

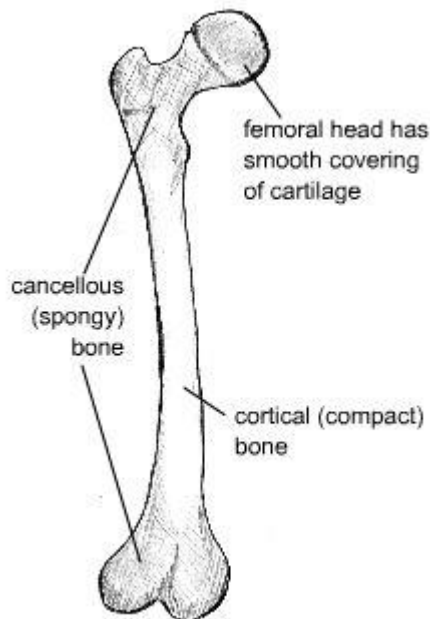
## Structure and Composition of bone

Long bones such as the femur contain two distinct morphological types of bone:

Cortical (compact) bone

Cancellous or Trabecular (spongy) bone

These are shown in the figure below.



*Diagram of distinct morphological types of bone*

Cortical bone forms a dense cylinder down the shaft of the bone surrounding the central marrow cavity. While cortical bone accounts for 80% of the mass of bone in the human body, it has a much lower surface area than cancellous bone due to its lower porosity.

Cancellous (or trabecular) bone is located at the ends of long bones, accounts for roughly 20% of the total mass of the skeleton, and has an open, honeycomb structure. It has a much lower Young's modulus than cortical bone, and this graded modulus gradually matches the properties of the cortical bone to the cartilage that forms the articulating surface on the femoral head.

### Composition

Bone itself consists mainly of collagen fibres and an inorganic bone mineral in the form of small crystals. In vivo bone (living bone in the body) contains between 10% and 20% water. Of its dry mass, approximately 60-70% is bone mineral. Most of the rest is collagen, but bone also contains a small amount of other substances such as proteins and inorganic salts.

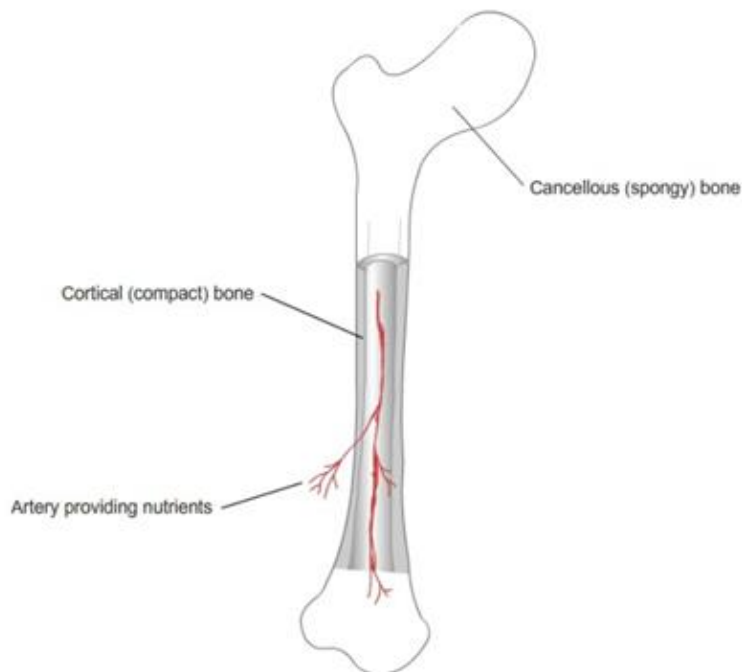
Collagen is the main fibrous protein in the body. It has a triple helical structure, and specific points along the collagen fibres serve as nucleation sites for the bone mineral crystals. This is shown in the animation below.

The composition of the mineral component can be approximated as hydroxyapatite (HA), with the chemical formula  $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ . However, whereas HA as has a Ca:P ratio of 5:3 (1.67), bone mineral itself has Ca:P ratios ranging from 1.37 - 1.87. This is because the composition of bone mineral is much more complex and contains additional ions such as silicon, carbonate and zinc.

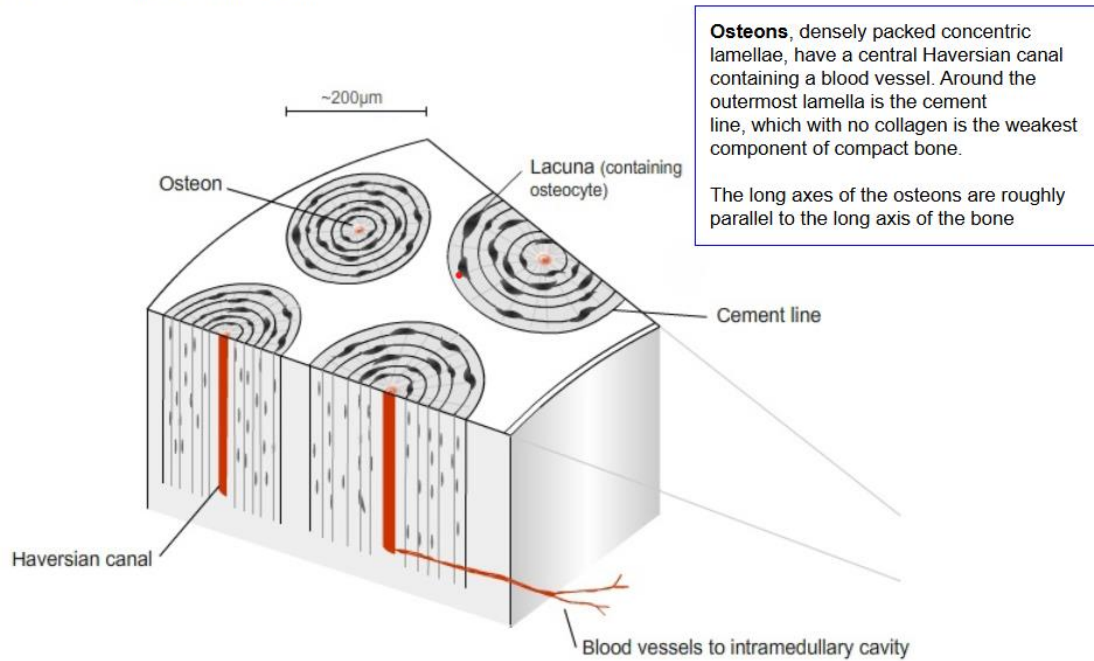
Cartilage is a collagen-based tissue containing very large protein-polysaccharide molecules that form a gel in which the collagen fibres are entangled. Articular, or hyaline, cartilage forms the bearing surfaces of the movable joints of the body. Mechanically, articular cartilage behaves as a linear viscoelastic solid. It also has a very low coefficient of friction ( $< 0.01$ ), largely attributed to the presence of synovial fluid that can be squeezed out upon compressive loading.

The animation below allows you to explore the microstructure of cortical bone.

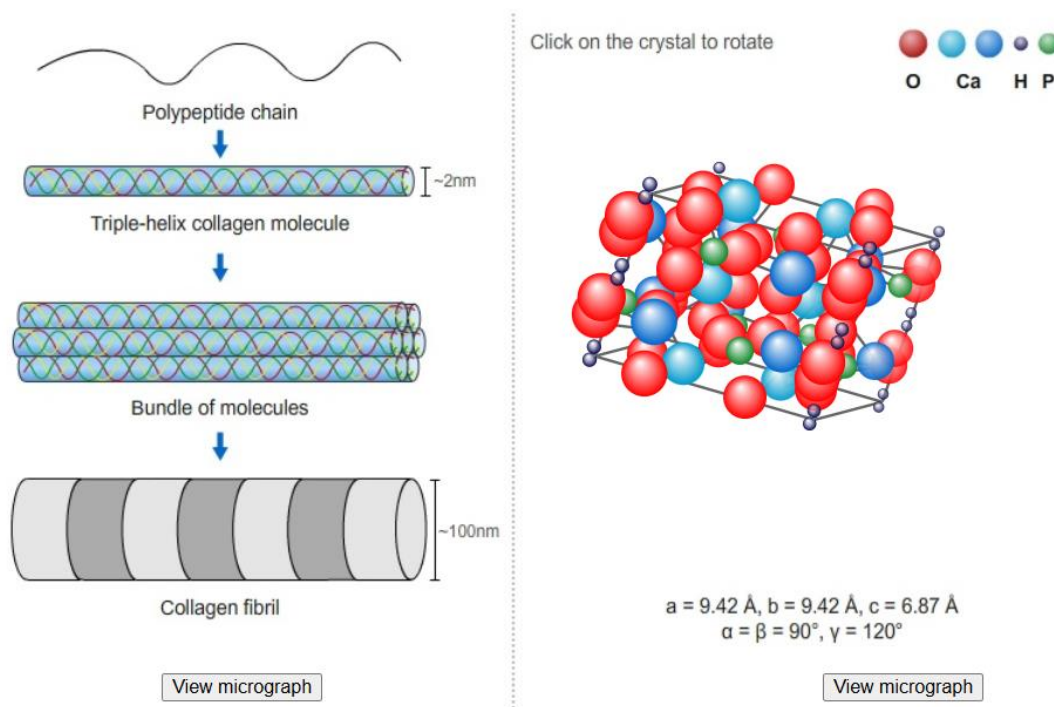
#### 1. Macrostructure of bone



## 2. Cross-section of cortical bone



## 5. Structure of collagen and hydroxyapatite



## Stresses

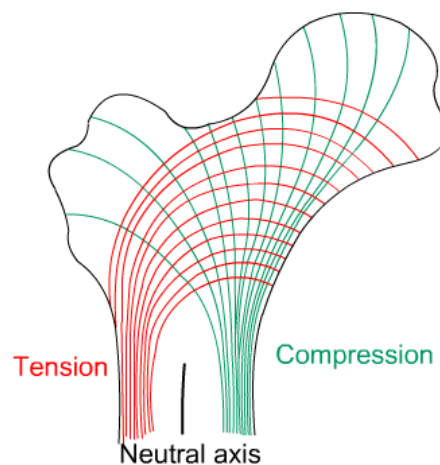
Bones such as the femur are subjected to a bending moment, and the stresses (both tensile and compressive) generated by this bending moment account for the structure and distribution of cancellous and cortical bone.

In the upper section of the femur, the cancellous bone is composed of two distinct systems of trabeculae. One system follows curved paths from the inner side of the shaft and radiates outwards to the opposite side of the bones, following the lines of maximum compressive

stress. The second system forms curved paths from the outer side of the shaft and intersects the first system at right angles. These trabeculae follow the lines of maximum tensile stress, and in general are lighter in structure than those of the compressive system.

The thickness of the trabeculae varies with the magnitude of the stresses at any point, and by following the paths of the principal compressive and tensile stresses they carry these stresses economically. The greatest strength is therefore achieved with the minimum of material.

The distribution of the compact bone in the shaft is also due to the requirement to resist the bending moment stresses. To resist these stresses, the material should be as far from the neutral axis as possible. A hollow cylinder is the most efficient structure, again achieving the greatest strength with the minimum of material.



### Formation and remodelling of bone

Bone formation is an essential process in the development of the human body. It starts during the development of the foetus, and continues throughout childhood and adolescence as the skeleton grows. Bone remodelling meanwhile is a life-long process, consisting of resorption (the breaking down of old bone) and ossification (formation of new bone), and is key to shaping the skeleton and to the repair of bone fractures.

There are three types of cell present in bone that are of particular interest – osteoblasts, osteocytes and osteoclasts, which are respectively responsible for the production, maintenance and resorption of bone.

#### **Osteoblasts**

Mononucleated “bone-forming” cells found near the surface of bones. They are responsible for making osteoid, which consists mainly of collagen. The osteoblasts then secrete alkaline phosphatase to create sites for calcium and phosphate deposition, which allows crystals of bone mineral to grow at these sites. The osteoid becomes mineralised, thus forming bone.

#### **Osteocytes**

These are osteoblasts that are no longer on the surface of the bone, but are instead found in lacunae between the lamellae in bone. Their main role is homeostasis – maintaining the correct oxygen and mineral levels in the bone.

## Osteoclasts

Multinucleated cells responsible for bone resorption. They travel to specific sites on the surface of bone and secrete acid phosphatase, which unfixes the calcium in mineralised bone to break it down.

During foetal development there are two mechanisms for creating bone tissue:

Endochondral ossification

Intramembranous ossification

Intramembranous ossification occurs in the formation of flat bones such as those in the skull, and will not be covered further here.

## Endochondral ossification

This involves bone growth from an underlying cartilage model, and is seen in the formation and growth of long bones such as the femur.

The initial step involves the development of a cartilage model, which has the rough shape of the bone being formed. In the middle of the shaft is the primary ossification centre, where osteoblasts lay down osteoid on the shaft to form a bone collar.

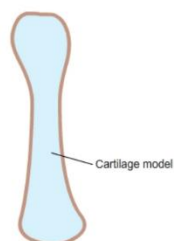
The osteoid calcifies, and blood vessels grow into cavities within the matrix. Osteoblasts then use the calcified matrix as a support structure to lay down more osteoid and form trabeculae within the bone. Meanwhile osteoclasts break down spongy bone to create the medullary cavity, which contains bone marrow.

Initially the bone material is deposited with the collagen fibres in random directions, meaning the strength is much lower than at the final stage in which the fibres are aligned. The primary structure is called woven bone because the collagen fibres are woven together randomly. This is then converted into lamellar bone over time, which is much stronger due to the aligned fibres. The osteoid deposited by the osteoblasts calcifies to initially produce primitive cancellous bone. At sites where cortical bone is required, further deposition of osteoid occurs to increase the density of the structure.

At birth secondary ossification centres appear at either end of long bones. Between the primary and secondary centres is the epiphyseal plate, made of cartilage, which continues to form new cartilage and be replaced by bone such that the bone increases in length. This continues until a person is in their mid-twenties, when the plate is finally replaced by bone and no further growth occurs.

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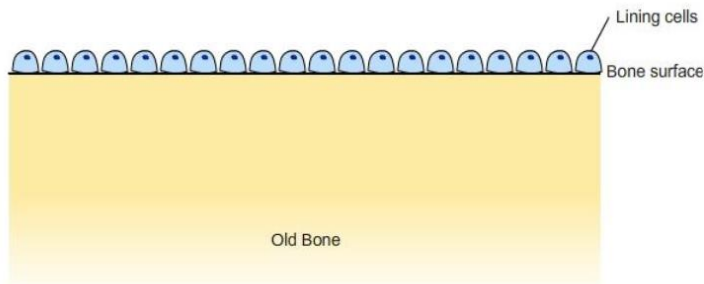
### Endochondral Ossification



## Remodelling of bone

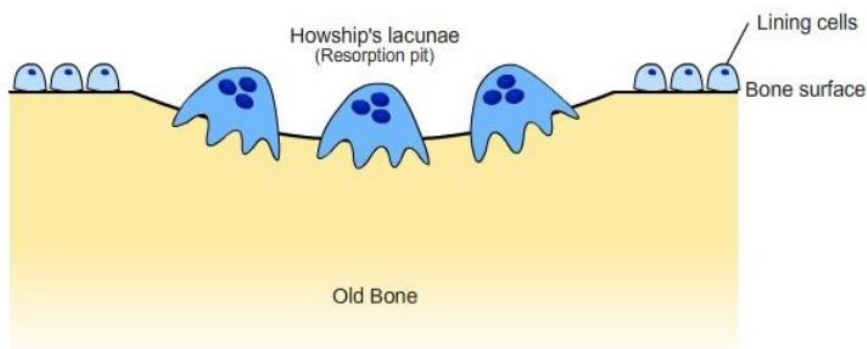
Ossification is also essential in the remodelling of bone. This occurs throughout a person's lifetime, with ossification and resorption (removal of bone tissue) working together to reshape the skeleton during growth, maintain calcium levels in the body, and repair micro-fractures caused by everyday stress.

### Bone Remodelling



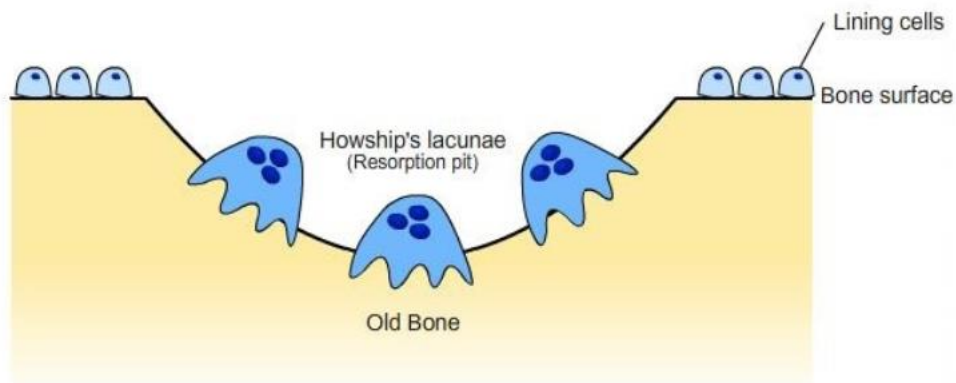
#### 1. Quiescence

Quiescence is the resting state of the bone surface.  
Lining cells are inactive osteoblasts.



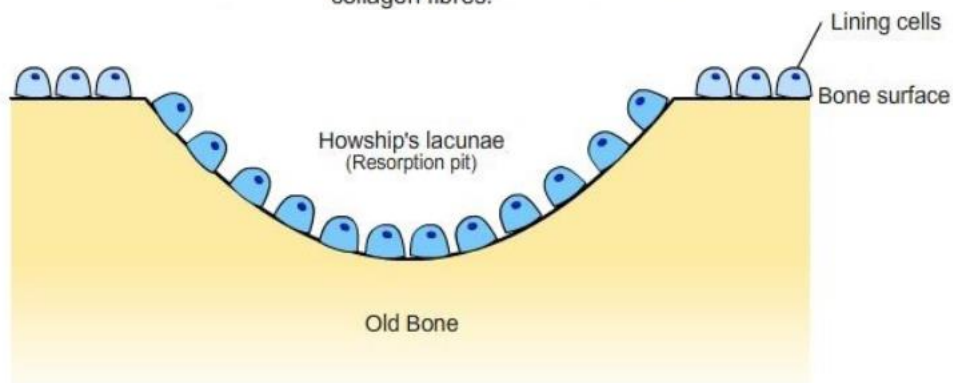
#### 2. Activation

Osteoclasts gather on the bone surface, in small pits known as *Howship's lacunae*.



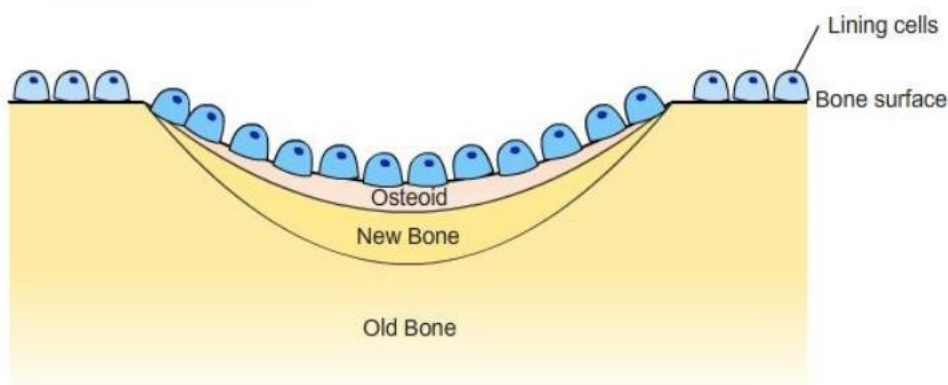
### 3. Resorption

Osteoclasts remove old bone tissue by removing the mineral matrix and breaking down the organic collagen fibres.



### 4. Reversal

The resorption process ends and the osteoclasts are replaced by osteoblasts.



### 5. Formation

Osteoblasts lay down new bone, firstly creating a matrix of collagen called *osteoid*. The osteoblasts then mineralise this matrix to form new bone.

The remodelling of cortical bone follows the same process as shown above, but with a different geometry in order to form the concentric lamellae seen in osteons.

### Responsive material

Bone is considered to be a responsive material. The formation and resorption of bone occur continuously: the body responds to stress levels in different areas of bone to ensure the right amount of healthy bone tissue is maintained and the bone can be continually reshaped.

A stress of 25–40 MPa is sufficient to maintain the correct levels of bone. If the bone is under-stressed for prolonged periods of time, bone wastage will set in, and the bones will become thinner. This can be an issue if a patient is bed-ridden for a long time, and is also observed in astronauts after long periods in space. A similar effect occurs during osteoporosis, in which the activity of osteoblasts decreases with age. This results in an imbalance of resorption and formation, causing bones to become thinner and weaker.

The opposite effect can be seen when bones are suddenly subjected to higher levels of stress than normal. Studies have been conducted that show an increase in bone mass in new recruits to the army as they begin intensive training.

### Mechanical properties of bone

#### Introduction

Although an organic material, bone can often be considered in the same way as man-made engineering materials. However, due to the nature of its synthesis it is likely to show more variation in measured properties than typical engineering materials. Factors include:

Age

Gender

Location in the body

Temperature

Mineral content

Amount of water present

Disease, e.g. osteoporosis

These variables can to an extent be dependent on each other. For example, the mineral content will vary according to the bone's location in the body, and with the age of the patient.

As humans age, their bones typically become less dense and the strength of these bones decreases, meaning they are more susceptible to fracture. Osteoporosis is a disease involving a marked decrease in bone mass, and it is most often found in post-menopausal women.

These variables mean that there is a range of measured properties for bone, and so values given in tables will always be an average, with quite a considerable spread possible in the data.

In addition, the anisotropic structure of bone means that its mechanical properties must be considered in two orthogonal directions:

Longitudinal, i.e. parallel to osteon alignment. This is the usual direction of loading

Transverse, i.e. at right-angles to the long axis of the bone

### Modulus

Bone can be considered to consist primarily of collagen fibres and an inorganic matrix, and so on a simple level it can be analysed as a fibre composite.

Composites are materials that are composed of two or more different components. They are commonly used in engineering and industry where the combination of the two materials creates a composite with properties that are superior to those of the individual components.

The Young's Modulus of aligned fibre composites can be calculated using the Rule of Mixtures and the Inverse Rule of Mixtures for loading parallel and perpendicular to the fibres respectively.

### **RULE OF MIXTURES**

$$E_{ax} = f E_f + (1 - f) E_m$$

### **INVERSE RULE OF MIXTURES**

Where

$E_f$  = Young's Modulus of fibres

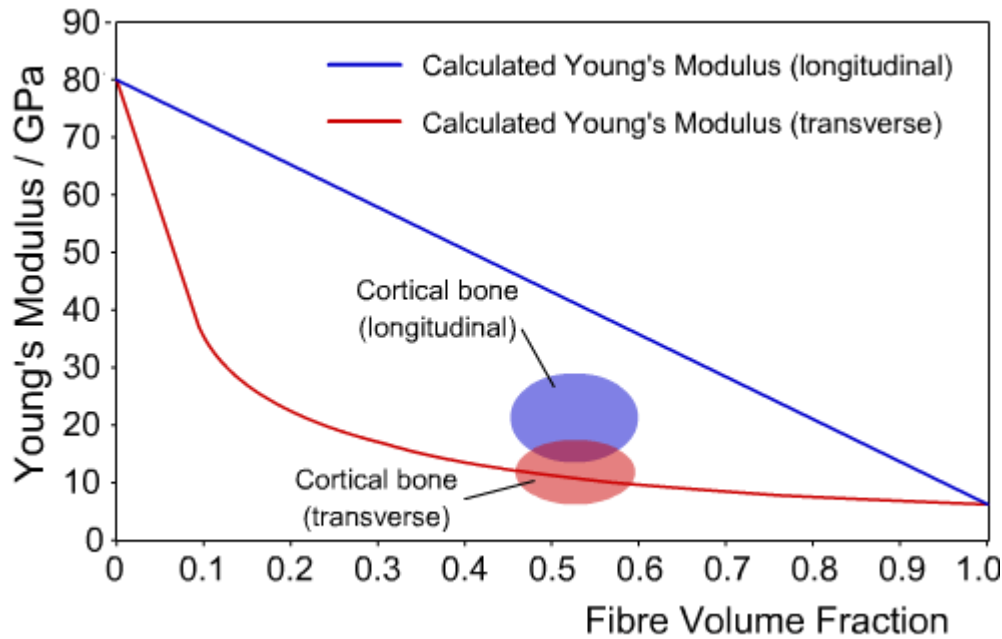
$E_m$  = Young's modulus of matrix

$E_{ax}, E_{trans}$  = Young's Modulus of composite in axial and transverse directions

$f$  = volume fraction of fibres

These formulae predict that the composite will be stiffer in the axial direction than the transverse, so cortical bone will be stiffer in the direction parallel to the osteons (i.e. parallel to the long axis of the bone).

The chart below shows calculated values for the Young's Modulus of bone in both the longitudinal and transverse directions, for a range of fibre volume fractions, as well as the actual values.



*Calculated and experimental values of Young's Modulus for cortical bone*

We can see that for the transverse direction, the composite model closely agrees with experimental values. However, in the longitudinal direction the difference is large, indicating the model does not give an accurate picture of the behaviour of bone.

This difference occurs because the composite model of the microstructure of bone is highly simplified, since the collagen fibres are not aligned parallel to the axis of the osteons, and the bone mineral exists as discrete crystals, rather than forming a continuous matrix.

A better approximation would be to model bone as a two level composite. One level is provided by hydroxyapatite-reinforced collagen in a single osteon, and the second level is obtained by the approximately hexagonal packing of osteons in a matrix of interstitial bone.

The actual values for the Young's modulus of bone, compared to collagen and hydroxyapatite, are shown in the table below. The measured value of Young's Modulus also depends on temperature, decreasing with an increase in temperature, and the strain rate, increasing in value with an increase in strain rate.

Material	Young's Modulus, E (GPa)
Collagen (dry)	6
Bone mineral (Hydroxyapatite)	80
Cortical bone, longitudinal	11-21
Cortical bone, transverse	5-13

#### Tensile and Compressive Strength

As [mentioned previously](#), bones such as the femur are subjected to bending moments during normal loading. These create both tensile and compressive stresses in different regions of the bone.

There is a large variation in measured values of both the tensile and compressive strength of bone. Different bones in the body need to support different forces, so there is a large variation in strength between them. Additionally, age is an important factor, with strength often decreasing as a person gets older.

	<b>Longitudinal direction</b>	<b>Transverse direction</b>
<b>Tensile strength (MPa)</b>	60-70	~50
<b>Compressive strength (MPa)</b>	70-280	~50

### Elasticity

Bone mineral is a ceramic material and exhibits normal Hookean elastic behaviour, i.e. a linear stress-strain relationship. In contrast, collagen is a polymer that exhibits a J-shaped stress-strain curve.

Typical stress-strain curves for compact bone, tested in tension or compression in the wet condition, are approximately a straight line. Bone generally has a maximum total elongation of only 0.5 - 3%, and therefore is classified as a brittle rather than a ductile solid.

### Fracture Toughness

In contrast to the findings for tensile and compressive strength and modulus, the values of toughness in the transverse direction are generally higher than those in the longitudinal direction. This is due to the presence of the cement lines in the microstructure. These are narrow regions around the outermost lamellae in the osteons, and they form the weakest constituent of bone. Crack propagation parallel to the osteons can occur much more easily through these regions and this significantly decreases the fracture toughness of cortical bone in the longitudinal direction. If a crack is propagating perpendicular to an osteon it will change direction when it reaches a cement line, thus blunting the crack. This is illustrated in the animation below.

As a result, although bone is classified as a brittle material (with the major component being mineral), its toughness is excellent. Bone's fracture energy,  $G_c$ , is approximately 1.5 kJ m<sup>-2</sup>, which is comparable to steel at low temperatures and wood when measured parallel to the grain. This is much tougher than man-made ceramics due to the presence of the collagen fibres in bone. Since the stress-strain curves for loading and unloading are different the elasticity is therefore time-dependent, a common feature of fibrous proteins.