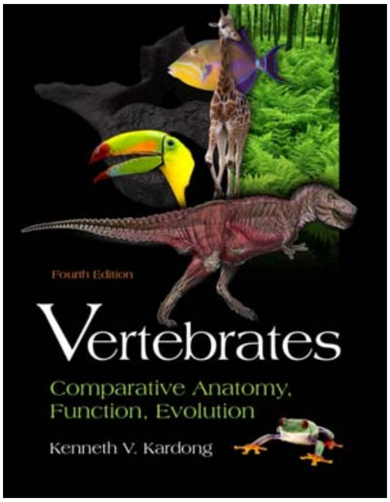


Bone Architecture

Follow up in Textbook: Chapter 4; pp.146-152

A. Objective:

Explain how bone design is influenced by the stresses imposed by loads.

B. Textbook Reference:

No textbooks are to be used during this exercise.

C. Introduction:

To survive, a vertebrate must catch prey, avoid its own predators, and reproduce. But predators and prey, climate and calamities are not the only demands placed on an organism. The organism must also be built to withstand the physical loads imposed upon its supportive system. But all physical loads are not the same, and materials incorporated into bones must be spent in an economical way. This exercise examines the relationship between these physical demands and bone design.

Tension versus Compression (and shear)

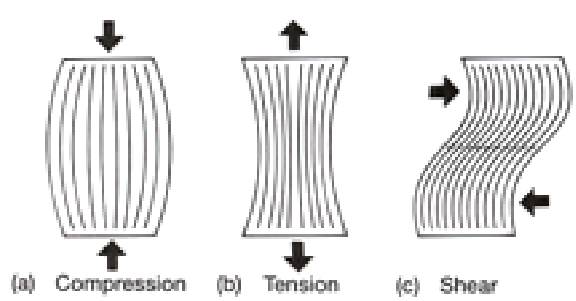


FIGURE 1: **Direction of force application.** The susceptibility of a material to breaking depends on the direction in which the force is applied (arrows). Most materials withstand compression best (a) and are weaker when placed in tension (b) or shear (c).

When loads are applied to a bone, or any supportive object, and it bends, compressive and tensile forces are experienced. The compressive forces push materials together; tensile forces tend to pull the material apart. (Shear stresses tend to slide material on itself, but we will not address these here (Figure 1).)

D. Preparation & Procedures:

Exercise 1: Examining zones of compression and tension

To examine the consequences of compression and tension on material, select a block of clay, slightly dry. Bend the block of clay.

Questions:

a. On which side of the clay, concave or convex, do cracks appear?

b. On which side of the clay, concave or convex, does the clay wrinkle?

You should observe that the clay on the convex side shows the appearance of cracks; on the concave side the clay wrinkles up. This is because compression and tension forces, although present, are not located at the same place in the block of clay. Compression forces arise on the concave side, pushing the clay into wrinkles. Tension forces arise on the opposite, convex side, pulling it apart and causing the clay to crack.

Exercise 2: The functional significance of the breaking strength of a material

The values in the table (Figure 2) below are determined by placing a small test piece of the material in compression, tension, or sheer and gradually increasing the force on it until it breaks. The force reached at the breaking point is recorded in the table. Note that a particular material, living or manufactured, generally breaks at a lower tensile than compressive force. Said another way around, materials are stronger in compression than in tension.

Question:

c. Why might this be significant to our understanding of bone design?

FIGURE 2. Strength of Different Materials Exposed to Compressive, Tensile, and Shear Forces

Material	Compressive Strength (Pa)	Tensile Strength (Pa)	Shear Strength (Pa)
Bone	165×10^6	110×10^6	?
Cartilage	27.6×10^6	3.0×10^6	?
Concrete	41.4×10^6	4.0×10^6	?
Cast iron	620.5×10^6	1.17×10^6	124×10^6
Granite	103×10^6	10×10^6	13.8×10^6

Ultimate strengths shown.

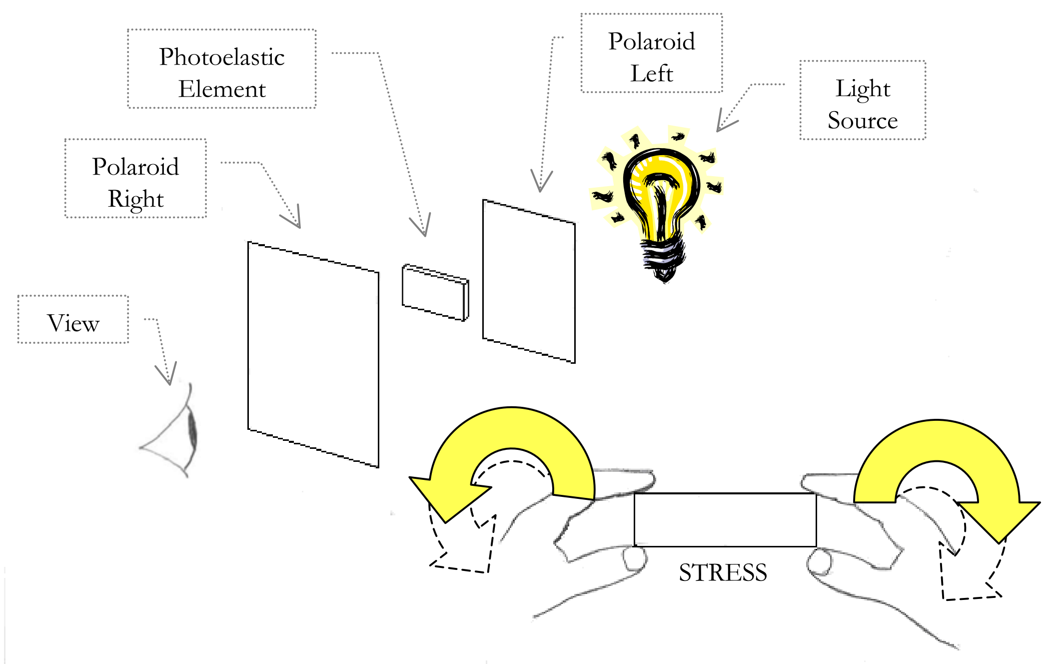
Source: Adapted from J. E. Gordon, 1978, Structures, or why things don't fall down, DaCapo Press, NY. Other sources have also been used.

Exercise 3: Distribution of forces within a supportive structure

Compression and tension forces per cross-sectional area are said to be stresses, physical demands on the supportive material, expressed in pascals (Pa). But stresses generally are not carried evenly within a supportive structure. To see how stresses are carried, examine photoelastic material in polarizing light.

PRECAUTION: Please help preserve the quality of these materials. The photoelastic material is easily scratched and thereby damaged for use. Even washing clay fingerprints off can scratch it. Thus, please wash hands and avoid fingerprints on the clear surface. THANK YOU.

Apparatus. Pairs of polarizing films are mounted on stands. When placed between them, a special photoelastic material appears clear when unstressed. However, when stressed, the internal distribution and level of stress can be visualized in polarized light.



Experiment.

Place a rectangular piece of photoelastic material between the mounted stands and view it through one of the films. Note that it appears clear. Now, with each hand, hold the material at opposite ends and slightly bend it. Note that colors appear. Generally red and blue indicate locations of high levels of internal stress; black or clear represent locations of low levels of stress.

Questions:

d. Where are most of the stresses located in this rectangular beam? At the core or near edges?

e. Most bones, like this rectangular beam, carry stresses in similar locations. If you were spending material on making a bone, why would you put most material at the surface and leave the interior hollow? Does this suggest why bones are generally tubular and not solid? How about bamboo?

Exercise 4: Stress Concentration

Stress concentration describes the situation wherein internal stresses carried by an object tend to localize around holes in the material. Although a load applied to a bone may not exceed its strength, when internal stresses concentrate, this may result in a concentration of forces that exceed the local strength of the material, and a fracture could be initiated.

Again take a rectangular piece of photoelastic material, but with two holes drilled in it at different locations. Place it between the polarizing films, and apply force (bend it as you did in Exercise 3).

Questions:

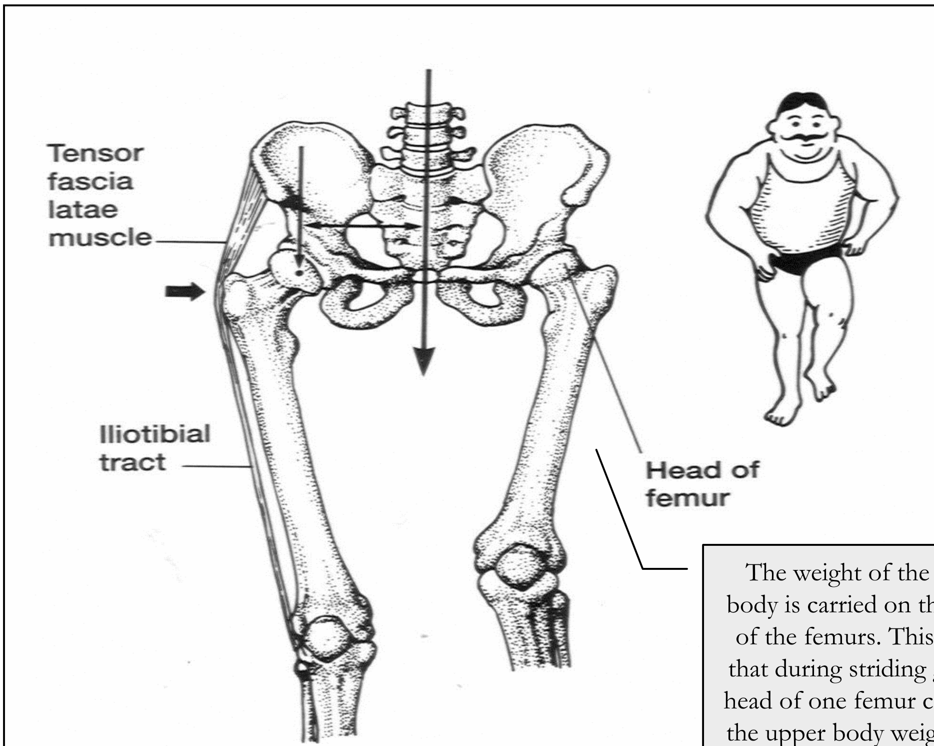
f. Which one of the two holes has the greatest stresses associated with it?

g. How might this information be important to a physician or veterinarian setting a broken bone? (Remember, a severe bone break often requires temporary screws to hold it. The screws are removed when the break is nearly healed.)

Exercise 5: Asymmetrical loading

If the load applied to a bone (or to any supportive column) is directly in line with its long axis, the bone receives the stress as compression and the bone does not bend. However, if the load is offset, asymmetrical, then the bone may bend, also producing tensile forces. When upright, the human femur holds the weight of the upper body on the head of the femur (See the figure below). This places the load off center, asymmetrical, to the long axis of the bone.

Place the photoelastic outline of the femur head between the polarizing films. Use clamps or your hands to squeeze enough to apply a force on the head of the femur similar to that, which might be experienced by the weight of the upper body. Note where stresses concentrate.



The weight of the upper body is carried on the heads of the femurs. This means that during striding gait, the head of one femur carries all the upper body weight, here the right leg. Consequently the long shaft of the femur is asymmetrically loaded.

Questions:

h. Where do the stresses tend to congregate?

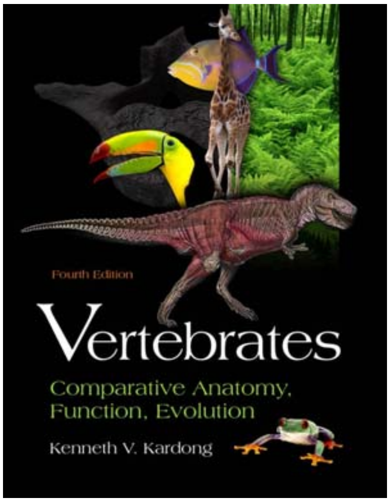
i. Might this suggest where materials in the femur head should be concentrated for strength? Examine a cross section of a real human bone to see if this occurs.

E. Synthesis:

Take advantage of what you have explored in these five exercises. Note that bone is a rather strong material compared to human-made materials (see the Table above).

Question:

j. If bone is so strong, why then does it break?



Instructor's Guide

Bone Architecture

Follow up in Textbook: Chapter 4; pp.146-152

A. Background

Bones support loads. When animals stand, bones resist gravity; when they move, they resist dynamic forces. That is obvious enough. But stresses applied to bones are carried internally. How stresses are carried depends upon their magnitude, direction, and location of loading. Consequently the internal design of the bone should reflect these stress demands. Further bones are energetically expensive to make and to maintain. Nature is thrifty, so the material of bone is distributed in such a way as to meet the stresses but not to be extravagant.

This exercise is designed to make it clear that bones are not inert posts, supporting static loads. The stresses they meet are complex, and even small features of design can increase the risk of failure. But visualizing these internal stresses is difficult, so we take advantage of plastics that, under polarizing light, reveal how and where stresses pile up within the structure.

Photoelastic material, subjected to load and viewed with polarizing light, exhibits color bands indicative of stress levels carried in the material. Each color is a different stress level. These colors could be calibrated and the stress level assigned specific values. But for purposes here, we are interested in qualitative reactions of the material and examination of how stresses are carried in the material. A uniform color represents a uniformly stressed area. Its location indicates where in the material those stresses reside.

B. Materials Preparation

Materials

Photoelastic Sheet Material $112 *
Type: PSM-1 10" x 10" Item Code: 17020 Thickness: 0.125 In. nominal
Supplier: Vishay/Measurements Group

Other materials:
Circular Polarizer Sheet (Left)
Circular Polarizer Sheet (Right)
Size 5 x 5 in.

* As this laboratory goes on the Web, traditional suppliers of these components have ceased selling these polarizing sheets. The hunt is on for alternate suppliers, but none are available at the moment. Check back with this web site or contact the author directly for an update:
kkardong@wsu.edu

Suppliers:
Vishay/Measurements Group
P.O. Box 27777
Raleigh, NC 27611 USA
Phone: (919) 365-3800
Call, select "Applications Engineering", and place your order.

Preparation of materials:

You will need two rectangular pieces of photoelastic plastic. These can be cut to size from commercially available sheets BUT it is important to keep the plastic cool during cutting. A table saw is best, as it is high-speed, sharp, and smooth. While running the photoelastic plastic through the saw, squirt generous amounts of tap water (spray bottle) directly on the site of cutting.

AFTER cutting to size, remove the protective paper covering each side of the plastic.

Each station:

The photoelastic plastic visually shows where stresses within are carried, if viewed in polarizing light. Therefore, suspend two pieces of the polarizing sheets from a support, such as a ring stand. You can build simple holders, or you can just have someone hold each of the sheets.

An illuminating light is placed behind the pair of sheets. The observer looks through the first then second sheet to see the light behind. The photoelastic plastic rectangles should be held BETWEEN the two sheets and stressed by bending it.

Colors should arise in the stressed plastic rectangles seen by the observer looking through the polarizing sheets.

C. Facilitating Tips

This exercise is specifically set up to lead each student from simple to more complex concepts about stresses and bone loading. It is important that each student answer, in writing, their best guess to each question as they meet it in sequence. Don't let them jump ahead. Progress in sequence. Build. This is part of the strategy, and part of facilitation. Students should step through the exercise but not skip around.

D. Assessment - Advice for Evaluating Responses

Questions a, b, & c: The direction of force application affects bone strength. So this first exercise is to distinguish compression from tension, and think about the consequences.

Questions d & e: Stresses tend to concentrate near the surface of a beam. That is shown here, and the students are invited to consider the consequences (e.g. hollow bone). Bamboo, bone, and other hollow biological structures put materials at the surface where stresses are greatest.

Questions f & g: Holes can concentrate stresses, and exceed breaking strength that is otherwise sufficient. Blood vessels reach interiors of bone via holes in the bone; screws used to set broken bones leave temporary holes when the break heals and the screw is removed.

Questions h & i: Asymmetrical loading bends bones, and therefore generates compression and tension forces. The slanted head of the human femur supports the weight of the body above, but is loaded asymmetrically, off the main line axis of the femur.

Question j: Bone is strong. It is designed to withstand stresses imposed. Material of bone is arranged economically, near surfaces where stresses concentrate. When bone breaks, this strength is exceeded. How does this happen?

1) Direction of force application: In compression, bone is exposed to heavy loads it can withstand. But its breaking strength is much lower in tension (and shear). Therefore, under heavy loads, if bone bends, tensile forces are experienced exceeding its strength and it breaks.

2) Stress Concentration. If holes pierce bone (or any engineering beam), the holes concentrate forces. Even small holes may do so, as the size is not so important as is the presence of punctures. In concentrating forces, the holes may magnify stresses and multiply them to levels that locally are well above the breaking strength of bone.

3) Asymmetrical Loading. If loaded asymmetrically, bone bends, tensile forces develop, these may exceed the strength of bone, and it breaks.