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Structures

Chapter 1 The structures in our lives

– or how to communicate with engineers

As men journeyed in the east, they came upon a plain in the land of Shinar and settled there. They said to one another, 'Come, let us make bricks and bake them hard'; they used bricks for stones and bitumen for mortar. 'Come,' they said, 'let us build ourselves a city and a tower with its top in the heavens, and make a name for ourselves; or we shall be dispersed all over the earth.' Then the Lord came down to see the city and tower which mortal men had built, and he said, 'Here they are, one people with a single language, and now they have started to do this; henceforward nothing they have a mind to do will be beyond their reach. Come, let us go down there and confuse their speech, so that they will not understand what they say to one another.' So the Lord dispersed them from there all over the earth, and they left off building the city. That is why it is called Babel (that is, Babylon), because the Lord there made a babble of the language of all the world.

Genesis 11. 2–9 (New English Bible)

A structure has been defined as 'any assemblage of materials which is intended to sustain loads', and the study of structures is one of the traditional branches of science. If an engineering structure breaks, people are likely to get killed, and so engineers do well to investigate the behaviour of structures with circumspection. But, unfortunately, when they come to tell other people about their subject, something goes badly wrong, for they talk in a strange language, and some of us are left with the conviction that the study of structures and the way in which they carry loads is incomprehensible, irrelevant and very boring indeed.

Yet structures are involved in our lives in so many ways that we cannot really afford to ignore them: after all, every plant and animal and nearly all of the works of man have to sustain greater or less mechanical forces without breaking, and so practically everything is a structure of one kind or another. When we talk about structures we shall have to ask, not only why buildings and bridges fall down and why machinery and aeroplanes sometimes break, but also how worms came to be the shape they are and why a bat can fly into a rose-bush without tearing its wings. How do our tendons work? Why do we get 'lumbago'? How were pterodactyls able to weigh so little? Why do birds have feathers? How do our arteries work? What can we do for crippled children? Why are sailing ships rigged in the way they are? Why did the bow of Odysseus have to be so hard to string? Why did the ancients take the wheels off their chariots at night? How did a Greek catapult work? Why is a reed shaken by the wind and why is the Parthenon so beautiful? Can engineers learn from natural structures? What can doctors and biologists and artists and archaeologists learn from engineers?

As it has turned out, the struggle to understand the real reasons why structures work and why things break has been a great deal more difficult and has taken much longer than one might have expected. It is really only quite recently that we have been able to fill in enough of the gaps in our knowledge to answer some of these questions in any very useful or intelligent manner. Naturally, as more of the bits of the jig-saw puzzle are assembled, the general picture becomes clearer: the whole subject is becoming less a study for rather narrow specialists and more one which the ordinary person can find rewarding and relevant to a wide range of general interests.

This book is about modern views on the structural element in Nature, in technology and in everyday life. We shall discuss the ways in which the need to be strong and to support various necessary loads has influenced the development of all sorts of creatures and devices – including man.

The living structure

Biological structures came into being long before artificial ones. Before there was life in the world, there was no such thing as a purposive structure of any kind – only mountains and heaps of

sand and rock. Even a very simple and primitive kind of life is a delicately balanced, self-perpetuating chemical reaction which needs to be separated and guarded from non-life. Nature having invented life – and with it individualism – it became necessary to devise some kind of container in which to keep it. This film or membrane had to have at least a minimum of mechanical strength, both to contain the living matter and also to give it some protection from outside forces.

If, as seems possible, some of the earliest forms of life consisted of tiny droplets floating in water, then a very weak and simple barrier, perhaps no more than the surface tension which exists at the interfaces between different liquids, may have sufficed. Gradually, as living creatures multiplied, life became more competitive, and the weak, globular and immobile animals were at a disadvantage. Skins became tougher and various means of locomotion were evolved. Larger, multicellular animals appeared which could bite and could swim fast. Survival became a matter of chasing and being chased, eating and being eaten. Aristotle called this *allelophagia* – a mutual eating – Darwin called it natural selection. In any case, progress in evolution was dependent upon the development of stronger biological materials and more ingenious living structures.

The earlier and more primitive animals were mostly made from soft materials because they not only make it much easier to wriggle and extend oneself in various ways, but soft tissues are usually tough (as we shall see), while rigid ones like bone are often brittle. Furthermore, the use of rigid materials imposes all kinds of difficulties in connection with growth and reproduction. As women know, the business of giving birth involves an engineering of high strains and large deflections. All the same, the development of the vertebrate foetus from conception onwards, like that of natural structures in general, is in certain respects from soft to hard, and the hardening process goes on after the baby has emerged.

One gets the impression that Nature has accepted the use of stiff materials rather reluctantly, but, as animals got bigger and came out of the water on to the land, most of them developed and exploited rigid skeletons, teeth and sometimes horns and armour. Yet animals never became predominantly rigid devices like most modern machinery. The skeleton usually remained but a small part of the whole, and, as we shall see, the soft parts were frequently used in clever ways to limit the loads upon the skeleton and thus to protect it from the consequences of its brittleness.

While the bodies of most animals are made preponderantly from flexible materials, this is not always true for plants. The smaller and more primitive plants are usually soft, but a plant cannot chase its food, nor can it run away from an enemy. It can, however, protect itself to some extent by growing tall, and, by doing so, it may also be able to get more than its fair share of sun and rain. Trees, in particular, seem to be extraordinarily clever at stretching out to collect the diffuse and fitful energy of sunlight and at the same time standing up to being bullied by the wind – and all in the most cost-effective way. The tallest trees reach a height of about 360 feet or 110 metres, being by far the largest and most durable of living structures. For a plant to reach even a tenth of this height, however, its main structure needs to be both light and rigid; we shall see later that it incorporates a number of important lessons for engineers.

It may seem obvious that questions like these about strength and flexibility and toughness are relevant in medicine and in zoology and botany, yet for a long time both doctors and biologists resisted all such ideas with considerable success and with the whole force of their emotions. Of course, it is partly a matter of temperament and partly a matter of language, and perhaps a dislike and fear of the mathematical concepts of the engineer may have had something to do with the matter. Too often biologists simply cannot bring themselves to make a sufficiently serious study of the structural aspects of their problems. Yet there can be no reason to assume that, while Nature uses methods of infinite subtlety in her chemistry and her control mechanisms, her structural approach should be a crude one.

The technological structure

Wonders there are many, but there is no wonder
Wilder than man –
Man who makes the winds of winter bear him,

Through the trough of waves that tower about him,
Across grey wastes of sea;
Man who wearies the Untiring, the Immortal –
Earth, eldest of the Gods, as year by year,
His plough teams come and go.
The care-free bands of birds,
Beasts of the wild, tribes of the sea,
In netted toils he takes,
The Subtle One.

Sophocles, *Antigone* (440 B.C.; translated by F. L. Lucas)

Benjamin Franklin (1706–90) used to define man as 'a tool-making animal'. In fact a good many other animals make and use rather primitive tools, and of course they quite often make better houses than do many uncivilized men. It might not be very easy to point out the exact moment in the development of man at which his technology could be said noticeably to surpass that of the beasts that perish. Perhaps it was later than we think, especially if the early men were arboreal.

However this may be, the gap both in time and in technical achievement between the sticks and stones of the earliest men – which were not much better than the tools used by the higher animals – and the sophisticated and beautiful artefacts of the late Stone Age is an immense one. Pre-metallic cultures have survived in remote places until only yesterday and many of their devices can be seen and admired in museums. To make strong structures without the benefit of metals requires an instinct for the distribution and direction of stresses which is by no means always possessed by modern engineers; for the use of metals, which are so conveniently tough and uniform, has taken some of the intuition and also some of the thinking out of engineering. Since the invention of Fibreglass and other artificial composite materials we have been returning at times to the sort of fibrous non-metallic structures which were developed by the Polynesians and the Eskimoes. As a result we have become more aware of our own inadequacies in visualizing stress systems and, just possibly, more respectful of primitive technologies.

As a matter of fact the introduction of the technological metals to the civilized world – probably between 2,000 and 1,000 B.C. –

did not make a very large or immediate difference to most artificial structures, because metals were scarce, expensive and not very easy to shape. The use of metals for cutting tools and weapons and, to some extent, for armour had its effect, but the majority of load-bearing artefacts continued to be made from masonry and from timber and leather and rope and textiles.

Using the old mixed constructions, the millwright and the coachbuilder, the shipwright and the rigger, needed a very high degree of skill, though of course they had their blind spots and they made the sort of mistakes one might expect from men without a formal analytical training. On the whole, the introduction of steam and machinery resulted in a dilution of skills, and it also limited the range of materials in general use in 'advanced technology' to a few standardized, rigid substances such as steel and concrete.

The pressures in some of the early engines were not much higher than our blood-pressure but, since materials like leather are incapable of withstanding hot steam, the engineer could not contrive a steam engine out of bladders and membranes and flexible tubes. So he was compelled to evolve from metals, by mechanical means, movements which an animal might have achieved more simply and perhaps with less weight.* He had to get his effects by means of wheels, springs, connecting rods and pistons sliding in cylinders.

Although these rather clumsy devices were originally imposed on him by the limitations of his materials, the engineer has come to look on this kind of approach to technology as the only proper and respectable one. Once he has settled in his rut of metal cog-wheels and girders the engineer takes a lot of shifting. Moreover this attitude to materials and technology has rubbed off on the general public. Not long ago, at a cocktail party, the pretty wife of an American scientist said to me 'So you're really telling me that people used to make *airplanes* out of *wood*? – out of *lumber*! I don't believe you, you're kidding me.'

To what extent this outlook is objectively justified and how far it is based on prejudice and a morbid passion for being up to date is one of the questions which we shall discuss in this book. We

* Compare pistons and bellows.

need to take a balanced view. The traditional range of engineering structures made from bricks and stone and concrete and from steel and aluminium have been very successful, and clearly we ought to take them seriously, both for their own sakes and for what they have to teach us in a broader context. We might remember, however, that the pneumatic tyre, for instance, has changed the face of land transport and is probably a more important invention than the internal combustion engine. Yet we do not often teach engineering students about tyres, and there has been a distinct tendency in the schools of engineering to sweep the whole business of flexible structures under the carpet. When we come to look at the question in a broad way we may perhaps find that, for solid quantitative reasons, there is a case for trying to rebuild some part of traditional engineering upon models which may well turn out to be partly biological in inspiration.

Whatever view we may take of these matters we cannot get away from the fact that every branch of technology must be concerned, to a greater or less extent, with questions of strength and deflections; and we may consider ourselves lucky if our mistakes in these directions are merely annoying or expensive and do not kill or injure somebody. Those concerned with electrical affairs might be reminded that a great proportion of the failures in electrical and electronic devices are mechanical in origin.

Structures can, and do, break, and this may be important and sometimes dramatic; but, in conventional technology, the rigidity and deflections of a structure before it breaks are likely to be more important in practice. A house, a floor or a table which wobbled or swayed would not be acceptable, and we should consider that the performance of, say, an optical device such as a microscope or a camera depends not only upon the quality of its lenses but also upon the accuracy and rigidity with which they are positioned. Faults of this kind are far too common.

Structures and aesthetics

Could I find a place to be alone with heaven,
I would speak my heart out: heaven is my need.
Every woodland tree is flushing like the dogwood,
Flashing like the whitebeam, swaying like the reed.

Flushing like the dogwood crimson in October;
Streaming like the flag-reed South-West blown;
Flashing as in gusts the sudden-lighted whitebeam:
All seem to know what is for heaven alone.

George Meredith, *Love in the Valley*

Nowadays, whether we like it or not, we are stuck with one form or another of advanced technology and we have got to make it work safely and efficiently: this involves, among other things, the intelligent application of structural theory. However, man does not live by safety and efficiency alone, and we have to face the fact that, visually, the world is becoming an increasingly depressing place. It is not, perhaps, so much the occurrence of what might be described as 'active ugliness' as the prevalence of the dull and the commonplace. Far too seldom is the heart rejoiced or does one feel any better or happier for looking at the works of modern man.

Yet most of the artefacts of the eighteenth century, even quite humble and trivial ones, seem to many of us to be at least pleasing and sometimes incomparably beautiful. To that extent people – all people – in the eighteenth century lived richer lives than most of us do today. This is reflected in the prices we pay nowadays for period houses and antiques. A society which was more creative and self-confident would not feel quite so strong a nostalgia for its great-grandfathers' buildings and household goods.

Although such a book as this is not the place in which to develop elaborate and perhaps controversial theories of applied art, the question cannot be wholly ignored. As we have said, nearly every artefact is in some sense a structure of one kind or another, and, although most artefacts are not primarily concerned with making an emotional or aesthetic effect, it is highly important to realize that there can be no such thing as an emotionally neutral statement. This is true whether the medium be speech or writing or painting or technological design. Whether we mean it or not, every single thing we design and make will have some kind of subjective impact, for good or bad, over and above its overt rational purpose.

I think we are up against yet another problem of communication. Most engineers have had no aesthetic training at all, and the tendency in the schools of engineering is to despise such matters as frivolous. In any case, there is little enough time in the crowded syllabuses. Modern architects have made it very clear to me that they cannot spare time from their lordly sociological objectives to consider such minor matters as the strength of their buildings; nor, indeed, can they spare much time for aesthetics, in which their clients are probably not much interested anyway. Again, furniture designers, incredibly, are not taught during their formal training how to calculate the deflection in an ordinary bookshelf when it is loaded with books, and so it is not very surprising that most of them seem to have no ideas about relating the appearance to the structure of their products.

The theory of elasticity, or why things do fall down

Or those eighteen, upon whom the tower in Siloam fell, and slew them, think you that they were sinners above all men that dwelt in Jerusalem?

Luke 13.4

Many people – especially English people – dislike theory, and usually they do not think very much of theoreticians. This seems to apply especially to questions of strength and elasticity. A really surprising number of people who would not venture into the fields of, say, chemistry or medicine feel themselves competent to produce a structure upon which someone's life may depend. If pressed, they might admit that a large bridge or an aeroplane was a little beyond them, but the common structures of life surely present only the most trivial of problems?

This is not to suggest that the construction of an ordinary shed is a matter calling for years of study; yet it is true that the whole subject is littered with traps for the unwary, and many things are not as simple as they might seem. Too often the engineers are only called in, professionally, to deal with the structural achievements of 'practical' men at the same time as the lawyers and the undertakers.

Nevertheless, for long centuries the practical men managed after their own fashion – at least in certain fields of construction. If you go and look at a cathedral you may well wonder whether you are impressed more deeply by the skill or by the faith of the people who built it. These buildings are not only of very great size and height; some of them seem to transcend the dull and heavy nature of their constructional materials and to soar upwards into art and poetry.

On the face of it it would seem obvious that the medieval masons knew a great deal about how to build churches and cathedrals, and of course they were often highly successful and superbly good at it. However, if you had had the chance to ask the Master Mason how it was really done and why the thing stood up at all, I think he might have said something like 'The building is kept up by the hand of God – always provided that, when we built it, we duly followed the traditional rules and mysteries of our craft.'

Naturally, the buildings we see and admire are those which have survived: in spite of their 'mysteries' and their skill and experience, the medieval masons were by no means always successful. A fair proportion of their more ambitious efforts fell down soon after they were built, or sometimes during construction. However, these catastrophes were just as likely to be regarded as sent from Heaven, to punish the unrighteous or to bring sinners to repentance, as to be the consequence of mere technical ignorance – hence the need for the remark about the tower of Siloam.*

Perhaps because they were too much obsessed by the moral significance of good workmanship, the old builders and carpenters and shipwrights never seem to have thought at all, in any scientific sense, about why a structure is able to carry a load. Professor Jacques Heyman has shown conclusively that the cathedral masons, at any rate, did not think or design in the modern way. Although some of the achievements of the medieval craftsmen are impressive, the intellectual basis of their 'rules' and 'mysteries' was not very different from that of a cookery book. What these people did was to make something very much like what had been made before.

As we shall see in Chapter 9, masonry is a rather exceptional case and there are some special reasons why it is sometimes safe

*There is an interesting discussion of pagan views on this subject in Gilbert Murray's *Five Stages of Greek Religion* (O.U.P., 1930). Again, the whole question of animism in connection with structures is worthy of study.

and practicable to scale up from small churches to large cathedrals, relying simply on experience and traditional proportions. For other kinds of structures this way of doing things will not work and is quite unsafe. This is the reason why, though buildings got bigger and bigger, for a very long time the size of the largest ships remained virtually constant. So long as there was no scientific way of predicting the safety of technological structures, attempts to make devices which were new or radically different were only too likely to end in disaster.

Thus, for generation after generation, men turned their heads away from a rational approach to problems of strength. However, if you make a habit of shelving questions which, in your secret heart, you must surely know to be important, the psychological consequences will be unhappy. What happened was just what one would have expected. The whole subject became a breeding-ground for cruelty and superstition. When a ship is christened by some noble matron with a bottle of champagne, or when a foundation stone is laid by a fat mayor, these ceremonies are the last vestiges of certain very nasty sacrificial rites.

During the course of the Middle Ages the Church managed to suppress most of the sacrifices, but it did not do much to encourage any kind of scientific approach. To escape completely from such attitudes – or to accept that God may work through the agency of the laws of science – requires a complete change of thinking, a mental effort such as we can scarcely comprehend today. It called for a quite exceptional combination of imagination with intellectual discipline at a time when the very vocabulary of science barely existed.

As it turned out, the old craftsmen never accepted the challenge, and it is interesting to reflect that the effective beginnings of the serious study of structures may be said to be due to the persecution and obscurantism of the Inquisition. In 1633, Galileo (1564–1642) fell foul of the Church on account of his revolutionary astronomical discoveries, which were considered to threaten the very bases of religious and civil authority. He was most firmly headed off astronomy and, after his famous recantation,* he was

*When he was forced to deny that the earth went round the sun. Giordano Bruno had been burnt for this heresy in 1600.

perhaps lucky to be allowed to retire to his villa at Arcetri, near Florence. Living there, virtually under house-arrest, he took up the study of the strength of materials as being, I suppose, the safest and least subversive subject he could think of.

As it happened, Galileo's own contribution to our knowledge of the strength of materials was only moderately distinguished, though one must bear in mind that he was almost seventy when he began to work on the subject, that he had been through a great deal and that he was still more or less a prisoner. However, he was allowed to correspond with scholars in various parts of Europe, and his great reputation lent prestige and publicity to any subject he took up.

Among his many surviving letters there are several about structures, and his correspondence with Mersenne, who worked in France, seems to have been particularly fruitful. Marin Mersenne (1588–1648) was a Jesuit priest, but presumably nobody could object to his researches on the strength of metal wires. Edmé Mariotte (1620–84), a much younger man, was also a priest, being Prior of Saint Martin-sous-Beaune, near Dijon, in the wine country. He spent most of his life working on the laws of terrestrial mechanics and on the strength of rods in tension and in bending. Under Louis XIV he helped to found the French Academy of Sciences and was in favour with both Church and State. None of these people, it will be noted, were professional builders or shipwrights.

By Mariotte's time the whole subject of the behaviour of materials and structures under loads was beginning to be called the science of elasticity – for reasons which will become apparent in the next chapter – and we shall use this name repeatedly throughout this book. Since the subject became popular with mathematicians about 150 years ago I am afraid that a really formidable number of unreadable, incomprehensible books have been written about elasticity, and generations of students have endured agonies of boredom in lectures about materials and structures. In my opinion the mystique and mumbo-jumbo is overdone and often beside the point. It is true that the higher flights of elasticity are mathematical and very difficult – but then this sort of theory is probably only rarely used by successful engineering designers. What is actually needed for a great many ordinary purposes can be understood quite easily by any intelligent person who will give his or her mind to the matter.

The man in the street, or the man in the workshop, thinks he needs virtually no theoretical knowledge. The engineering don is apt to pretend that to get anywhere worth while without the higher mathematics is not only impossible but that it would be vaguely immoral if you could. It seems to me that ordinary mortals like you and me can get along surprisingly well with some intermediate – and I hope more interesting – state of knowledge.

All the same, we cannot wholly evade the question of mathematics, which is said to have originated in Babylonia – possibly at the time of the Tower of Babel incident. Mathematics is to the scientist and the engineer a tool, to the professional mathematician a religion, but to the ordinary person a stumbling-block. Yet all of us are really using mathematics through every moment of our lives. When we play tennis or walk downstairs we are actually solving whole pages of differential equations, quickly, easily and without thinking about it, using the analogue computer which we keep in our minds. What we find difficult about mathematics is the formal, symbolic presentation of the subject by pedagogues with a taste for dogma, sadism and incomprehensible squiggles.

For the most part, wherever a 'mathematical' argument is really needed I shall try to use graphs and diagrams of the simplest kind. We shall, however, need some arithmetic and a little very, very elementary algebra, which – however rude we may be to the mathematicians – is, after all, a simple, powerful and convenient mode of thought. Even if you are born, or think you are born, with an allergy to algebra, please do not be frightened of it. However, if you really must skip it, it will still be possible to follow the arguments in this book in a qualitative way without losing too much of the story.

One further point: structures are made from materials and we shall talk about structures and also about materials; but in fact there is no clear-cut dividing line between a material and a structure. Steel is undoubtedly a material and the Forth bridge is undoubtedly a structure, but reinforced concrete and wood and human flesh – all of which have a rather complicated constitution

– may be considered as either materials or structures. I am afraid that, like Humpty-Dumpty, when we use the word 'material' in this book, it will mean whatever we want it to mean. That this is not always the same as what other people mean by 'material' was brought home to me by another lady at another cocktail party.

'Do tell me what it is you do?'

'I'm a professor of materials.'

'What fun it must be to handle all those dress-fabrics!'

Part One

The difficult birth of the science of elasticity