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; abductin 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 fractureKeratins 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
Use of ceramics within fibrous composites: the filler effect. Melanin in keratin structures. Mineralised cuticles in crustaceans; mantis shrimp claws. Use of ceramics to reinforce soft tissues: the case of spicule reinforcement of sponges and the effects of number, size and shape of ceramic particles. Bone, a composite of apatite and collagen. Types of bone and their properties; effects of ceramic percentage on mechanical properties: antler, femur and bulla. Toughness of bone and microcracking; compression and tension bone. Haversian bone and remodeling. Tooth ceramics; dentine and enamel, their structure and properties. Shell, a composite of calcium carbonate and soft matrix. Types of shell structure: simple, nacre, crossed lamellar, foliate and prismatic. Toughness and crack stopping/diversion in shells.

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
How membranes resist out-of-plane forces. The stresses in pressurised tubes, cyliners and spheres: why sausages split along their length. Design of bat wings to resist out-of-plane aerodynamic forces: use of numerous fingers like the booms of Chinese junks. The mystery of the pterosaur wing: postulated use of atkinofibrils for membrane support. The stresses in the walls of arteries. Prevention of aneurysms by use of the j-shaped stress/strain curve due to orientation of collagen. The stresses in the alveoli of lungs; prevention of lung collapse by the use of surfactants. Design of cartilage as a hydrostatic structure. The design of fibre-wound cylinders; orthogonal reinforcement and the design of the mammalian penis. Helical reinforcement and the effect of winding angle. The growth mechanics of plant cells. Limits to the flexibility of nemertean worms and leeches. Fibres as muscle antagonists: design of the squid mantle; design of nematode worms.

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

How materials fail in compression: conditions for compressive, shear and tensile failure. The problem of Euler buckling in long rods. Use of Euler buckling in the development of camber in locust wings; prevention of Euler buckling in the stings of Hymenoptera. Design of cork cells to allow extensive compression for energy absorption. Compressive pressure vessels: the structure and ecology of gas vesicles in Cyanobacteria and Halobacteria.

13: Structures in Torsion

Torsion and shear; the pattern of stresses in twisted structures. The contrast between closed and open tubes in torsional rigidity. Torsion prevention in feathers. Extensive torsion and camber control in insect wings. Torsional asymmetry of curved plates and butterfly wing design. Contrasting torsional resistance of plants stems: high torsional compliance of daffodil and sedge stems and banana leaf stalks and its importance in reconfiguration. Bending behaviour of twisted plant stems.

14: Joints and Levers in Organisms

How to make joints. Use of controlled flexibility; narrow linkages and soft materials; arthropod abdominal joints. Arthropod joints with small hard bearings. Vertebrate joints with large cartilage joints. Lubrication of joints. Design of knees to prevent rubbing and the cruciate ligaments. Levers and moving joints. Mechanical advantage of horse and armadillo. Use of pinnate muscles to magnify forces and its use in arthropod legs and crab claws. The hydraulic straightening of spider' legs.

Part 4: Mechanical Interactions Between Structures and the Environment

15: Mechanical Attachment and Root Anchorage

Attaching to a solid substrate: mechanical attachments and biological analogues to anchors, velcro, zips, poppers and knots. Holding onto objects; the design of birds' feet and claws. Properties of particulate materials: sands, clays and soils: the Mohr/Coulomb theory. Vertical support by soils and footprints. Horizontal resistance: friction and movement of snakes, sand lizards and feet. Burrowing through soil and sands: worms, snakes and roots. Attaching to a particulate substrate: friction and the mechanics of root anchorage. Design of root systems to resist uprooting and overturning.

16: Attachment to Flat Surfaces
Forces to overcome when attaching to a flat substrate; tension, shear and peel. Permanent attachments: glue. The glues of barnacles, bivalves and mussels and avoidance of peel forces. Temporary attachments: the use of suckers using elastic recoil and muscles action. Attachment using liquid films: surface tension and Stefan adhesion. Attachment using Van der Waal's forces: frogs' toes, insect feet and gecko feet. Gripping and pushing on solids: the breakdown of the Coulomb theory of friction. Rubbery friction and the design of insect feet and human fingerpads.

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.