Chapter 2
Bats and Balls

> *The ball is a sphere weighing not less than 5 nor more than 5 1/4 ounces avoirdupois and measuring not less than 9 inches nor more than 9 1/2 in. in circumference. It shall be formed by yarn wound around a small core of rubber, cork or combination of both and covered by two pieces of white horsehide or cowhide tightly stitched together. The coefficient of restitution (COR) of a baseball cannot exceed 0.555.*
>
> *Wood bat. The bat must be a smooth, rounded stick not more than 2 3/4 in. in diameter at its thickest part nor more than 42 in. in length. Nonwood bat: The maximum length is 36 in. and the maximum diameter is 2 5/8 in.*
>
> – NCAA Baseball Rule 1, Sections 11 and 12, 2010

2.1 Introduction

A good place to start our discussion of the physics of baseball and softball will be to examine the basic equipment used, namely bats and balls. We will have a lot more to say about bats and balls in other chapters, but first it will be useful to look at the basic properties of bats and balls, mention briefly some of the history of the subject, and then consider how bats are designed to appreciate the main differences between solid wood, and hollow aluminum or composite bats.

From a practical point of view, the technical question of greatest interest to baseball and softball players is likely to be one that concerns the performance of various bats. The same questions are asked by golfers and tennis players. If they were allowed one technical question, it would probably be "Which club, or which racquet will work best for me?" Many such questions can be posed about bat performance. Is maple better than ash? Is a heavy bat better than a light bat? Is an aluminum bat better than a wood bat? Are composite bats better than aluminum bats? What is the best shape for a bat? Should extra weight be added at the tip end, or is it better to add weight at the handle end? Does it help to cork a bat? And so on. We will try to answer all of these questions in this book, and more, at least from the point of view of the physics of the problem.

When a physicist looks at the performance of a bat, he or she does so with a biassed point of view. It is not necessarily the best point of view, since physicists tend to ignore many of the practical issues that batters themselves regard as being important. For example, when we measure the performance of any given bat, we are not interested in the durability of the bat, or how many ball impacts it takes to dent or crack the bat, we would not be concerned with how it feels or sounds or smells, we would not be interested in the color or the fancy decals stuck on the bat, and we would not be interested in the price. All of these things might be important to the player, but they have no direct effect on the performance. They might have a

R. Cross, *Physics of Baseball & Softball*, DOI 10.1007/978-1-4419-8113-4_2,

psychological effect, in that a player with a fancy, new, brightly colored, expensive bat might feel more confident with such a bat, concentrate harder on hitting the ball, and end up performing better because he or she is in a better frame of mind to perform well.

The sound of a bat, like the sound of a club or a racquet, also has a strong psychological influence on a player. A ball impacting a wood bat makes a nice "crack" sound when hit properly, while a hollow bat "pings" like a bell. Some players prefer to play in wood bat leagues simply because the crack of the bat sounds more like the real thing, or more like the bat used by a Major League player. Batters are not alone. Professional tennis players are very fussy about the sound of the shot. About half of them use string dampeners to change the ping to a thud, and the other half don't, depending on what they are accustomed to hearing. It makes no difference to the performance of the racquet, but if the shot sounds "wrong" then it won't "feel" right. However, bats that ping generally perform better than bats that crack, for reasons that we will explore later.

From a physics point of view, the performance of a bat depends only on its physical properties, the five most important being the length, diameter, weight, weight distribution, and stiffness. The actual materials used to construct the bat are important only insofar as they might affect those five properties. In that respect, there is very little difference between maple and ash since they are both good quality wood materials. Maple is slighter harder and its surface is not so easily damaged, but that is a durability issue rather than a physics issue. Nevertheless, bats can develop tiny cracks with repeated use, and if that affects the stiffness and hence the performance of the bat then it can become a physics as well as an engineering issue.

There is one other very important issue that we won't dwell on in this book, and that is the performance of the player. The best bat in the world, if such a thing could be found, will not help to dramatically improve a batter's performance. Good batters need, above all else, good eyesight, good athletic ability, lots of practice, strength, good coaching, and a natural ability to swing the bat and connect with the ball. A good bat also helps, but it ranks below most of the other factors. The reason that batters are so interested in bat performance is that an extra few mph in batted ball speed can make a significant difference in the batting average and in the number of home runs scored in a season. In that respect, every little bit helps a batter to perform better.

Baseball

Baseball had its origins in the 1850s when players started making their own wood bats. In those days, they were free to experiment with bats of any size, shape and weight they liked. Players discovered that they could hit the ball farther with round bats rather than using bats with a flat surface, mainly because round objects are stiffer and stronger than flat objects. In general, the greatest strength to weight ratio is achieved when a material is constructed as a hollow tube, but hollow wood bats are not heavy enough or strong enough to be of any practical use. A rule was introduced in 1859 to limit the maximum bat diameter to 2 1/2 in. Another rule was introduced in 1869 to limit the maximum length to 42 in. The maximum allowable bat diameter was increased to 2 3/4 in. in 1895. These dimensions have been maintained in the rules of baseball for the last 115 years. The pitching mound was first moved to its present position, 60 ft 6 in. from the home plate, in 1893.

Most of the early bats were made from hardwoods such as hickory or elm. About half of today's wood bats are made from white ash, while other wood bats are made from maple and other hardwoods. Hickory is harder, denser, and stronger than maple, while maple is harder, denser, and stronger than ash. Hickory has a density of about 0.46 oz $\mathrm{in.}^{-3}$, maple has a density of about 0.40 oz $\mathrm{in.}^{-3}$, and white ash has a density of about 0.37 oz $\mathrm{in.}^{-3}$. The actual density depends on the moisture content and on the species of wood. For example, sugar maple is generally preferred for bats since it is denser than red or black maple. Water has a density of 0.578 oz $\mathrm{in.}^{-3}$, while softwoods like cedar, pine, or fir have densities of around 0.17–0.28 oz $\mathrm{in.}^{-3}$. Softwoods have never been used to make bats since they are not heavy enough or strong enough. Light maple bats with thin handles have a reputation for splintering and sending sharp spears through the air when they break. From a physics point of view, it is interesting to note that a broken bat often signals a well struck ball rather than a weak hit. The point here is that takes a short time for the bend in the barrel to propagate down to the handle, by which time the ball is on its way to its destination. However, broken bats are a safety issue and continue to be closely monitored and researched by most baseball and softball organizations.

If two bats have the same length and shape, so that they have the same volume, then a hickory bat will be heavier and stiffer than a maple bat, and a maple bat will be heavier and stiffer than an ash bat. Many batters still prefer the feel of the softer ash bats, possibly because it is what they are used to, while others prefer to use maple. Personal preferences can be a more significant issue than small differences in bat performance.

The construction of a wood bat is an art that has developed over the last 150 years, and involves careful selection of the right grades of wood, control over moisture content and drying times, and even the number of growth rings [1]. About eight growth rings per inch in a white ash bat seems to be favored by most players, although some bats are made with 15 growth rings per inch since a large number of growth rings indicates an increase in the density and strength of the wood. The direction of the wood grain is also important, since bats bend and break more easily in one particular direction, which is why players are taught to swing a bat with the manufacturer's trademark facing upward. Viewed end-on, a wood bat appears to be made from many thin slices of wood glued together. That is just the visual effect of the grain, but the end result is the same. The bat is strongest when the ball impacts each slice edge-on rather than at right angles. The effect is similar to bending a ruler, or a stack of rulers that can slide on each other. It is much harder to bend or break a ruler if it is bent edge-on rather than across the wide face of the ruler. At least, that is the case for ash bats. Recent research has shown that maple bats are stronger in the opposite direction, so maple bats are now rotated 90° before the trademark is attached.

Softball

Softball was invented in Chicago, Illinois, in 1887 as a winter version of baseball that could be played indoors, and was originally called "indoor baseball." The name changed to softball in 1926 since by that time a relatively large, soft ball was being used which was 16 in. in circumference and could be fielded safely with bare hands. These days, slow pitch and fast pitch versions of the game are played outdoors, usually with a much harder ball that is 10–12 in. in circumference depending on the particular league. Eleven inch balls are commonly used in youth softball and 12-in. balls are used in most adult versions of the game. There are many different versions of softball rules, designed to be played by men or women or by mixed teams of all ages. As a result, softball is now one of the most popular outdoor sports in the USA, and it is a game that is played throughout the world by more than 40 million players. Women's fast pitch softball was introduced into the Olympic Games in 1996 but softball and baseball were both dropped as Olympic sports for the 2012 Summer Olympics.

There are many organizations throughout the world that govern the sport. In the USA, three of the largest are the Amateur Softball Association (ASA), established in 1933, the United States Speciality Sports Association (USSSA) founded in 1968 and the National Collegiate Athletic Association (NCAA). The International Softball Federation has over 100 member countries.

One of the differences between softball and baseball is that softball is played with a bigger ball and a thinner bat. A softball bat can be no more than 34 in. (86.4 cm) long, 2 1/4 in. (57 mm) in diameter or 38 oz (1.08 kg) in weight. The bat can be made of wood, aluminum or composite materials, although wood bats are not commonly used in softball.

Aluminum Bats

Hollow aluminum bats were first introduced in the 1970s, their main advantage being that they did not break as often as wood bats. When manufacturers improved the design to outperform wood bats, they quickly became the preferred choice of bat type in most amateur leagues. The improvements involved the addition of small amounts of copper or scandium for increased strength, thereby allowing for thinner walls, lighter bats, and greater durability. Another innovation was to construct bats with two thin walls close together rather than one thick wall. Today, many more aluminum bats are sold than wood bats.

One of the advantages of aluminum, from a design and performance point of view, is that the weight distribution can be altered by varying the shape and wall thickness. Solid wood bats have most of their weight in the barrel end. A hollow bat of the same outside dimensions, and the same overall weight, has its center of mass closer to the handle end. As a result, a hollow bat of any given weight is easier to swing than a solid wood bat of the same weight, making it easier for the batter to direct the bat onto the ball, and allowing the batter to swing the bat faster.

The disadvantage is that weight is moved away from the region where most balls are struck, closer to the barrel end. However, the wall of a hollow bat is flexible, allowing for a trampoline effect that makes up for the lower mass of the barrel. The physics of the trampoline effect is examined in Chap. 13. Mainly as a result of the enhanced ball speed arising from the trampoline effect and the higher swing speed, all baseball and softball associations, since about 2000, have placed strict limits on the performance of aluminum and other hollow bats made from composite materials such as fibreglass, graphite, and kevlar. The measures adopted by the associations are described and explained in Chap. 11.

Composite Bats

Carbon or graphite composite materials are very light and very strong and are used in the construction of the frames of tennis racquets, many other sporting goods and in the aircraft industry and elsewhere. Composite bats were originally introduced around 2000 by bonding a braided graphite sleeve with an epoxy resin onto a wood or aluminum bat to increase the strength of the bat. Such bats are still manufactured, although a modern trend is to construct 100% composite bats that are made completely from composite materials that include graphite and fibreglass and other materials such as kevlar. Another modern trend is to construct bats with a composite handle and an aluminum barrel, in which case the bat is classed as a hybrid bat.

Composite bats tend to be relatively stiff when they are new and then soften up with repeated impacts. The softer the bat, the bigger the trampoline effect. Impacts create small, almost invisible cracks, which soften the bat. Baseball and softball associations are well aware of this effect and now insist that composite bats be tested after an initial softening up period. Softening up can be accelerated by rolling a bat between rollers, a practice that is relatively widespread (see, for example, BatRolling4u.com). It is not illegal but it gives those with a softer bat a competitive edge.

2.2 Typical Properties of Bats and Balls

Bats are about six times heavier than balls and about six times lighter than a batter's two arms. This is no mere coincidence. Tennis racquets are also about six times heavier than tennis balls. The factor of 6 is about the best ratio to ensure that energy in the batter's arms is well coupled to the bat, and that energy in the bat is well coupled to the ball. If a bat was a lot lighter than a batter's arms, then most of the effort of the batter would be used up in swinging his arms, and only a small part of the total energy available would end up in the bat. Furthermore, a very light bat would tend to bounce off the ball rather than transferring its energy to the ball.

The factor of six can be partly understood in terms of an analogous problem in mechanics. If a heavy ball makes a head-on collision with a light ball at rest then the heavy ball will transfer some of its energy to the light ball, but the heavy ball will continue to move forward and will retain most of its original energy. The transfer of energy from a heavy ball to a light ball is not very efficient. The efficiency can be improved if the heavy ball first collides with a medium weight ball and then the medium weight ball collides with the light ball. It turns out that the efficiency is a maximum if the mass ratios (heavy/medium and medium/light) are the same. If the heavy ball happens to be 36 times heavier than the light ball, then the energy transfer can be maximized by using an intermediate weight ball that is six times lighter than the heavy ball and six times heavier than the light ball. In this respect, a bat functions as a device that helps to improve the transfer of energy from a batter's arms to the ball. The arms of a batter don't actually collide with the bat, but they do act to transfer energy from the batter to the bat.

Some typical properties of bats are shown in the following table (1 oz = 28.35 g, 1 in. = 25.4 mm). These are popular values, players being free to choose bats of some other length, weight or diameter if they want to, within certain allowed limits.

Property	Little league	Softball	Baseball
Length	30 in.	34 in.	33 in.
Weight	20 oz	28 oz	30 oz
Diameter	2-1/4 in.	2-1/4 in.	2-5/8 in.

In Little League, there is no difference between a baseball and a softball bat. At the adult level, softball bats are thinner and usually lighter than baseball bats, and the shape of the barrel is also different. Most adult baseball bats have a barrel that tapers over most of its length, being fattest near the far end. Softball bats have a cylindrical barrel that is constant in width over the whole length of the barrel. Fast pitch softball bats usually have a longer barrel than slow pitch bats and have a shorter taper region connecting the barrel to the handle. The longer barrel allows players to make better contact with the ball for inside pitches. Fast pitch bats are also lighter since the player needs to swing the bat into position more quickly.

Typical ball properties are shown in the following table, although the coefficient of restitution (COR) and stiffness values vary with ball speed and can't be taken too literally. The values in the table are those commonly listed in various rule books and are measured under conditions that don't necessarily represent playing conditions. The COR is a measure of how well the ball bounces, and is normally measured by firing a ball at a speed of 60 mph at a heavy wood block. The COR is the ratio of the rebound speed to the incident speed.

Property	Little league	11 in. softball	12 in. softball	9 in. baseball
Weight	5.25 oz	6 oz	6.75 oz	5.25 oz
Diameter	2.9 in.	3.5 in.	3.8 in.	2.9 in.
COR	0.55	0.44 or 0.47	0.44 or 0.47	0.55
Stiffness	1,500 lb in.$^{-1}$	1,400 lb in.$^{-1}$	1,400 lb in.$^{-1}$	1,500 lb in.$^{-1}$

In most leagues, softballs are not soft. They are just as hard as baseballs. Baseballs are constructed by winding wool yarn around a central cork and rubber pill. The yarn is sourced from Australia since it is stronger than most and can be wound more tightly. Most softballs are now made with a solid polyurethane core. The stiffness of a ball is officially defined by the force in lbs needed to squash a ball by 1/4 in. That value is multiplied by 4 in the above table, assuming that it takes four times the force to compress the ball by 1 in. The stiffness written on a ball (e.g., 350) is the force in lbs needed to compress the ball slowly by 1/4 in. If a ball was compressed slowly by 1 in. then it would probably be destroyed or at least permanently deformed in the process. Nevertheless, the ball can easily squash by 1/2 in. or more in a solid hit but it expands back to its original diameter very quickly before any permanent damage is done. The ball stiffness increases the more it is compressed, with the result that the stiffness can actually be as large as 10,000 lb in.$^{-1}$ when the ball squashes rapidly by 1/2 in. or more. The rules refer only to a slow compression of 1/4 in. in a materials testing machine.

The rules of the game allow for variations in all these quantities, partly since manufacturers cannot guarantee that all balls will be absolutely identical. In fact, there is a wide variation in ball stiffness between different manufacturers. Hendee et al. [2] selected 11 different baseballs in 1998 and found that their mass varied by 4% (from 140.1 to 145.8 g), their COR at 60 mph varied by 6% (from 0.546 to 0.577), their static (slow compression) stiffness varied by 70% (from 1939 to 3307 N cm^{-1}) and the maximum force on the ball in a 90 mph impact on a force plate varied by 48% (from 21 to 31 kN). The impact force is a measure of the dynamic (very rapid compression) stiffness of a ball.

In 2004, Lloyd Smith and Joseph Duris at Washington State University tested 150 different softballs by compressing each ball by 1/4 in. in a materials testing machine [3]. The balls varied in static stiffness from 1,000 to 2,000 lb in.$^{-1}$. They then fired each ball at 95 mph onto a fixed, solid cylinder and found that the dynamic stiffness varied from 5,000 to 10,000 lb in.$^{-1}$. The stiffness of a softball can therefore vary by 100% from one manufacturer to another and by much more than 100% with increasing ball compression or ball speed.

Such wide variations in ball stiffness have a strong effect not only on batted ball speed with non-wood bats, but also on the impact force on a player if he or she is struck by a ball. These issues are discussed in detail in Chaps. 10 and 12.

2.3 Bat and Ball Rules

There are many different rules concerning bats and balls, developed by the various national organizations that govern each sport. Most of the rules developed by each organization are similar, but there are often significant differences. The interested reader will probably be familiar with bat and ball rules issued by their own favorite organization. The specific parameters are important for the success of each sport, but are not essential in terms of the physics involved. One of the nice aspects of physics is that the equations we use do not depend on the specific parameters of the problem. For example, if we denote the mass of a ball by m, and the force on the ball by F, then the acceleration of the ball will be F/m regardless of the actual mass or the actual force. For that reason, it is not necessary in this book to list the mass and diameter of every bat and every ball used in every version of the sport. The following examples are chosen simply to quote some typical values.

Major League Baseball

In Major League baseball (MLB), bats can be up to 42 in. long, up to 2 $3/4$ in. in diameter, can be fitted with a grip extending up to 18 in. along the handle, and are allowed to have a small cupped section in the far end of the barrel up to 1 in. deep and between 1 and 2 in. in diameter. In other words, they can be about 1 oz lighter at the far end than an equivalent uncupped bat. Major League bats must be made from a smooth, round piece of solid wood. In practice, most bats used in Major League are 32–34 in. long and 32–34 oz in weight.

Major League balls must be between 5 and 5.25 oz avoirdupois in weight, must have a circumference between 9 and 9.25 in., must be made from yarn wound tightly around a small core of cork, rubber or similar material, and covered with two strips of white horsehide or cowhide tightly stitched together. The word avoirdupois here refers to the system of units where 16 oz $=$ 1 lb. There are other ounce measures such as the troy ounce used to measure gold and silver, and the fluid ounce which is a measure of volume and is approximately equal to the volume of one avoirdupois ounce of water.

NCAA Baseball

The rules for wood bats are the same as those for Major League. Non-wood bats can be up to 36 in. long, up to 2 $5/8$ in. in diameter and the weight of the bat in oz must be greater than the length (in inches) -3. For example, a 34-in. bat must weigh 31 oz or more. The ball is essentially the same as a major league ball but its circumference can be between 9 and 9.5 in., and its COR can be no larger than 0.555.

NCAA Softball

Softball bats used by the NCAA can be no more than 34 in. long, no more than 38 oz in weight and no more than 2.25 in. in diameter. In practice, most bats used in adult softball are 33 or 34 in. long. The bats used in adult slow pitch softball are typically about 28 oz in weight, while in adult fast pitch softball bats tend to be lighter, around

23 oz since the batter needs to react faster. In fact, many bats in fast pitch softball have a bat drop of −10 or −11. The bat drop is the weight in oz minus the length in inch. The bat drop in baseball is typically −3, while a 33 in., 23 oz bat used in fast pitch softball has a drop of −10.

The ball must be optic yellow, with a circumference between 11 7/8 and 12 1/8 in., a weight between 6.25 and 7.0 oz, and a COR no larger than 0.47. The compression force, to compress the ball by 1/4 in., must be between 300 and 400 lb.

2.4 Bat Performance

In theory, a bat can be constructed to have almost any mass and length and barrel diameter that the designer or the player wants, but in practice there are now strict rules in all baseball and softball leagues, both amateur and professional, that govern the allowed properties of bats and balls. The rules are determined in the USA by MLB, the ASA, the NCAA, National Federation of State High School Associations (NFHS), Little League, USSSA and others. Each organization has a different set of rules, but they are all designed with the common objectives of having a good balance between offense and defense and maintaining the sport's safety. The safety issue is related primarily to increases in batted-ball speed with improvements in bat technology.

A slightly confusing aspect of the various tests is that different organizations use different tests, and each organization varies the test method from time to time as they each gain more experience in the practical aspects of designing and performing the various tests. At first sight, it might seem like a relatively simple task to test a bat to see how well it performs. One could simply swing each bat at a speed of say 60 mph at a ball pitched at say 70 mph and then measure the exit speed of the ball coming off the bat. If the ball exits at more than say 100 mph then the bat might be declared illegal. That is indeed the basic method now used to test all bats, but there are many subtle features that require careful consideration to interpret the results in a valid manner.

Some of the problems in testing bats this way are the following:

What allowance should be made for the fact that some balls bounce better than others, and that the bounce of a ball depends on its temperature and moisture content or on the humidity?

What allowance should be made for the fact that light bats can generally be swung faster than heavy bats?

What allowance should be made for the fact that the ball bounces best at a point near the sweet spot?

What allowance should be made for the fact that the best bounce point is not actually a fixed point on the bat but varies according to the actual bat speed and the actual ball speed?

Anyone reading the details of these tests for the first time will probably have trouble understanding all the various technical terms that are used. Some of those terms include the BBS = Batted Ball Speed, the BESR = Ball Exit Speed Ratio, the BPF = Bat Performance Factor, COR = Coefficient of Restitution, COP = Center of Percussion, and two new terms introduced in 2011 called the BBCOR = Ball–Bat COR and the BWCOR = Ball–Wall COR. The idea behind the BWCOR is that the bat and the ball need to be tested separately so that any differences in ball properties don't interfere with the primary objective of testing the bat. A discussion of the various test methods will be given in Chap. 11.

2.5 Real Bats and Toy Bats

The design of modern baseball bats has evolved over many years, partly by trial and error, partly by engineering calculations and innovations [4–8] and partly driven by marketing requirements to produce new, improved models almost every year. Cosmetic features can be added to bats so that they appear to have certain advantages, and can be advertised as being better, but the actual difference in performance might be negligible. The main physics and engineering principles behind bat design can be understood by considering a few hypothetical bats with simple geometric shapes to keep the calculations simple. We will shortly describe a few such "toy" bats to see how they compare with real bats. But first we look at two real bats for clues to see how they were designed.

Two Real Bats

Figure 2.1 shows the profile of two real bats. One is a Louisville Slugger R161 wood bat of length 33 in., weight 31 oz and barrel diameter 2-5/8 in. The other is an Easton BK7 aluminum bat of length 33 in., weight 30 oz and barrel diameter 2-5/8 in. Both bats look very similar, but the balance point of the wood bat is 22.2 in. from the

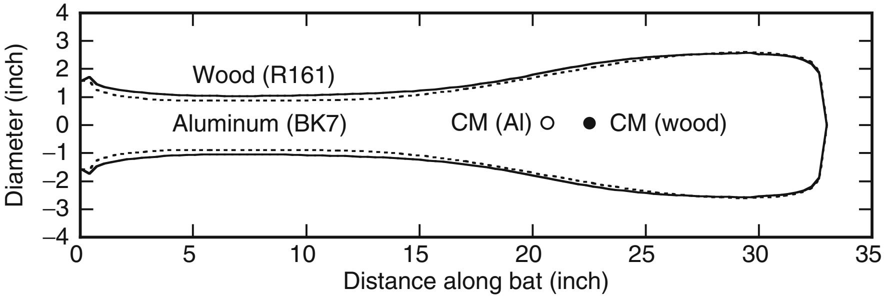

Fig. 2.1 Profiles of two real bats, one wood (with the larger diameter handle) and one aluminum. The vertical scale is not the same as the horizontal scale, hence the bats appear stubby

knob, and the balance point of the aluminum bat is 20.7 in. in from the knob. The balance point, or the center of mass, is the point where the bat can be balanced by supporting it on one finger.

The measured swing weights were 10,600 oz in.^{2} for the wood bat, and 9,530 oz in.^{2} for the aluminum bat, both measured about an axis 6 in. from the knob. The aluminum bat is therefore easier to swing. The term "swing weight" is explained in Chap. 1 (Basic Physics) and in Project 7. It is a number that describes how the weight is distributed along the bat and it determines how easy it is to swing the bat.

The total volume of the wood bat is 81.92 in.^{3} so the wood density is 0.38 oz in.$^{-3}$, indicating that it is made from ash. Small holes drilled in the aluminum bat indicated that the wall thickness was 3.5 mm (0.138 in.) along its whole length, which is consistent with a total aluminum volume of 19.2 in.^{3}, given that the density of aluminum is 1.56 oz in.$^{-3}$.

Each bat can be regarded as consisting of a handle of length 11 in., a barrel of length 11 in. and a middle section of length 11 in. From the bat profiles, it was found that the handle of the wood bat weighed 4.4 oz, while the handle of the aluminum bat weighed 5.6 oz. The middle 11 in. of the wood bat weighed 7.2 oz, and the barrel weighed 19.4 oz. The middle section of the aluminum bat weighed 7.5 oz and the barrel weighed 16.9 oz. The aluminum bat therefore had a lighter barrel and a heavier handle, which resulted in a balance point closer to the knob and a smaller swing weight.

Toy Bats with One or Two Sections

Three simple toy bats are shown in Fig. 2.2, all of the same weight (31 oz) and length (33 in.). Bat A is the simplest possible bat design, being a straight hickory cylinder of diameter 1.61 in. Such a bat could be used for training purposes. Bat B is an improved design, consisting of an ash handle of length 23 in. and diameter 1.28 in., with a cylindrical ash barrel of length 10 in. and diameter 2-5/8 in. (the maximum allowed diameter). Bat C is similar in shape to bat B but it is made from two lengths of aluminum tube welded together, each tube having a wall thickness of 0.136 in. Bat C has a handle of length 22 in. and diameter 1.0 in., plus a barrel of length 11 in. and diameter 2.62 in. Real bats are tapered and have a knob, but the same basic design principles apply to both real bats and our simplified bats. The question is, how will the three bats differ from each other and from real bats? Will they all be fairly similar or will there be some significant differences?

The average baseball or softball player looking at the toy bats might be excused for thinking that the bats are so badly designed that they couldn't possibly work and that they wouldn't use one even if they cost only $1 each. That might indeed be the case, but if we can pinpoint exactly why they are so bad, then we will be in a much better position to understand what it is that does make a good bat, and why. Simply saying that our bats don't "look" right is not going to tell us anything useful.

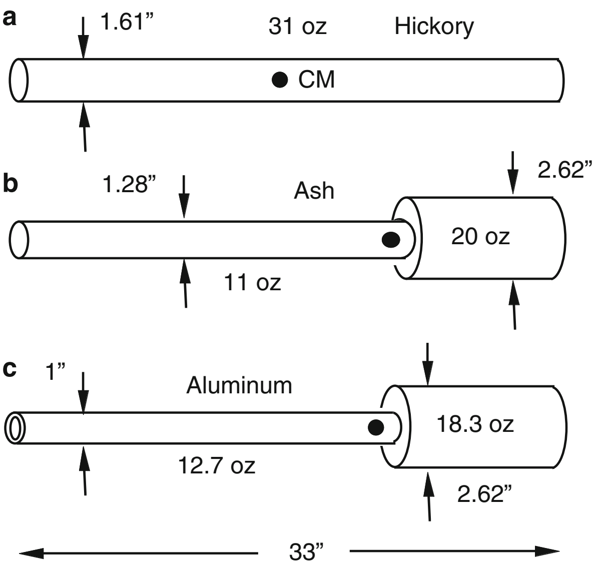

Fig. 2.2 Three 31 oz, 33 in. toy bats. The *black dots* denoted the balance point (center of mass)

The weight of each bat is determined by the density and by the volume of the material used. Hickory has a density of about 0.46 oz in.$^{-3}$ and ash has a density of about 0.37 oz in.$^{-3}$. Hickory was more popular in the past when players liked using heavy bats, and it is a suitable wood for Bat A given that the handle and the barrel have the same diameter. Obviously, a thinner handle and a thicker barrel would be better, but the question we first need to ask is whether Bats B and C are dramatically different or just slightly different from Bat A in terms of their balance point and swing weight.

Bat A has a volume of 67.2 in.^{3} so its mass is $67.2 \times 0.46 = 31$ oz. Bat B has a total volume of 83.8 in.^{3} so its mass is $83.8 \times 0.37 = 31$ oz. Bat C has a total volume of only 19.9 in.^{3} of aluminum but it also has a mass of 31 oz since aluminum is about four times denser than wood. Aluminum bats therefore need to be hollow if the barrel is to be more than about 1 in. in diameter. We could make a solid aluminum bat if we wanted to but it would need to be a solid rod similar to Bat A and it would be only about 0.9 in. in diameter.

For a given mass or volume of material, the dimensions of Bats B and C could be almost anything. Bat B was chosen so that it had the same length, mass and balance point as the Louisville Slugger R161 wood bat. The balance point is just another term for the center of mass. An older term no longer used is the “center of gravity.” The balance point of Bat B was 22.2 in. from the end of the handle, and its swing weight was 10,664 oz in.$^{-2}$. Bat B therefore has physical properties that are almost identical to the real wood bat and should therefore perform in a very similar manner. However, Bat B would not be as strong and would probably break at a point near where the handle joins to the barrel.

It was difficult to design Bat C so that it had the same balance point as Bat B without ending up with an impractically small wall thickness in the handle or an impractically small diameter and very flexible handle. Bat C was, therefore, designed with a wall of uniform thickness in both the handle and the barrel, but the balance point then ended up being 20.7 in. from the end of the handle, 1.4 in. closer to the handle than Bat B. The weight and balance point of Bat C ended up being exactly the same as the real aluminum bat (the Easton BK7) and it also had an almost identical wall thickness (0.136 in. vs. 0.138 in.). The swing weight of Bat C was 9,473 oz in.^{2}, only 0.6% less than the Easton aluminum bat. Bat C should therefore behave in a very similar manner to the "real" bat.

The aluminum bat, like the real one, was just as heavy as the wood bats but it was not possible to design an aluminum bat with as much weight in the barrel as in a wood bat. The essence of the problem is that the area and volume of any section of a solid bat is proportional to its diameter squared. For example, if the barrel is twice the diameter of the handle then any given length of the barrel will be four times heavier than the same length of the handle. For a hollow cylinder with a thin wall, the volume of material in any given length is proportional to the diameter, not the diameter squared. So, if the barrel is twice the diameter of the handle, and if it has the same wall thickness, then any given length of the barrel will be only twice as heavy as the same length of the handle. A hollow bat will therefore have a relatively light barrel and a relatively heavy handle compared with a solid bat. The balance point of a hollow bat will therefore be closer to the handle.

Bat A ended up with a swing weight of only 6,231 oz in.^{2} so it would be much easier to swing than the other bats. However, it would not work as well as the other bats since the barrel end would be too light, even allowing for the fact that Bat A can be swung faster. That is why all real bats have a skinny handle and a fat barrel. Bats are tapered so that the stress on the bat is spread out over a reasonable length of the bat and is not concentrated at a small transition region.

2.6 Stiffness of Bats and Balls

One of the properties of a bat that determines how well it performs is its stiffness. We use the word "stiffness" here in its usual sense, to describe how easily the bat bends. However, we will also use the word "stiffness" to describe how easily a bat or a ball can be compressed. For example, a baseball is lot stiffer than a tennis ball since it is much easier to squash a tennis ball than a baseball. Whenever we use the word stiffness in this book it will be clear from the context whether we are referring to bending or compression, but the reader should remain alert to the fact that bending and compression are two different, but related things. If you bend a long wood or metal rod or bar, one side lengthens or stretches and the opposite side shortens or compresses. Consequently, a material that is easy to stretch or compress will also be easy to bend.

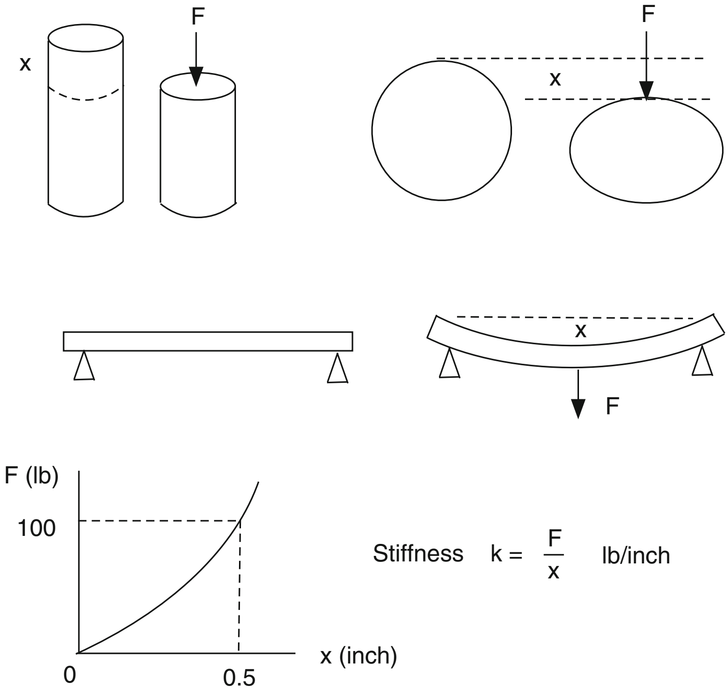

Fig. 2.3 The stiffness of a cylinder, a ball or a length of wood is defined by stiffness $k = F/x$. A graph of F vs. x is usually not a straight line. If the line curves upwards, then the stiffness, F/x, increases as x increases

A bat can bend in different ways. For example, if you were to place each end of a bat on a brick and stand on the bat in the middle, then the bat would bend in the middle, as shown in Fig. 2.3. If you put the barrel in a vice and tighten the vice, the bat would bend out of shape and squash across its diameter. In either of these circumstances, a stiff bat or ball will not bend or squash as much as a flexible bat or ball.

A bat is not necessarily stiff along its whole length. In fact, the handle end is always more flexible than the barrel end since the handle is thinner. Stiffness depends on several factors. One is the nature of the material. For example, rubber is a very flexible material, wood is stiffer, and steel is stiffer than wood. But stiffness also depends on the shape and thickness of the material in the bending direction. It would be easy to bend a thin steel wire, and much harder to bend a thick plank of wood. A ruler is very stiff if you try to bend it edge-on, and quite flexible if you bend it across the flat face.

Stiffness is measured in $\mathrm{lb\,in.}^{-1}$ (or in $\mathrm{N\,m}^{-1}$ in SI units). If a force F is applied to a ball and if it compresses by an amount x, then we define the stiffness, k, of the ball by $k = F/x$. For example, if it takes a force $F = 375\,\mathrm{lb}$ to compress a ball by $x = 0.25\,\mathrm{in.}$, then $k = 375/0.25 = 1,500\,\mathrm{lb\,in.}^{-1}$.

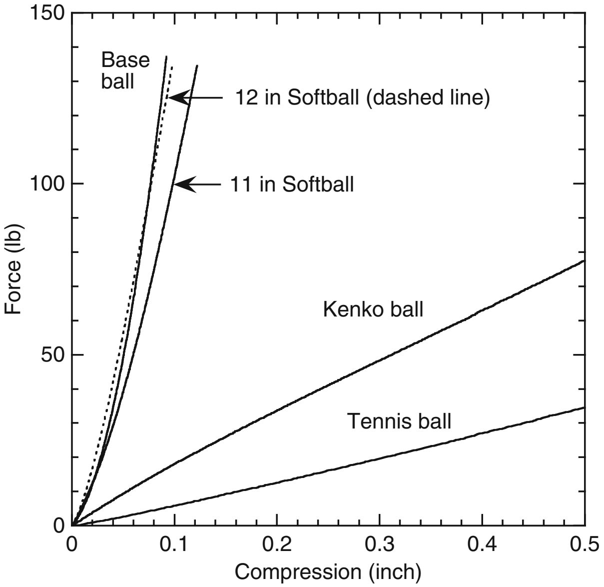

Fig. 2.4 Force vs. compression for several different balls, showing that baseballs and softballs are typically about 30 times stiffer than a tennis ball. The Kenko ball is a hollow rubber youth baseball used in Japan and elsewhere

F vs. x graphs for several different balls are shown in Fig. 2.4, obtained by compressing each ball in a materials testing machine at a rate of 20 mm per minute. The stiffness of a baseball or a softball increases the more it is compressed, being about 1,500 lb in.$^{-1}$ at a compression of $1/4$ in. and about 8,000 lb in.$^{-1}$ at a compression of 1 in., since it takes a force of about 8,000 lb to squash a ball by 1 in. The adult baseballs and 12 in. softballs tested were almost equal in stiffness, while the 11 in. softball was softer. The Kenko ball (a hollow rubber ball) is softer still, and is used in many countries around the world as a youth baseball for safety reasons. For comparison, a tennis ball was also tested, indicating that baseballs and softballs are typically about 30 times stiffer than a tennis ball.

Results of a simple experiment to compare the stiffness of bats and balls are shown in Fig. 2.5. Using a materials testing machine, the author squashed a baseball using a force of 120 lb and found that it compressed by 0.08 in. The ball stiffness was therefore $120/0.08 = 1{,}500$ lb in.$^{-1}$. An attempt was made to compress the barrel of some bats in the machine, but the barrels were tapered and could not be compressed evenly between the two parallel plates. So a ball was placed on top of the bat and compressed together, as if the bat and ball were colliding in the usual way. That way, the same force was applied to both the bat and the ball. The results showed that an aluminum bat compressed slightly more than a white ash wood bat, but neither compressed as much as the ball. If they had, then the total compression of the bat and the ball, at a force of 120 lb, would have been $2 \times 0.08 = 0.16$ in.

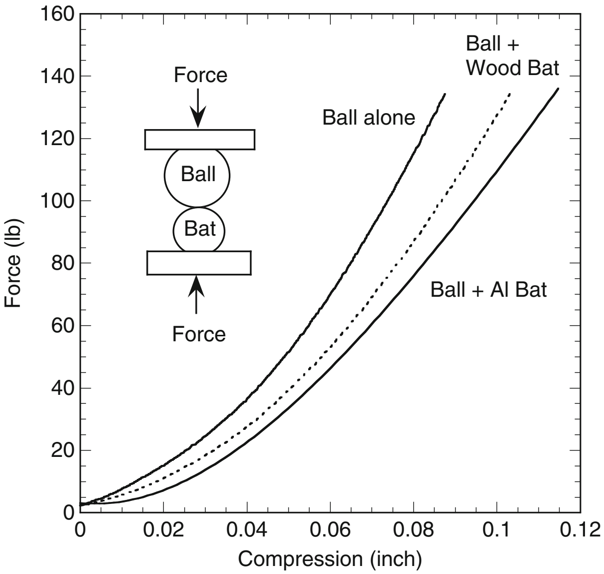

Fig. 2.5 Force vs. compression for a baseball by itself and for a baseball plus a wood or aluminum bat squashed together as shown in the inset

When a bat collides with a ball, the ball squashes, and the bat also squashes across its diameter. The bat doesn't squash as much as the ball, so the bat is stiffer than the ball. Nevertheless, hollow bats squash more than solid wood bats, leading to a bigger trampoline effect. We will examine the trampoline effect in Chap. 13. For the moment, we simply want to point out that bat stiffness is one of the important properties that determine how the bat will perform.

It was surprising that the wood bat compressed almost as much as the hollow aluminum bat, given that there is a much stronger trampoline effect with aluminum bats than with wood bats. The usual explanation is that wood bats are much stiffer than the ball, so there is very little compression of the wood and almost no elastic energy is stored in the wood. What I found was that the wood bat was about five times stiffer than the ball, while the aluminum bat was about three times stiffer than the ball. The ball or the bats were not compressed very far, and different results can be expected at large compressions, but the results should not be drastically different. Nevertheless, the relative softness of a wood bat at low compressions is not all that surprising. It is easy to dent the surface of a wood bat by striking it on a hard surface, since only a small amount of material on the surface is squashed in the process. In a similar way, only a small amount of surface material is squashed when a bat is squeezed gently in a vice, so the required force is relatively small. It would be far more difficult to squash a wood bat in half by squeezing it in a vice, partly because more of the material is being squashed, so the bat would then be much stiffer.

The difference between wood and aluminum was not as large as expected so a drastic experiment was devised to investigate whether wood is elastic. The end of the wood bat was cut off and machined into a white ash wood ball. The wood ball did not bounce very well at all. Dropped onto a concrete slab, the wood ball bounced to a slightly smaller height than a baseball. So, part of the reason that wood bats show no trampoline effect is that wood is not very elastic. An advantage of aluminum is that it is more elastic, behaving more like a spring. When a ball collides with a hollow aluminum bat, the bat compresses like a spring and then ejects the ball as it springs back to its original shape.

References

1. P.R. Blankenhorn, B.D. Blankenhorn, A.G. Norton, Selected quality characteristics of white ash used in professional baseball bats. Forest Prod. J. **53**(3), 43–46 (2003)
2. S.P. Hendee, R.M. Greenwald, J.J. Crisco, Static and dynamic properties of various baseballs. J. Appl. Biomech. **14**(4), 390–400 (1998)
3. J. Duris, L.V. Smith, Evaluating test methods used to characterize softballs. 5th International Conference on the Engineering of Sport, vol. 2 (Davis, CA, 2004), pp. 80–86. www.mme.wsu.edu/~ssl/pubs/pubs.html
4. A.T. Bahill, W.J. Karnavas, The ideal baseball bat. New Scientist **130**, 26–31 (1991)
5. L.P. Fallon, J.A. Sherwood, A study of the barrel constructions of baseball bats. 4th International Conference on the Engineering of Sport, Kyoto, Japan, 2002
6. L. Noble, Inertial and vibrational characteristics of softball and baseball bats: research and design implications, in Proceedings of the 1998 Conference on International Society of Biomechanics in Sports, 1998
7. P.J. Drane, J.A. Sherwood, J.W. Jones, T.P. Connelly, The effect of baseball construction on the game of baseball, in Proceedings 7th ISEA Conference, Biarritz, Paper 275, 2008
8. R.K. Adair, The Physics of Baseball. Phys. Today **48**, 26–31 (1995)

http://www.springer.com/978-1-4419-8112-7

Physics of Baseball & Softball
Cross, R.
2011, XI, 324 p. 151 illus., Hardcover
ISBN: 978-1-4419-8112-7