Session 3: The influence of materials on the selection of structural form

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SESSION 3

The influence of materials on the selection of structural form

Influence des matériaux sur le choix du système et de la forme des structures

Einfluss der Materialien auf die Wahl des Systems und der Form von Tragwerken

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I

Form in nature

La forme dans la nature

Formen in der Natur

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SUMMARY
Bodies in nature are built only from appropriate materials: mistakes are extinct. Biological materials are composite: crystalline polymeric fibers in hydrated polymer gel matrix; some have calcium salts or silica included. Hydrated materials confer low shear modulus on the more flexible bodies and joints. Orientation of fibrous polymers allows appropriate reinforcement of pressurized bodies. Rigid materials allow for systems of levers and their attendant mechanical or speed and displacement advantages.

RESUME
Les corps dans la nature ne sont construits qu'à partir de matériaux appropriés: les erreurs sont éliminées. Les matériaux biologiques sont composites: fibres cristallines polymérisées dans une matrice gelée de polymères hydratés; certains ont des sels de calcium ou de silicium à l'intérieur. Les matrices hydratées confèrent, aux corps les plus flexibles et aux joints, un faible module de cisaillement. L'orientation des fibres des polymères permet un renforcement approprié des corps pressurisés. Les matériaux rigides permettent de réaliser des systèmes de leviers présentant des avantages d'ordre mécanique ou de vitesse et de déplacement.

ZUSAMMENFASSUNG
Natürliche Körper bestehen immer aus geeigneten Materialien, Fehler sind ausgeschlossen. Biologische Materialien können zusammengesetzt sein aus kristallartigen polymeren Fasern in hydratisiertem Polymer-Gel; einige enthalten auch Kalziumsalze oder Silikate. Hydratisierte Materialien übertragen kleine Schubmoduli auf flexible Körper und Verbindungen. Die Beeinflussung der polymeren Fasern ermöglicht eine zweckmässige Bewehrung beanspruchter Körper Steife Materialien bringen Systemen von Hebeln mechanische oder Geschwindigkeits- und Verschiebungs-Vorteile.

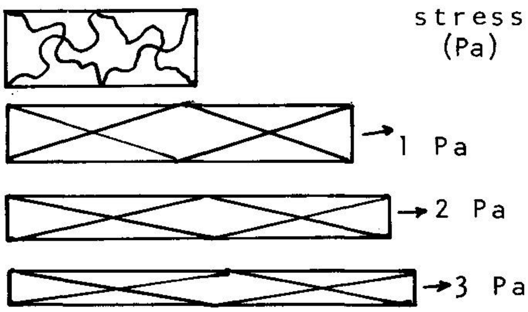
The predominant form of bodies in nature is the cylinder. The bodies of plants and animals are either simple cylinders or branched cylinders. The cylindrical form of organisms arose from the action of environmental selective forces on a set of materials that have been organized into bodies. The materials were and still are produced at climatic temperatures and pressures from carbon, hydrogen, oxygen, nitrogen, sulfur and phosphorous in compounds that are dissolved in water surrounding the organism. Some natural cylindrical bodies are stiff and some are limber. An important observation is that all of them bend - some more than others, some actively, some passively, but they all bend.

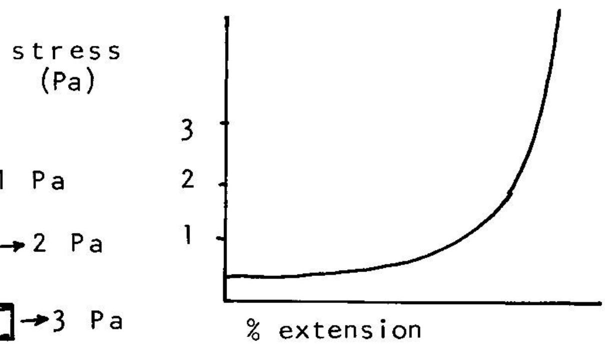
The materials

Basically the materials of which organisms are made are of three general kinds. They are polymers, water and calcium salts. The polymers are polyanionic proteoglycans whose configuration and mechanical properties depend on their thermal energy, on the ionic environment surrounding them, on their crosslinking and on the included calcium salts between them. These polymer molecules are usually very long, straight-chained proteins or polysaccharides and since they are highly hydrated and polyanionic, they are, in fact, fibers in an aqueous matrix. These polymeric materials are composite from the very beginning. They are indeed soft and flexible and such stiffening devices as calcium salts are present in only a few of the many materials that occur in organisms.

Let us look at more complicated soft connective tissues in animals, materials such as skin or the mesenteries that hold our intestines together. These are flimsy, stretchy, flexible materials. They are made up of many cells, of course, but outside the cells there is a voluminous fiber and gel matrix composite. These are not all alike, but a predominant polymer acting as a fiber in such composites is the macromolecular protein, collagen. Now collagen is the material of which tendons and ligaments are made, and tendons and ligaments are not stretchy and cannot be deformed in the tensile mode very much at all, and yet the soft connective tissues in animals can be deformed by hundreds of percent. This means that the collagen molecules in the soft connective tissues are not connected one to the other by short crosslinks in a network as they are in tendons and ligaments.

When one pulls on a piece of skin one finds that the first few millimeters of deformation come very easily: very small forces are necessary to make this deformation. But as one continues to pull, one notices that within a few more millimeters of stretch the material becomes very stiff indeed. We reckon this interesting increase in stiffness with strain is caused by the collagen and other fibrous polymers in the skin becoming progressively oriented in the direction of the force and that in fact they are linked together in a network which ultimately comes to be pulled on and responds by pulling back with the stiffness of collagen, even as it is known in tendons and ligaments. This means in engineering terms that skin has a stress-strain curve shaped much like the letter J





and Professor Gordon has brought this phenomenon to the attention of biologists and he has told us what it is about. One thing we can add further to his discussion is that it is quite clear that the increased stiffness of such materials acts as a safety factor in organism design. It says to the organism, "Stop pulling!" and it even pulls back at the organism, further preventing rupture. It tells you when to stop stretching your skin, but at the same time it has allowed you to stretch your skin by 50 to 100 percent. So we have stiffness ultimately, but we have permission for a great range of changes of shape on the way to that great stiffness. This strain-dependent stiffness and the viscoelastic nature of the polymeric connective tissues of animals make them unique in the world and make them of unusual interest to engineering material scientists.

Stiffer animal tissues such as cartilage are similar to the soft connective tissues just described but they simply represent the stage where much of the water has been taken out and there is a greater degree of crosslinking among the polymer molecules in the hydrated polymeric composites. Cartilage at the end of our long bones is not very flexible, extensible or compressible and when force is applied to it, as when we stand up and put our entire weight on the ends of our leg bones, this material is squashed and is deformed slightly because water is actually squeezed out of the pores of the material. As soon as we take the weight off our legs this water is actually sucked back into the cartilage by combination of the ionic strength of the molecules in the cartilage and the actual stiffness of the material itself.

One of the stiffest of all the natural composite materials is the crisp outer covering of insects and shrimps and some crabs. This exoskeletal cuticle is almost entirely dehydrated. In fact the current theory of Dr. Vincent of Reading University says that the reason that cuticle is such a remarkable material is that when it is formed it is in a highly hydrated state and it is soft and flexible and then, by mechanisms as yet unknown, the water is drawn out of it leaving a very rigid material indeed. The most famous component of this material is a polysaccharide named chitin but there are equal parts of large molecular weight proteins that are tightly linked to the chitin and to each other. One of the major differences between a caterpillar and a butterfly is that the caterpillar has a soft, more highly hydrated cuticle and the butterfly, especially in its wing membranes, has a dehydrated, rigid material for its flapping airfoils.

Looking at plants for a moment, the floppy seaweeds have given rise over evolutionary time to much stiffer land plants. If you are going to be a successful plant out on land and you are going to compete with your fellow plants for the sunlight, you're going to have to be rigid, and in the extracellular materials in land plants the same thing has happened that has happened in the animals, namely a progressive loss of hydration. The water goes and the agar is replaced with a particular material called lignin that polymerizes and forms a rigid glue. Perhaps we can say that the major difference between a seaweed and an oak tree is that the shear modulus of the polymeric material between cells in the seaweed is low whereas that in the oak tree is very high. Another major difference consistent with this is that the volume percent of fibrous material, namely cellulose, is far greater in the wood of trees than it is in seaweed.

And finally we come to the very rigid calcareous materials of animals and plants. In our own bodies, bone is simply a calcified polymer and, as a matter of fact, less than half of the material of bone is calcium salt: most of it is polymeric. This means that although a bone is a rigid object and we depend on its rigidity as we walk and run and ski and fall down, the actual viscoelastic properties of the polymeric matrix material in the bones allow a bone to absorb far more energy in its breaking than it would be if it were made only of calcium salts.

Bone must be made at great cost by sequestering calcium from the foods we eat and then putting it through complex physiological processes to form salts in our bones. Crabs and corals and sea urchins would seem to have an easier task because the sea water around them is rich in both calcium and the other elements necessary to make calcium salts.

The body

Now a body that is a random aggregate of polymers is just a blob. In order to create a cylindrical body, a certain property of the polymers in such a blob is necessary and this is the ability of these polymer molecules to become preferentially oriented. When this happens then long cords of molecules lying parallel to one another can exist and give elongated form to the body. Materials made of highly oriented polymer molecules are anisotropic in many kinds of properties: mechanical, optical, electrical and so on. The ability of similar molecules to achieve any degree of preferred orientation is one of the bases of diversity in biological systems and I maintain it is one of the bases for the formation of the first cylindrical body. There are species of lower plants and animals that are only just plate-shaped or cylindrical in their form and that can be easily described as a system of cells in a gel matrix reinforced with oriented polymers.

Structural types of bodies

The three familiar body types that we see in natural forms are the branched solid cylinders of corals, seaweeds, bushes and trees, the stretched membrane hydrostats of worms, sea anemon es, sea cucumbers and caterpillars and the braced jointed frameworks that are familiar to us in insects, crabs, shrimps as well as fishes, frogs, birds and mammals. First we will look at the branched solid cylinders. Here we will see a continuum from the floppy seaweed to the flexible soft coral, the flexible palm tree, to the much more rigid oak and maple trees and the very rigid, brittle, stony coral. The plants are aggregates of cylindrical cells held together by tensile forces in a continuous network of cellulose filaments. In the floppy seaweed, cellulose is wound in tight helical array around columns of cells that are dispersed in a highly hydrated gel-like matrix. Because these cellulose columns are central in the stem of the plant and because the matrix has a very low sheer modulus, the seaweed body bends readily with the flow and in so bending it becomes streamlined and avoids the high drag forces associated with high rates of flow that come with wave action. As they flop down into the boundary layer they further avoid the higher rates of flow. So the seaweed plant has an integrity that is due to the tensile strength and stiffness of cellulose as it reinforces a gel-like matrix of intercellular agar and it depends on extreme flexibility for survival.

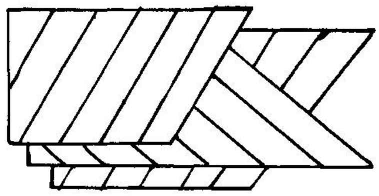
Next we come to the oak tree or the maple tree. In wood the matrix is reduced to submicroscopic layers of very rigid glue material called lignin that cross-links the cellulose. These thin layers of rigid glue confer a very high shear modulus to the material and make the tree and its parts very rigid in torsion. When the wind blows, oak and pine trees do bend especially at the branch tips and their leaves flow out in streamlines with the wind thus reducing the drag on the entire tree. The entire tree and especially the trunk does not bend nearly as much as the palm trees and seaweed.

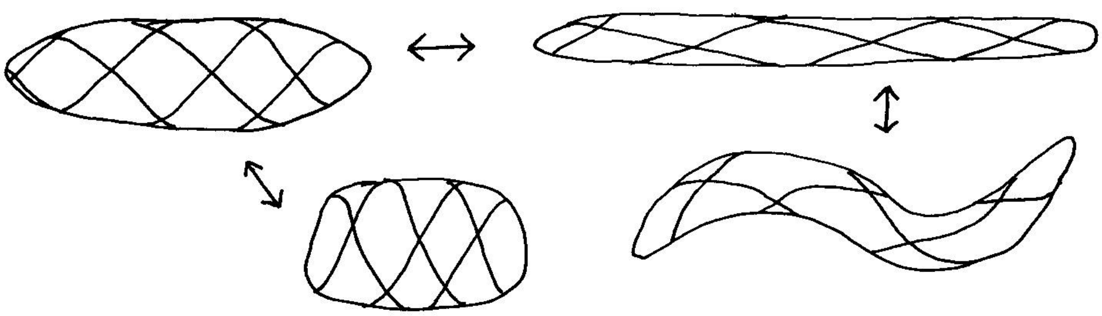
The seaweed and the palm tree and the oak tree all have a tensile integrity of cellulose throughout their entire plant body. This tensile integrity is especially important at the branch points where the design is clearly suited for the stable and smooth transmission of stresses from the limbs to the trunk as the limbs are effected either by gravity or by wind forces. To build a body form with branches that transmit forces as smoothly as do those of branches of trees must be a marvel indeed in the engineer's eyes. There are no new and different materials put at these branch points, there are no new aspects of design, but the fibers of the trunk and the fibers of the branch interdigitate perfectly in complete compatibility of materials for the smooth transmission of forces across the joint.

Also in the branched solid cylinder category we have the coral. Coral shapes are made up of skeletal material that is entirely extracellular. They are not made up of columns of fiber wound cells as the seaweed and the various trees we have just discussed. The stony corals are made of solid, polycrystalline calcium carbonate. The crystals are for the most part submicroscopic but there is mass continuity of mineral throughout the skeleton. The material is extremely brittle. The branching pattern is similar to that in plants and the smooth transmission of forces across joints is characteristic of corals.

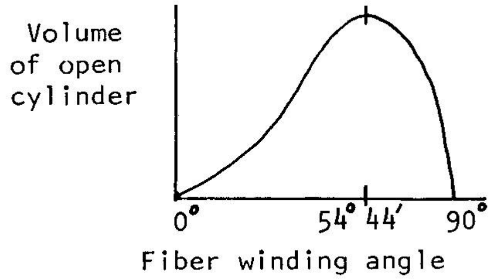
The stretched membrane hydrostat shows the influence of preferred orientation of polymer fibers in the gel matrix on the behavioral properties and capabilities of the fully formed body.

Soft tissues in animals have interesting J-shaped stress-strain curves that arise as described above. Now collagen, a macromolecular protein, is the predominant polymer in these soft tissues. The J-shaped stress-strain curve occurs in material where in the polymers may be initially randomly oriented or in a polymeric material whose polymers are in parallel array in layers that alternate their orientation. In the case of the sheets of oriented polymers, if such a material is wrapped into a cylinder, we have a model for all cylindrical plant cells, all bodies of polyps and worm-like animals as well as the guts and arteries of some of us less worm-like creatures. As a direct result of being thus crossed helically wound, these bodies and tubelike organs can lengthen and shorten but, most important of all, they can bend without kinking. I cannot stress enough the importance of this simple observation that bodies in nature can bend without kinking and that this behavior is due to the fact that they are cylindrical shapes reinforced by a helical array of fibrous polymers.





Cylinders can have quite directional mechanical properties. The winding angle of their reinforcing fibers combined with that unique animal invention, the muscle, give us the most interestingly diverse systems ever to have evolved. Most worms have a sheet of muscle oriented longitudinally and another sheet oriented circumferentially and can perform many contortions, but one very large and successful group, the nematodes, lack the circumferential set of muscles and yet these animals still wiggle because the fiber winding angle is about 75 degrees. The figure shows that contraction of any longitudinal muscle in such a cylinder will tend to decrease the volume of the cylinder. Since the volume cannot decrease, the internal pressure rises and this stretches the body wall with the crossed helical array of fibers in it. These fibers then become stretched and they store elastic energy. When the longitudinal muscle relaxes, the internal pressure falls and elastic recoil causes the animal to return to its resting shape. Thus the animal has made a compensatory movement without having a set of antagonistic muscles to do so. It is simply using elastic recoil that resides in a material due to its particular array of polymer molecules.



The stretched membrane hydrostat must be powered by sheets of muscle that apply distributed loads to the membrane. They must not leak or be liable to be punctured, therefore these are hard to maintain on land away from easy access to bulk water and they are obviously too bulky and heavy for flying organisms. They are however, excellent body forms for locomotion in low Reynold's number situations: small animals in water, larger animals burrowing in soft soil such as mud and sand and the leaf litter of the forest floor. And it is in these habitats that animals with the stretched membrane hydrostat have their greatest diversity and success.

The braced jointed framework is really just a stretched membrane hydrostat in which the compression resistance of the fluid is replaced by that of rigid solid materials. These rigid solid materials will either be polymeric as in the insect cuticle or they may be calcareous as in crabs, snails, fishes, frogs, dinosaurs and people. Fluids resist only changes in volume and the hydrostatic skeleton resists changes in shape because many constraints upon its design arise from this particular design problem. Since rigid solid materials can resist changes in shape directly, bodies made from them can have long, stiff limbs supported by long, thin rigid elements and these limbs can be powered by spindle-shaped muscles that apply point loads to rigid elements in the system. This becomes then a system of levers that can have either mechanical advantage or displacement and speed advantage. This adaptable system produces fast running and that most extreme form of locomotion, powered flight. It is characteristic of these braced jointed frameworks to be branched: have arms and legs. The joint in this case is much more flexible than those in plants and involves a change in materials at the point where it joins the body. Here we have the problem of maintaining compatibility of materials across the joint for the smooth transmission of forces and it may be here in the design of joints that the great groups of animals including the insects and the mammals and birds have attained their greatest degree of engineering sophistication. Stiffness in bending is a matter of both the material modulus of the material and the shape or the second moment of area of the cross section. Both of these tactics have been involved in the design of animal skeletons in the evolution of braced jointed frameworks: both the material modulus and the second moment of area have been varied in the evolution of the wide variety of point, hinge and sliding joints that exist.

SUMMARY

We have seen three quite distinct ways to make cylindrical bodies. Cylindrical bodies confer on organisms, the ability to orient to environmental stimuli, the ability to locomote effectively with sense organs at the leading end. Locomotion is accomplished either by undulating the cylindrical body itself or by the action of cylindrical branches. Such branched cylindrical bodies demand cleverly built, cleverly designed joints where forces can be transmitted across the joints smoothly without interruption in function or disruption of structure. In all the three types of bodies we have met, the integrity of the body is effected by tensile stresses in long straight chained polymers of either polysaccharides such as cellulose in plants or the great macromolecular protein known as collagen in various kinds of animals. In all forms these polymers are distributed throughout a gel-like matrix and according to how stretchy or flexible the cylinder is, the gel-like matrix will be more hydrated. In the more rigid ones such as the design of trees, the gel-like matrix is reduced to an exceedingly thin layer of rigid glue.

If you are going to be a stretched membrane hydrostat, it is pretty clear you must be made of a polymeric material. If you wish to run about on land or to fly you must have rigid materials so that you can have a lever system that will confer upon you the mechanical and particularly the displacement and speed advantages that lever systems can give. We do not see seaweeds or trees that can crawl or swim, we do not see animals with stretched membrane hydrostats running or flying and we don't find animals with braced jointed frameworks wasting their time being attached to the surface of the earth like a plant waiting for the environment to bring them food. So in this sense the materials that constitute each part of natural forms are precisely those that are most appropriate.

It is amusing to a biologist to think of this particular set of ideas that we are thinking about in this session, namely the influence of materials on the selection of form, because if you start where evolution started with polymers in water, outside of cells, and you try to build bodies with the materials at hand, you simply would not build bodies that are inappropriate for the materials at hand. In evolutionary language, inappropriate designs are eaten by better ones. You would not think of trying to build a house or a car without rigid material. Houses and cars certainly did not come first as far as evolving organisms are concerned, they had to work with what they had and they did so. They first built blobs and then they built small, simple, soft, cylindrical worms or simple plants. The plant forms became larger and more complex and then branched and became more rigid as they came out on land and withstood gravity and could bear heavy fruits high in the air. Animal bodies also became more complex and used the rigid materials in jointed frameworks in combination with the actively contractile material, muscle, to produce the most remarkable living machines of all, flying insects, birds and bats.

Further reading

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I

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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Materials and components

Matériaux et éléments de construction

Materialien und Teilkomponenten

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SUMMARY
There have been immense advantages in the last few years in the engineering materials available which have given new design possibilities. Yet all structures are formed of a system of components. It is from the choice and combination of components with different characteristics together with the performance of the connections, which determines the efficiency of the structure.

RESUME
D'immenses progrès ont été réalisés ces dernières années dans les matériaux de construction, qui ont ouvert de nouvelles possibilités dans la conception et le projet. Toute structure est formée d'un système d'éléments de construction. Le choix et la combinaison des éléments de caractéristiques différentes, combinés avec la résistance des assemblages, déterminent l'efficacité de la structure.

ZUSAMMENFASSUNG
Dank der grossen Fortschritte der letzten Jahre auf dem Gebiet der Baumaterialien haben sich neue Entwurfsmöglichkeiten ergenben. Alle Tragwerke bestehen aus einem System von Bauteilen. Die Tauglichkeit eines Tragwerks wird durch die Wahl und die Kombination dieser aus verschiedenen Materialien bestehenden Bauteile sowie die Ausführung deren Verbindungen erreicht.

MATERIALS AND COMPONENTS

A structure has been defined as 'a fabric or framework of material parts put together' and structural engineering as 'the organisation of the path of physical forces in space to enable moderation of the environment'. As well as redirecting external forces, structures often themselves contain and enclose gases, solids or liquids at different pressure densities, temperature or states other than the medium in which the structure itself is located. Such structures are made up of components, defined as 'constituent parts', connected by joints which are defined as 'whereby two members or parts of an artificial structure are joined or fitted together either so as to be rigidly fixed or in a hinge or pivot or swivel' (1).

Broadly the requirements on the designer of the materials and joints of a structure are that they should not allow excessive deformation, have a reasonable maintenance free life, retain adequate strength in a fire, provide adequate imperviousness, insulation, transparency and so on as required and are also cheap to manufacture, assemble and erect.

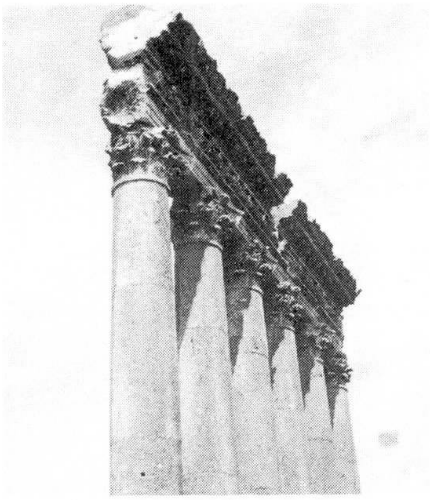

Fig 1 Beam and Post Baalbeck

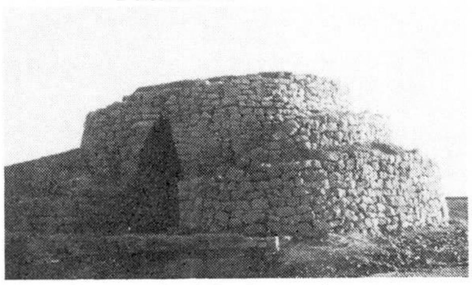

Fig 2 Corbelled arch

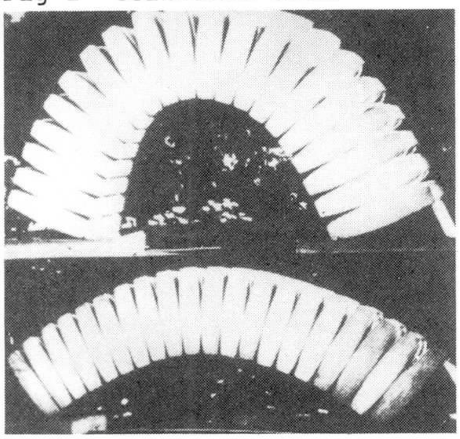

Fig 3 Voussoir arch

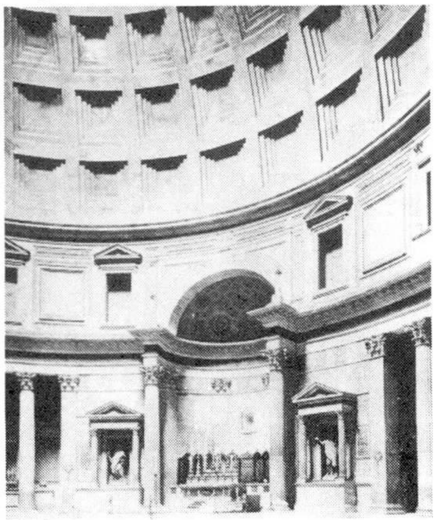

Fig 4 The Pantheon

HISTORY:

The traditional range of structures grew up because people had to build with available materials; stone, timber, bricks etc. What was successful became documented in codes of practice and continued to be repeated.

Reliable tension materials did not last so all major structures were compression structures. The earliest beam and post solutions were in stone or timber, the size determined by what people could work with handtools or lift with their techniques. But the joints cracked, even the stone often cracked, and often enough courses in any wall had to be provided so that arch action could be sustained anyway. Long spans were achieved by arches, either the corbelled arch - building out stepwise from either side - or in the arch made of 'voussoirs'. The advantage of the voussoir arch especially was that it could be made using relatively small stones or bricks and the joints really only needed these gaps filling since the structure was purely in compression. However for large spans the weight of the arch became important so such structures as the Pantheon, built by Hadrian in AD120, was coffered and that of Hagia Sophia, built about AD532, was made of pumice to save weight.

In mediaeval times there was the same limited range of materials: stone and brick, strong in compression but limited in size and difficult to joint in tension. It is not surprising that the timber frame, with wattle or brick infill, dominated the domestic scale of building and the arch and dome the design of large buildings. The geometrical difficulty of bringing the round dome or arch to a rectangular plan became the problem which produced a whole series of architectural styles.

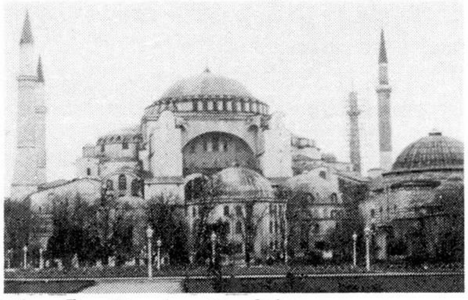
Fig 5 Hagia Sophia

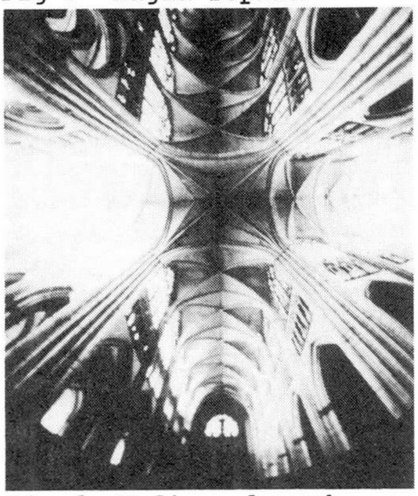
Fig 6 Mediaeval arch

The advances in the eighteenth century in iron and steel production led to the great innovation in structures. The first iron bridge was erected at Coalbrookdale in 1779 and within a very few years larger beam spans and suspension bridge structures were being built. Because the components were factory made, wrought or cast iron members pinned or bolted together, repitition was desirable, quality control became important and the systemisation of the building process developed. Thus for the Crystal Palace in Hyde Park for the Great Exhibition of 1851 the iron columns and beams were cast in Smethwick, transported to Euston Station by railway and from there to the site by pair horse wagons. Each beam, as it was removed by crane from the cart, was placed first on a weighing machine to check the class of load it was to take and then moved to an arrangement of Bramah hydraulic rams for strength testing before being erected. It was not uncommon for an entirely stable 'square' of columns and beams to be erected and bolted in twenty minutes. The glazing, guttering and woodwork was all mass produced. Even the vertical posts and horizontal planks of the hoarding round the site were chosen so that they could later be used to make the joists and floorboards of the finished building. In twenty two weeks a building of enclosed volume 33,000,000 cu ft was erected, in another sixteen it was fitted out and painted (2).

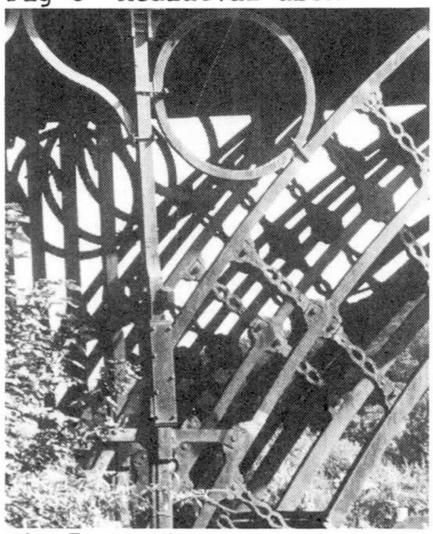
Fig 7 Bridge at Coalbrookdale

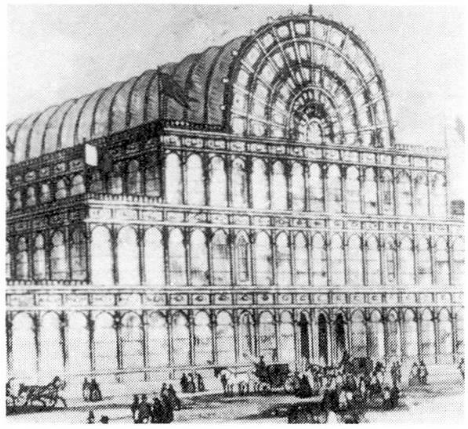
Fig 8 Crystal Palace

The engineers leapt to use this new material because of its strength/weight ratio, its ability to take tension and perhaps also because it was easier to predict performance. Certainly Victorian engineers arrived at minimum material structures because they saw them as having only to satisfy strength criteria .... hence the beautiful open trusses; an aesthetic which still moves us. As James Marston Fitch has said 'the three triumphs of the nineteenth century were the enclosure of great areas in the Crystal Palace, the spanning of great voids in the Brooklyn Bridge and the reaching of great heights in the Eiffel Tower' (3).

So started a concept of structure as frameworks of struts, ties and beams reflecting the forces induced by an assumed worst loading condition, usually treated as static loads. The materials characteristics looked for were strength in compression and tension and materials were regarded as Hookian with a linear stress-strain relationship. Engineers, since achievement was the measure of success, tested either physical models or the actual structures, for example William Fairbairn tested different possible sections for Robert Stephenson in the design of the Menai Tube Bridge (4). With cast and wrought iron there was a strong tendency for pinned joints. There was great sense in this approach because it caused the actual structure to 'perform' fairly closely to the 'model' which was analysed. As the use of structural steel developed, full or partial fixity at joints became assumed but inaccuracies in analysis were tolerated because joints were rivetted, over-loaded joints usually yielded plastically and erection connecting techniques such as reaming punched holes before bolting prevented crack propagation.

As problems other than strength were exposed by time engineers views of how to use materials became confused. For example corrosion, especially of mild steel, became a problem and the painting of their lattice frames was difficult. So designers started to use tube members which were seen as the 'true' expression of steel in structures - but with the consequent difficulty of jointing and tolerancing.

BENDING STRUCTURES:

Solid beams or cantilevers in terms of use of materials are ineffective but materials availability and functional reasons induce their use. Architectural planning, not pure statistical reasoning, often defines the nature of framed structures. For example a housing tower in London has its vertical support and wind resisting components, the walls which provide fire and sound insulation between the apartments constructed and reinforced concrete because of cheapness and availability. The floors can be given flat soffits because the climate only requires heating and radiant gain is never great and so a servicing void is not

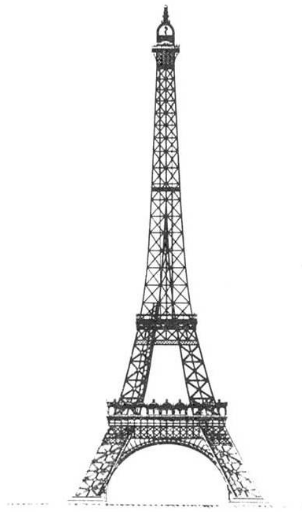

Fig 9 Eiffel Tower

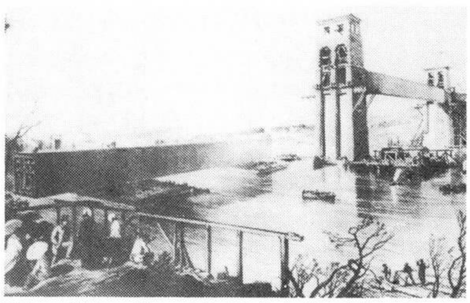

Fig 10 Menai Tube Bridge

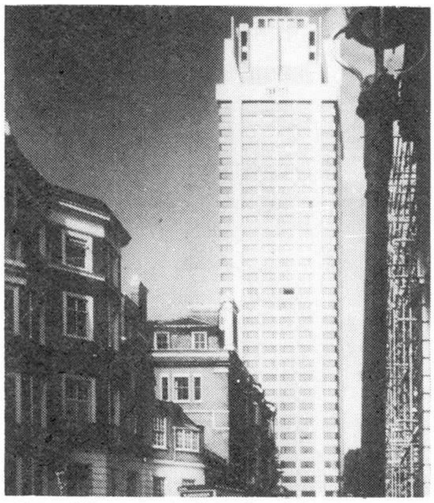

Fig 11 Knightsbridge Tower London

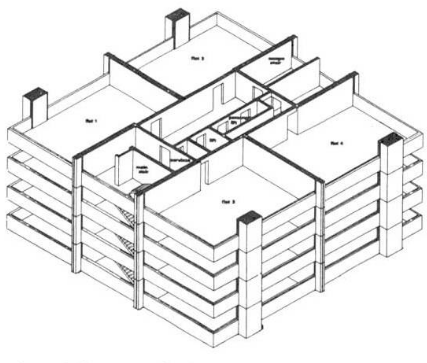

Fig 12 Knightsbridge Tower London

needed. Materials effectiveness in terms of the volume of concrete per floor (inclusive of all supports) is equivalent to a 14" thick slab overall. However reinforced concrete is slow to set and therefore to use but appropriate to the economics of the UK construction industry. In essence such a structure does not have joints as the reinforced concrete is continuous, lowly stressed and tolerant. Structural steel however has a very efficient strength to weight ratio and structures made of it ask more of their joints. Comparatively in Chicago where the climate, both literally and financially, is entirely different, the braced tubes of Skidmore, Owings and Merrill are a much more defined structural answer. Criteria for the structure is still rigidity and the joints are also relatively lowly stressed.

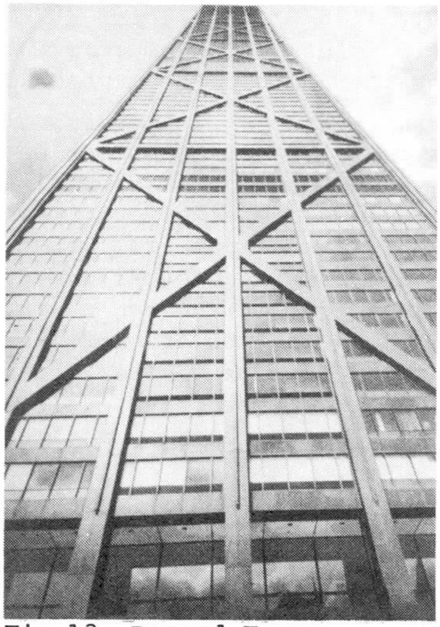

Fig 13 Braced Tower Chicago

However, whether in steel or concrete, it is the relative ease of making such joints which is the designer's constructional problem. The old rivetted joint had great structural advantages. The holes acted as crack stoppers and any tendency to stress raising was reduced by reaming. Such joints were easy to inspect and relatively easily distorted if over-stressed. However the heating, hammering and handling of rivets was expensive and time consuming and they are unlikely to be seen again.

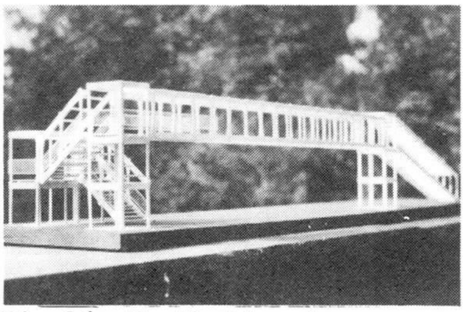

Fig 14 Footbridge in West Germany

The welded joint has now largely taken over and is relatively easily checked for adequacies though its requirements for precise dimensioning, lack of forgiveness to constructional errors, susceptibility to crack propagation and the risk of crystalline embrittlement due to metallic changes resulting from greater energy imput than assumed in the specified design, are all to offset greater joint efficiency. Site connections on framed structures can now be carried out with friction grip bolts which hold the two members together in such a way that it is the friction between them which provides the moment or shear resistance required. One of the advantages of this type of joint is that if overloaded it can be allowed to slip thereby shedding load and reducing the stress and then regaining its load capacity. Such joints can not only be used for traditional beam connections but also to standardise connections between members joining at different angles, such as in a design for a steel footbridge for West Germany or double lattice shell for the Mannheim Bundesgartenschau to allow movement during erection before being clamped tight in the constructed state (5). The author has been involved in studies of structures in brittle materials such as glass in which risk of catastrophic failure was eliminated by the

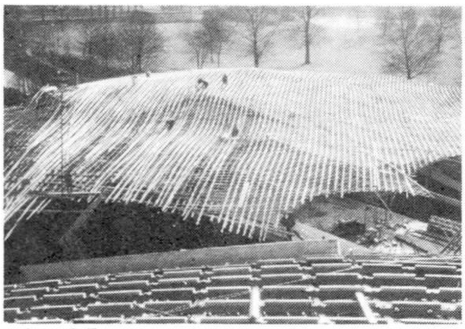

Fig 15 Mannheim Lattice shell

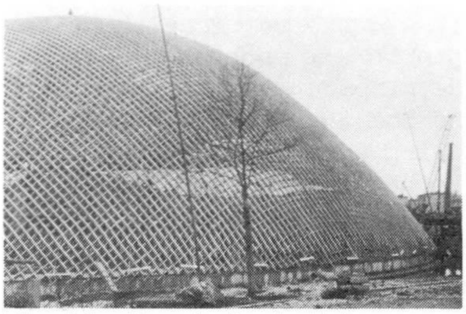

Fig 16 Mannheim Lattice Shell

provision of plasticity by the use of friction grip joints which could reduce load by angular rotation should the members become overloaded.

As the scale of construction increases, such as in bridges, when thermal and rotational movements are considerable and jointing is complex and expensive, the provision of joints with a predictable performance has increasing attraction for the engineers. In the building field the joints are more lightly loaded and the use of inexpensive bearings such as neoprene pads allow attractive expression of forces and resolution of thermal movement problems.

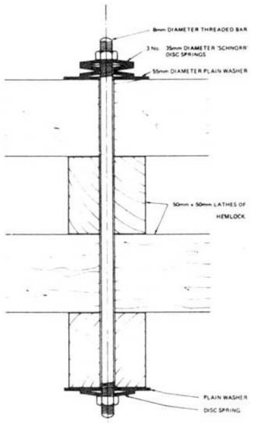

Fig 17 Mannheim Lattice Shell

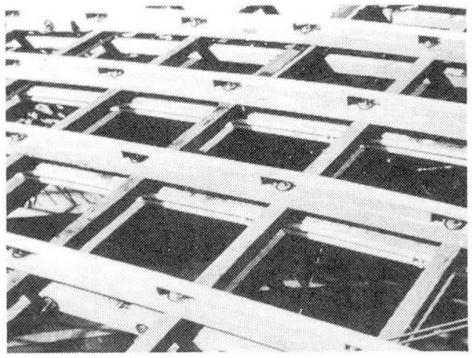
Fig 18 Mannheim Lattice Shell

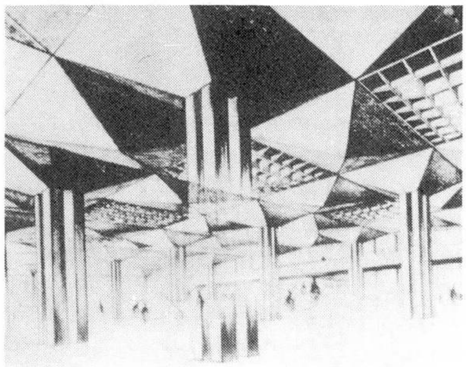
Fig 19 Articulation for thermal movement Conference Centre Riyadh

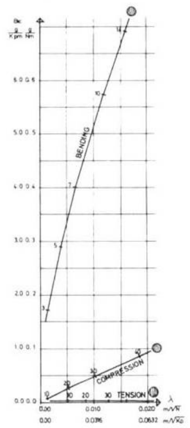

Fig 20 Curve of Efficiency Frei Otto

SKELETAL STRUCTURES IN COMPRESSION AND TENSION:

The discussion so far has concentrated on the constructional aspects of framed members and joints. However there is a tendency, probably an increasing one, in a world of diminishing resources, that the cost of any structure is reflected by its own weight so that of two structures, both equally adequate and efficient, the lighter one is the cheaper and therefore preferable.

This is a field which has attracted several workers. I owe to Professor James Gordon (6) my introduction to H L Cox's (7) arithmetical treatment on the design of structures of least weight. Professor Frei Otto (8) is working in the same field in which he is physically measuring the form, the force, the path and the mass of a wide range of structures both manmade and in nature. The relative effectiveness of structures in these terms is well known to most engineers - a bending element is noticeably less efficient than a compression one which, in turn, is less efficient than a tension member. This is of course why a truss uses much less material than a beam, a fact which the Victorian engineers, in the days of expensive materials, well understood.

It was the realisation of solutions for secondary problems - such as corrosion (especially with the development of the use of mild steel) which led to the introduction of plate or tube members which were easier to paint - or for fire protection which stimulated the use of reinforced concrete. These changed the aesthetic of structures.

Yet developments in 'rusting steels', reintroduction of cast iron as a structural material, the invention of water filled tube members or intumescent paints as fire protection which have revived the possibilities of earlier structural aesthetics. The sophisticated steel joint, economic because of its repetitious nature, is now coming more into use due to these developments. Centre Pompidou was a conscious exercise in reviving such aesthetic.

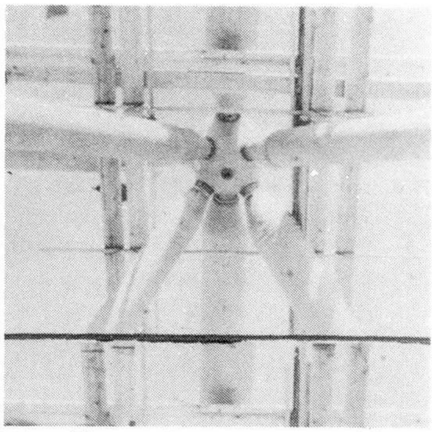

Fig 21 Joint at Expo '70 Osaka

End fittings are not required on columns, you can just put a strut on the ground and sit on it. The problem of the compression carrying gap filler was solved a long time ago. So struts can be cheaper in carrying load over short distances than ties. But for larger distances the buckling mode dominates and for a simple strut is $\frac{\Pi^2 EI}{\ell^2}$.

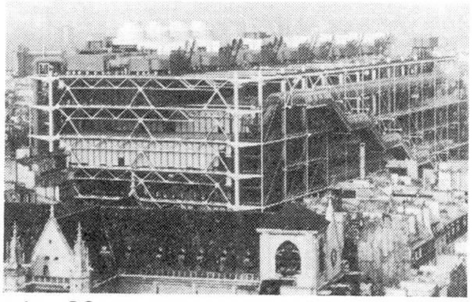

Fig 22 Centre Pompidou

Which means that the compression strength diminishes as the length increases and because of the geometrical properties of I dividing the load into several members increases their total weights. So it is not surprising that for a compression structure frames are provided for the structure even if cladding is required to enclose space. In a panelled geodesic dome the panels buckle and, by and large, all forces are carried at the junctions where stiffness occurs. Incidentially this division of structure from cladding has also suited the organisation of site works whereby separate trades have built the two elements and the present economics of the construction industry certainly now favour this solution.

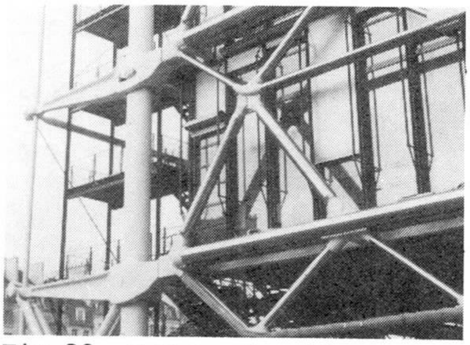

Fig 23 Centre Pompidou

However for larger lengths the tensile member becomes increasingly more economic. As it is not limited by problems of instability the weight of the element itself is proportional to the length, while the weight of the end fitting is the same for a given load whether the length of the tension member is long or short. As an additional determinant of economy for a given load the weight of the end fittings of several tension bars are less than that of a single larger tension rod. So for a long cable for a suspension bridge the cost of end fittings will be very low proportional to its length but for short lengths (like a cable roof) it is cheaper to have several members rather than one because of the cost of end fittings. A statement which is obvious to those who work in prestressed concrete. So where an enclosure is also required fabrics should provide the cheapest structure of all.

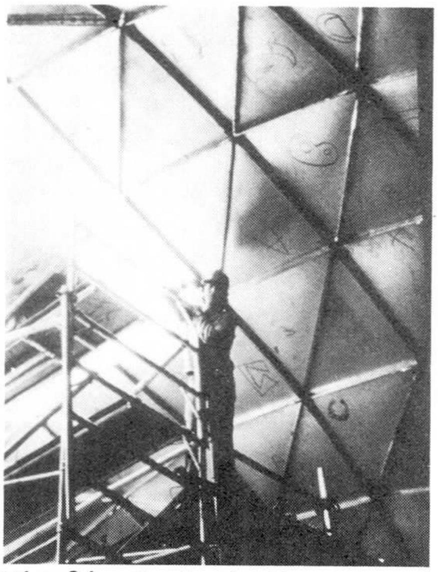

Fig 24 Geodesic Dome Beaulieu

SURFACE STRESSED TENSION STRUCTURES:

For enclosed structures such as buildings the use of surface stressed tension structures are likely to develop for economic reasons. For such structures concentrated loads are distributed over large areas by gross deformation and these areas are provided by plates or nets usually, though not always, composites or laminates. Since the performance of the surface biaxially is non-linear the material, its form or its fabrication must allow for these movements if overstressing is to be avoided. An orthogonal grid of cables either coated or supporting a membrane is such a surface. The joints of the cables usually have the advantage that they 'slip' under overload allowing stress relief and this is now an accepted element in the design of such structures.

The problem with such tent structures is to take the distributed load from the tension members into the supporting mast(s). The earliest cable roofs, such as the Raleigh Livestock Terminal, took the cables to stiff edge beams arches which had to be of considerable size to take the forces. In contrast cable net roofs, such as the pavilions for the Lausanne Exhibition, took the forces from the mesh to the mast top by main cables and, for the first really large flexible roof the German Federal Pavilion for Expo 67 in Montreal cable loops from the mast tops relaxed the surface forces. Obviously the provision of reinforcing main cables is an additional expenditure of material yet a continuum membrane cannot readily accept stress concentrations at mast heads without reinforcement. A traditional answer is by bearing over a large area as for the tent at Dyce. The design of the Munich Aviary is a prime example of the principle of minimising material for end connections. Stainless steel wire grid was used as a fabric with each wire supported at the mast zone by a system of small beams linked together and taken by a series of 12mm cables to the mast top. The design of the Gatlinberg Centre develops this further in that the individual wires of an area of grid are individually taken to the mast top and locked off.

One might say that the use of the structure of a building as defined by the first paragraph of this paper reaches its extreme in air supported structures where the structural component is also the climatic moderator. In theory the use of a single skin requires joints only at the edges though, since the material

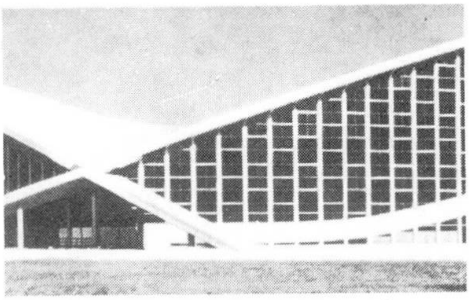
Fig 25 Raleigh Livestock Terminal

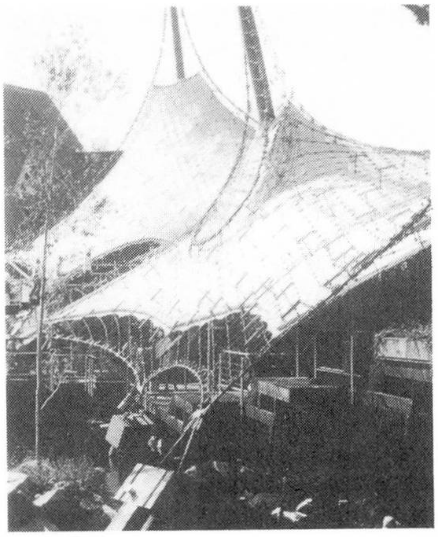
Fig 26 West German Pavilion - Expo 67

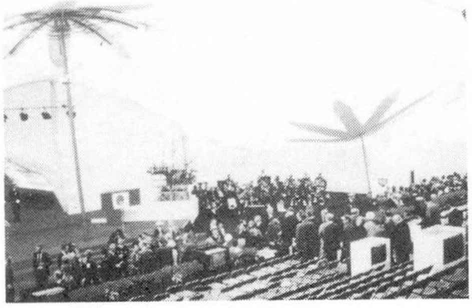
Fig 27 Tent at Dyce Scotland

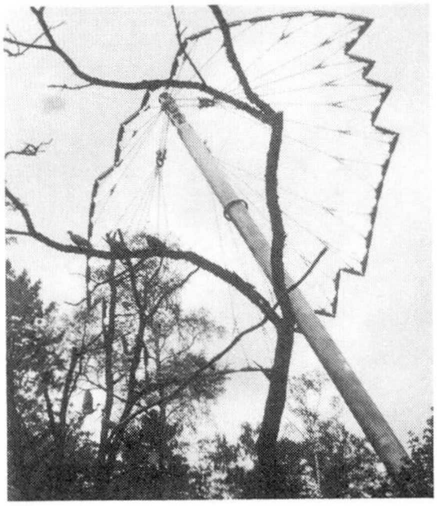
Fig 28 Munich Aviary

always comes on rolls, there are a considerable length of joints. They are all lowly stressed and welding is now commonplace. It is interesting that as the dominant mode of failure is by puncturing, the joints exist as crack stoppers.

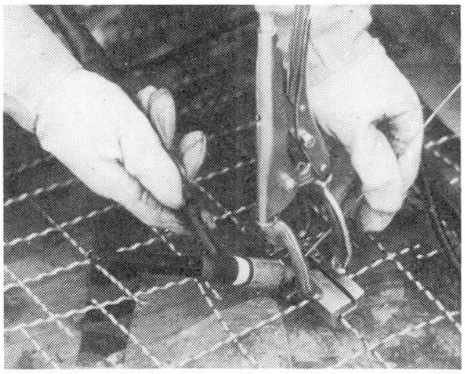

Fig 29 Jointing Munich Aviary

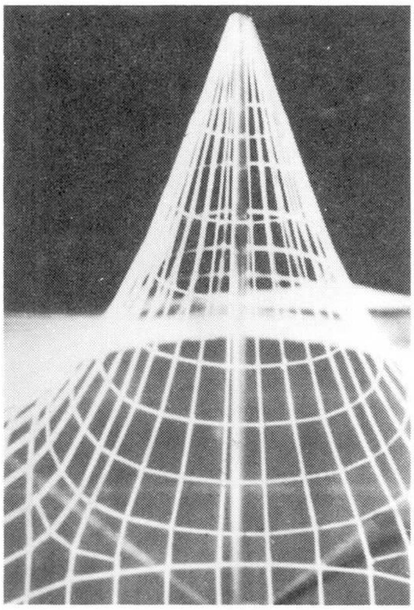

Fig 30 Mast top for Gatlinburg

Summarising we can generally say that it is tension rather than compression which gives problems in joint design. We can also probably say that where structures are required for rigidity rather than strength the component sizes are generally so stiff that the joints are relatively lowly stressed and inaccuracies of analysis of behaviour and construction tolerances are usually fairly easily allowed for.

The tendency back towards framework structures in which tension joints are highly stressed is more of a problem and joints with an increase of flexibility to allow load shedding or to reduce the risks of stress concentration are desirable.

The increasing use of composities and adhesives, or at least adhesion, raises problems for which the structural engineering world has more limited experience. The preference is not to use them because they often give little if any warning of failure. The objective is to avoid stress concentration and if a joint such as the scarfed joint in timber can be developed the engineer feels secure. But certainly there is a need for more return to the old engineering technique of physical testing rather than the current expectation that everything should be able to be done by scholarship and mathematics.

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I

Structural forms in steel for earthquake resistance

La rèsistance de structures en acier aux tremblements de terre

Erdbebensichere Stahlbauten

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SUMMARY

The performance of steel structures in strong earthquakes is highly dependent on form — both exterior and interior form. The exterior form includes the basic concept of the building, shape, symmetry, continuity or lack thereof, and such architectural features as flexible first story. Internal form includes redundancy, choice of details, and moment frame as compared to the use of braced frames and shear walls.

RESUME

La résistance de structures en acier aux tremblements de terre dépend essentiellement de la forme extérieure et intérieure de la structure. La forme extérieure comprend le concept de base du bâtiment, sa forme, sa symétrie, sa continuité ou discontinuité, et aussi des aspects architecturaux tel qu'un premier étage souple. La forme intérieure comprend la redondance, le choix des détails constructifs et le système de cadres rigides ou contreventés ou parois reprenant les efforts tranchants.

ZUSAMMENFASSUNG

Das Verhalten von Stahlbauten während eines starken Erdbebens hängt grösstenteils von der äusseren und inneren Form des Tragwerks ab. Die äussere Form beinhaltet das grundlegende Konzept des Gebäudes, die Ausbildung, die Symmetrie, die Kontinuität oder das Fehlen derselben und architektonische Eigenschaften wie Flexibilität des ersten Stockwerks. Die innere Form umfasst statische Unbestimmtheiten, die Wahl von Details, Rahmentragwerke mit und ohne Aussteifung sowie Schubwände.

Traditionally, the form of a building consists of a roof and floors supported by exterior walls and possibly using interior columns as additional supports. In earlier days, walls were of masonry. This type of construction was limited in height and/or the number of floors due to the large thickness of the walls which supported the floors around the perimeter of the building. This form of construction is still the most prevalent in low and moderate height buildings although in many countries, concrete or reinforced concrete has replaced the masonry. Often the building is rectangular in plan but many shapes are used, as for example, in churches.

Cast and wrought iron structures (both bridges and buildings) with masonry walls or piers were developed in the late 18th and 19th Century, both in Europe and the United States. The reconstruction after the Chicago fire of 1871 led to a new style of building construction using the newly developed steel in a framework that included columns in the walls to carry the vertical loads permitting the walls to be much smaller and lighter.

At about the same time as the modern steel frame was developing, the Mino-Owari, Japan earthquake of 1891 led to the first modern-day attempts to design structures to rationally resist earthquakes. The successful performance of steel framed structures to resist both the San Francisco 1906 and the Tokyo 1923 earthquakes encouraged engineers to demand this type of construction for all truly large structures. Subsequent earthquakes have tested much larger structures and so far the performance has been very good.

FORCES AND MATERIALS

Earthquake forces - unlike most other forces that engineers must consider - are really unknown but are known to be so large that it would be prohibitively expensive to design the resisting elements in the elastic range. When we say that the forces are unknown, we mean that all of the nice straight or curved line plots we see and use as design guides are "averages" of widely scattered plotted points that look like a shotgun pattern using a log-log graph as a target. This "average" may be raised a standard deviation or two as an attempt to account for the large data spread. For certain critical areas, such as close in records of very large earthquakes there are not even any points to plot, so assumptions are made. Different researchers use different assumptions and arrive at very different results. But we do know that the forces are large, cyclic and erratic, so that the knowledge of the performance of the structural material far beyond the elastic limit is of prime importance.

In the design of structures to resist earthquakes, it is the quality of toughness or ductility that is more important than mere brute strength. Few engineers seem to realize this. It is a characteristic of modern steels that they can be strained dependably and repeatedly far beyond yield. It is this quality of steel that makes it the preferred material for earthquake resistance. The hysteresis curves at large strains are remarkably stable. This is important in resisting earthquakes since the structural material is strained above the elastic limit in both directions for many cycles. The number of cycles depends upon the length of time of shaking. The length of time of shaking in turn varies somewhat with the size of the earthquake.

Steel framing has other advantatages. It ties the building together so that it acts as a unit. It is light as compared to the loads it must resist and is probably the most uniform and dependable of all structural materials. It is easy and fast to erect.

Steel framing, however, has some disadvantages. It must be protected from corrosion and from exposure to fire. The very thick steels that are necessary for large buildings may not be as uniform as engineers may desire. The ductile properties of the more usual sizes and thicknesses of steel - say up to 1-1/2 or 2 inches - are often lacking in the thick welded steel details where triaxial strains become important. Steel framed structures that do not use braced frames or shear walls can be quite flexible and if current drift limitations are used as a design standard, the PΔ forces may be such as to to cause instability.

One of the disadvantages of structural steel concerns its availability in many parts of the world. Except for the largest, most unusual or critical structures, local economic conditions may dictate the use of other materials. Those of us who practice engineering in regions where steel is plentiful and our technicans and workmen know how to fabricate it are fortunate.

TYPES OF FORM

The performance of any structure in a major earthquake is very dependent upon the form of the structure and this is no less true of a steel structure than it is for structures using other materials. The form of the structure can have two aspects - the exterior form such as shape, continuity, regularity and the distribution of mass and resistance and the interior form such as redundancy, type of resisting elements, choice of details, etc.

Concerning the exterior form, the ideal, of course, is a symmetrical, regular, rectangular shape without set-backs and with regularly distributed mass and resistance. Because of utilitarian restraints and architectural fashions, we rarely encounter such a structure although our basic codes, standards and design guides are based on that concept. This discrepancy may not be of great importance for gravity or wind loadings where the forces are known (or can be approximated) and where the load resistance is expected to be within the elastic limit of the structural material. However, for design earthquake forces that are expected to strain the structure beyond the elastic limit by a factor of several times, many ordinary concepts familiar to the structural engineer are not valid. The importance of this limitation is specially great for the non-symmetrical, irregular building.

ANALYSIS

Consider first the principle of superposition - a principle which we all use and is valid for elastic structures. A structure can be analyzed for each loading condition separately and the resulting stresses or forces combined as desired. Loadings can be repeated and each loading cycle will cause comparable stresses. Loads can be reversed by changing sign. This is especially convenient when designing complicated, irregular structures. However, after the elastic limit is reached and hinges form, loads cannot be combined in this way. Repeated cycles of combined loadings may not give repeating stresses, i.e. the stresses may be different for each cycle of loading. A more detailed discussion of this problem with illustrations, can be found in Reference 1.

At the present time, there are no non-linear computer programs that are reasonable and adequate for use in a building design engineering office. Universities and research firms have studied and reported the effects of earthquake loadings on regular structures. They have made parametric studies of a few of the irregularities. Some of the results of the studies on regular buildings have been incorporated into codes and standards but there is little quantative data for the design of the irregular building. As a result, the designer of an irregular building has to recognize that he must pay a premium of (1) less accurate analysis and (2) increased safety factor to account for the uncertainties caused by his choice of form.

Some of the most troublesome problems are those arising from required irregularities in the distribution of mass, strength, and stiffness throughout the height of a tall building. The most common illustration of this problem is the building having a high flexible first story. It is similar to a massive, heavy, stiff, building supported on stilts. A similar discontinuity can exist at any location in the height of a building, where the regular framing is changed for some reason or other.

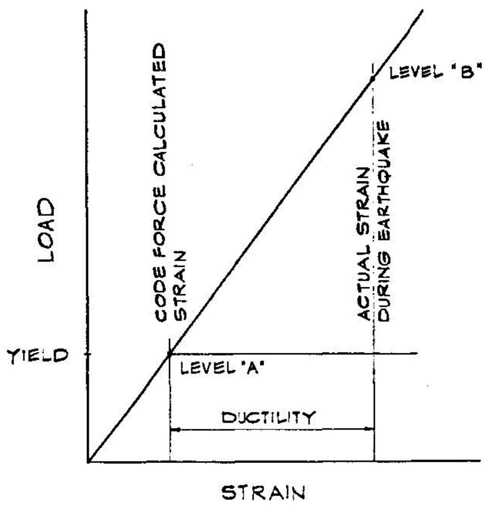
The normal building code or standard requirements are based on a uniform vertical distribution of strength, stiffness and mass. When applied to the irregular building these usual formulae for period and vibration characteristics are not applicable and consequently the base shear and distribution of the lateral loads throughout the height are not valid. If the loads are small enough so that the strains are within the elastic limit of the structural material, the usual dynamic analysis, either by time-history or modal analysis, can furnish a reasonable basis for design. However, when the strains are beyond the elastic limit, even the usual dynamic analytical methods do not indicate the true response. The actual deformations at the critical locations are generally much greater than the elastic dynamic analysis would indicate. If the engineer were to design strictly according to the results of his dynamic analysis as well as to the requirements of normal codes, the structure would be seriously overstressed at certain critical locations. When the earthquake hits, failures occur as they did at the Olive View Hospital in San Fernando and the Terminal Hotel in Guatemala City. This weakness has been observed in many earthquakes.

For those whose everyday work is not constantly related to earthquake resistant design, a quick review of the ductility effects in earthquakes may be in order. The ductility required to resist a given earthquake is illustrated in Figure 1.

If a given single degree of freedom structure is constructed using a strong elastic material and subjected to the ground motion of the design earthquake, it would respond at a load and deformation at level "B". If the material is ductile and is not strong enough to reach level "B", it will yield at level "A" and "stretch" to the same deformation as "B". This bilinear stress-strain curve is the "ideal" ductility usually assumed in many analytical studies.

Some material may increase in load capability under progressive cycles in cyclic loading and some material may decrease. But for simplicity in calculations, most research and analytical work has been performed assuming a bilinear or trilinear stress-strain curve.

If the material in the structure is ductile enough to reach the actual strain at level "B" (neglecting secondary stresses such as $P\Delta$), the structure will not fall. This has been proven for single degree of freedom structures and is assumed to be true for multi-degree-of-freedom structures.(2) A corollary



CALCULATION OF DEFLECTION
OR DRIFT

FIGURE 1

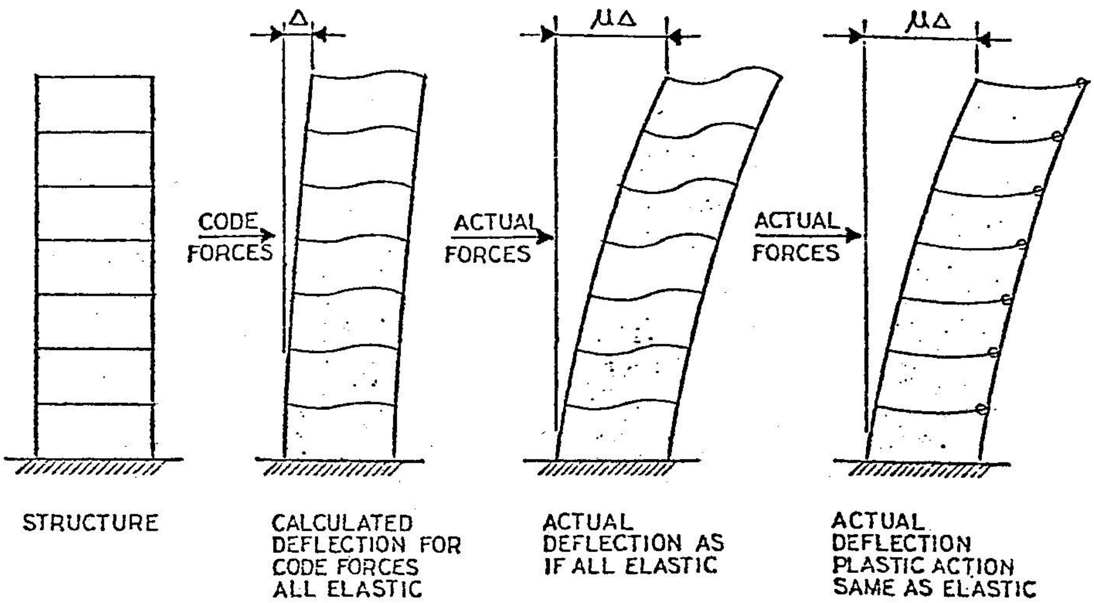
of the above statement is that if code level forces are specified at level "A" to account for ductility, it must be recognized that the actual deflections or drift of the structure in the design earthquake will be at level "B" - generally several times that calculated for the code level forces.

EXTERIOR FORM

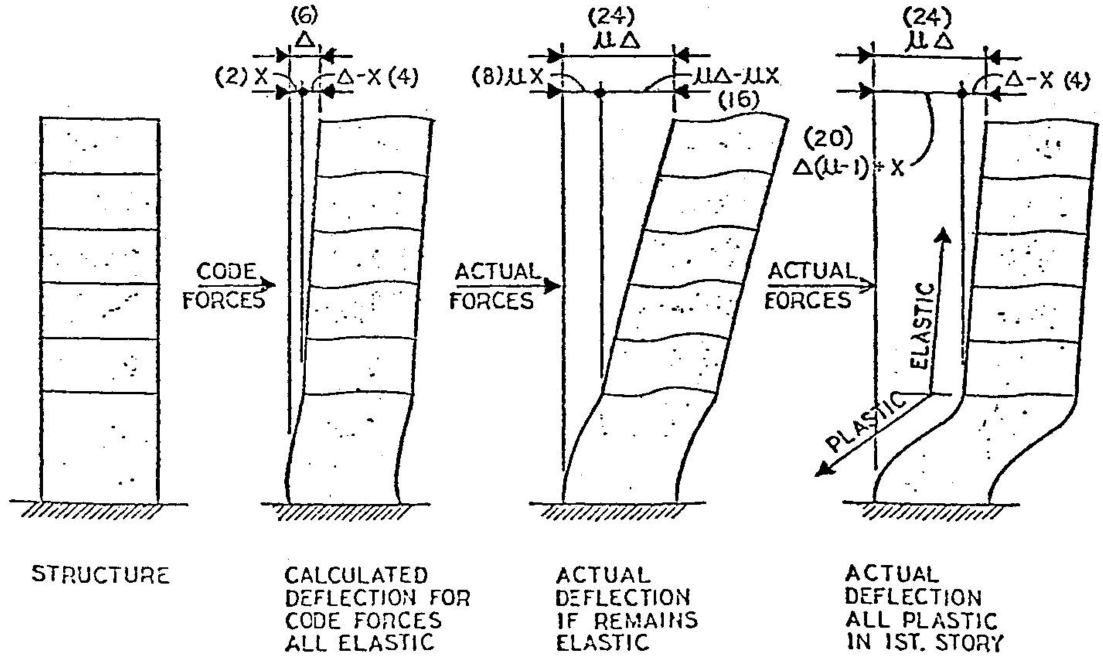
How does ductility influence the choice of exterior form of the building?

As an example consider a typical building frame for the seven story structure shown in Figure 2. If we consider the average structure in the top portion of the figure where the mass, stiffness and strength are well distributed along the height, the code forces will indicate a deflection at the top equal to Δ. But we know that the actual forces are greater by the ductility factor and from the principles discussed above in Figure 1, the actual deflection will be the ductility factor times Δ (point B instead of point A in Figure 1). If the properties of the structure are uniformly distributed throughout the height, this increase in deflection is more or less uniform, permitted by the hinging of the girders (or columns) throughout the height of the building.

Now if we consider a similar structure with a "soft" first story as shown in the lower portion of the figure, the code forces will give an elastic deflection as shown at the left. This is made up of the elastic deflection of the first story "X" plus the deflections from the rest of the structure Δ-X. The actual earthquake forces will again cause the total structure to deflect by the amount of ductility times Δ as indicated in the center bottom. But if the structure above the first story is so stiff and so strong as compared to the first story that the first story must absorb all of this excess deflection in



AVERAGE STRUCTURE



SOFT FIRST STORY

ASSUMED $X = 2$, $\Delta = 6$, $\mu = 4$

FIGUPE 2

the plastic range and the top remains elastic, it can be seen that the first story is deflected much more than an elastic analysis would indicate.

If a given strength and ductility combination are satisfactory for the uniform building and the upper stories of the flexible base building, the first floor of the flexible base building would require much more strength and ductility. The same principle applies to any other major discontinuity in the height of a building. The elastic analysis does not indicate the true dangers of these discontinuities even when dynamic methods are used and many engineers are trapped unknowingly by their architectural clients who like their buildings to appear as if they had no visible means of support. Every recent earthquake has its examples of the poor performance of this form of building.

Without going into detail, buildings with setbacks may have similar problems. Usually a dynamic elastic analysis should give results as reliable as for a more regular building, but the designer must be very careful at major stress concentrations and transfers.

In the earthquake analysis of a structure, it is usually assumed that the entire base of the structure is subject to the same ground motion and the motions of all portions of the base are in phase. Actually, this is not true, since the various earthquake waves come from some source and have a finite velocity. This has two effects. One, described by Yamahara(3) is that high frequency waves tend to be out-of-phase, considering the foundation as a whole, and so reduce the response of the superstructure. This is beneficial. The other effect is to induce torsion into even a perfectly symmetrical structure.(4) The amount of research on torsion in multistory structures has been limited, and in the usual dynamic analyses of buildings, the various modes of vibration are uncoupled. As a result there is a considerable amount of uncertainty as to the actual torsional effects.

This uncertainty is greatly magnified when the form of the building is such that large known torsions must be resisted. To provide some measure of protection, many seismic codes require that a building be analyzed and designed for a minimum "accidental" torsion. In practice, this is often ignored.

In view of the various factors discussed above, as well as others, it can be seen that the external form chosen by the building designer has a major effect on the performance of the building in a damaging earthquake. Known loads can be reliably resisted where all factors are known. Sufficient research has been performed on regular, symmetrical buildings of the "usual" proportions so that the effects of various uncalculated parameters can be estimated by the experienced engineer. However, when an unusual shape is encountered, where there are discontinuities in the vertical distribution of mass, strength or stiffness, or where a building has an inherent imbalance between the location of loads, and the location of resisting elements thereby causing torsion, the engineer has to make estimates - really guesses - based on his experience because the analytical methods readily available are not valid in the load and deformation levels reached in damaging earthquakes.

INTERIOR FORM

The other aspect of seismic resistant design relates to the interior form including such factors as choice of framing system, redundancy, choice of and inter-dependency of resisting elements and choice of details.

The first factor to consider in a structural steel building is the choice of framing system. Three general choices are available: 1) all moment frame, 2) shear wall, or braced frame, and 3) a combination of "dual" system, combining the moment frame with either shear walls or braced frames. Each has its advantages and disadvantages.

MOMENT FRAME

The moment frame, wherein all lateral forces are resisted by moment resisting connections between columns and beams is the system generally preferred by architects since there are no permanent structural walls nor diagonal members and so permits the greatest freedom in space planning. It is also the system generally discussed in research papers and because of its relative simplicity is the easiest to analyze and design. On the other hand, it is by far the most flexible permitting greater movements and non-structural damage in strong earthquakes and requires more steel to resist a given size of earthquake. Because of the greater deformations that it will undergo, it is subject to larger secondary stresses and may be subject to damaging mechanisms that have not been foreseen in present and past research studies of damage observations

Traditionally, in the moment frame system, all columns and beams were moment connected as in Figure 3, thereby attaining the maximum redundancy and reliability. In recent years, the tendency has been to make only certain members parts of the resisting elements, as shown in Figure 4. This reduces redundancy to the minimum possible in order to reduce costs. Obviously, for certain loadings as for earthquakes, if all other factors are equal, the greater redundancy reduces risk of collapse. An extreme case is shown in Figure 4(b) where the collapse of a single column ensures the collapse of the building. Note that, when using cast-in-place concrete frames, all connections are moment resisting. In a structural steel frame, the designer has the choice of making his beam connections either simple or moment resisting. This may be one case where a freedom of choice can lead to an inferior building.

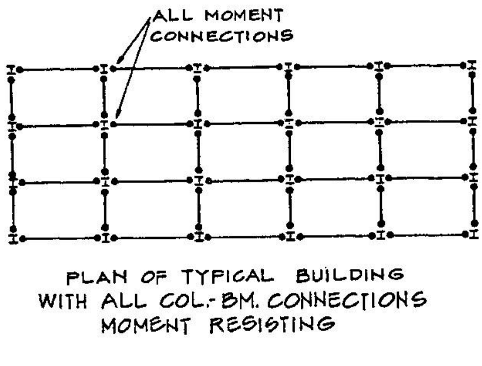


FIGURE 3

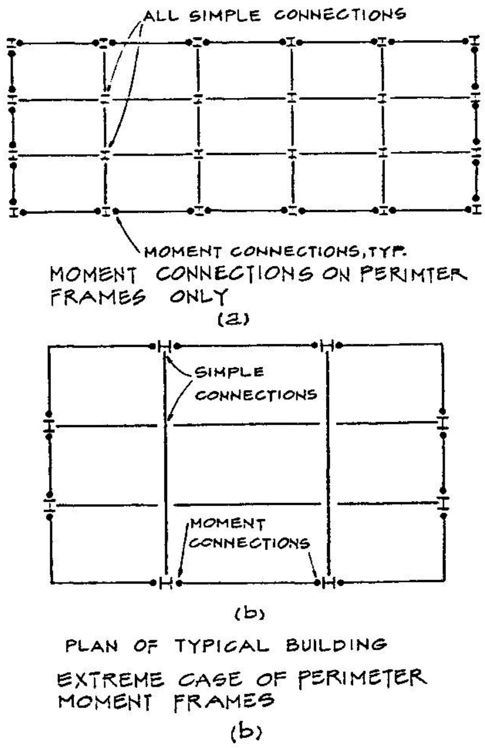
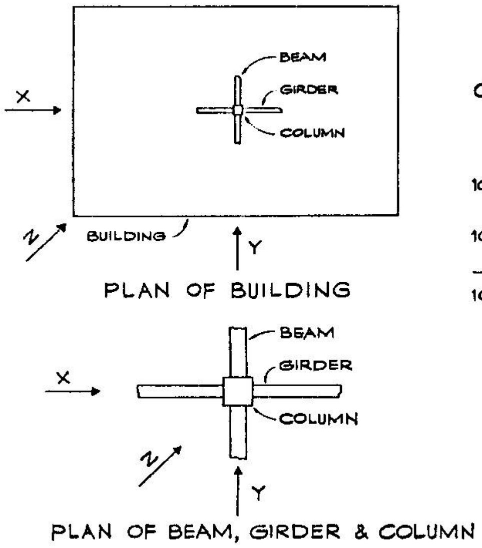


FIGURE 4

In the past, it has been a common practice to consider wind or earthquake loadings to occur in two orthogonal directions but not simultaneously. With the present emphasis on clean moment frames, matching the code forces with available ductility, and the effort to keep hinges out of the columns, it becomes necessary to review the stresses when the earthquake forces are oriented in an intermediate direction. From Figure 5, it can be seen that, as far as beams and girders are concerned, the loads on the main axes create the maximum stresses, but the diagonal direction requires a greater demand for strength or ductility.



CALCULATED STRESS IN ELEMENT

	COLUMN	BEAM	GIRDER
100% FORCE IN X-DIRECTION	100%	0	100%
100% FORCE IN Y-DIRECTION	100%	100%	0
100% FORCE IN Z-DIRECTION			
X-COMPONENT	71%	0	71%
Y-COMPONENT	71%	71%	0
TOTAL	142%	71%	71%

FIGURE 5

SHEAR WALL SYSTEMS

The bracing system that is in most common use for low and medium height buildings is the shear wall system. It provides considerable stiffness for protection of non-structural elements and is usually quite economical. The category "shear wall" is very broad and there is no adequate definition at present. Figure 6 shows four general types that are often used by architects. All are shear walls but the performance of each in earthquakes are quite different. Type A, the inverted pendulum, has performed badly in the past - similar to the Four Seasons Building in the Alaska, 1964 earthquake. Type B, with the small piers, has also performed badly as illustrated by the performance of schools in the 1968 Tokachi-Oki earthquake. Type C, with large piers performs excellently and is the forerunner of the coupled shear wall system which is being advocated both in the United States and New Zealand. Type D also performs excellently. In earthquake prone regions there is usually a height limit on buildings braced entirely by shear walls. The counterpart of the concrete shear wall in structural steel is the braced frame. The most economical bracing systems are those with concentric connections using any of

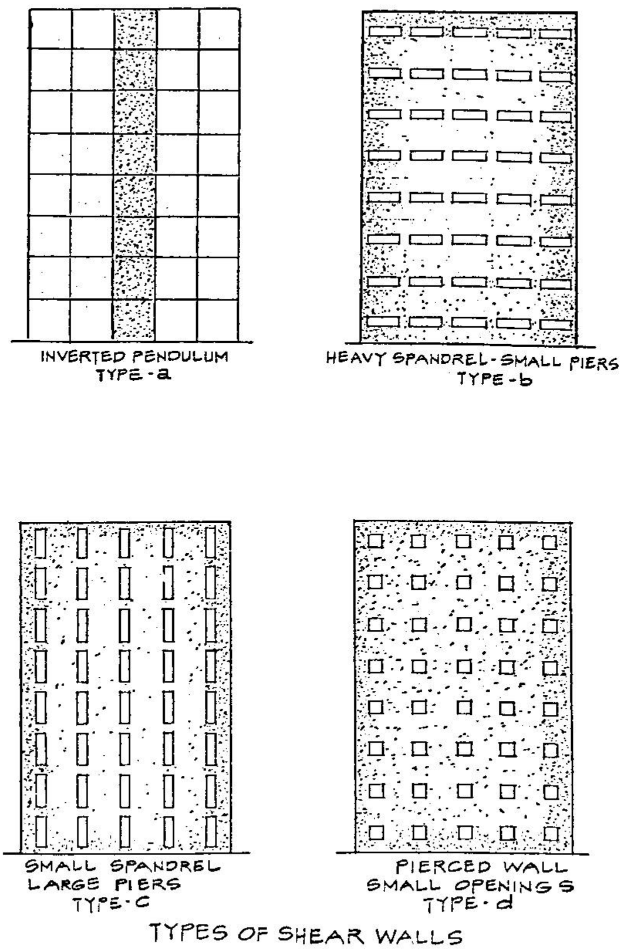
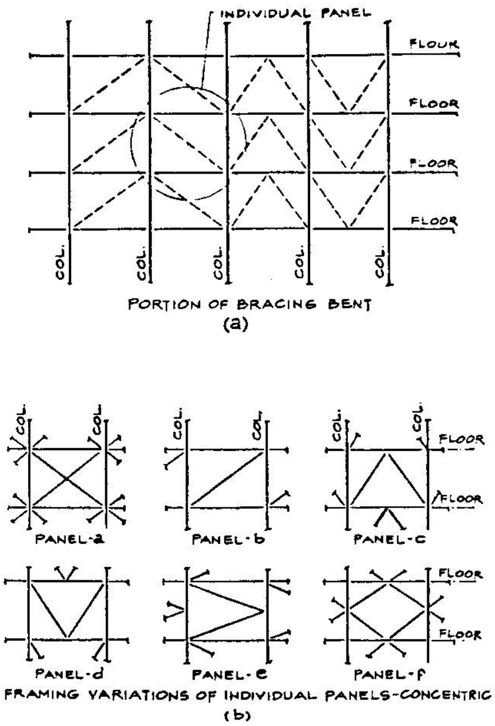


FIGURE 6

the patterns indicated in Figure 7. While these systems can readily be designed to resist code forces, they do not have much ductility. In past earthquakes, members have buckled and connections torn apart. Recently a considerable amount of study has been directed at making the joints eccentric as shown in Figure 8 in order to be able to absorb large amounts of energy. A more detailed discussion is presented in Reference 1 and the references given therein.

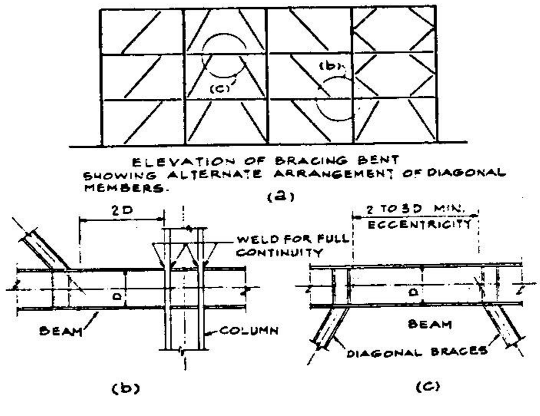
DUAL SYSTEM

In the writer's opinion, the best, most efficient and safest framing system for moderate and high rise buildings in earthquake country is the dual system.



Generalized layouts of normal braced frames with (a) showing general layout where each individual panel may have various configurations as shown in (b).

FIGURE 7



"Braced frame" bracing arrangements using eccentric connections to absorb energy. (a) Elevation of bracing bent showing alternate arrangement of diagonal members.
(b), (c) Enlargements of areas shown in (a).

FIGURE 8

This combines the shear wall or braced frame to give stiffness with the moment frame with the moment frame furnishing the backup strength with a ductile moment frame. It is this general type of framing that has given the best performance in past earthquakes and has led to the excellent reputation of structural steel framing in earthquakes. It is also an example of a system furnishing ductility as opposed to the material only. It can be seen that this system has the maximum amount of ductility.

DETAILS

After selecting the exterior form of the building and the general type of framing system, a choice of type of detail must be made. In structural steel, there are two general types of details used that depend on the form of the column. Connections are or should be moment resisting and today they are usually welded. In low and medium height buildings the columns are usually H sections. In high rise construction, they may be either H sections or box sections. The H section columns usually have the traditional type of moment connection using stiffeners in the bosom of the column. It is necessary here to accommodate the shear stresses in the panel portion of the joint. One disadvantage of this connection is the fact that bending capacity in the weak direction of the column is only about one third that of the strong direction. However, this type of detail has been tested in earthquakes and has been found to be reliable.

In an effort to balance the bending capacity in both directions, the box column has been developed in recent years. This is a welded box made up of plates. The stiffeners needed at the top and bottom flanges of the beams generally must be placed on the interior of the box and this creates some difficulties in welding. Very often the plates needed to form the column must be quite thick and the restrained situation at the stiffeners has caused plate cracking on several projects. While this system is theoretically more efficient than the H section system, it has not been tested in a major earthquake. The combination of very thick plates and welding raises some apprehensions as to the ductility that may be available.

SUMMARY

From the discussion above, it can be seen that the forms chosen in the design of a building have a major effect on the building's performance in a major earthquake.

The exterior form - its regularity, distribution of mass and strength, and arrangement of resisting elements - may have more effect on the building's performance in an earthquake than the engineer's calculations. The regular compact, symmetrical form has fewer unknowns whose effects the engineer must estimate.

Similarly, the choice of framing scheme and details - those items making up the interior form - determine the reliability and redundancy of the structure. Under loadings that cause major strains such as major earthquakes, these choices are of more influence on performance than the size of earthquake coefficient.

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Effective use of concrete

Utilisation effective du béton

Zweckmässige Verwendung von Beton

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SUMMARY
The fundamental characteristic of concrete is that it can be formed into virtually any shape thereby bestowing great freedom on the designer. The author stresses the other good qualities of concrete and urges that it should be used more imaginatively.

RESUME
Le béton a pour caractéristique essentielle de pouvoir prendre n'importe quelle forme, conférant ainsi une grande liberté au projeteur. Les autres qualités principales du béton sont soulignées. L'auteur recommande plus d'imagination dans l'utilisation du béton.

ZUSAMMENFASSUNG
Die wesentliche Eigenschaft des Betons liegt darin, dass er jegliche Formen annehmen kann, was dem Entwerfer grosse Freiheiten zugesteht. Andere wichtige Qualitäten des Betons werden unterstrichen. Der Autor empfiehlt, bei der Anwendung von Beton mehr Phantasie walten zu lassen.

If cement, gravel, sand and water are put together, the result is a mixture which in fact is liquid stone. Within a few days rock is obtained from this liquid form - rock which is similar to that which forms the high mountain walls of our planet. The artificial rock is called concrete.

This property - being initially liquid - is the most fundamental characteristic of the building material, concrete. On one hand it poses problems and limits; on the other hand it provides enormous freedom for the designer.

The first problem lies in the fact that a liquid must have a container in which to be poured: the formwork. Generally it is constructed in timber, sometimes in steel, when the need arises for multiple usage. The formwork must be watertight and strong enough to take high pressure. Concrete having a specific weight two and a half times that of water, produces pressure on the formwork two and a half times higher than the pressure of water. On the other hand the container can be realised in an absolutely unlimited range of shapes or forms. Concrete fills any cavity and runs into the finest details of the cavity.

There are no limits to the shape of concrete. Enormous freedom lies before the designer, an astonishingly vast field. It is astonishing that in fact very little use is made of this freedom. It is astonishing that the great majority of concrete buildings follow the typical shapes of wood and steel, namely the straight beam, the flat slab and the plane wall.

What is the reason for this fact? Are the adopted criteria valid ? Surely a slab should be flat. Unevenly shaped floors in a home or in an office would not be very practical. Yet walls and roofs need not be flat and straight. Round rooms are more intimate and it is well known that domeshaped roofs induce much more comfortable feelings.

Is it lack of imagination? Or, have we not learned to handle the non-linear?

Design and calculation of curved shapes is not easy. The problem of building technique is another impediment. Curved formwork is complicated and expensive, at least in the traditional sense.

When physical requirements suggest curved lines, then they are built. For instance in highway structures curved shapes today are quite common. The moving vehicle demands curves. Therefore they are constructed.

New techniques have been invented and developed to construct non-linear formwork. Therefore other buildings - houses, stores, hangars - could make use of them. This is a very interesting field for creative minds.

Concrete is a wonderful material. It is not only cheap but is still available without limit. It has very good strength properties - high compression strength by its very nature, tension strength obtained by combination with reinforcement, by use of prestressing cables or by reinforcing with special glass or wires or fibres.

By itself concrete has a very high weathering resistance. If cracks are avoided by good, correct design it can endure for centuries without maintenance. It resists the worst weather conditions, prevalent from mountain peaks to heavy seas. It can resist high temperatures as well as extreme cold by the use of modern additives in the concrete mix. It needs no protection, no painting, no cladding.

Concrete allows monolithic structures. Being cast in place, columns and beams, walls and slabs can be joined without hinges or joints. By this means the structures gain additional safety without additional cost. The advantage is really seen in cases of emergency or accidents; monolithic structures then demonstrate their high capacity to carry extraordinary loads.

Concrete has the highest fire resistance of all building materials. It also gives protection from weapons and radiation.

Today in most countries it is very easy to obtain concrete. It is purchaseable, it is delivered by concrete mixer lorries, it can be pumped to any place required. There is no longer a need for expensive installations, heaps of gravel, sand and cement; there is no more dirt and dust. Concrete is poured and a few days later one has the solid, unburnable slab one seeks. It is so easy.

Why then, one might ask, has concrete a rather bad reputation in the modern world? It may be because it is so widespread. It has become the symbol of man's intensive building activity, imposing more and more on the natural environment and nature. Concrete has become a symbol for destroying nature, and has become its apparent enemy. Because of the fact that it is durable, that in itself it disintegrates so slowly and invisibly man feels defeated or at least frustrated. It is left for future generations be it for their good or be it as an obstacle.

It is not concrete which should be criticised. It is human overactivity, the lack of respect for natural resources, landscapes and nature itself which are aspects for criticism.

It is not the high dam inundating a whole valley which is bad, but the fact that soon every valley will be drowned.

It is not the useful concrete highway which is bad, but the fact that motorisation constantly increases and that man believes he can only find his fortune in other places, never where he actually is.

When this background is understood and tackled, concrete need no longer be the scapegoat.

It is a medium in the hands of architects and engineers. It is neutral. The politician decides what has to be done and the technician decides how it is to be done. Be it exaggerated or sound. Be it ugly or beautiful.

Let us hope that concrete will be applied more and more for the well-being, prosperity and joy of man.

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