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On the future of structural form—a natural reaction?

L'avenir de la forme structurale — une réaction naturelle?

Ueber die Zukunft von Tragwerksformen — eine natürliche Reaktion?

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SUMMARY
Most present day forms of steel and concrete construction are inherently better suited to high than to low structure loading coefficients. For a number of reasons such as the increasing scarcity of concentrated energy sources the future tendency is likely to be towards much lower loading coefficients. For such purposes we can profit by studying not only biological models but traditional forms of technology, such as sailing ships.

RESUME
De nos jours, la forme de la plupart des structures en acier et en béton est mieux adaptée à des coefficients de chargement élevés plutôt que bas. Pour de nombreuses raisons, telle que la raréfaction des sources d'énergie concentrées, la tendance est plutôt vers un coefficient de chargement plus petit. L'étude de modèles biologiques et également de formes traditionnelles de technologie, telle que les bateaux à voiles peut être très bénéfique.

ZUSAMMENFASSUNG
Die meisten der heute bei Tragwerken aus Stahl oder Beton realisierten Formen sind an sich mehr auf hohe Belastungskoeffizienten als auf tiefe ausgerichtet. Aus verschiedenen Gründen, z.B. zunehmende Knappheit konzentrierter Energiequellen, weist die zukünftige Tendenz eher in Richtung kleinerer Belastungskoeffizienten. Zu diesem Zweck ist es sinnvoll, nicht nur biologische Modelle, sondern auch traditionelle Techologien, z.B. Segelschiffe, zu studieren.

INTRODUCTION

As long ago as 1965 Mr. H. L. Cox published a slim volume called 'The Design of Structures of Least Weight' [1]. Although it is, to my mind, an important book it aroused only very moderate interest either in engineering or in biological circles and it has been out of print for some time. This neglect may have been partly due to the fact that the book is undeniably difficult to understand but I think that a more important reason may have been that engineers at any rate did not *want* to understand it - for it might lead them into regions of thought which were both frivolous and heretical. It might lead them into the study of things like plants and animals and sailing ships which everybody knows have no place in 'proper' engineering.

'Proper' engineering is, of course, largely about things like steel and concrete - and, if the result is heavy and ugly, well, that can't be helped. But how is it that engineers have come to think in this sort of way? As the Greeks were well aware, success inevitably sows the seeds of future failure and, although engineers are often unconscious of it, their successes since the Industrial Revolution have been due, in a large measure, to the exploitation of higher and higher structure loading coefficients. That is to say, the loads became much larger in relation to the distances over which they had to be carried.

In 1781 a 10 horse-power engine, with its appurtenances, might have weighed nearly 100 tons, nowadays it might weigh little more than 10 lbs; and the first cost has come down nearly as dramatically. The improvement was not primarily due to increases in thermal efficiency - or even to improvements in metallurgy - it was chiefly due to the adoption of higher working pressures and higher rates of rotation which enabled the dimensions to be reduced and the stresses to be increased. The progress of engineering over the last 200 years might be summed up as 'putting more and more into less and less' - as passengers in modern aircraft are painfully aware.

But one cannot go on doing this sort of thing indefinitely and, in any case, there are many areas of technology where the idea of using higher structure loading coefficients is simply not applicable. This tends to be true in housing, in many vehicles and containers, in furniture, and so on. It is also true of most of the devices with which we are nowadays seeking to extract energy from diffuse sources, such as the wind. Machines intended to convert energy from the sun or the wind must most probably be wholly different in their character and philosophy from the engines which have been devised to convert energy from concentrated sources, such as coal or oil. Many of the attempts of conventionally minded modern engineers to design things like windmills remind one of the attempts of Don Quixote to turn himself into a traditional knight, even down to the obsolescent armour or metal monocoque construction. For, like medieval chivalry, structural engineering has tended to harden into a series of conventions or mystiques which, although they are held with an almost religious fervour by the initiated, inevitably become irrelevant in a changing world. The time is, I think, already in sight when traditional metal and concrete construction will join the steam-engine in the filing-cabinets of history.

As both energy and labour become more expensive the engineer will have to learn new tricks. Except for the beasts of prey, living structures depend upon diffuse sources of energy and their manufacturing processes are fully automated - which are two good reasons why we should look to Nature for models.

But, of course, the danger of all 'back to Nature' movements is that they confuse means with ends and tend to see some sort of absolute good in Nature. Nature is devilishly clever, but she is often devilishly cruel; at best she is morally neutral. I, for one, have no sympathy with 'conservationism' or any other form of Pantheism. Nature is there to be exploited; we had better do it intelligently.

THE EFFECTS OF STRUCTURE LOADING COEFFICIENTS

When the structure loading coefficient is high - as it is in most conventional machinery, for instance - there may not be much difference between the weights of tension and compression members designed for equivalent loads. However regimes where the structure loading coefficients are high represent special, and highly 'artifical', cases which have been brought into being by engineers in modern times. Even in technology such a state of affairs is in fact comparatively rare and it never exists in Nature.

As the load is diminished in relation to the dimensions the weights and also the costs of tension and compression members diverge dramatically. The weight of members intended to carry 1 ton over a distance of 20 or 30 centimetres will be much the same whether the load is in tension or in compression. To carry the same load, 1 ton, over a distance of 10 metres the difference is enormous for, in tension, the necessary member (including its end fittings) will weigh about 3.5 kg; in compression the necessary metal column is likely to weigh about 200 kg, that is 50 or 60 times as much and the relative costs may well be in proportion. Of course most practical design cases are more sophisticated than this but the principle remains the same.

Steel is a material which is peculiarly unsuited for carrying compressive loads over long distances; in fact it is probably one of the worst materials ever conceived for diffuse structures. When Nature wants to make a large, lightly loaded and comparatively rigid structure which is unavoidably subject to compression and bending she uses wood.

Wood is not a 'primitive' material: it is one of the most efficient and sophisticated structural materials which has ever been designed. For the construction of panels it is about six or seven times as efficient as steel. Which is why it is used for things like floors and furniture.

Wood is a much more complex material than any metal alloy. We have been studying wood as an engineering material at Reading for a number of years in the light of modern materials science [2], [3]. One can only express amazement at the layers and layers of sophistication which are built into the design of wood as a load-carrying device. From the technological point of view wood has the disadvantage that it shrinks and swells and, what is perhaps more serious, it rots. However, as many people are aware, there are a number of attempts in various parts of the world to produce artificial versions of wood which do not have these drawbacks.

An interesting thing about trees and other woody plants is that they solve their erection problems by starting as blown-up tension structures, or bladders, inflated by osmotic pressure. These soft structures are then hardened so that the plant is capable of resisting compression and bending without the aid of the turgo-pressure of the sap. Surely there is a lesson here for engineers?

But, on the whole, animals do not do this sort of thing for they are not really hard structures. A skeleton is a deceptive exhibit for it shows only the compression members of the animal's structure; in fact the tension members are much more numerous and important. Indeed a great many animals manage without bones at all and are very possibly better and safer as a result. Animals like worms are like soft plants and balloons and air-houses. Vertebrate animals are like tents, that is to say primarily tension structures propped here and there by a limited number of struts. No doubt a monocoque shell or skull is necessary to protect our brains but complete exo-skeletons are mostly confined to smallish animals like beetles and lobsters. In other words Nature seems to use tension members in animals as far as she can and to economise on compression members - there is no equivalent to a masonry cathedral in Nature. Furthermore Nature seems to go to great lengths to avoid having to deal with shear and torsion.

TENSION STRUCTURES

As we have said, at low structure loading coefficients the economic advantage of carrying a load in tension rather than in compression or bending is generally very great. A suspension bridge is lighter and cheaper than an arch and it would also be much lighter than a truss if it were not for the need to resist torsional oscillations; a problem which Nature always manages to evade. And tents are much lighter and cheaper than cathedrals.

But the problem of making a large tension structure safe is not a trivial one. In many ways it was better understood by the old shipwrights and riggers than it is by modern engineers who are obsessed with the current fashion for metal plate structures.

The trouble with large metal monocoques is that they are liable to crack. The critical Griffith crack length is an absolute, not a relative, distance. Cracking is not a serious problem in small shell structures, it becomes very important in large ships and aircraft and box-girders. In order to get a 'safe' critical crack length of a metre or so in a large structure it is necessary to use a weak, ductile alloy and to work it at stresses which are an absurdly small fraction of the potential strength of the material. Even then these structures break quite often.

In modern suspension bridges the change from mild steel plate links to brittle high-tensile wire cables has enabled the working stresses to be put up tenfold with, most probably, an actual increase in safety. The problems with modern suspension bridges lie, not in the highly stressed brittle cables, but in the welded mild steel box girders. This is, of course, because in the cables the tension members are subdivided,, like animal tendons, in such a way that strain energy cannot be transmitted from one member to the next. In a welded shell the engineer is ignoring the rather obvious fact that a joint which will transmit an anticipated load will also transmit an un-anticipated release of strain energy. There is a good deal of justified grumbling about the poor quality of welding in large structures but I suppose that, from the fracture mechanics point of view, it could be argued that the better the welding the more dangerous the structure is likely to be, for a good weld not only transmits energy but provides no barrier to crack propagation.

A rope is a very safe and sophisticated way of transmitting tensile loads but it is essentially one-dimensional. The problem gets more difficult when we want to transmit tensile loads in two dimensions, in other words, to provide a membrane such as might be used for a sail or a tent or an air-house. The traditional technological way of doing this is to make a fabric, that is cloth woven out of twisted yarns which are, in effect, ropes.

This all very well as long as one does not want to make the membrane impermeable, that is as long as the yarns in the cloth are not 'properly' stuck together. The flax canvas which was used for sails in Nelson's navy was a superb engineering material in the sense that it did not tear, but it was porous and ships 'in chase' had to wet their sails to make them airtight. When one comes to the provision of fabrics for aircraft the problems of doping are serious, if the yarns are too well stuck together the fabric will be brittle. The immediate technical cause of the loss of the airship R 101 was the improper doping of the fabric of the outer skin, which tore after a few hours in the air. At the time it was suggested by technical journalists that it would have been better if the airship had been covered by thin metal sheet; but, of course, thin metal sheets inevitably tear very easily for reasons connected with the geometry of dislocations.

In fact it is probably impossible to make a *tough* thin membrane which obeys Hooke's law. Natural membranes only obey Hooke's law when they are intended by Nature to tear easily - such as the amniotic membrane in childbirth. Almost without exception tough natural membranes do not obey Hooke's law even approximately, they exhibit a characteristic J-shaped curve. There is no reason to suppose that a tough artificial membrane can be very different.

In fact, of course, Hookean behaviour only seems to be really necessary or desirable in materials which are liable to buckle under compressive loads - a condition which is to be avoided as far as possible. In tension there is nothing canonical, or even particularly desirable, about Hooke's law. All the same, when engineers come to be faced with the problem of designing elaborate tension structures from non-Hookean membranes they will presumably have to do a good deal of re-thinking, for not many of the traditional formulae will apply.

Buildings and similar structures must be aerodynamically stable, nobody wants their house to flap in the wind. This seems to imply that the outer membrane, at least, should have two-dimensional curvature, whether spherical or anti-elastic. This requirement seems to be in line with modern observations on the behaviour of junctions in arteries. In both cases the calculations are very difficult to do. Also any break with orthogonality is a break with both architectural and engineering tradition.

ON ONE-HOSS SHAYS

The great object in designing tension structures is to avoid all-or-nothing characteristics - however 'modern' and 'scientific' such systems may appear to be; for, in such structures, once a defect has exceeded its critical size, there must be an explosive release of energy. And the same principles must apply to more complex arrangements such as beams and wings and containers and ships.

It is often true that the mathematical or text-book solutions to design problems often seem to indicate continuous shells or monocoques; but then, these sums are done on the assumption that similar materials and similar factors of safety are used in all cases. In a subdivided structure however one can often afford to make use of much stronger materials (e.g. high tensile steel wires in the case of a bridge) and perhaps to work at lower factors of safety. According to Professor McNeil Alexander the factors of safety in animals seem to be quite low - yet animals never break in two like oil-tankers.

A very simple technological example is afforded by an ordinary roof. Most domestic roofs are covered by slates or tiles, that is by quite small scales or cantilevers. In this case subdivision enables a material which is weak and brittle - but also cheap and durable - to be used to cover large areas. Large ceramic panels would be impractical and absurd for roofing because, of course, when they cracked the result would be troublesome, damp and expensive.

In a similar manner birds are not covered, like aircraft, with a continuous monocoque of shiny aluminium plates - however 'scientific' that might be. They are covered with small separate cantilevers called 'feathers'. A bird can fly around quite safely with several feathers missing and they frequently do. An aeroplane cannot fly with a number of plates missing from its wings or its fuselage. Judging by the distances covered by migrating birds and by their energy consumption it seems likely that the bird is at least as 'efficient' as the aeroplane.

Similar principles were applied, consciously or unconsciously, to the design of traditional wooden sailing ships, which do not seem to get, from engineers, either the study or the respect which they deserve. They were, in fact, both safe and highly intelligent structures. We might bear in mind that at Trafalgar, one of the most decisive battles in history, no ship on either side was sunk as direct effect of enemy action. These ships could sustain a tremendous amount of damage and were practically indestructible by the cutting action of cold shot.

ON COMPRESSION AND BENDING

The simplest, lightest and cheapest way to cope with compression and bending loads operating at low structure loading coefficients is nearly always to take them in tension, that is by some sort of inflated bag structure. But of course there will be times when this is impractical, especially in large constructions, and bones, masts or tent-poles - or their equivalents,- become necessary. This of course raises the awkward question as to how far the ever-recurring demand for rigidity in technological structures is inherent in engineering and how far it is a constraint which the engineer has, so to speak, inflicted on himself. Trees, especially large ones, apparently have to be fairly rigid but large animals seldom are and birds manage to dodge out of the exacting requirements of aero-elasticity with which the aircraft designer tortures himself. In this respect traditional sailing ships seem to be more intelligently designed than contemporary aircraft.

However this may be, the problem of providing an efficient 'rigid' column or beam or panel is one where we can learn from Nature. On the simplest parametric analyses the weight of a member which is subject to Euler conditions will vary roughly according to the values of $\frac{\sqrt{E}}{\rho}$ or $\frac{\sqrt[3]{E}}{\rho}$ for its material. On criteria like these steel, of course, shows up very badly indeed. But, as we all know., steel can be turned into a useful material for diffuse structures by flanging it or corrugating it or turning it into tubes. These are the early stages of the process of cellularisation which is analysed extensively in Cox's book and which is utilised in practice - to an even more sophisticated level - in Nature.

Although things like rolled steel joists and corrugated iron are used so widely and so successfully in technology it is doubtful if the process of cellularisation can be taken much further with metals. Even if it were practical to manufacture metals in highly cellularised forms we should have to face problems both of corrosion and of fracture mechanics, for thin metal sheet is not only susceptible to local buckling in compression, it is also inherently brittle in tension because of its thinness. It may be true that one could get round some of these difficulties by applying to metals modern composite theory - but then non-metals are probably inherently more suitable for making sophisticated low-density materials. By the time we have got to this stage we have abandoned the main virtue of metals, their cheapness and their ductility.

Cellurisation is the most effective way of providing Euler stability, for the reason that holes, that is air, are cheaper than things like carbon fibres. But of course, as we cellularise a material, we soon run into a condition where the cell walls become liable to local buckling so that the material as a whole is likely to be much weaker in direct compression than it is in tension. For a symmetrical beam, such as a tree, this is a wasteful condition; the tree meets the situation by putting the outer layers of wood into tension at the expense of compression in the heartwood. It thus achieves the opposite of the condition which exists in a pre-stressed concrete beam - but with similar beneficial results.

Although a great deal of attention has been given to the fracture mechanics of tensile failure, the fracture mechanics of compressive failure has been rather neglected - though similar principles must apply. Fibrous materials tend to fail, locally, in compression by the formation of compression creases which result from the local buckling of fibres or cell walls. In a 'solid' composite, where no change of volume can occur, compression creases must form at, or near, to an angle of 45^{o} to the applied stress. Such creases behave much like Griffith cracks and can easily become unstable and propagate: which is why the behaviour of many conventional composites have the reputation of being unreliable in compression. However, as Dr. Richard Chaplin has pointed out, in a cellular material like wood, where there is room for volume changes to occur, the compression crease can be arranged to initiate in a direction normal to the applied stress. Such creases are inherently stable and do not tend to propagate. It is this characteristic which accounts for the 'safe' behaviour of wood in such applications as pit-props. There ought to be no difficulty in reproducing this mechanism in artificial composites, it would contribute notably to the safety of structures.

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