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Perspective on Structural Form

Nouvelles perspectives dans le choix des structures

Perspektiven der baulichen Formgebung

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SUMMARY
In structural engineering economy is achieved by an understanding of forces, materials and construction methods. To date structural engineers have tended to specialise in types of structures using non-renewable resources. Recently there has been a broadening of this approach stimulated by an increased desire for energy efficiency. This paper explores this development with examples from the author's experience.

RESUME
Dans le domaine des structures, l'économie s'obtient grâce à une meilleure compréhension des efforts des matériaux et des méthodes de construction. Les ingénieurs se sont spécialisés dans des types de structures utilisant des ressources non renouvelables. Récemment on s'est lancé dans une approche plus large afin d'améliorer l'efficacité énergétique.

ZUSAMMENFASSUNG
Im konstruktiven Ingenieurbau erreicht man Wirtschaftlichkeit durch das Verständnis des Kräftespiels und die Kenntnis der Materialien und der Baumethoden. Bis heute herrschte bei den Ingenieuren die Tendenz vor, sich auf gewisse Konstruktionsarten zu spezialisieren, unter Verwendung von nicht erneuerbaren Rohstoffen. Durch den Wunsch einer besseren Energieausnützung angeregt, ergibt sich neuerdings eine umfassendere Betrachtungsweise. In diesem Beitrag wird diese Entwicklung anhand von Beispielen aus dem Erfahrungsbereich des Autors untersucht.

"When we look at ancient works of art we habitually treat them not merely as objects of aesthetic enjoyment but also as successive deposits of the human imagination. It is indeed this view of works of art as crystallised history that accounts for much of the interest felt in ancient art by those who have but little aesthetic feeling and who find nothing to interest them in the work of their contemporaries, where the historical motive is lacking, and they are left face to face with bare aesthetic values."

"Art and Life" by Roger Fry. 1917.

As structural engineers we suffer greatly from public misunderstanding of what we do together with a general misconception of the roots of the different disciplines in the construction industry and what their objectives and contributions are to our society.

It is generally accepted that the three main divisions of knowledge are the Arts, Science and Technology.

Where the expression "the Arts" once meant any skill as the result of knowledge and practice it is now limited to meaning the study of history, languages, philosophy, music, painting, architecture, the law and so on. In other words it is the study of some aspect of human behaviour which, after all, were the earliest academic studies. Discussion on morals was essential to define laws, laws were essential to support governments. The broad subject area has immense respectability because of its antiquity. In a basically agricultural society not much more was needed; it is still essential, though not exclusively, to modern society.

Science is about studying nature and determining how it acts and evolves. By the time of the Renaissance the study developed in Europe and, at the beginning of the sixteenth century, the arts and science parted company. To Michaelangelo, Palladio and Vanbrugh architecture was primarily a matter of aesthetics. They were interested in planning, proportion, massing and decoration [1]. It was the start of architecture as fashion. Separate from this were scientists such as Galileo with his conception of force and movement, Newton with his articulation of the composition of forces and his laws of motion, Hooke with his definition of elasticity and so on. Starting as an intellectual exercise science has become extremely important because it enables the prediction of performance. Since its objective is to be exact it has developed mathematics as its language. With increased intervention with nature science has become increasingly important in understanding the implications. It is generally viewed with suspicion and yet as essential.

Technology really took off around 1760 when two foremen at an iron works in Coalbrookdale produced iron using coal, not wood, as fuel. It was the beginning of the era of using non-renewable resources - metals and fossil fuels (1). In 1779 the world's first iron bridge at Coalbrookdale was complete (2). In 1801 the first steam carriage was built by Richard Trevithick (3). In 1826 Telford's great suspension bridge over the Menai was completed and so on (4).

Technology is about change. It is about the development of useful objects or processes which are new and which change our lives. It does this in response to people's aspirations or is restrained by people's fears; in this it relates to the arts. What it does must obey the laws of nature, which is why it uses science to examine behaviour. Technology is the making of things while science is the explaining.

In fact everything in the built environment has been achieved by technology. Every single man made object in the world is the product of technology - or engineering if you prefer that word. Structural engineering has a unique position within that body of knowledge.

Yet there is a constant desire by many people to tame and control technology. This control is largely achieved by arguing for visual beauty and that visual beauty to comply with criteria set up by those who have studied the arts. I have written before about the division of thinking into a romantic mode, seeing the world primarily in terms of immediate appearance, or the classical mode, seeing the world primarily as having underlying forms [2]. The latter can, at its best, produce original art; the former tends only to develop existing forms. The technologist is primarily a classicist and his craft is intensely creative; at its best it is art in that it extends people's vision of what is possible and gives them new insights. But the aesthetic is "bare" and more likely to relate to a precedent in nature than a historical one.

What are the qualities which are essential to practise our craft well? Structural design is primarily about the choice of form. The forces on that form and the analysis of its behaviour follow that. The whole is controlled by the responsibility for execution. Success is proved in use.

The structural engineer needs to understand materials, their nature, their behaviour, their manufacture into elements and how to joint them. He needs to understand natural and man made forces and how he can amend them. He needs to know construction methods and how to organise them. He needs to know the business and political environments because he is in the business of achievement (5).

His ambition is, I think, to achieve elegance as well as value. Elegance in the sense mathematicians use the word; an economy as well as appropriateness. As a French aircraft designer once said, "When you cannot remove any element then you have the right design".

We hope that some of the work our group has carried out over the years illustrates some of these points - both successes and failures - in the hope that they may help to illuminate areas of developing importance and possibilities. And here I must state that we do not just see our structures as designed to resist or amend wind and man made forces but also in terms of thermal, acoustic and lighting performance - in other words the whole area of passive energy transfer.

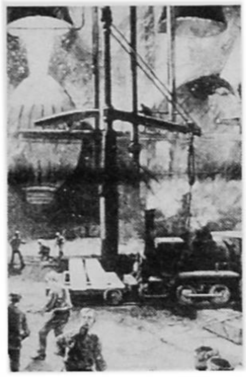

Fig. 1 Iron Works

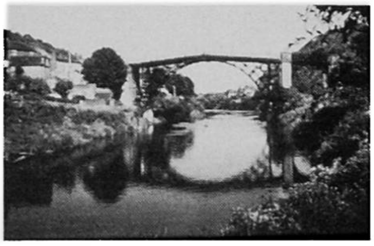

Fig. 2 The Iron Bridge at Coalbrookdale

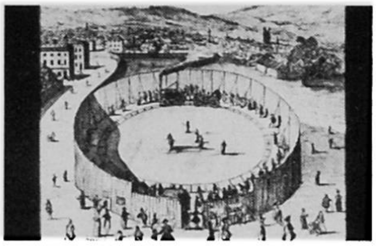

Fig. 3 Richard Trevithick's steam carriage, 1801

Fig. 4 Telford's Conway suspension bridge, 1826

Let us look at one of my failures, caused I believe because I accepted repeating a historical style rather than continuing to try for function and economy. A core group of five of us, three architects and two engineers, with help from some others, entered for an open competition for a cultural centre with spaces to be allocated to specific separate functions with shared spaces between [3]. The assumption in the competition was that most visitors would come by car and parking for nearly 1000 vehicles had to be provided. The size of site and soil profile was such that a three storey basement car park would provide this with the problem of entrance identification provided by a single shaft of light where elevators and escalators rose up. The main building was seen rising as a transparent block out of a piazza with the elevators rising across the front so that people arriving could either see from a distance or from a trip up the facade of the building what was on offer inside and make their choice accordingly. The multi storey building itself had bays which could, to a limited extent, be raised or lowered to provide variable space to the separate sections and, more importantly, to the shared space between in order to reduce the "boundary maintenance" which occurs in bureaucracies. The floors could have to be heavily serviced so plant was on the roof and in the basement with flexible servicing provided down the back of the building and under the separate floor bays. The floors, long span, were supported on external twin framed "walls" like the crane walls on either side of ship construction docks. These framed walls would also provide viewing walkways and "information" could be exhibited. They would be exposed steelwork, water cooled for fire protection, systemised, with rust resistant members and cast steel compression joints so, hopefully, providing a minimum material structure like those of the 19th century (6). Success in the competition brought problems. The car park was not needed to link with the building above and the total height had to be reduced. The spans had to be increased and the floor depths reduced. There was a shortage of money for the elevators and escalators. More crucially there was only five years allowed for the design and construction rather than the nine years we had shown on our competition programme. The architects asked me if we could do it and I said I would have trouble with the moving floors. They said they never believed in them anyway. I had to spend most of my own time dealing with contractual management. So now there is an exposed support system with compression on the inside columns and tension the outer, with the cantilevers which support the fixed floors made of castings (7). The whole may be visually interesting and certainly unusual but, the omission of the moving floors and the changes in use of steels seems to lack an appropriateness and an economy which the original design conceived.

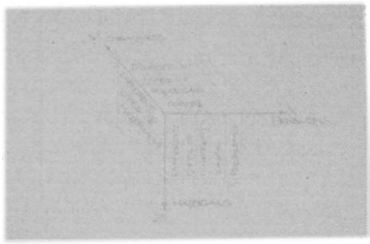

Fig.. 5 The engineer's 3 areas of experience

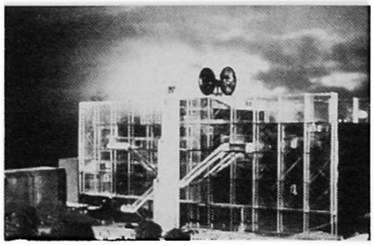

Fig. 6 The winning entry, Centre Beaubourg Competition, Paris

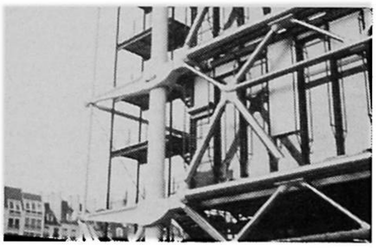

Fig. 7 The reality, Centre Pompidou, Plateau Beaubourg, Paris

Fig. 8 The winning entry, Vauxhall Cross Competition, London

Compare it with our more recent open competition win in London where a major site along the river was to be developed for offices, some shopping and some housing [4]. The site is bisected by a road crossing the Thames and, parallel to this, is an Underground railway station which had to be bridged. So any buildings not only have to be piled down to around 30 m. because of the clay but many of the piles have to be sleeved to reduce drawdown. I have written before about Cox's work [5] on the design of structures of least weight and how, because of the weight of the end fittings to tension members it generally follows that weight is saved by subdividing a tensile load between two or more tension members instead of carrying it in a single one. The obverse is true in compression where it is proportionately very much more economical to support a heavy load than a light one and over the fewest number of members. Thus the pattern of the main blocks is one of widely spaced columns and where the Underground runs beneath, hanging columns are provided giving a major space in the building where the escalators rise from the station. Like Pompidou the structure is exposed, partly so that the suspended section becomes evident to everyone (8). The office blocks, staggered to reduce height and with a first floor level shopping and viewing mall, look down courts enclosed by housing blocks, to the river repeating the language of the best of Thameside development so well illustrated in Greenwich Palace (9).

The desire to minimise materials leads one inevitably to trying to reduce or utilise the forces on a structure. I have always admired the aerodynamic deck Freeman Fox and Partners designed for the Severn suspension bridge. We carried out perceptional studies on a system of footbridges for a new town where we found that the main reason people are apprehensive is because they do not like the slight wind chill they are exposed to. Wind down motorways can be reduced by planting [6] but the concept of shaping the bridge parapets so that still air zones can be induced in the cross section seemed worthy of study in a wind tunnel [7](10). Covering was ruled out on cost and security grounds. The profile selected had the added advantage of discouraging children from bombing cars! Taken further we used a wind tunnel to carry out the actual preliminary design of a grandstand roof for the existing Olympic stadium in Berlin where no columns were acceptable to the client (11).

Real cost is about energy cost and all nature is about energy. Some engineers have always studied structures in nature because those structures have to be totally appropriate: mistakes become extinct. Such structures are extremely complex chemically, made up of polymers, water and calcium sales but with many other trace elements, produced as composites. Reinforced concrete is a composite - albeit a crude one. Glass is the most

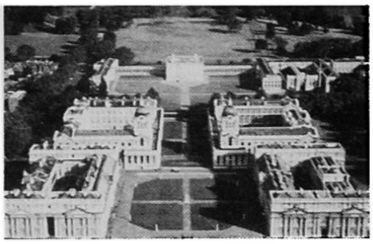

Fig. 9 Greenwich Palace, London

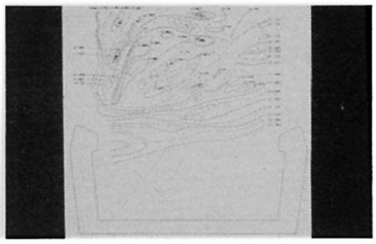

Fig. 10 Wind profile for a footbridge

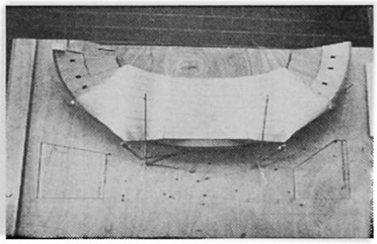

Fig. 11 Olympic Stadium, Berlin

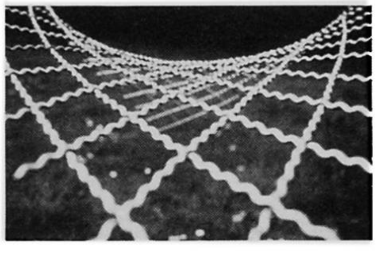

Fig. 12 Crimped wire mesh, Munich Germany & San Diego USA Aviaries

commonly occurring material in the world and theoretically as strong as steel. Man is achieving a performance factor close to its theoretical strength by spinning it and coating it; teflon coating is one of the most inert materials known to man, one whose life appears almost infinite; silicon glass is another extremely interesting material.

But it is not just the chemical characteristics which are interesting, though many of these materials are organic and therefore possibly relatively easily renewable, but also it is the way composites in nature are formed and their physical characteristics that are so fascinating. First, many of them start deforming easily under load so allowing load distribution, and they then become progressively stiffer. This strain-dependent stiffness and the visco-elastic nature of the polymeric tissue makes them of great interest. An airship must keep an aerodynamic shape to achieve any speed yet is subjected to enormous short period loads. The airship that Frei Otto and ourselves are working on is designed like the spine and rib cage of a horse, with hydraulic 'discs' between the vertebrae to enable changes of potential energy to be stored temporarily as 'strain energy' to smooth the loading. The structure also totally copies nature in that the skin of the air bag acts as tendons to the skeleton, like the human arm. It is the same characteristic that we tried to model in mesh for the Munich & San Diego aviaries where the crimping of the wires acts like a spring enabling a similar smoothing and distribution of the loads (12). But in no way are we as efficient as in nature, where animal tendons manage 40 times the strain energy, and some timbers manage four times that of our Munich steel.

I have written [8] about our 80 m. span timber lattice shell for Mannheim in Germany before and I thought for a long time that its economy was solely due to the erection system of merely pushing the grid up with scaffolding towers lifted by a fork lift truck (13). Recent comparative studies [9] have shown us that it is the strain energy characteristic which also reduces the cost so radically. Timber, in proportion to its weight, is comparable in strength and stiffness to high strength steels. But the problem with timber has always been achieving an effective tension connection between members, and it is only since the discovery of epoxy adhesives impregnated with fibres that 'high strength' collinear connections have been possible [10].

For many years carpenters have resisted removing any more of a tree than the bark. This is because the tree, subjected to sudden gusts of wind and not wishing its outer capillaries to buckle, orientates some of its fibres diagonally around the capillaries so that in containing the sap an element of longitudinal

Fig. 13 Timber lattice shell, Mannheim, Germany

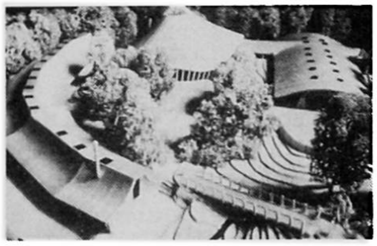

Fig. 14 School for New Woodland Industries at Hooke Park, England

Fig. 15 Tents for the Pink Floyd

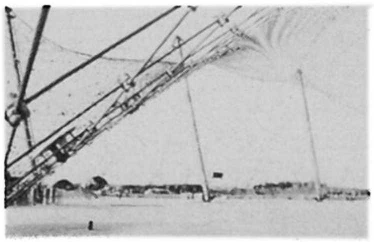

Fig. 16 Steel cable net, Jeddah Sports Centre, Saudi Arabia

prestressing is given to the outer fibres (to the order of 14 MN/m^2), while the centre of the tree is in compression. When the wind blows, the outer capillaries stay in tension, which they are well able to carry. Combining advances in timber connections with the tensile properties of raw timber made possible the hanging forms in the School for New Woodland Industries at Hooke Park which we are working on now (14).

Cox's work tells us that the most materials efficient structure is the bell tent and we have designed a large range of this type of structure throughout the world (15). For longer spans the membrane can be supported on a steel cable net and we like a closely spaced orthogonal net for erection and safety considerations and to provide standardization (16). One can attempt to provide climatic moderation by multi skinning, like in our Jeddah Sports Centre, but more solid construction can be provided, as in Vail Town Centre (17), while retaining the ability to store energy by deformation.

Light of course is the most powerful source of energy and mankind is extremely sensitive to it. Buildings largely exist to conserve our own energy, and designing covered cities in the Arctic is simply an extreme version of this. To achieve a satisfactory all year round environment under such a cover the quality of light is all important and that quality is dependent on as much of the spectrum being transmitted as possible. This is why glass is used for windows even though it does reduce the ultraviolet part of the spectrum creating a 'greenhouse' effect. Studies have been carried out for an air-supported cover over a proposed 36 acre city in the Athabasca region of Alberta [11] (18). These show that some of the new laminates transmit more of the light spectrum than glass - making even the growing of grass a possibility in the Arctic (19). A town centre project for Basildon uses the properties of these laminates but here the critical problem is smoke control in case of a fire in the shops surrounding the square (20).

But man has not excelled at utilising energy from light. We now try to use it through glass roofs when we are cold. When it is too hot we shade ourselves, like plants do with their leaves. But we still cannot build firm organic substances from carbon dioxide, water and light as plants do. We must find out how before the slight surplus store of carbon - coal, oil, gas and timber - which has been built up over millions of years, is finally depleted.

But people will evolve methods of extracting or combining elements to give them what they require. One should remember that the best seller of 1865 was a book by W S Jevons [12] in which he argued that life in

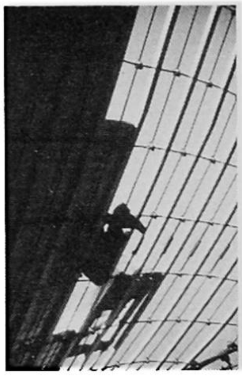

Fig. 17 Vail Town Centre building, USA

Fig. 18 Proposed 36 acre cover over city in Alberta, Canada

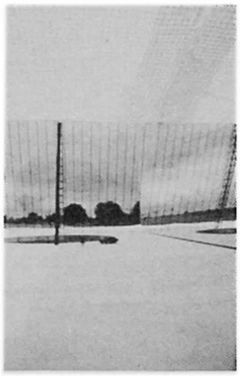

Fig. 19 Perceptual Light Studies for Alberta

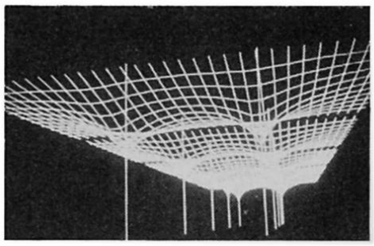

Fig. 20 Basildon Town Centre roofs, England

Victorian England depended so heavily on the steam engine, and that accessible deposits of coal were by then so limited that the nation's material prosperity was about to decline. We never need to fear for our opportunities to practice our art.

Notes

1. Vanbrugh designed an enormous bridge, with 33 rooms in it, for the entrance to Blenheim Palace. Then a lake had to be created for the bridge.

2. Design and the profession. E. Happold. The Structural Engineer. Oct 1983. Vol.61A No.10. Such decisions have been proposed by many writers. But the clearest and most readable, from which I have taken my terminology and which every engineer should read, is in Zen and the Art of Motorcycle Maintenance by T.M. Pirsig, Corgi Books, 1976.

3. Centre Beaubourg Paris Competition 1971, designed by Renzo Piano, Peter Rice, Richard and Su Rogers and Edmund Happold.

4. Vauxhall Cross Competition London 1982 by Kit Allsopp, Andrew Sebire and Edmund Happold.

5. Materials and components. E. Happold. IABSE Symposium London 1981. I owe to Professor James Gordon whose book "Structures or why things don't fall down" Pilican Books 1978, an introduction to "The Design of Structures of Least Weight" H.L. Cox, Pergamon 1965.

6. "The Climate Near the Ground" Geiger, Harvard Press, covers this subject well.

7. We then found it had been done before and I owe to Ben Glover of Ove Arup & Partners and Dr Brian Lawson of Bristol University their results though I do not think they built a footbridge to that section.

8. Timber Lattice roof for the Mannheim Bundesgartenschau. E. Happold & W.I. Liddell. The Structural Engineer. March 1975. Vol.53 Number 3.

9. Report to the Property Services Agency, Department of the Environment, United Kingdom, 1984.

10. Much work has been done on this especially in Japan. I owe considerable help to Gougeon Bros. Inc. of Bay City, Minnesota, "Test Evaluation of a Laminated Wood Wind Turbine Blade Concept" by J. Faddoul of US Department of Energy, May 1981.

11. Technical reports to the Government of Alberta by Buro Happold, Bath, England, 1982.

12. "The Coal Question: an Inquiry concerning the Progress of the Nation, and the Probable Exhaustion of our Coal-Mines, W. Stanley Jevons, London & Cambridge, 1865.