The Mechanics of Biological Materials and Structures

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Introduction
Organisms have evolved over the last 4 billion years from tiny unicellular organisms, which behaved like floppy water-filled balloons, to complicated multicellular animals and plants. First and foremost this process has required the evolution of sophisticated materials and their arrangement into efficient structures. Plants such as trees have evolved strong wooden trunks, resilient branches and efficient root systems that enable them to withstand gale force winds without being pulled out of the ground or snapping. Animals, meanwhile, have evolved rigid skeletons, with muscle-powered limbs articulated with ingenious joints. Evolutionary success has also been down to other engineering achievements than just giving structural support: the evolution of skin to protect tissues underneath for instance; the evolution of efficient mouthparts in animals to cut up and grind food and conversely the evolution of mechanical defences in plants; the evolution in fungi of techniques to puncture holes in organic tissues; and the evolution of techniques whereby bacteria can modify their buoyancy.

This unit will examine the mechanics of the solid parts of organisms. After giving some background in mechanics of materials it will examine how, despite a limited number of building blocks, organisms have managed to produce a formidable array of materials. Second, it will examine how those materials have been arranged into structures that provide support and flexibility. Finally it will examine the mechanical interactions between organisms and their environment.

Throughout the unit will investigate how biomechanics have studied the natural world, and look at the ways in which their discoveries can be used to help us mimic or replace natural materials and structures.

Aims
The unit aims to:
1) Give students an overview of the mechanical designs of the materials and structures that have been evolved by organisms.
2) Give students an overview of the uses of biological materials and the way they can be replaced or mimicked by man.
3) Train students in the mathematical and computational skills to analyse solid biomechanical systems
Course Content

Part 1: Physical Background

1: The Properties of Materials and Structures

Part 2: Materials

2: Biological Rubbers
3: Gels, Mucus and Silks
4: Composites with Continuous Fibres
5: Composites with Short Fibres
6: Biological Ceramics

Part 3: Structures

7: Structures in Tension
8: Biological Pressure Vessels 1
9: Biological pressure Vessels 2
10 Structures in Bending 1
11 Structures in Bending 2
12: Structures in Compression
13: Structures in Torsion
14: Joints and Levers in Organisms

Part 4: Interactions with the Mechanical Environment

15: Mechanical Attachment
16: Attachment to Hard, Flat Surfaces
17: Optimising Design
18: Biomechanical Interactions Between Organisms
Synopsis of Course Material

Part 1: Physical Background

1: The Physical Background and the Properties of Materials and Structures
The atomic theory of matter and the way in which crystalline materials withstand forces. The types of forces on materials and the resultant deformation: tension, compression and shear. The concepts of stress and strain and the mechanical properties of materials: stiffness, breaking and yield stress and strain; energy storage and resilience. Mechanical testing. The relationship between axial and shear stresses: Poisson’s ratio and the relative values of elastic and shear modulus. The problem of cracks and stress concentrations. Fracture mechanics and work of fracture. Everyday examples of materials with contrasting properties.

Part 2: Materials

2: Biological Rubbers
The need for stiff materials to produce a skeleton for larger organisms. The problem of the limited materials that organisms possess; all they have are polymers such as proteins and sugars, usually dissolved in water. The first way of stiffening polymers: adding cross-bridges. The role of entropy in keeping them the same shape and the causes of stiffness. Analysis of rubber stiffness. The typical stress-strain behaviour of rubbers. Types of natural rubber and their uses: resilin, insect flight and flea jumping; abductedin and swimming in scallops; elastin, arteries and the ligamentum nuchae in ungulates.

3: Polymers, Mucus and Gels and Silks
Assumptions of rubbery model. The time-dependent behaviour of polymers: glassy, leathery, rubbery and liquid behaviour. Methods to investigate the viscoelastic behaviour of polymers: creep tests and stress relaxation; dynamic testing. Examples of man-made polymers; plastic bags and potty putty. Biological examples: the polymeric body walls of sea-anemones; behaviour of slug mucus. A second way of stiffening polymers; stiffening up the interatomic bonds. With or without cross-links forms mucus (in slugs, snails etc) and gels (eg add cross-links to mucus). Mucopolysaccharides, agar gelatin. A third way of stiffening polymers: incorporating straightened molecules in a rubbery matrix; producing fibres by lining up molecules to form fibrils: slug mucus at night. Ordered molecules: the alpha helix and beta sheets. Silks: ordered regions within rubbery matrix: moth cocoon silk; lacewing silk. Spider silks and their variability: energy storage and enhanced stretchiness in viscid silk vs nanosilks.

4: Composites with Continuous Fibres
Models of the stiffness of composite materials with continuous length fibres. Hagfish slime. Tendon: an ordered pliant composite with collagen fibres in a rubbery matrix, forming a hierarchical structure. Making rigid composites: incorporating fibres into a glassy matrix. Role of the matrix in protecting the fibres and crack stopping by the Cook
Gordon mechanism. Fibre pullout and increased work of fracture
Keratins and their odd stretching properties and dependence on hydration.

5: Composites with Short Fibres
Mechanical behaviour of composites with short fibres. Evidence that tendon and keratins actually have short fibres. Biological fibrous composites. Insect cuticle and the control of its properties by composition, hydration and fibre angle: membrane, apodeme and plate material with helicoidal structure; expansion during moulting. Fungal, algal and plant cell wall; fibre orientation and stiffness. Wood: the ultimate material; mechanism of toughening.

6: Biological Ceramics

Part 3: Structures

7: Structures in Tension
One dimensional tensile structures: the design of ropes and strings. Central reinforcement and use of isolated strands. Biological examples: lianas, mussel byssus thread, silk threads and tendons. Two dimensional tensile structures: the design of sheets to prevent in-plane tearing: veins in leaves; edge reinforcement in insect wings and leaves; use of hems; use of a j-shaped stress/strain curve in skin by collagen feltwork preventing tearing. Pretension and high Poisson ratio of skin, allowing smooth covering without restriction. Conversely the straight stress/strain curve in egg membrane which allows tearing.

8 and 9: Biological Pressure Vessels
10 and 11: Structures in Bending
How structure deform when they are bent. [Box: Simple beam theory and second moment of area.] The advantage of concentrating material in a single beam: evolution of horses’ legs and tree trunks. Advantages of I girders: the lateral roots of trees. Advantages of tubes: the ubiquity of tubular designs in nature. The problem of local buckling and how it can be overcome: bulkheads, stringers and central pith in plant stems and hedgehog spines. Building trusses with compression and tension members. A false truss: the design of fish tails. Real trusses in nature: the necks of ungulates; the necks and tails of dinosaurs; trusses in planar bones and leaves. Corrugated structures: insect wings. Reinforced Beams and prestressing: turgor in herbaceous plant stems to avoid compression of cell walls; prestressing in tree stems to avoid buckling: compression and tension woods.

12: Structures in Compression

13: Structures in Torsion

14: Joints and Levers in Organisms

Part 4: Mechanical Interactions Between Structures and the Environment

15: Mechanical Attachment and Root Anchorage
16: Attachment to Flat Surfaces

17: Interactions with the Mechanical Environment
Factors of safety in organisms’ structures and how they are optimised: bones, tendons, tree trunks. Mechanisms of optimisation: natural selection; dynamic optimisation. [Box: Finite element analysis]. Remodelling of bone and its possible mechanism; constant stress hypothesis in trees; experimental evidence for the mechanism and testing the theory of buttress formation in tropical rainforest trees.

18: Interactions Between Organisms
Biomechanics of feeding and mechanical defences. Gripping prey and the design of claws and jaws. The mechanics of cutting and breaking and the fracture properties of biological materials. Breaking up food items: the design of teeth and the use of gastroliths. Mechanical defences of plants; toughness of leaves; silica defences in grasses; design of fruit and woody seeds. Infection of plants by fungi; the effects of infection on wood. Design of feathers, nails, hooves and claws.