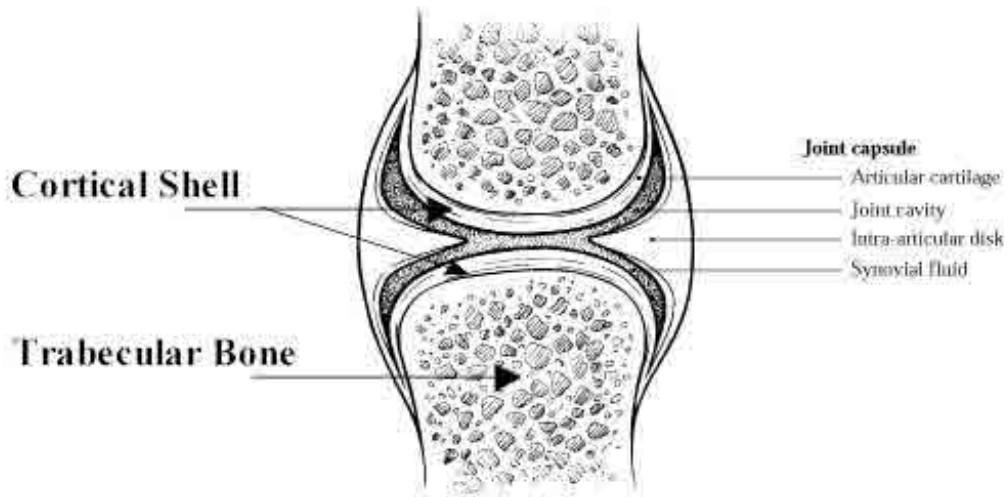# Bone Structure

I. Overview

   We start our section on tissue structure function and mechanically mediated tissue adaptation with bone tissue. This is for two reasons: 1) from a mechanical standpoint, bone is historically the most studied tissue, and 2) due to 1) and the simpler behavior of bone compared to soft tissues, more is known about bone mechanics in relation to its structure. Bone is also a good starting point because it illustrates the principle of hierarchical structure function that is common to all biological tissues. In this section, we illustrate the anatomy and structure of bone tissue as the basis for studying tissue structure function and mechanically mediated tissue adaptation. We first begin by describing the hierarchical levels of bone structure (anatomy) and then describe how these levels are constructed by bone cells removing and adding matrix (physiology).

II. Cortical Bone versus Trabecular Bone Structure

   Bone in human and other mammal bodies is generally classified into two types 1: Cortical bone, also known as compact bone and 2) Trabecular bone, also known as cancellous or spongy bone. These two types are classified as on the basis of porosity and the unit microstructure. Cortical bone is much denser with a porosity ranging between 5% and 10%. Cortical bone is found primary is found in the shaft of long bones and forms the outer shell around cancellous bone at the end of joints and the vertebrae. A schematic showing a cortical shell around a generic long bone joint is shown below:

From: Yun

The basic first level structure of cortical bone are osteons. Trabecular bone is much more porous with porosity ranging anywhere from 50% to 90%.   It is found in the end of long bones (see picture above), in vertebrae and in flat bones like the pelvis. Its basic first level structure is the trabeculae.

III. Hierarchical Structure of Cortical Bone

As with all biological tissues, cortical bone has a hierarchical structure. This means that cortical bone contains many different structures that exist on many levels of scale. The hierarchical organization of cortical bone is defined in the table below:

Cortical Bone Structural Organization

Level	Cortical Structure	Size Range	h
0	Solid Material	> 3000 mm	—
1	Secondary Osteons [A] Primary Osteons [B]	100 to 300 mm	< 0.1

From: Yun

Plexiform (C)
Interstitial Bone

_____

| 2 | Lamellae [(A,B*,C*)] | 3 to 20 mm | < 0.1 |

Lacunae [(A,B,C,D)]

Cement Lines [(A)]

_____

| 3 | Collagen- | 0.06 to 0.6 mm | <0.1 |

Mineral

Composite [(A,B,C,D)]

[A] - denotes structures found in secondary cortical bone

[B] - denotes structures found in primary lamellar cortical bone

[C] - denotes structures found in plexiform bone

[D] - denotes structures found in woven bone

* - indicates that structures are present in b and c, but much less than in a

Table 1. Cortical bone structural organization along with approximate physical scales. The parameter η is a ratio between the level i and the next most macroscopic level i - 1. This parameter is used in RVE analysis.
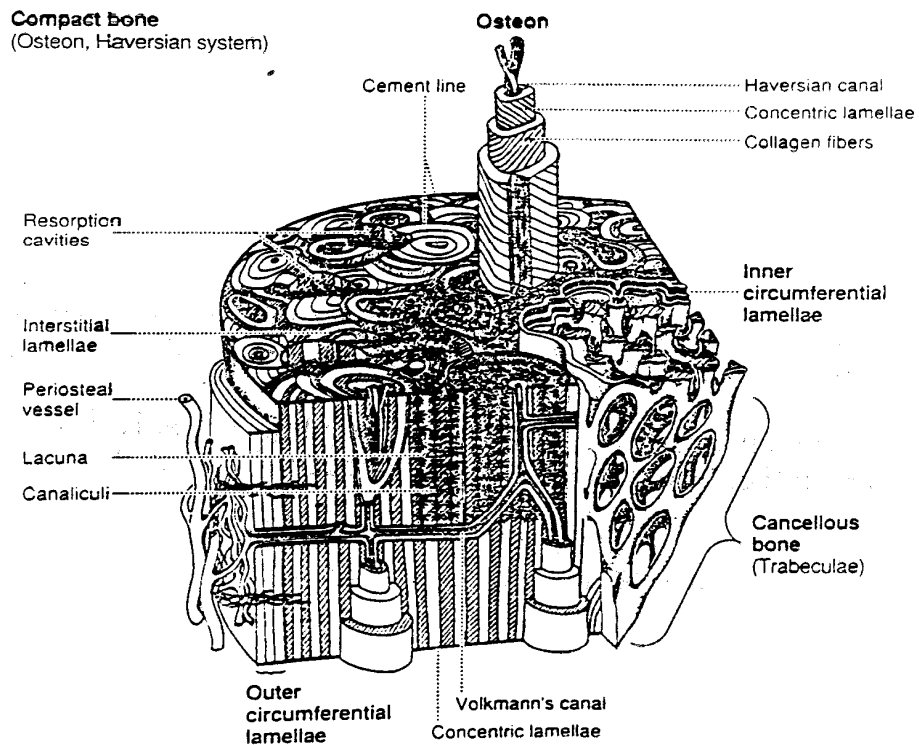
There are two reasons for numbering different levels of microstructural organization. First, it provides a consistent way to compare different tissues. Second, it provides a consistent scheme for defining analysis levels for computational analysis of tissue micromechanics. This numbering scheme will later be used to define analysis levels for RVE based analysis of cortical bone microstructure. The 1st and 2nd organization levels reflect the fact that different types of cortical bone exist for both different species and different ages of different species. Note that at the most basic or third level, all bone, to our current understanding, is composed of a type I collagen fiber-mineral composite. Conversely, all bone tissue for the purpose of classic continuum analyses is considered to be a solid material with effective stiffness at the 0th structure. In

other words, a finite element analysis at the whole bone level would consider all cortical bone to be a solid material.

Different types of cortical bone can first be differentiated at the first level structure. However, different types of first level structures may still contain common second level entities such as lacunae and lamellae. We next describe the different types of 1st level structure based on the text by Martin and Burr (1989). As you will see, the different structural organizations at this level are usually associated with either a specific age, species, or both.

III.1   First Level Cortical Bone Structure

As discussed by Martin and Burr (1989), there are four types of different organizations at what we have described as the 1st structural level. These four types of structure are called woven bone, primary bone, plexiform bone, and secondary bone. A general view of cortical bone structure showing some of the 1st and 2nd level structures is shown below:

From: Yun

Compact bone
(Osteon, Haversian system)

Osteon

Cement line

Haversian canal

Concentric lamellae

Collagen fibers

Resorption cavities

Inner circumferential lamellae

Interstitial lamellae

Periosteal vessel

Lacuna

Canaliculi

Cancellous bone (Trabeculae)

Outer circumferential lamellae

Volkmann's canal

Concentric lamellae

III.1.1   Woven-fibered cortical bone

Woven cortical bone is better defined at the 1st structural level by what it lacks rather than by what it contains. For instance, woven bone does not contain osteons as does primary and secondary bone, nor does it contain the brick-like structure of plexiform bone (Fig. 1). Woven bone is thus the most disorganized of bone tissue owing to the circumstances in which it is formed. Woven bone tissue is the only type of bone tissue which can be formed de novo, in other words it does not need to form on existing bone or cartilage tissue. Woven bone tissue is often found in very young growing skeletons under the age of 5. It is only found in the adult skeleton in cases of trauma or disease, most frequently occurring around bone fracture sites.   Woven bone is essentially an SOS response by the body to place a mechanically stiff structure within a needy area in a short period of time. As such, woven bone is laid down

From: Yun

very rapidly which explains its disorganized structure. It generally contains more osteocytes (bone cells) than other types of bone tissue. Woven bone is believed to be less dense because of the loose and disorganized packing of the type I collagen fibers (Martin and Burr, 1989). It can become highly mineralized however, which may make it somewhat more brittle than other cortical bone tissue with different level one organization. Very little is known, however, about the mechanical properties of woven bone tissue. Christel et al., (1981) suggested that woven bone is less stiff than other types of bone tissue based on the premise that fracture callus is composed mainly of woven bone and is much less stiff than normal bone tissue. Direct measurements of woven bone tissue stiffness have not been made.

III.1.2   Plexiform Cortical Bone Tissue

Like woven bone, plexiform bone is formed more rapidly than primary or secondary lamellar bone tissue. However, unlike woven bone, plexiform bone must offer increased mechanical support for longer periods of time. Because of this, plexiform bone is primarily found in large rapidly growing animals such as cows or sheep. Plexiform bone is rarely seen in humans. Plexiform bone obtained its name from the vascular plexuses contained within lamellar bone sandwiched by nonlamellar bone (Martin and Burr, 1989). In the figure below from Martin and Burr lamellar bone is shown on the top while woven bone is shown on the bottom:

From: Yun

Plexiform bone arises from mineral buds which grow first perpendicular and then parallel to the outer bone surface. This growing pattern produces the brick like structure characteristic of plexiform bone. Each "brick" in plexiform bone is about 125 microns (μm) across (Martin and Burr, 1989). Plexiform bone, like primary and secondary bone, must be formed on existing bone or cartilage surfaces and cannot be formed de novo like woven bone. Because of its organization, plexiform bone offers much more surface area compared to primary or secondary bone upon which bone can be formed. This increases the amount of bone which can be formed in a given time frame and provided a way to more rapidly increase bone stiffness and strength in a short period of time. While plexiform may have greater stiffness than primary or secondary cortical bone, it may lack the crack arresting properties which would make it more suitable for more active species like canines (dogs) and humans.

III.1.3   Primary Osteonal Cortical Bone Tissue

When bone tissue contains blood vessels surrounded by concentric rings of bone tissue it is called osteonal bone. The structure including the central blood vessel and surrounding concentric bone tissue is called an osteon. What differentiates primary from secondary osteonal cortical bone is the way in which the osteon is formed and the resulting differences in the 2nd level structure.

Primary osteons are likely formed by mineralization of cartilage, thus being formed where bone was not present. As such, they do not contain as many lamellae as secondary osteons. Also, the vascular channels within primary osteons tend to be smaller than secondary osteons. For this reason, Martin and Burr (1989) hypothesized that primary osteonal cortical bone may be mechanically stronger than secondary osteonal cortical bone.

III.1.4   Secondary Osteonal Cortical Bone Tissue

Secondary osteons differ from primary osteons in that secondary osteons are formed by replacement of existing bone. Secondary bone results from a process known as remodeling. In remodeling, bone cells known as osteoclasts first resorb or eat away a section of bone in a tunnel called a cutting cone. Following the osteoclasts are bone cells known as osteoblasts which then form bone to fill up the tunnel. The osteoblasts fill up the tunnel in staggered amounts creating lamellae which exist at the 2nd level of structure. The osteoblasts do not completely fill the cutting cone but leave a center portion open. This central portion is called a haversian canal (see cortical bone schematic). The total diameter of a secondary osteon ranges from 200 to 300 microns (denoted as μm; equal to 0.2 to 0.3 millimeters). In addition to osteons, secondary cortical bone tissue also contains interstitial bone, as shown in the cortical bone schematic. A histologic view of compact bone (from http://www.vms.hr/vms/atl/a_hist/ah062.htm) is seen below:
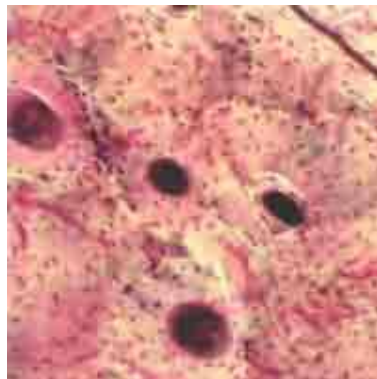
Some other pictures of compact bone histology may be viewed at http://www.grad.ttuhsc.edu/courses/histo/cartbone/intro.html, such as the histology section of cortical bone shown below:
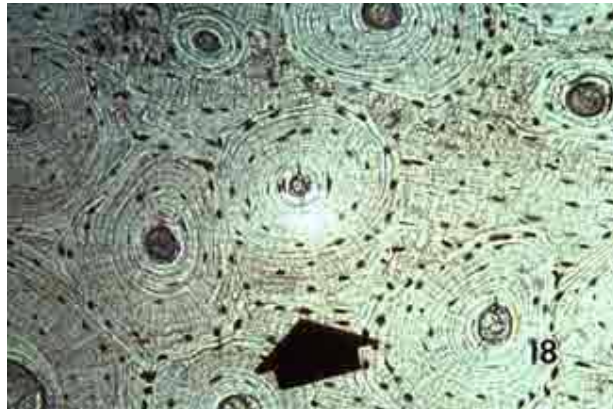
showing another cross section of osteonal cortical bone, and the following longitudinal section shown below:

Notice the haversian canals (large dark circles) and the rings of lamellae that surround them to form an osteon. The smaller dark circles are lacunar spaces within the bone.

.   The haversian canal in the center of the osteon has a diameter ranging between 50 to 90 μm. Within the haversian canal is a blood vessel typically 15 μm in diameter (Martin and Burr, 1989). Since nutrients which are necessary to keep cells and tissues alive can diffuse a limited distance through mineralized

From: Yun

tissue, these blood vessels are necessary for bringing nutrients within a reasonable distance (about 150 μm) of osteocytes or bone cells which exist interior to the bone tissue. In addition to blood vessels, haversian canals contain nerve fibers and other bone cells called bone lining cells. Bone lining cells are actually osteoblasts which have taken on a different shape following the period in which they have formed bone.

III.2   Second Level Cortical Bone Structure

The second level cortical bone structure consists of those entities which make up the osteons in primary and secondary bone and the "bricks" in plexiform bone. Woven bone is again distinguished by the fact that no discernible entities exist at the second structural level. Within osteonal (primary and secondary) and plexiform bone the four major matrix 2nd level structural entities are lamellae, osteocyte lacunae, osteocyte canaliculi, and cement lines. Lamellae are bands or layers of bone generally between 3 and 7 μm in thickness. The lamellae are arranged concentrically around the central haversian canal in osteonal bone. In plexiform bone the lamellae are sandwiched in between nonlamellar bone layers. The lamellae in osteonal bone are separated by thin interlamellar layers in which the orientation of bone mineral may be altered. Lamellae contain type I collagen fibers and mineral.

The osteocyte lacunae and canaliculi are actually holes within the bone matrix that contain bone cells called osteocytes and their processes. Osteocytes evolve from osteoblasts which become entrapped in bone matrix during the mineralization process. As such, the size of osteocyte lacunae if related to the original size of the osteoblast from which the osteocyte evolved. Osteocyte lacunae have ellipsoidal shapes. The maximum diameter of the lacunae generally ranges between about 10 to 20 μm. Within the lacunae, the osteocytes sit within extracellular fluid. Canaliculi are small tunnels which connect one lacunae to another lacunae. Canalicular processes starting at osteocytes travel through the osteocytes canaliculi to connect osteocytes.

13   From: Yun

Many people believe that these interconnections provide a pathway through which osteocytes can communicate information about deformation states and thus in some way coordinate bone adaptation. A color view of 2nd level cortical bone structure is shown below (this picture was posted on the website http://medocs.ucdavis.edu/CHA/402/studyset/lab5/lab5.htm, which has a good collection of bone and cartilage histology):
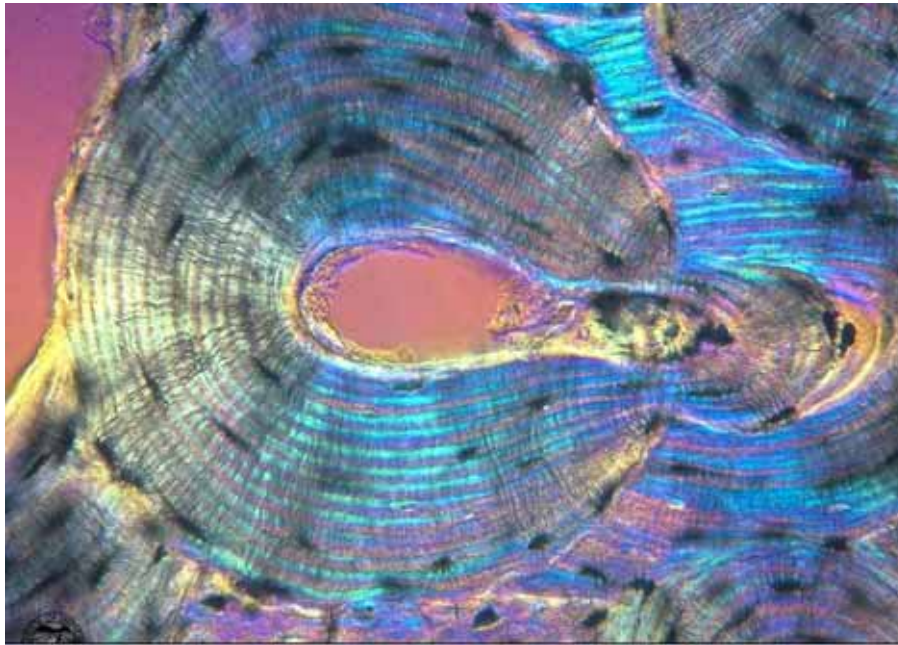

One of the most intriguing 2nd level structural entities from a mechanical point of view is the cement line. Cement lines are only found in secondary bone because they are the result of a remodeling process by which osteoclasts first resorb bone followed by osteoblasts forming bone. The cement line occurs at the point bone resorption ends and bone formation begins. Cement lines are about 1 to 5 microns in thickness. Cement lines are believed to be type I collagen deficient structures. Beyond this, the nature of cement has been widely debated. Schaffler et al. (1987) found that cement lines were less mineralized than the surrounding bone tissue. Many people have suggested that cement lines may serve to arrest crack growth in bone being that they are very compliant and likely to absorb energy.

From: Yun

III.3   Third Level Cortical Bone Structure

The farther down the hierarchy of cortical bone structure we go, the more sketchy and less quantitative the information. This is because it becomes more difficult to measure both bone structure and mechanics at increasingly small levels.   Most information about third level cortical bone structure mechanics is based on some quantitative measurements mixed with a great deal more theory.

Third level cortical bone structure may be separated into two basic types, lamellar and woven. Each type contains the basic type I collagen fiber/mineral composite.   What differentiates these two structures is how the composite, primarily the collagen fibers are organized. In woven bone, the collagen fibers are randomly organized and very loosely packed. A picture of woven bone forming at a fracture from the website http://www.pathguy.com/lectures/bones.htm is shown below:
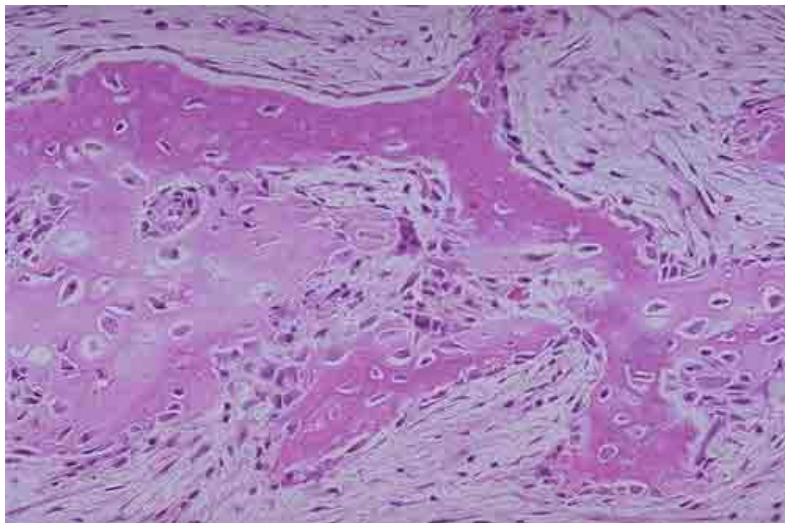

As noted earlier, this results from the rapid manner in which bone is laid down. Lamellar bone, which is found in plexiform, primary osteonal, and secondary osteonal bone, is laid down in a more organized fashion (as seen in the picture above) and constrasts very clearly to the woven bone above.. Although there is

probably some continuum of structure between woven and lamellar bone, both bone structure is most frequently organized into these two categories. The structure of lamellar bone is still widely debated, so we will discuss here the competing theories

III.3.1 Intra and Inter-Lamellar Type I Collagen Orientation

One of the earliest theories to gain acceptance will be denoted here as the parallel collagen fiber orientation theory. This is based largely on the work of Ascenzi and Bonucci (1970, 1976). This theory suggests that collagen fibers within the same lamella are predominantly parallel to one another and have a preferred orientation within the lamellae. The orientation of collagen fibers between lamellae may change up to 90° in adjacent lamellae. Based on this, three types of osteons containing three different type of lamellar sub-structures have been defined as drawn in Martin et al. 1998:


a   b   c
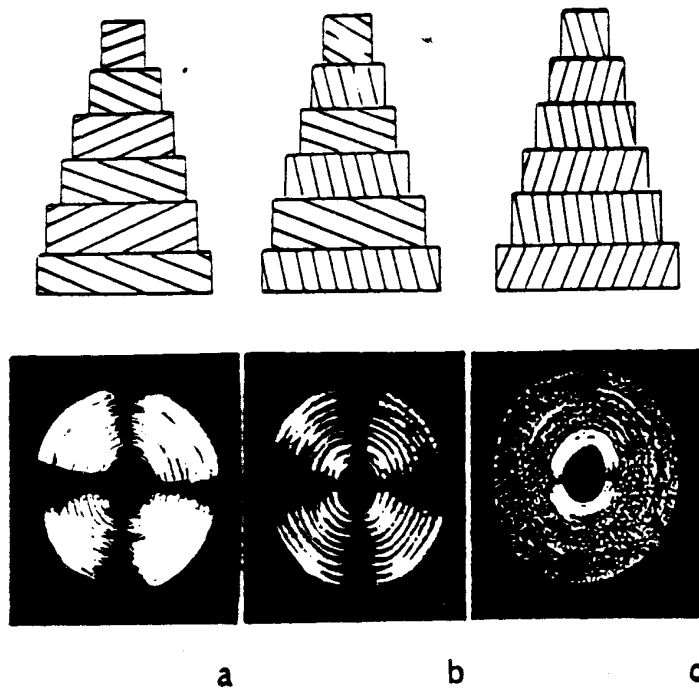
. In the figure above, a is Type T, b is Type A, and c is Type L. Type L osteons are defined because there lamellae contain collagen fibers which are oriented perpendicular to the plane of the section, or parallel to the osteon axis. These type of osteons appear dark under polarized light. Type A osteons contain alternating fiber bundle orientations and thus give an alternating light and dark pattern under polarized light. Finally, type T osteons contain lamellae with fiber bundles that are oriented parallel to the plane of the section. With respect to the osteon axis, these bundles are oriented in a transverse spiral or circumferential hoop perpendicular to the center of the osteon.

Giraud-Guille (1988) presented the twisted and orthogonal plywood model of collagen fibril orientation within cortical bone lamellae. Giraud-Guille noted that the twisted plywood model as shown in Martin et al., 1998:
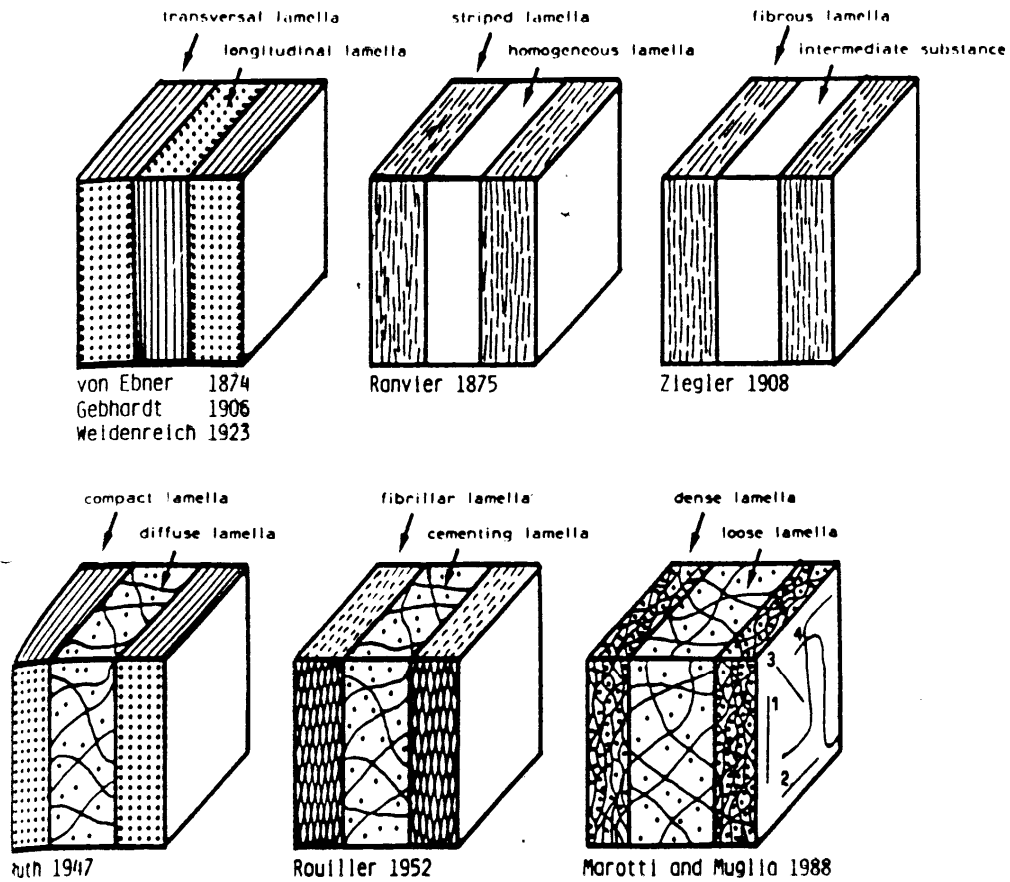
From: Yun
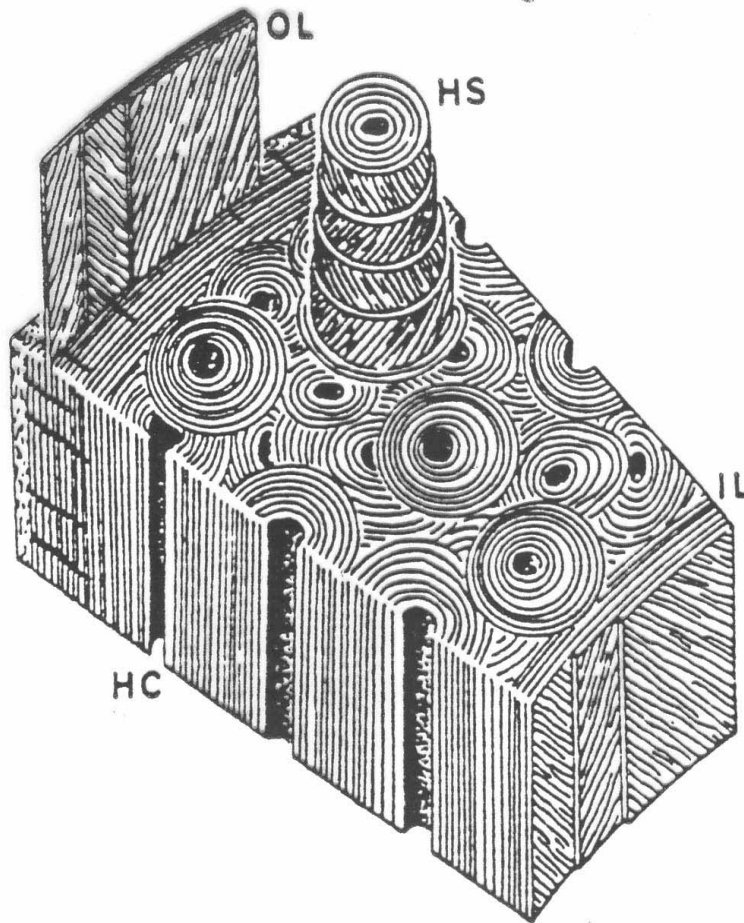
allows for parallel collagen fibrils which continuously rotate by a constant angle from plane to plane in a helical structure. Another schematic of the twisted plywood model from Martin et al. (1998) is shown below:

From: Yun
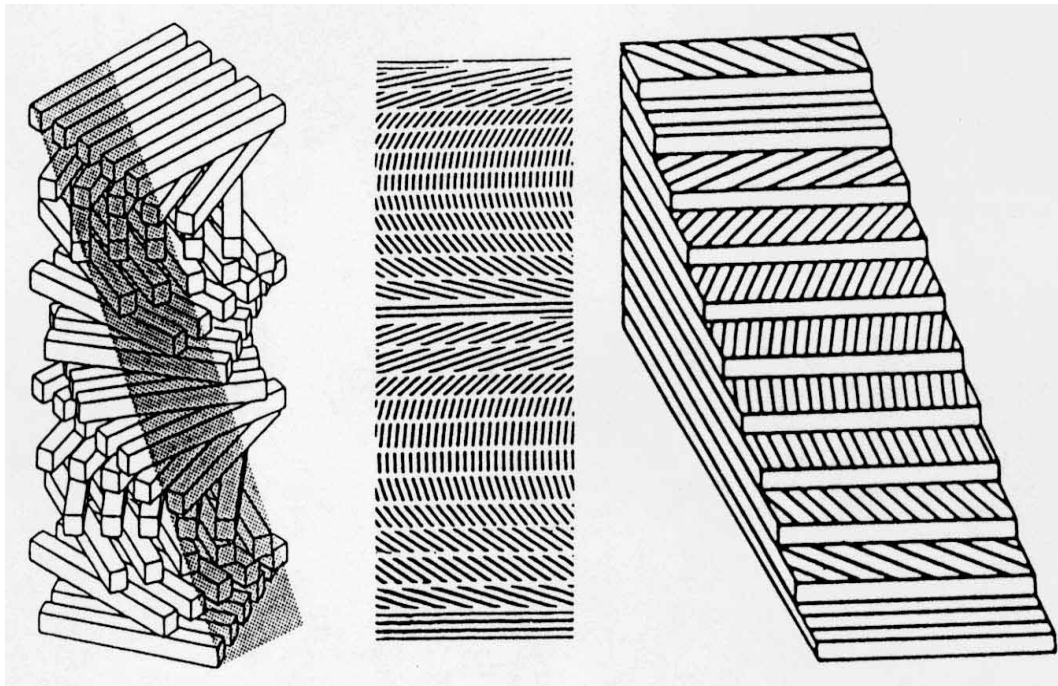
The orthogonal plywood model consists of collagen fibrils which are parallel in a given plane but unlike the twisted plywood fibrils do not rotate continuously from plane to plane. Instead, the fibrils can only take on one of two directions which are out of phase 90° with each other. Giraud-Guille believed that the orthogonal plywood model most closely resembles the type L and type T osteons from Ascenzi's model while the twisted plywood model would most likely explain the type A or alternating osteons from Ascenzi's model. However, instead of three distinct structures creating three different polarized light patterns there would now be only two.

Whereas both Ascenzi and colleagues and Giraud-Guille proposed models of collagen orientation assuming parallel fibers, Marotti and Muglia (1988) proposed that collagen fibrils were not parallel to each other, but instead had random orientations. The alternating dark and light patterns seen in polarized light Marotti and Muglia believed were not the product of changes in orientation but were rather the result of different packing densities of collagen fibrils. They defined dense and loose packed lamella (shown in Martin et al., 1998):

From: Yun

transversal lamella
longitudinal lamella

striped lamella
homogeneous lamella

fibrous lamella
intermediate substance

von Ebner 1874
Gebhardt 1906
Weidenreich 1923

Ronvier 1875

Ziegler 1908

compact lamella
diffuse lamella

fibrillar lamella
cementing lamella

dense lamella
loose lamella

Ruth 1947

Rouiller 1952

Marotti and Muglia 1988

. The light bands in polarized light microscopy they attributed to the loosely packed lamellae while the dark bands could be attributed to the densely packed lamellae. Marotti and Muglia that the dense and loose packed lamellar model corresponded better with how bone was formed. They suggested that alternating collagen orientations would require that osteoblasts somehow rotate when they were laying down bone. Their model would require that osteoblasts would lay down an intertwined mesh of collagen fibers, but the density with which osteoblasts would lay down collagen fibers would change.

From: Yun