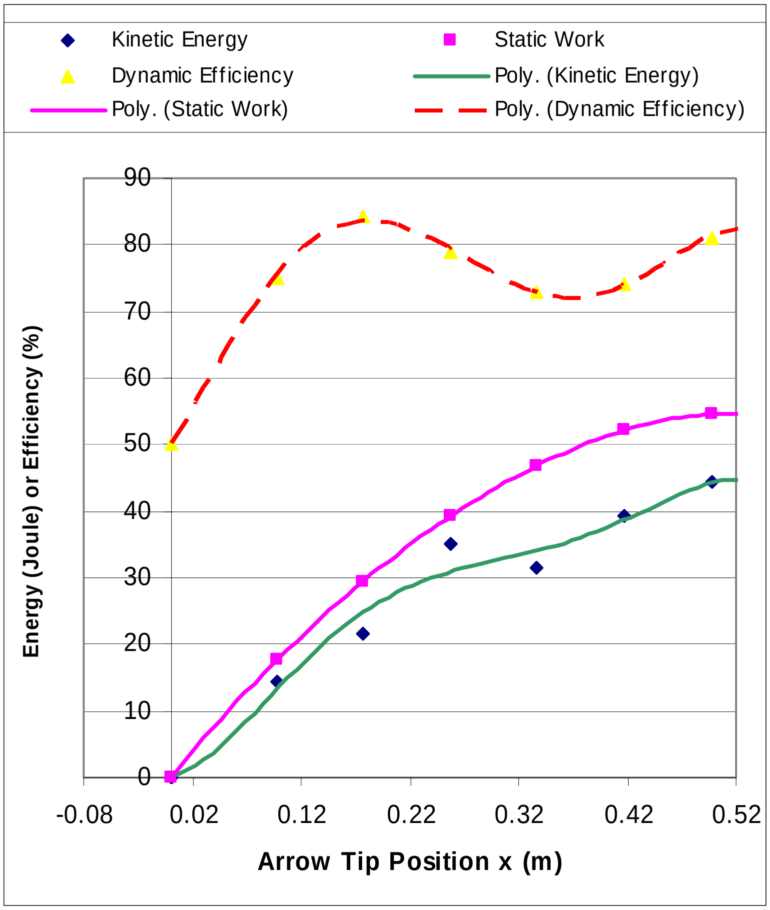


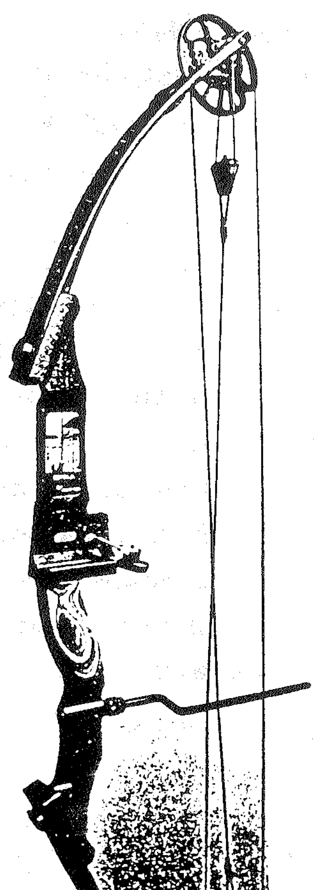
Fig. B-2. Kinetic energy of the arrow as a function of arrow tip position, in a green curve; static elastic energy release of the bow in a purple curve; dynamics efficiency in a red dash curve, for a recurve bow.

Appendix C: Excel Template of Data Processing

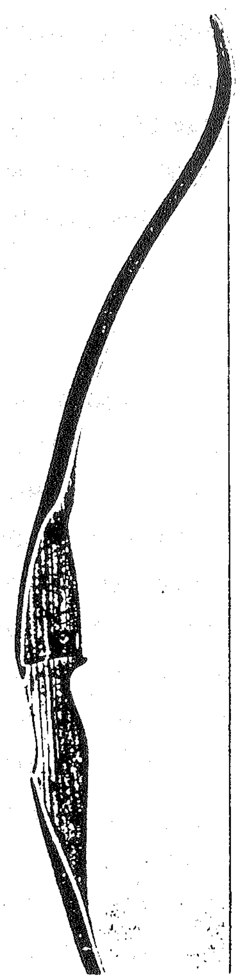
Download the file here.

PUSHING THE LIMIT OF ARROW SPEED WITH MATERIALS SCIENCE

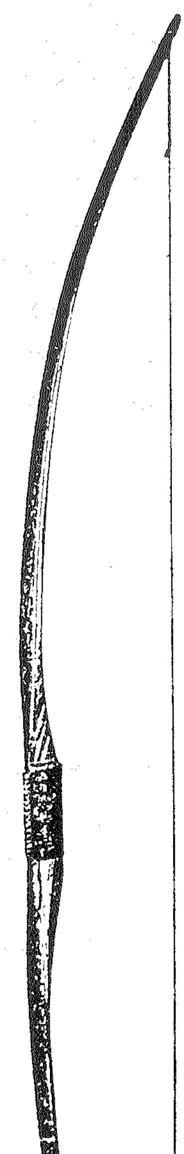
Contents



Compound Bow



Recurve Bow



Long Bow

Introduction

Principles of dynamics have been applied to understanding and designing various cultural instruments as well as engineering products. Examples include musical instruments, sporting goods and tools for daily living (e.g. the baby walker that we will test for the second project) as well as computer disk drives, gyroscopes, cars (we will have experiments on race-car suspensions for the third project), airplanes, rockets and scientific facilities such as various particle accelerators. One example that we are going to explore in the first laboratory project is "Dynamics of Bows and Arrows."

The bow and arrow is one of the most basic mass accelerators. The most common mass accelerator that we experience in our daily life is the gravitational field. Galileo, Newton and Einstein observed and analyzed the properties of the gravitational field, and a French engineer, Eiffel, used it effectively for aerodynamic experiments on the Eiffel Tower. However, the gravitational field is a naturally arising phenomenon in contrast to other engineered mass accelerators, such as the bow and arrow, guns, rockets, various vehicles and particle accelerators, e.g. cyclotron (a modern David's sling!). Even in sports, applications of these different acceleration methods are contrasted; skiing and diving are typical applications of gravitational acceleration, while archery is a typical application of the man-made accelerator, the bow and arrow, that uses human muscle power through an efficient energy transfer mechanism. The nomenclature of the bow and arrow is given in Appendix A.

* * * * *

Known evidence of human use of the bow and arrow goes back at least as far as 7000 BC; 9000 years ago! In the early stage of its use it might have been used mainly as a survival tool for hunting as well as a weapon. However, many interesting applications have been developed in later stages. (Even as a teaching tool for EN4!) Old stories tell us that sometimes arrows were used to deliver messages between two forbidden lovers. It has been also used for various symbols. Cupid and his bow symbolized love; the huntress Diana (goddess of moon; sister of Apollo; Artemis in Greek mythology) was pictured with a bow; the bow has been used as a metaphor for their direct and indirect expressions among the Zen Buddhists. Archery became a symbol of power and its representation appeared on the seal of the United States. It also became a symbol of historical romance through Robin Hood, whose feats with the bow made him a legendary hero.

No longer a weapon of survival, the bow today is an instrument of scientific perfection for a rapidly growing sport. Archery as a sport in the United States took root in the nineteenth century. With the establishment of the National Archery Association in 1879, archery grew in stature to encompass local, state, regional, and national tournaments. The

International Federation of Archery (FITA) now sponsors a world championship tournament every two years, and archery is included in Olympic competition every four years.

* * * * *

Other than Robin Hood's legend, the British developed a famous bow, the *English long bow* [see Appendix B]. Unfortunately, however, Robin Hood could not use this bow! The English long bow was developed in the period of Edward I, the late 13th century, whileRobin Hood's legend was during King John's period, the 12th century. Many different countries and tribes also have their own historical bows and arrows and legends. Central Africans used round cross-section (long) bows, American Indians used mainly flat cross-section (long) bows, and the Japanese developed asymmetric long bows. The English long bow, 6 ft long in average, is basically a durable, easy-production power bow that is suitable for close to medium range target archery; however, it has a characteristic of low cast (cast: distance the bow can shoot), and it is not suitable for horse riding archery.

Another famous bow in history is the Asiatic composite bow. The tough wood core of this bow is backed by sinew from the great neck tendon of an ox or stag, and the belly of the bow is reinforced by animal horns. This bow was mainly developed and used, since 2500-3000 years ago, by Ural-Altai people; Turks, Mongols and Koreans as well as ancient nomadic central Asians such as the Scythians and Sarmatians. The power of the Asiatic composite bow has been well known to the western world (Europe) through the Turkish bow, while it was rather well recognized in Chinese history through Korean archery [see Appendix C]. Like other countries associated with historic bows and arrows, Korea has a legend of a 7th-century patriotic archer Yang, Manchoon [see Appendix C]. The Asiatic composite bow has three main characteristics; it is short (4 ft long in average), it is a recurve bow (i.e. the bow is curved back near the tip ends) and it has a great reflex (i.e. when it is unbraced the bow recoils back). This bow is basically a high-efficiency, high-cast bow that is suitable for long range target archery and horse riding archery; however, it is not as durable as other simple bows and it has difficulties in mass production. As the materials technology advanced, the recurve and some reflex characteristics of the Asiatic bow have been adopted in laminated bow design in the United States since late 1930s. Now the modern laminated bow that has curved-back tips is called the *Recurve Bow.*

Other well-known bow designs are the cross bow and the compound bow [see Appendix D]. For these bows, strong muscles can be used to load the bow, and it can be locked to hold the required pull force at a release pose. The cross bow was widely developed and used in Europe since the 11th century. This bow is associated with the well-known legend of Willam Tell; a legendary Swiss patriot of c1300 forced by the Austrian governor to shoot an apple off his son's head with a cross bow. Essentially, the cross bow is a heavy power bow mounted across a stock at a right angle. Recently engineers have combined all the technical advantages of the above mentioned bows to develop a bow called *Compound Bow*. This bow uses a cam pulley at the tips of the bow to increase the efficiency of energy storage and semi-lock the pull force at a release pose.

* * * * *

Appendix A: Nomenclature of The Bow and Arrow

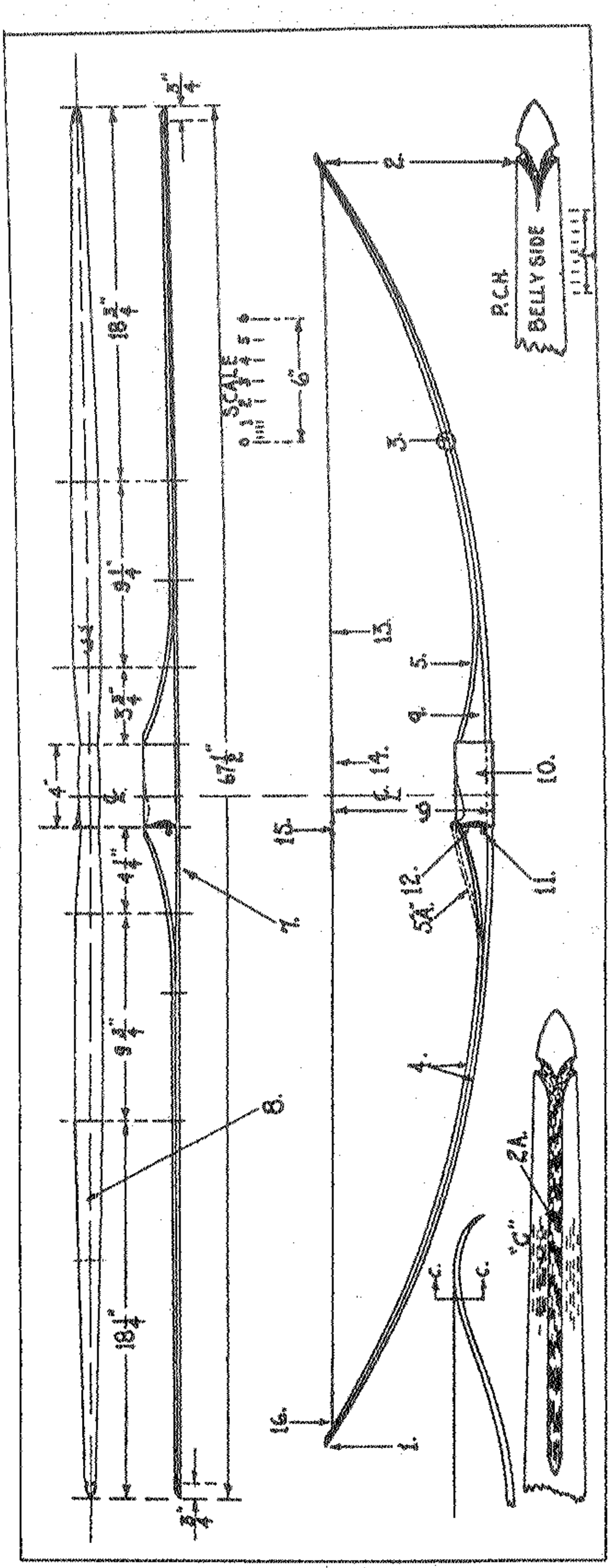


Fig. 1.—Nomenclature drawing of a bow.

1. Tip ends
1*. Siyahs for Composite Bow
2. Bow nocks
2A. String or nock groove
3. Bow limbs
4. Belly and Back lamination
5. The Bow Riser
6. Fistmele; 7" - 8.25"
7. Side Profile of Bow
8. Belly or Back Profile
9. Riser Insert
10. Handle of Bow
11. Arrow Plate (optional)
12. Arrow Rest
13. Bowstring
14. String Serving
15. Nocking Point on Bowstring
16. Bowstring Loop

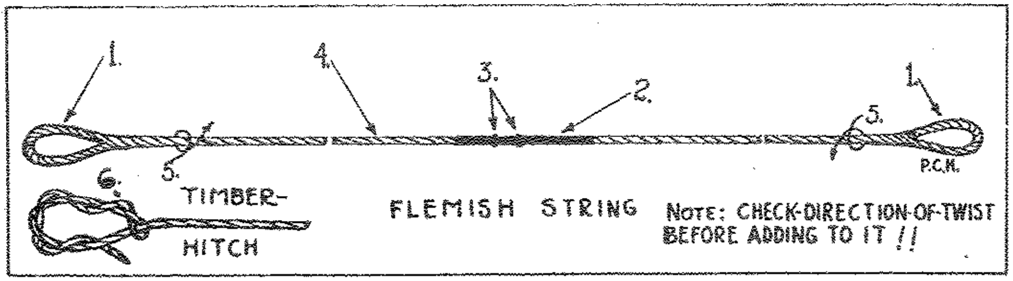


Fig. 2.—Nomenclature drawing of a bowstring.

1. The loops:
(A) Flemish or corded loop
(B) Endless strings, bound loop
(C) Timber Hitch
2. The String Serving
3. The Nocking Points
4. The Main Bowstring
5. String Twist
6. Timber Hitch; Bow Knot

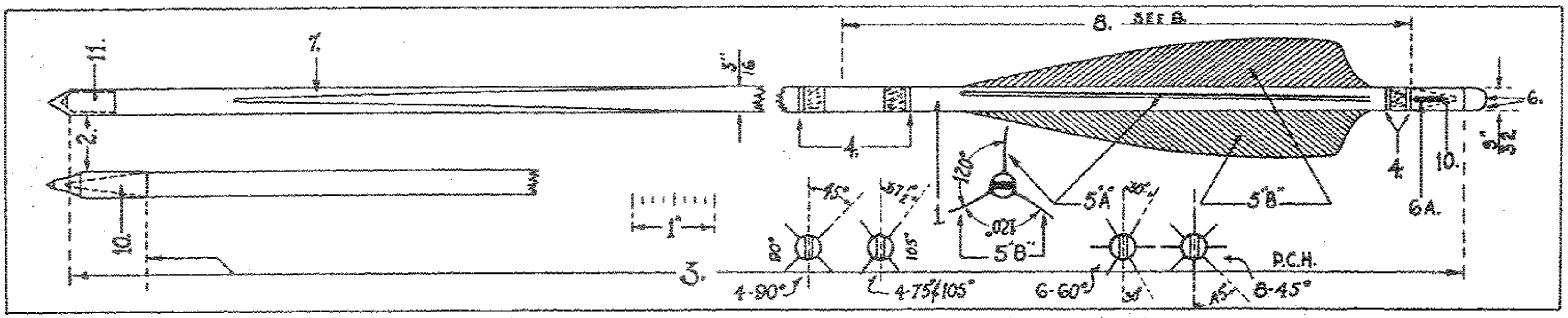


Fig. 3.—Nomenclature drawing of an arrow.

1. Shaft
2. Point or Pile
3. Arrow Length
4. Crest
5. Fletching
(A) Cock feather
(B) Hen feathers
6. Nock
7. Footing (arrow)
8. Shaft Taper
9. Barreled Shaft Tapers
10. Nock and Point Taper
11. Shaft Tennon

Appendix B
A Story of The British Long Bow

OF ALL THE vast armory of weapons which man has used throughout the centuries, one of the most lengendary is the English longbow. Undeniably it was a great weapon. However, some military historians question some of the prowess assigned to it.

This famed English weapon had its inception in Wales. During the Welsh campaigns of Edward I, in the latter half of the Thirteenth Century, the native archers wrought such havoc among the ranks of the English that Edward made peace with them and enlisted them in his own army. The Welsh bow was short and rather thick and was, at times, used as a club when combatants closed on each other in hand to hand fighting.

The English immediately improved upon the Welsh weapon, developing it into the storied longbow. Some six feet long, on the average, it was made of yew by choice. However, ash, elm or witch-hazel also were used. In fact, yew was considered so superior and was used up so rapidly that it became necessary to forbid its sale outside England. Furthermore, it was required by law that any merchant ship coming to England from abroad had to bring along four bowstaves for every ton of merchandise carried.

For a long time during this period, the Lombards supplied the English with quite respectable quantities of high quality bowstaves. Apparently unable to stand prosperity, they began sending along bowstaves of poor quality, meantime increasing the price. As a result, it was decreed by the English government that the Lombards must supply ten good bowstaves free of charge along with every butt of wine shipped into England. Since this wine business was a most important part of the Lombard trade, this was punishment indeed! Incidentally, little yew grows wild in England today, so extensively was it used during the days of the longbow.

The arrows used with the longbow were commonly called clothyards. The arrow was as long as the distance measured between the outstretched hand and the ear. This was approximately the length of measurement used by weavers and cloth merchants.

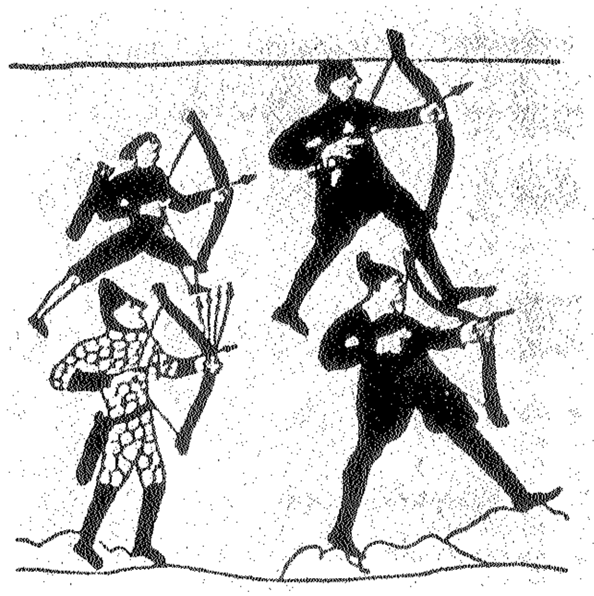
Arrows usually were made of ash, oak or birch, and were winged with gray goose feathers. However, the feathers of the peacock and of swans also were used for the purpose. The head of the arrow was of steel. It was, of course, of prime importance that all arrowheads be of the best materials and workmanship. In this connection, in the year 1405 some faulty arrowheads were delivered for military use. Thereupon a royal decree provided that "All head for Arrows...after this Time to be made, shall be boiled or brased, and hardened at the Points with Steel." In order to insure that responsibility for poor materials and workmanship could be promptly fixed, the decree went on to say that "Every Arrow head...be marked with the Mark of him that made the same."

The longbowmen stood with his side to the target, the bow held straight out with fully outstretched arm. Using the tips of the first three fingers, he drew the string back to his ear. The arrow was held steady between the first and second fingers of the other hand, its head lying on the hand, against the bow. Medieval manuscripts on the subject of warfare refer to both left and right-hand archers.

Many years of hard training were required to develop a good longbowman. English youths were given their first bow while quite young and archery was practiced on every village green. Practice was required by law and a fine was imposed for shooting at a target less than two hundred yards distant. Any longbowman worthy of the name could shoot between twelve and fifteen aimed arrows a minute. It was a common saying of the time

When mounted men began to utilize the bow for combat, it was necessary to shorten its length. This is evidenced in this ancient drawing, which was made in the year 1544.

Originally, English longbows were fashioned from yew and measured six feet in length. Today, because of the wide use of this type of wood, there is little yew in England.



that a longbowman carried the lives of twelve of the enemy at his belt, that being the number of arrows in his quiver. So powerful was this weapon that its arrows pierced mail easily and it, along with the crossbow, was responsible for the change to plate armor.

The longbowman, himself, wore little armor, usually only an iron or steel skull cap or helmet and a stout leather jacket. In addition to his bow he usually was armed with a sword or dagger. These were most useful in finishing off the enemy wounded.

Although the longbow was a superior weapon for its time, it is well to note that many English victories of this particular era were also due, in no small measure, to tactics, organization and patriotism. The kings of England had begun to realize the weakness of armies composed of a comparatively few nobles or knights and a host of untrained serfs, the latter fighting only because they had to. English rulers began more and more to place their reliance upon trained free men, paid for their services to the crown. Consequently it wasn't too difficult at all to come by numbers of trained longbowmen ready to sign up for long terms of service, since they knew that they would be paid a wage in addition to anything they might come by in the way of plunder. At the same time, these Englishmen were developing a great sense of national pride and were ready to fight for it. It is indeed significant that, at a time when the ranks of the armies of Europe were made up largely of serfs, Englishmen were regarding military duty as an obligation of all free men, an obligation not at all restricted to the knightly class.

The battles of Crecy, Poictiers and Agincourt often are pointed out as the three great battles in which the longbow reached it greatest heights. At Crecy, in 1346, the English forces under Edward III consisted of some 4000 men-at-arms, 10,000 or so archers, and 5000 foot troops. The French, under Philip, had nearly 12,000 armored horsemen, at least 6000 crossbowmen, and 20,000 foot troops.

Edward dismounted his horsemen and placed them in the center of a crescent-shape formation the ends of which, pointing toward the enemy, were composed of longbowmen positioned behind pointed stakes. In an exchange of fire between the longbowmen and the crossbowmen, the latter were completely routed. The French knights were so scornful of their fleeing crossbowmen that they cruelly rode them down as they galloped into a charge against the English. As the French headed for the dismounted English knights, they came under a heavy cross-fire from the longbowmen. On-coming night finally put an end to a total of sixteen foolhardly attacks. Thousands of French were killed, including 1500 knights and members of noble families. Only fifty Englishmen were killed. Overnight, England became a military power to be reckoned with, mainly because of carefully planned use of the longbow.

Ten years later, in 1356, Edward, the Black Prince, with only 6000 men defeated almost three times that many French, led by King John and his son, Philip. A mere handful of longbowmen, craftily placed to pour in flanking fire, easily fought off all attacks. Then an English counter-attack by what amounted to little more than a so-called corporal's guard of longbowmen and mounted knights resulted in the complete collapse of the French. When the fighting was over, 2000 French knights and nobles were dead, plus thousands of common soldiers. Furthermore, the king, his son, and 2000 knights were captive.

In the combat at Agincourt, fought in 1415, some 40,000 French attacked about 10,000 English, including 6000 longbowmen, under the leadership of Henry V. The longbowmen had a field day and the French suffered a horrible bloody defeat. Although less than two hundred English were killed, French losses totaled thousands, including at least 5000 of noble birth. Among the nobles killed were the Constable of France, three dukes, five counts, and ninety barons. Thus a few commoners armed with the longbow practically wiped out the French aristocracy.

The longbow for many years was superior in accuracy, range and rate of fire to the crude early firearms. It was not until around the mid-1500s that it finally was displaced. A shortage of trained archers was one of the major causes contributing to the abandonment of the longbow when it did occur. It took years of hard training, as has been noted, to develop a good longbowman. The steadily growing use of firearms for sport in times of peace at length resulted in a shortage of young willing to train as archers. Consequently when war came there were few archers and although the firearms of the day were inferior to the bow they were used in ever increasing numbers. In an effort to reverse the tide, Henry VIII prohibited the use of guns except by special permission of the Crown. He also decreed that every man under the age of forty had to provide himself in use of the bow. All such efforts were futile and at length were given up.

The end of the longbow, as noted above, came to an end about the middle of the Fifteenth Century. However, it took many years for the fact to be recognized, so slowly does the mind of some military leaders adjust to new weapons and new tactics. By this time France had developed an efficient standing army. In addition, her gun founders had developed the culverin, a comparatively light, long barrel, muzzle-loading cannon, into an effective field piece. Among other things, they mounted the piece on wheel instead of on a cumbersome sled and provided it with a screw arrangement which allowed rapid changes in elevation. They had also improved the quality of their gunpowder.

At the battle of Formigny, in 1450, a small force of 4000 French, including some well trained artillerymen, bloodily routed a host of more than 7000 English. Skillful employment of the culverins cut the longbowmen to pieces and rendered the survivors easy prey for the French horsemen. Nearly 3000 English were killed, as contrasted to only twelve French dead. The lesson was repeated two years later at a placed named Castillon. There French cannon all but annihilated an attacking force of 6000 English and their Gascon allies, including a large force of longbowmen.

Yet the lesson had to be repeated again and again until it was finally admitted that reeking, noisy firearms had supplanted the bow and arrow. – *Robert H. Rankin*

Appendix C
A Story of The Asiatic Composite Bow

The range of the Turkish bow was tremendous indeed, distances of 600 to 800 yards having been regularly accomplished. Mohammedan archers considered themselves rank amateurs if they could not exceed 600 yards. Consider for a moment the fact that the famed English long bow had a range of some 250 yards and the military crossbow of medieval times had a range around 380 yards and you will have some idea of the power of the Turkish weapon.

Korea has a very ancient tradition of excellence in archery. The Chinese referred to the people of Korea as

夷

a character comprised of 大 (great)

and 弓 (bow).

This character translates as barbarian but carries with it the implication of Korean prowess with the bow. The pride of this tradition has been carried up to the present time; the Korean palace guard carried bows well into this century, and target archery remains a common recreation today.

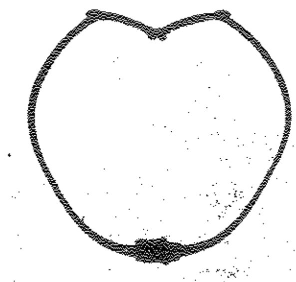
Records from the Silla period state that Chinese T'ang emperors attempted to recruit Korean bowyers to learn the secrets of their composite bows capable of shooting 1000 po or 5000 feet. (The old Korean foot is 7/10 of our own. This puts the range at about 1000 yards.) It is unknown whether or not the composite bow spread to Korea from central Asia or was an independent invention. It is clear, however, that Korean ingenuity worked long and hard on the bow, resulting in a design dramatically different from those of neighboring countries and in the end producing a weapon distinctly Korean.

Perhaps the most highly strained of all bows, the Korean composite bow pushed the materials used to their limits. Despite the short length of around 48-50 inches, the bows commonly drew 32 inches, the archer using the thumb lock and an anchor point behind the ear. The reflexed handle and the sharply bent ears or siyahs gave the unstrung bow a nearly circular sweep. Even on heavily used specimens the tips still touched as often as not.

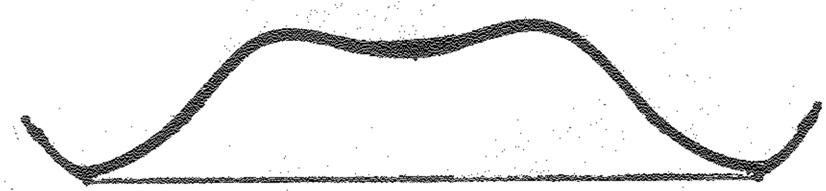
This design differed significantly with respect to other composite bows. The Chinese, Indian, and Middle Eastern bows in general employed limbs with virtually no taper in either width or thickness over the bending portion of the limb.

The Korean bow was of unique and singular design which, today, seems geographically out of place, being situated between the long cumbersome Chinese composites and the long, seven and a half foot Japanese bow.

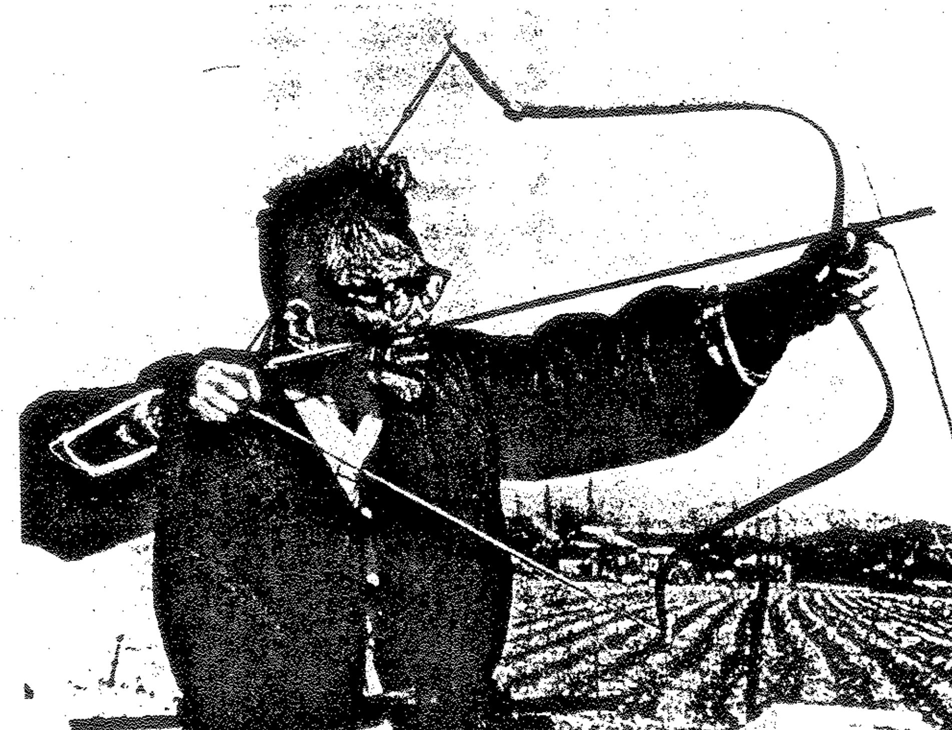
More so than the other composites, the Korean bow had the greatest reflex concentrated just above and below the grip. The central part of the limbs was almost straight, and the recurve was pronounced.



Korean bow relaxed. Profound reflex near center section, long recurve, short siyahs, bridges or shoulders at angles.



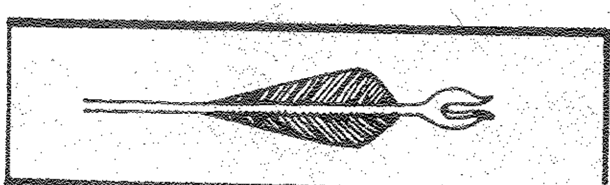
Korean bow braced.



Shin Hai Oke, 75-year-old former national champion of Korea, uses method of ten centuries ago. Note how thumb is up and away from bow, wrist and his bow hand relaxed.

Korean painting of the 6th century (Moo-Yong Chong Tomb Wall)

Mr. Manchoon Yang is a legendary Korean archer who defended his castle, in 644 AD, against the 300,000 troop army of the founding emperor of the Tang dynasty (China). After two months of tough defense he hurt the emperor with his arrow. The emperor was impressed with his archery, and he withdrew his troops, rewarding him with the gold and chinese silk.



Most arrows had nocks that had their sides shaped so they had to be parted to fit into the Turkish bowstring.

In the autumn of 512 B.C. a great army of nearly 700,000 warriors — one of the largest armies of antiquity — was encamped on a rolling, grassy plain on the Steppes of southern Russia, somewhere north of the Sea of Azov. This vast army was under the command of King Darius I of Persia, an ancient kingdom in what is now Iran. At the time, Persia was the most powerful nation on earth, with an empire stretching from Egypt to India.

King Darius and his army — composed mostly of infantry — had embarked on the campaign two years earlier. His goal: subdue the Scythians, a fierce, nomadic tribe of Steppe herdsmen who were noted for their horsemanship and their skill with their powerfully-reflexed composite bows. The long campaign had been a disaster for the Persians; the skirmishes and running battles against the Scythians always seemed to end in frustration. The tactics of the nomads had been to retreat and attack and then retreat again. The Scythian horse-archers were excellent fighters, toughened from a harsh life on the Steppes and disciplined from the daily grind of making and breaking camp, forever moving in search of forage for their horses, sheep, and cattle.

Pressed by the huge Persian army, the Scythian horsemen led their pursuers deeper and deeper into the wilderness of the Steppes, periodically moving in with quick skirmishes to pick off the Persian infantry from long range with their horn-reinforced bows. As they retreated, the Scythians filled in the wells and springs, torched the surrounding grasslands and destroyed food supplies, depriving the Persians of food, water, and forage. Morale of the Persian army was at an all-time low.

The light of dawn on that autumn morning in 512 B.C. revealed a relatively small band of a thousand Scythian horsemen on a grassy hill two miles from the main Persian force. The Scythian horse-bowmen paused for a moment atop the hill and then charged directly down toward the great Persian host. The thunder of their approaching hoofbeats was instantly matched by a clamor from the Persian infantrymen as they realized they were being attacked by this puny force. The clamor became a roar as thousands of foot soldiers uttered battle cries as they hastily grabbed lances and swords and prepared to do battle.

Then came the inevitable deadly whistle as the attacking horse-archers closed, released their arrows in a black cloud and then wheeled about in unison and galloped away, leaving in their wake hundreds of dead and wounded Persian soldiers. The Persian infantry and some mounted lancers gave chase — and were ambushed by a force of ten thousand Scythian bowmen waiting on the other side of the hill. The Persians withered under the onslaught. The Scythians were too swift, too mobile. The extreme range of the Scythians' powerful horn-wood-sinew bows barely allowed the Persians to make contact.

This two-year campaign against the Scythians — a group of Indo-European tribesmen who had moved onto the Steppes of southern Russia two centuries earlier — ended in bitter defeat for the invading Persians. Those battles which took place between 514 and 512 B.C. are among countless others which were to occur on the Steppes of Asia for nearly two thousand years, as entire nations of horse-archers rose to power and then fell, like waves of grass rolling across the windswept Steppes.

The power of the Scythians was eventually broken on the Steppes — not by the army of any civilized nation, but by the Sarmatians, another group of nomadic horse-archers like themselves. The Sarmatians were in turn followed by many other nomadic tribes, including the Parthians, the Massagetae, the Hsiung-nu, the Avars, the Huns, the Bulgars, the Turks, the Mongols, and a host of other Indo-European and Turko-Mongol groups. All of these peoples were expert horsemen whose principal fighting weapon was the Asiatic composite bow.

These nomadic horsemen had a profound impact upon the entire civilized world — from the Roman Empire to ancient China. Echoes of their hoofbeats can even be found in the writings of the ancient prophets of Israel.

Appendix D

A Story of The Cross and The Compound Bows

Interestingly enough, the military crossbow of the Middle Ages once was considered too cruel and inhumane for general use in war. In 1139, high church officials, meeting in council in Rome, prohibited the use of this weapon, except against infidels, under pain of excommunication. It was declared that the crossbow was a weapon hateful to God and therefore unfit for use against Christians. Then, at the close of the 12th Century, Pope Innocent III confirmed this prohibition.

Nonetheless the crossbow was far too effective a weapon to be discarded. The missile fired by the crossbow could punch through the heaviest armor at considerable distances.
It was widely used throughout Christendom, except for a few isolated spots. For instance, Conrad III, King of Germany, prohibited the use of the crossbow within his kingdom. This was the exception and not the rule. Some folks, however, apparently never quite forgot the Church's ban against the weapon. When Richard I of England was killed by a crossbow bolt during the siege of a castle near Limoges, France, it was whispered about that his death was due to the wrath of Heaven because he used crossbowmen in his army.

Surely such a weapon deserves to have its history reviewed, if only briefly.

Known variously as *arbalest*, *arbelast*, and *arblast*, the crossbow, according to some military historians was invented by Zaphyrus, a resident of the Greek city of Tarentum, as early as 300 B.C. Our concern, however, is with the military crossbow of the Middle Ages.

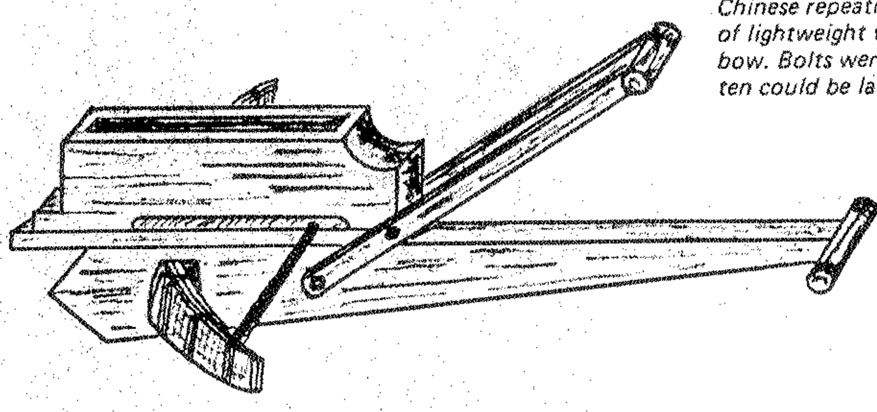
This weapon appears to have been introduced into England by the Normans during their invasion in 1066. During the next few hundred years, it gained military popularity both in England and in Europe. However, it never did achieve the popularity in England accorded the famed longbow. The longbow was, of course, a much faster shooting weapon than the crossbow. Used against moving targets, it was a wonder to behold. Be that as it may, the crossbow fired a heavier missile and had greater range. Furthermore, it did not require the skill and strength necessary to use the longbow properly. The crossbow was particularly effective against, or in defense of, fortifications of all kinds.

Although all nations of any consequence developed their own crossbowmen and considered them elite troops, the Genoese became widely famous as makers and users of the weapon. They hired out extensively as mercenary troops at fancy fees. They were so adept at their profession that their mere presence among the ranks of the enemy was often cause enough to strike stark terror into the hearts of defending forces.

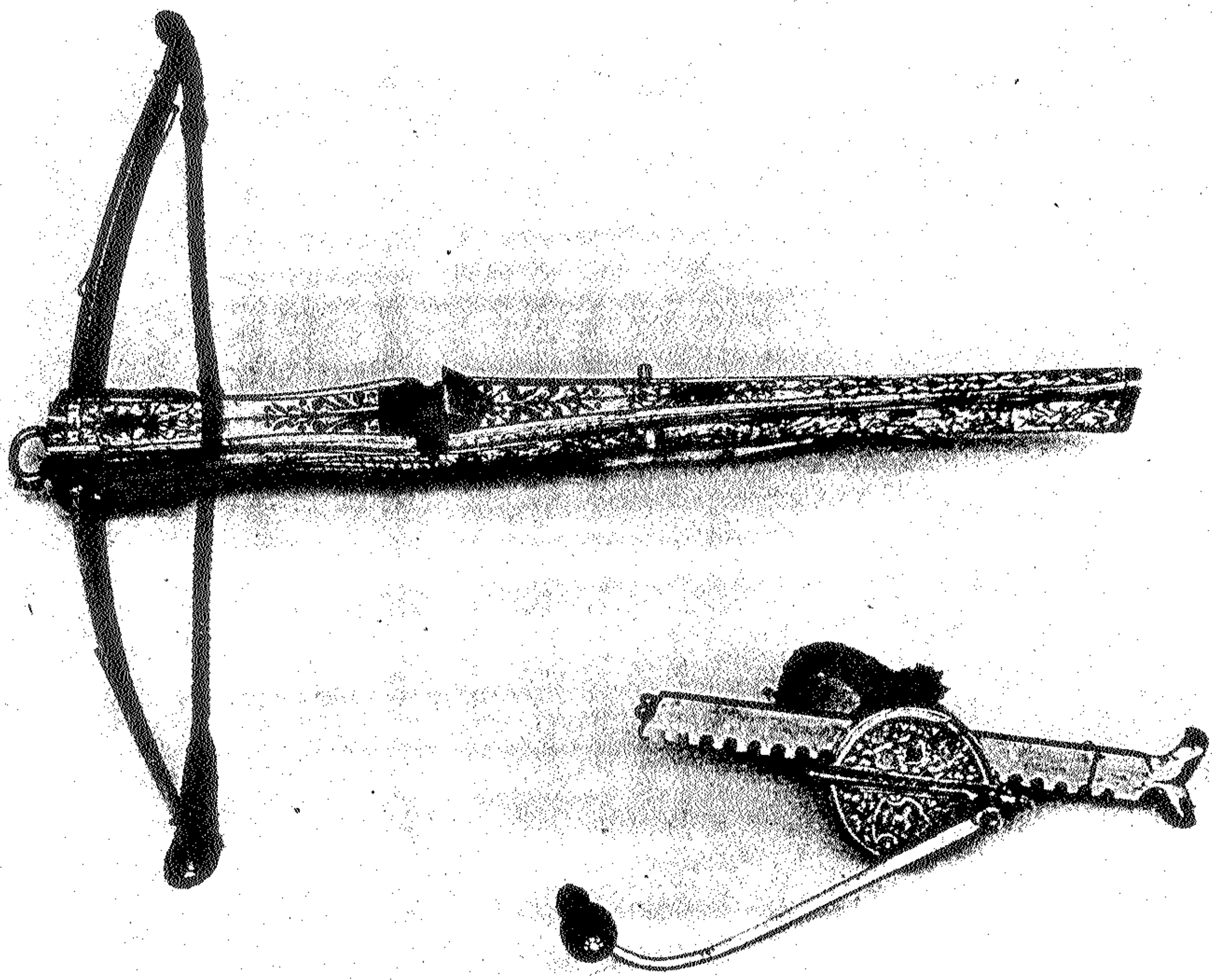
But what of the weapon itself? Basically the crossbow consists of a heavy bow mounted across a stock at a right angle. A groove or channel runs lengthwise of the top of the stock. The bolt or quarrel, as the short arrow is known, moves along this groove. Near the rear of the stock is a simple trigger-tripped mechanism for holding and releasing the bowstring.

Early crossbows were lightweight, hand-drawn affairs with bows of wood, horn, or whalebone. Composite bows, built up of the same materials, were introduced from Asia by the Turks during the Crusades. These found considerable favor in Europe. At the highest period of its development, steel bows were used for military crossbows.

The average military crossbow with steel bow weighed in the neighborhood of fifteen pounds. Siege crossbows, designed to be mounted on stands or up on a parapet, often weighed eighteen pounds or more. These bigger jobs had a bow at least three feet long, one inch thick and two and a half inches wide at the center. They had a range of around 450 yards! The range of the average military crossbow of that era, however, was some 380 yards. The usual rate of fire of the crossbow was a bolt per minute. Accuracy was very good.



Chinese repeating crossbow was made of lightweight wood with a bamboo bow. Bolts were short in length, but ten could be launched in 20 seconds.



This German crossbow, circa 1550, is highly decorated. Also shown are rack, pinion and cranequin to bend bow.

When you pull the compound bow, the pull force drops near the full draw; it is called *let-off*. In general, cam pulleys are used to make the let-off. However, some other mechanisms can be employed for the let-off as shown on the right figures. This mechanism provides 80 % let-off. The compound bow that we are testing in the laboratory makes 65 % let-off.