Tom Duncan

ADVANCED PHYSICS for Hong Kong

Volume I: Materials and Mechanics

ADVANCED PHYSICS
FOR HONG KONG
Volume I: Materials and Mechanics

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Preface

This edition incorporates recent 'A' level syllabus revisions; it meets the requirements of Boards who examine the topics covered, as core material or as options.

Changes have been made throughout the text, and two new chapters added. The first, chapter 1, deals with *Materials and their uses* (especially in structures such as bridges) and provides a practically orientated introduction to chapters 2 and 3 on the structure and mechanical properties of materials. The second new chapter 10, is concerned with *Energy and its uses*, a topic of considerable current and future importance, and discusses sources of energy (finite and renewable), energy conversion, energy consumption and losses, and pollution.

As in the previous edition, the treatment permits considerable flexibility in the order in which the chapters are followed. On the assumption that the book will be used selectively, certain topics (e.g. aspects of geometrical optics, surface tension) which are no longer examined at this level by most Boards, are retained for those students who require them.

The influence of the Nuffield Advanced Physics Course will be evident and is again acknowledged.

It has been ensured for this printing that full account is taken of the Hong Kong Advanced Level Physics 1992/93 syllabus. Questions taken from the H.K.A.L.E. 1986–1991 appear at ends of chapters and in the banks of objective-type revision questions.

This book and its companion, *Volume II: Fields, Waves and Atoms*, offer a complete 'A' level course. The two volumes are also available in a combined edition, *Physics: A Textbook for Advanced Level Students* (currently in its second edition).

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I am much indebted to Dr J. W. Warren and to Mr J. Dawber, both of whom read the original manuscript and made many helpful comments and suggestions. I must also thank Professor J. Stringer and Dr J. C. Gibbings. The former very kindly commented on chapters 2 and 3, and useful discussions were held with the latter on chapter 12. My sincere thanks are also due to Mr B. Baker, who constructed and tested the objective-type questions, and to my son-in-law and daughter Drs B. L. N. and H. M. Kennett, who checked the answers to the numerical problems. Thanks are also due to my wife for preparing the typescript.

For permission to use questions from their examinations, grateful acknowledgement is made to the various examining Boards, indicated by the following abbreviations: *A.E.B.* (Associated Examining Board); *C.* (Cambridge Local Examination Syndicate); *H.K.A.L.E.* (Hong Kong Advanced Level Examinations, by permission of the Hong Kong Examinations Authority); *J.M.B.* (Joint Matriculation Board); *L.* (University of London); *O.L.E.* (Oxford Local Examinations); *O. and C.* (Oxford and Cambridge Schools Examination Board); *S.* (Southern Universities Joint Board); *W.* (Welsh Joint Education Committee.

T.D.

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Contents

MATERIALS

Film interference on the surface of diamond

1 Materials and their uses

Mankind's use of materials

It has been said that a scientific discovery is incomplete and immature until the technologist has found a practical application for it and improved mankind's lot. One of the essential requirements for any technological advance is the availability of the right materials. The importance of this is shown by the use of names such as Stone Age, Bronze Age and Iron Age for successive cultures in ancient times.

(*a*) *Stone Age*. In this period, dating from the earliest times recorded up to about 2500 BC, tools and weapons were made of stone. Clay was fired to make pottery, while the weaving of plant and animal fibres provided cloth, fishing nets and baskets.

When agriculture was developed, the settled existence required for tending crops and animals all the year round encouraged the building of permanent houses of wood and stone. Villages and towns grew up, requiring roads, drains, bridges and aqueducts. The resulting wealth of some communities led to envy among others and the need for town dwellers to construct fortifications for protection and to develop weapons technology.

(*b*) *Bronze Age*. This era began with the discovery around 2500 BC in eastern Europe that copper became harder and tougher when alloyed with tin to make bronze. The consequent advances in technology were, however, small compared with those of the Iron Age.

(*c*) *Iron Age*. Although iron farm implements were used in China for centuries before, it was not until about 1000 BC or so that iron came into widespread use in other countries. Iron is one of the commonest metals in the earth's crust. It is extracted from its ore (iron-bearing rock) by *smelting*.

More recently, in the nineteenth century, steel (an iron alloy) became the dominant material for making tools, utensils, machinery, bridges, ships, weapons, cars and many other items.

(*d*) *Modern era*. The twentieth century has seen the arrival of plastics (p. 5) and composite materials (p. 36) which have opened up a whole range of possibilities.

Materials in tension and compression

Different materials are used for different jobs, the choice depending, among other things, on the properties of the material. There are good reasons why concrete is used for constructing large buildings, wood for furniture, glass for windows, aluminium for saucepans, plastics for washing-up bowls, cotton and nylon for clothes, and rubber for elastic bands.

We shall be concerned in particular with the use of materials in structures such as buildings and bridges, and in these cases it is their *mechanical* properties that are important. For example, it is essential to know how they behave under *tension* and *compression*. Stretching a material puts it in tension, Fig. 1.1*a*, while squeezing it puts it in compression, Fig. 1.1*b*. A material which is strong in tension can be weak in compression, and vice versa.

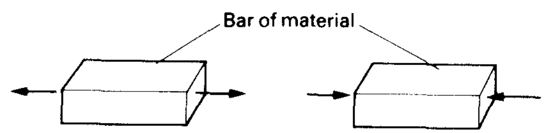


Fig. 1.1

The properties of some common types of material will now be considered. The mechanical properties are discussed in detail in chapter 3.

Metals and alloys

(*a*) *Iron and steel*. Pure iron is seldom used; it is usually alloyed with other substances to form steel. *Mild steel* is iron containing a very small proportion of carbon.

It is strong in both tension and compression and, being cheap, is used in large quantities for mass-produced goods like cars, cookers and refrigerators. In the construction industry scaffolding, girders, bridges, power pylons and the reinforcing for concrete are made of it.

Two disadvantages of mild steel are first that it is a heavy metal and second that it rusts. To counter rusting, an alternative to painting is to coat it with another metal which resists corrosion, such as tin, forming tinplate. *Galvanized* steel is covered by a thin layer of zinc; corrugated sheets of this are used as roofing for sheds. Chromium-plated steel is protected chiefly by a layer of nickel, on top of which a very thin layer of chromium (a hard, shiny metal) is added by electroplating.

Stainless steel contains large proportions of chromium and nickel. It is more expensive and difficult to work than mild steel but it is much stronger and harder and very resistant to corrosion.

Titanium steel has a very high melting-point and is used to make parts of jet engines, rockets, supersonic aircraft and space-shuttle nose-cones.

(*b*) *Aluminium and duralumin.* Aluminium is the most widely used metal after iron but is much more expensive to extract from its ore (bauxite). Its density is one-third that of iron and the thin, tough layer of oxide which forms on the surface when exposed to the air makes it very resistant to atmospheric corrosion. The pure metal tends to be weak and brittle.

Duralumin is made by alloying aluminium with small amounts of copper, manganese and magnesium. The tensile strength is then as great as that of mild steel and this, combined with its low density, makes it highly suitable for aircraft bodies.

Timber

There are two main types of wood. *Softwoods* like pine, besides being soft, are usually light in both weight and colour. They are used for general carpentry to make doors, window frames, floors and roof trusses in house-building. *Hardwoods* like oak and teak are stiff (see p. 27) and strong and are suitable for making furniture.

A tree grows from the centre outwards, a ring of wood being produced in the trunk each year, Fig. 1.2*a*. These annual rings are the *grain* marks that are seen when the trunk is cut into long planks, Fig. 1.2*b*. In hardwoods these marks are closer than in softwoods, which explains why the former are stiffer and stronger. In tension, the strength along the grain is greater than across it because wood consists of long tube-like fibres running up and down the tree trunk. Wood is less strong in compression.

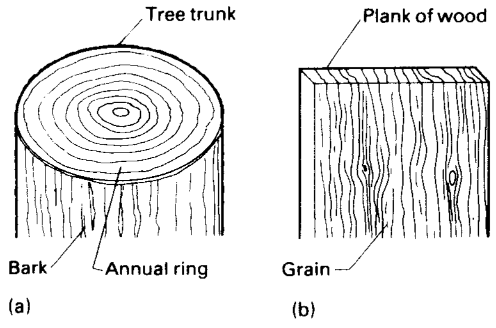


Fig. 1.2

New wood contains a great deal of moisture, most of which must be removed by *seasoning* before it is used. This is generally done naturally by stacking the freshly cut planks with spacers between, to allow air to circulate and dry them out slowly. The operation may take anything from a few weeks to several years. If a piece of wood is not properly seasoned it will gain or lose water unevenly when it is very damp or very dry. Gain of water produces expansion, loss of water causes shrinking and the result is warping.

(*a*) *Plywood.* Thin sheets of wood need less time to season than thick planks. Plywood is made by glueing thin, seasoned sheets together with the grains of alternate sheets at right angles to each other, Fig. 1.3*a*. An odd number of sheets is always used (to give, for example, 3-ply or 5-ply) so that if a crack passes between the grains of one sheet it meets the next sheet across the grain, Fig. 1.3*b*, and does not spread. For this reason, plywood is stronger than a piece of solid wood of the same thickness. Since it consists of sheets it is called a *laminate*.

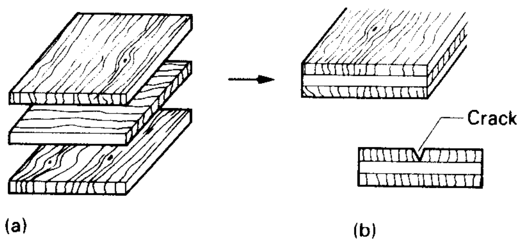


Fig. 1.3

(*b*) *Blockboard* is a sandwich made by filling the space between two thin sheets of wood with strips of solid wood, as in Fig. 1.4. The grain on the outside sheets goes the same way. Like plywood, blockboard should not warp and can be fixed down firmly (e.g. as a worktop) with no fear of it moving.

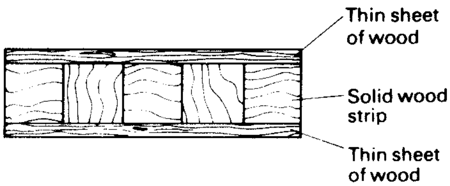


Fig. 1.4

(*c*) *Chipboard* is made from wood particles and resin, Fig. 1.5*a*. It can be sawn like wood and, being reasonably strong though heavier than solid wood, it can be used as floor boards or in other situations where appearance does not matter.

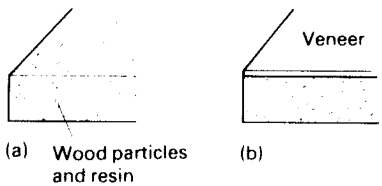


Fig. 1.5

For making furniture, shelves, etc., it is sold with a thin, more attractive sheet (a veneer) already on one or both surfaces, Fig. 1.5*b*. Veneers of white plastic, of plastic with wood grain or colour effects, or of wood itself are used.

Stone, bricks and concrete

A variety of materials is used to construct houses, buildings, bridges, roads and dams. Cost, climate and availability are often factors that have to be considered when deciding which to use.

(*a*) *Stone*. Deposits of stone are found in many parts of the world. They occur as granite which is hard and long-lasting, marble which is hard and attractive but does not last as long, and sandstone which is soft, easy to work and fairly long-lasting.

Stone is strong in compression but weak in tension. In cities where there is atmospheric pollution, stone buildings need cleaning periodically if they are to retain their appearance.

(*b*) *Bricks* are a cheap alternative to stone and have a convenient size. They are made by mixing clay with water and are then moulded into shape before being baked in ovens at a high temperature. The colour and hardness of the brick produced depends on the clay used and the baking temperature. Bricks, like stone, are weak in tension and strong in compression.

(*c*) *Cement and mortar*. Cement is a cream-coloured powder, made by heating a mixture of clay and lime to a high temperature. If mixed with sand and water, cement becomes a thick paste called *mortar*. Mortar is used to hold bricks or stones together since it becomes a hard, stone-like material when it dries.

(*d*) *Concrete* is now used more than any other material for building and construction work. It is made by mixing cement, sand and gravel (called 'aggregate') with water. A typical mix is 1 part cement, 2 parts sand and 4 parts aggregate, but this is varied for different purposes. If allowed to dry in a mould, any shape can be obtained and it sets as a hard, white stone.

Concrete weathers well and is strong in compression but weak in tension due to the large number of small cracks it inevitably contains. As a result, it is brittle and unsuitable when large tensile strength is required.

In *reinforced concrete* the strength of concrete in tension is improved by inserting wires or rods of steel through the wet concrete, Fig. 1.6. As the concrete dries it sticks to the steel, giving a combination which is strong in both compression and tension.

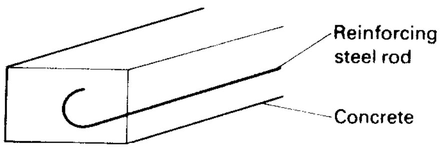


Fig. 1.6

In *prestressed concrete* even greater tensile strength is obtained, as explained in chapter 3 (p. 35). In *lightweight concrete* cinders are used as the aggregate.

Polymers

The properties of some of the commoner man-made polymers are outlined here; (*a*) to (*f*) are *thermoplastics*, (*g*) and (*h*) are *thermosets* (see chapter 2, pp. 24–5, where the molecular structure of polymers is discussed). The mechanical properties of rubber, a natural polymer, are considered in detail in chapter 3 (p. 41).

(*a*) *Polythene* is tough (i.e. not brittle) but flexible, and resistant to water and most solvents. It can be rolled into thin sheets and moulded into complicated shapes. It is a very good electrical insulator.

(*b*) *Polystyrene* is more brittle than some plastics but its stiffness is taken advantage of for making small containers and toys. *Expanded* polystyrene is a solid foam containing a large number of air bubbles. Its very low density and ease of moulding to almost any shape make it a good packaging material. It is also a good heat insulator.

(*c*) *PVC* (polyvinyl chloride) is strong, tough, flexible and waterproof, which makes it suitable for protective sheeting and floor coverings. Being a good electrical insulator it is used to cover electric cables.

(*d*) *Perspex* is stiff and transparent but not so hard and brittle as glass for which it is sometimes used as a substitute. It is easily cut and drilled, but scratches.

(*e*) *PTFE* (polytetrafluorethylene) or *Teflon* has a much higher melting-point than most plastics and also has 'non-stick' properties. These make it useful for coating the insides of saucepans and other cooking containers and for making bearings that do not need lubricating.

(*f*) *Nylon* fibres are used to make strong ropes and hard-wearing fabrics. Being water-resistant, clothing made from it dries quickly and requires no ironing. However, nylon shirts and blouses often feel damp to wear in hot weather because they do not absorb sweat. *Terylene* is another fibre used in the textile industry.

(*g*) *Bakelite* is hard and brittle, but is much strengthened by the addition of, for example, sawdust. Its cheapness, low density and resistance to corrosion have made it popular for electrical fittings.

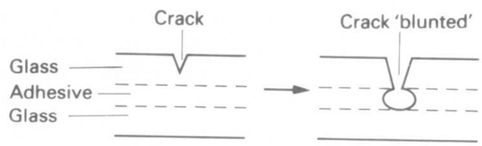
(*h*) *Formica* and *melamine* are two other thermosets with hard, smooth surfaces which make them suitable veneers for table tops and other surfaces.

Other materials

(*a*) *Fibre-reinforced materials.* The properties of composite materials using fibres of glass or carbon in a plastic resin (GRP and CFRP) will be considered in chapter 3 (pp. 36–9).

(*b*) *Laminated glass*, often called 'bullet-proof' glass, is even stronger than toughened (prestressed) glass (p. 35). It is made by fixing together layers of toughened glass with a transparent adhesive. More layers give greater strength. It is used for aircraft as well as car windscreens. If a crack gets through one layer of glass, it gets 'blunted' on meeting a layer of adhesive and is unable to penetrate the next layer, Fig. 1.7*a*. So when struck, it cracks but does not break into lots of small fragments; Fig. 1.7*b* shows the effect.

(*c*) *Ceramics* are made by mixing clay, fine sand and water into a paste which is shaped as required and fired at a high temperature. Very fine clay (e.g. china clay or kaolin) when fired at a sufficiently high temperature forms porcelain. Ordinary clay is unable to withstand such high temperatures and is used to make earthenware or pottery. Porcelain is usually 'glazed' by adding a layer of glass.



(a)

(b)

Fig. 1.7

Beams

Beams or 'girders' form parts of larger structures such as bridges.

(*a*) *Simple beams.* You can see what happens when a beam is loaded by drawing lines on a piece of foam rubber, Fig. 1.8*a*, and then pushing down on its top surface. The lines at the top become shorter while those at the bottom become longer. The length of the central line is unchanged, Fig. 1.8*b*. Therefore, when a beam is loaded and bends,

the top is in compression (squeezed),
the bottom is in tension (stretched), and
the centre, called the *neutral layer, is neither squeezed nor stretched.*

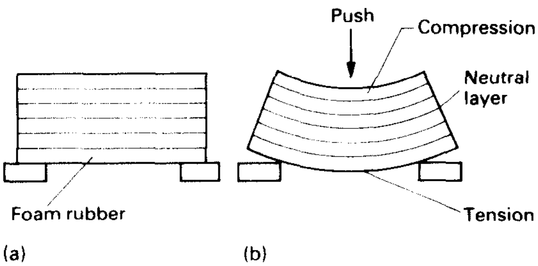


Fig. 1.8

In a solid beam, most of the material in the central region (the neutral layer) is not needed. It is wasted material whose weight simply acts as an extra load that has to be supported. If this material is removed, the much used I-beam is obtained, Fig. 1.9, which is as strong as a solid beam but much lighter. The top and bottom flanges withstand the compression and tension forces produced when the beam is loaded. Other common types of girder are L- and T-shaped.

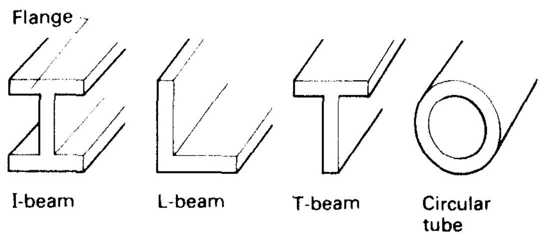


Fig. 1.9

Tubes use the same idea, the removal of unstressed material giving similar advantages. Circular tubes are most common, being equally strong in all directions at right angles to the surface.

(*b*) *Trussed beams.* A simple beam can be strengthened if a *truss* is joined to it as in Fig. 1.10. If, for example, the structure is a bridge, the weight of a car on it makes CBD bend down. AB moves down too, but AC and AD hold it back so CBD does not bend so much. Loading the trussed beam therefore tends to stretch AB and puts it under tension. A beam in tension is called a *tie*.

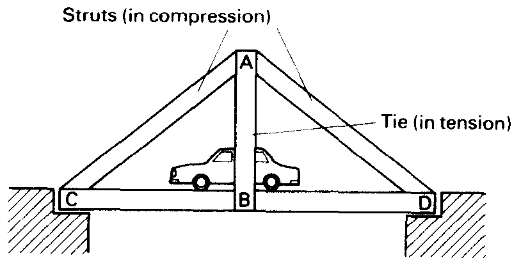


Fig. 1.10

On the other hand, AC and AD are under compression and are called *struts*. They are put in this state by AB pushing down on them at A and by the bridge supports pushing up on them at C and D. The latter forces arise because the truss transfers the load to the supports.

Bridges

In its simplest form a bridge consists of a beam, called the *bridge-deck*, supported at the ends, Fig. 1.11.

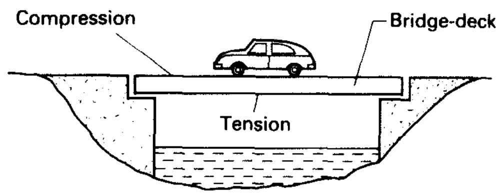


Fig. 1.11

As we have seen, when a beam is loaded it bends and, since bending involves compression and tension, bridge-decks must be made of materials which can withstand both compressive and tensile stresses. They must also be fire- and water-resistant. Other important factors are cost and the amount of maintenance required.

Early bridges were built of stone, then came steel, and today reinforced, prestressed and lightweight concrete are most common. Where steel and concrete or stone are used, the design is often such that steel bars are in parts under tension, while the stone or concrete is arranged to experience compression. Cables (of steel) are only used for parts in tension. If steel is to be under compression it is usually in the form of I- or T-shaped girders. There are many different types of bridge.

(*a*) *Beam and pier*. As well as having supports at both ends, this type has one or more pillars or piers in the middle, Fig. 1.12. The piers stop the bridge-deck from bending too much and make the bridge much stronger.

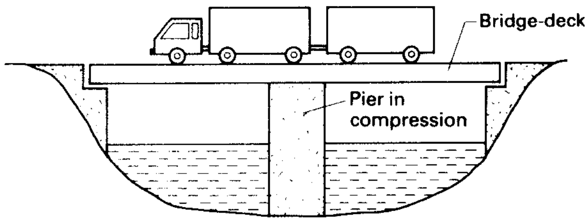


Fig. 1.12

A load on the bridge puts the piers under compression but, being made of stone, brick or concrete, they can withstand this.

(*b*) *Arch*. In an arch bridge the bridge-deck is supported by an arch either from above, as in Fig. 1.13*a*, or from below as in Fig. 1.13*b*. The arch may be of reinforced concrete or of steel girders.

A load on the bridge-deck causes slight compression of the arch, whether it is above or below the deck. The material of the arch should therefore be strong in compression. Stone or brick bridges often have arches below the bridge-deck, Fig. 1.13*c*.

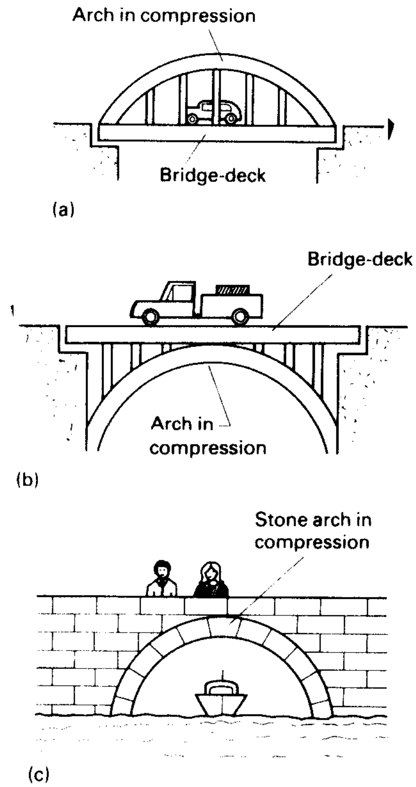


Fig. 1.13

(*c*) *Suspension*. Most of the world's largest bridges use this construction, Fig. 1.14. They are in effect beams supported by steel cables, all of which are in tension. The main cables hang from tall towers (pylons) at each end, which must be built on rocks that can withstand the large downward forces exerted by the towers.

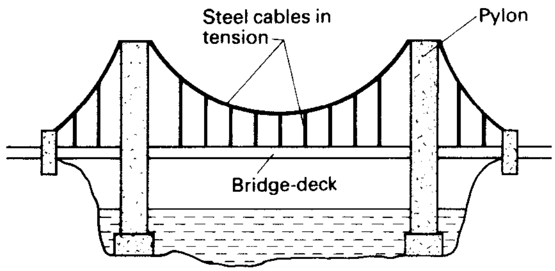


Fig. 1.14

The Forth road bridge in Scotland, Fig. 1.16, is of this type.

(*d*) *Cantilever*. A cantilever is a beam which is supported only at one end, Fig. 1.15. The top is in tension while the bottom is in compression.

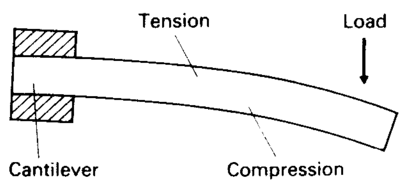


Fig. 1.15

The Forth railway bridge, built in 1890, part of which is visible in the background of Fig. 1.16, uses the cantilever principle.

(*e*) *Girder*. Larger bridges made from steel girders are of several types. They are designed so that there is no material in the neutral layer. The top of the bridge is under compression and the bottom is in tension. Fig. 1.17*a* shows a *truss girder* bridge and Fig. 1.17*b* a *lattice girder* type. Fig. 1.17*c* shows how a modern *box girder* bridge is built from steel boxes.

Fig. 1.16

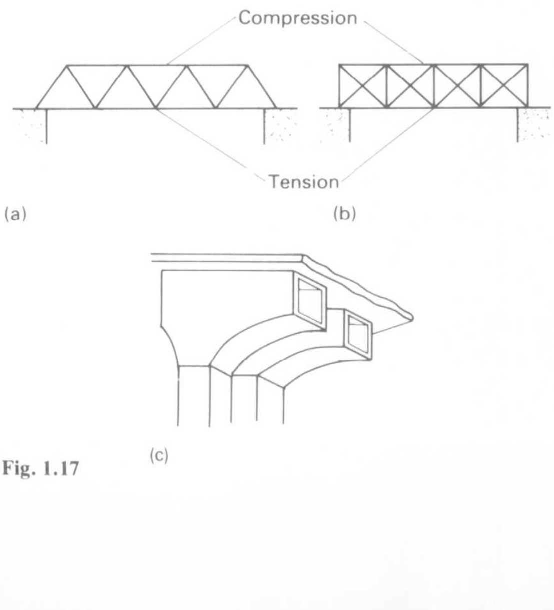


Fig. 1.17

Some other structures

(*a*) *Roof truss of a house.* The walls of a house with a tiled or slated roof would be pushed outwards, Fig. 1.18*a*, if the roof were not supported by a truss and tie beam, Fig. 1.18*b*. The walls are in compression, the tie beam is in tension.

Fig. 1.18

(*b*) *Balconies*. The floor of a flat and its adjoining balcony are shown in Fig. 1.19. The prestressed concrete beam supports both. The steel reinforcing bar is at the bottom of the beam in the floor of the flat, because it is in tension (like a bridge-deck). However, the reinforcing steel bar is in the top of the beam forming the balcony because it is a cantilever and is in tension at the top.

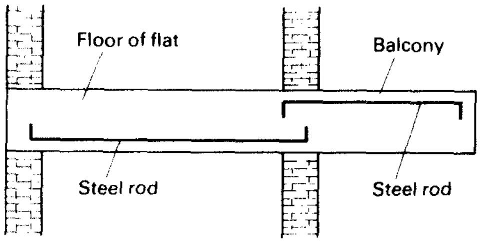


Fig. 1.19

QUESTIONS

1. (*a*) A metal is softened or *annealed* if it is heated to a dull red heat and cooled slowly. If after heating it is plunged into cold water instead, it is hardened or *tempered* and becomes brittle. Which of the following articles have been (*i*) annealed, (*ii*) tempered: a paper clip, a needle, a knife blade, a pin, a file?

(*b*) Why does wood split more easily along the grain than across it?

(*c*) List some of the advantages of concrete over stone.

(*d*) Why are fabrics used for clothing often combinations of plastics like Terylene and natural fibres such as cotton?

(*e*) Why do cracks not spread so readily through laminated glass?

2. (*a*) Which of AB, AC and AD in Fig. 1.10 (p. 7) could be replaced by a cable?

(*b*) A beam can also be strengthened by a truss underneath it, as in Fig. 1.20. Which of AB, AC and AD are in (*i*) tension, i.e. ties, (*ii*) compression, i.e. struts?

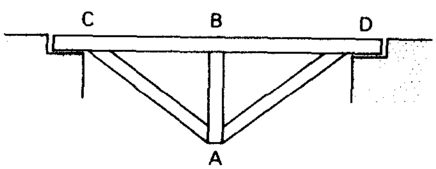


Fig. 1.20

3. (*a*) What are (*i*) the advantages, (*ii*) the disadvantages, of wood as a material for building a bridge?

(*b*) Why do reinforced concrete bridge-decks have steel rods at the *bottom*, Fig. 1.21?

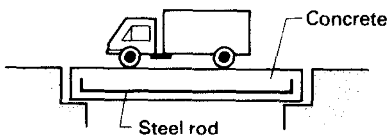


Fig. 1.21

4. (*a*) Why does a dome not fall down?

(*b*) What property of stone did some cathedral builders employ when they used flying buttresses to prevent the roof pushing the top of the walls outwards?

5. The crane in Fig. 1.22 is mounted on a wall and supports a load.

(*a*) Is AB a tie or a strut?

(*b*) Is BC a tie or a strut?

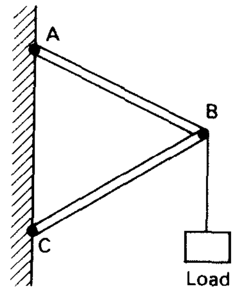


Fig. 1.22

6. In the girder bridge shown in Fig. 1.23 which girders are (*a*) ties, (*b*) struts?

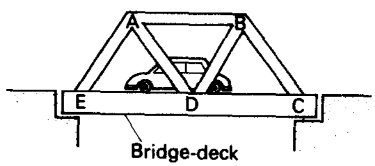


Fig. 1.23

2 Structure of materials

Materials science

Advances in technology depend increasingly on the development of better materials. This is especially true of those industries engaged in aircraft production, space projects, telecommunications, computer manufacture and nuclear power engineering. Structural materials are required to be stronger, stiffer and lighter than existing ones. In some cases they may have to withstand high temperatures or exposure to intense radioactivity. Materials with very precise electrical, magnetic, thermal, optical or chemical properties are also demanded.

A great deal has been known for many years about materials that are useful in everyday life and industry. For example, the metallurgist has long appreciated that alloys can be made by adding one metal to another, and that heating, cooling or hammering metals changes their mechanical behaviour. Materials *technology* is a long-established subject. The comparatively new subject of materials *science* is concerned with the study of materials as a whole and not just with their physical, chemical or engineering properties. As well as asking *how* materials behave, the materials scientist also wants to know *why* they behave as they do. Why is steel strong, glass brittle and rubber extensible? To begin to find answers to such questions has required the drawing together of ideas from physics, chemistry, metallurgy and other disciplines.

The deeper understanding of materials which we now have has come from realizing that the properties of matter in bulk depend largely on the way the atoms are arranged when they are close together. Progress has been possible because of the invention of instruments for 'seeing' finer and finer details. The electron microscope, which uses beams of electrons instead of beams of light as in the optical microscope, reveals structure just above the atomic level. The field ion microscope and X-ray apparatus allow investigation at that level.

The scanning electron microscope, Fig. 2.1*a*, is a development from the electron microscope and 'scans' a surface with electrons in the way that a television screen is scanned. It gives higher magnifications and much greater depth of focus than optical microscopes using reflected light. It is useful for examining the surfaces of semiconductors, the hairlike fibres and 'whiskers' that are so important in the manufacture of the new generation of composite materials, man-made fibres, and corroded and fractured surfaces. A view of the end of a torn wire (×75) is shown in Fig. 2.1*b* and of lead–tin telluride crystals (×30) in Fig. 2.1*c*.

Materials science is a rapidly advancing subject with exciting prospects for the future. Its importance lies in the help it can give with the selection of materials for particular applications, with the design of new materials and with the improvement of existing ones. The strength of even a tea cup has been improved by research into ceramics, as Fig. 2.1*d* shows.

Atoms, molecules and Brownian motion

The modern atomic theory was proposed in 1803 by John Dalton, an English schoolmaster. He thought of atoms as tiny, indivisible particles, all the atoms of a given element being exactly alike and different from those of other elements in behaviour and mass. By making simple assumptions he explained the gravimetric (i.e. by weight) laws of chemical combination but failed to account satisfactorily for the volume relationships which exist between combining gases. This required the introduction in 1811 by the Italian scientist, Amedeo Avogadro, of the molecule as the smallest particle of an element or compound capable of existing independently and consisting of two or more atoms, not necessarily identical. Thus, whilst we could only have atoms of elements, molecules of both elements and compounds were possible.

At the end of the nineteenth century some scientists felt that evidence, more direct than that provided by