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

Chairman: Nickola Hajdin, Yugoslavia

Co-ordinator: A. R. Cusens, UK

Discussion leader: George Somerville, UK

Leere Seite

Blank page

Page vide

I

Form in nature

La forme dans la nature

Formen in der Natur

S. A. WAINWRIGHT
Professor
Duke University, Zoology Dept.
Durham, NC, USA

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
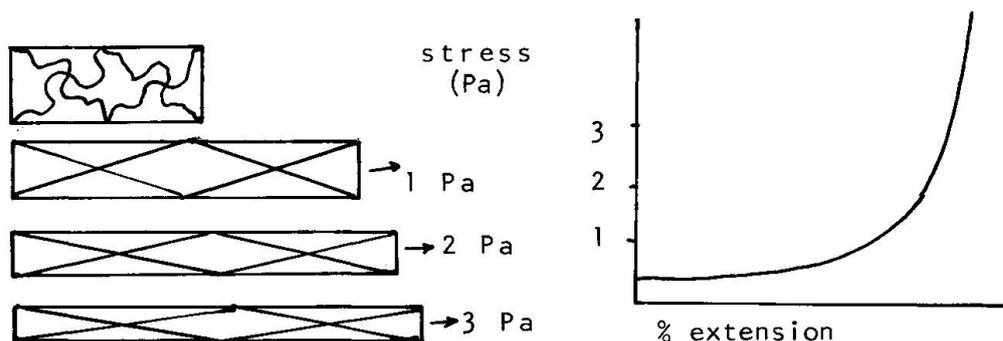
and Professor Gordon has brought this phenomenon to the attention of biologists and he has told us what it is about. One thing we can add further to his discussion is that it is quite clear that the increased stiffness of such materials acts as a safety factor in organism design. It says to the organism, "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 preferen-
tially 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 inter-
cellular 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 espec-
ially 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.
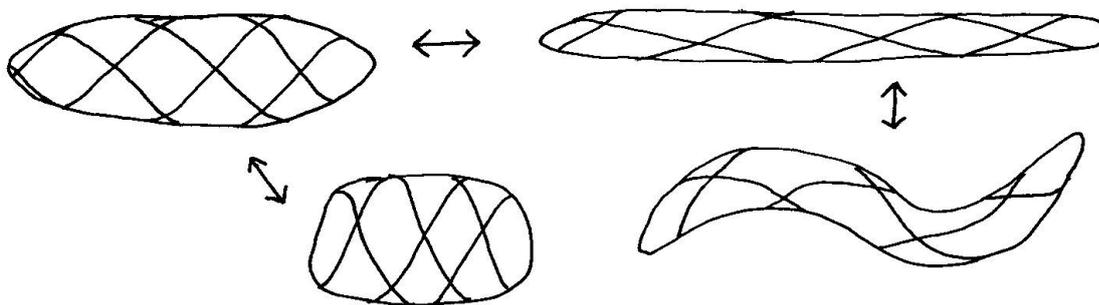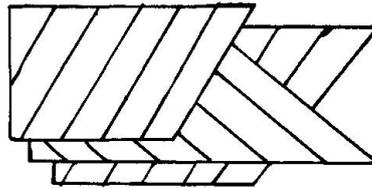
Cylinders can have quite directional mechanical properties. The winding angle of their reinforcing fibers combined with that unique animal invention, the muscle, give us the most interestingly diverse systems ever to have evolved. Most worms have a sheet of muscle oriented longitudinally and another 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 contrac-
tion 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 lon-
gitudinal 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.
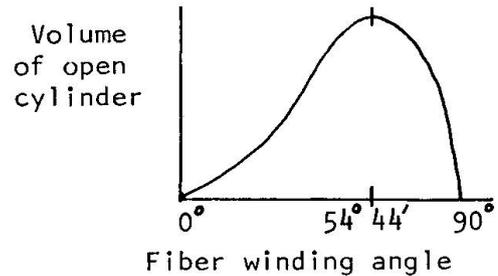
The stretched membrane hydrostat must be powered by sheets of muscle that apply
distributed loads to the membrane. They must not leak or be liable to be punc-
tured, therefore these are hard to maintain on land away from easy access to
bulk water and they are obviously too bulky and heavy for flying 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 spin-
dle-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 slid-
ing 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. Loco- motion 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 poly- saccharides 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 flexi- ble 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 con- tractile material, muscle, to produce the most remarkable living machines of all, flying insects, birds and bats.

Further reading

Gordon, J. E. 1978. Structures, or Why Things Don't Fall Down. Penguin Books, Harmondsworth.

Wainwright, S. A., W. D. Biggs, J. D. Currey and J. M. Gosline. 1976. Mechanical Design in Organisms. Edward Arnold, London.

Leere Seite

Blank page

Page vide

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?

J. E. GORDON
Emeritus Professor
University of Reading
Reading, Berks., UK

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 air-
craft 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 hous-
ing, 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 charac-
ter 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 con-
ventionally 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 con-
struction 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 dif-
fuse 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 trans-
mit 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 engineer- ing 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 dislo- cations.

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 approxi- mately, 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 archi- tectural 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 cellularisa-
tion can be taken much further with metals. Even if it were practical to manu-
facture 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 suscep-
tible 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° 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.

REFERENCES

1. COX, H. L.: The Design of Structures of Least Weight. Pergamon, 1965.
2. GORDON, J. E. & JERONIMIDIS, G.: Nature, London. 252 116, 1974.
3. JERONIMIDIS, G.: Wood Structure in Biological & Technological Research.
      Leiden University Press, 1976.

Leere Seite
Blank page
Page vide

I

Materials and components

Matériaux et éléments de construction

Materialien und Teilkomponenten

E. HAPPOLD
Professor of Building Engineering
University of Bath
Bath, UK

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.

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
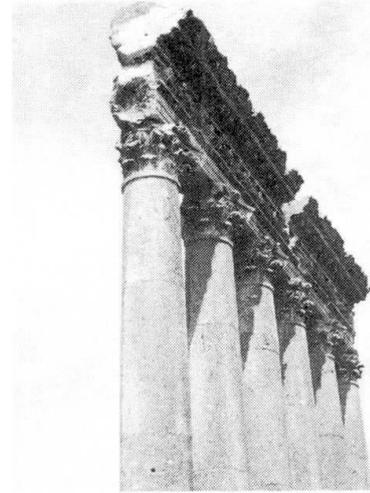that of Hagia Sophia, built about AD532, was

Fig 1   Beam and Post
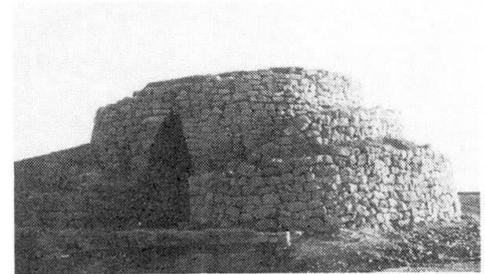   Baalbeck

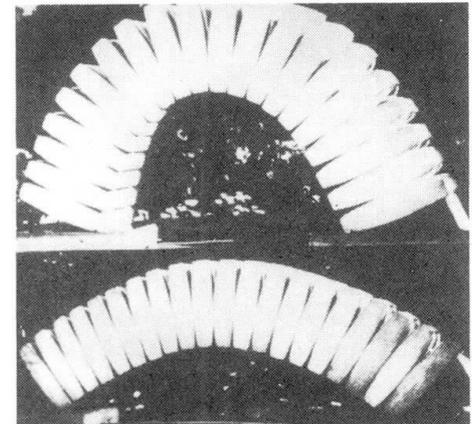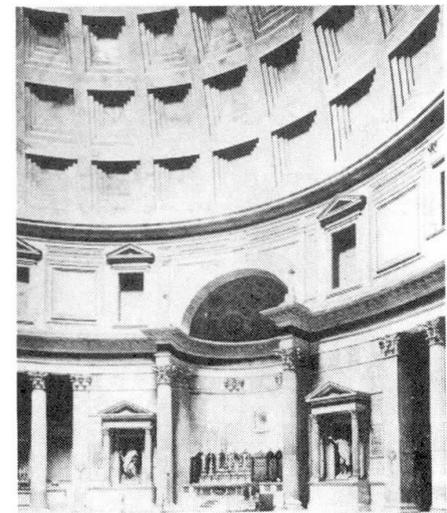Fig 2   Corbelled arch

Fig 3   Voussoir arch

Fig 4   The Pantheon

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.

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).

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
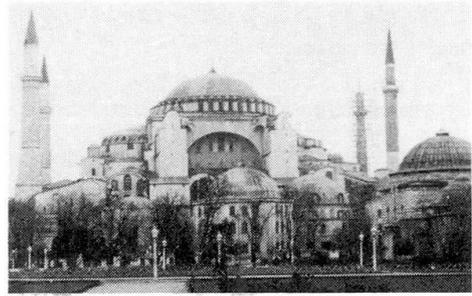triumphs of the nineteenth century were the
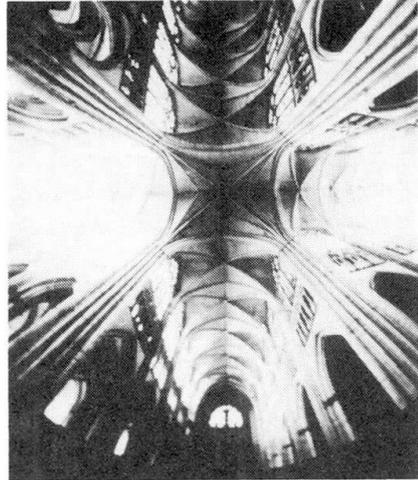

Fig 5   Hagia Sophia

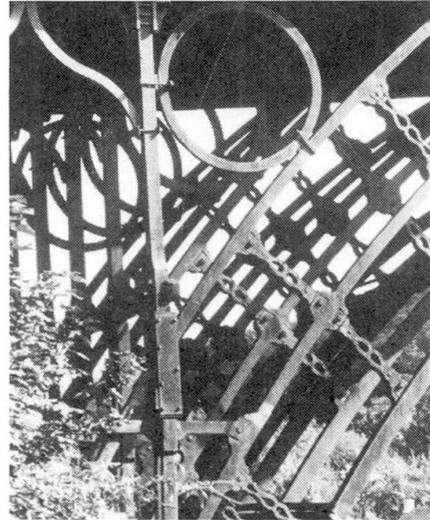Fig 6   Mediaeval arch

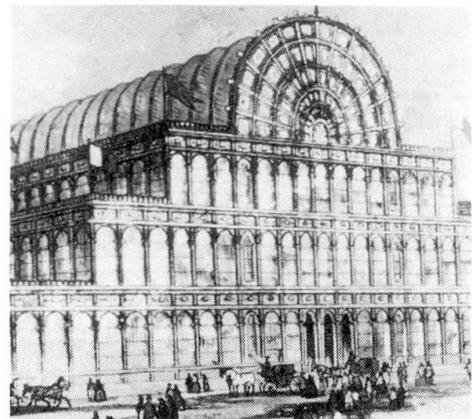Fig 7   Bridge at
        Coalbrookdale

Fig 8   Crystal Palace

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
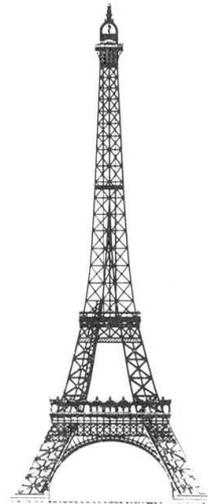

Fig 9   Eiffel Tower
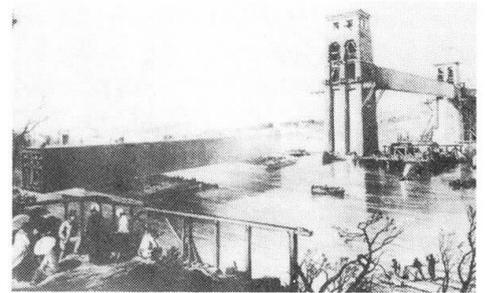

Fig 10   Menai Tube Bridge
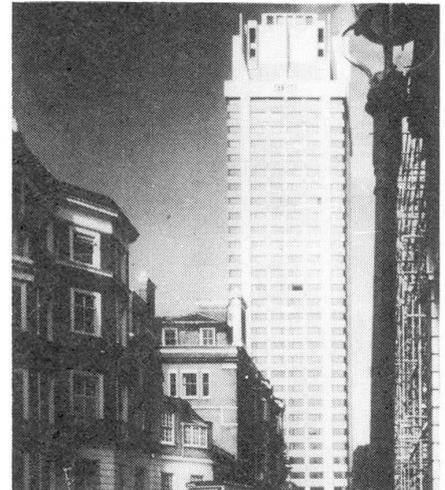

Fig 11   Knightsbridge Tower
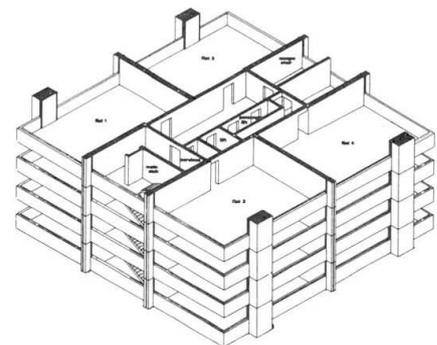   London

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.

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.

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

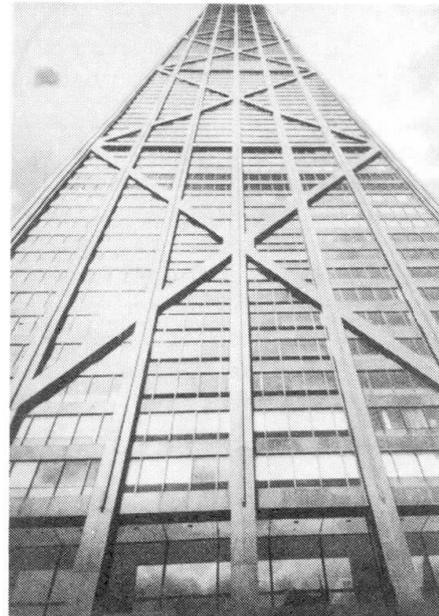Fig 13   Braced Tower
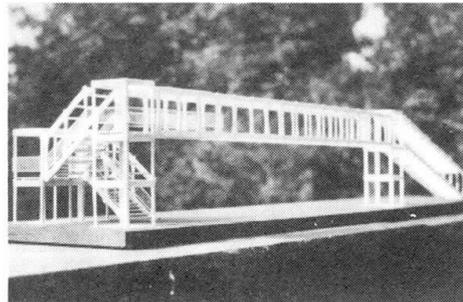   Chicago

Fig 14   Footbridge in
         West Germany
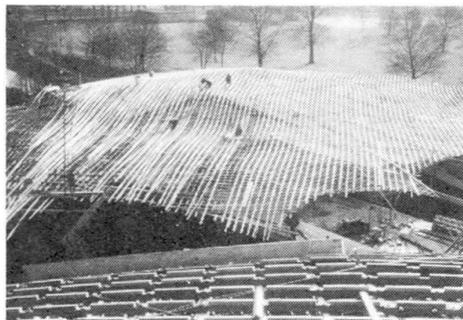

Fig 15   Mannheim Lattice
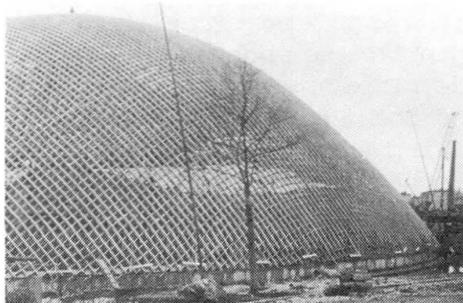   shell

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
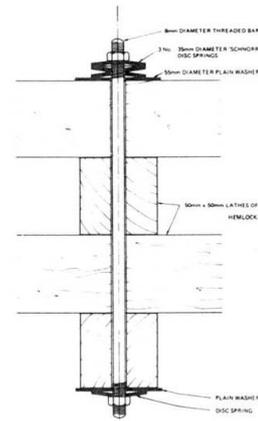resolution of thermal movement problems.

SKELETAL STRUCTURES IN COMPRESSION AND TENSION:
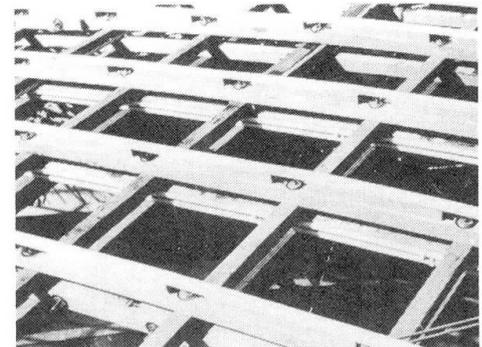
The discussion so far has concentrated on the
constructional aspects of framed members and
joints. However there is a tendency,
probably an increasing one, in a world of
diminishing resources, that the cost of any
structure is reflected by its own weight so
that of two structures, both equally adequate
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

Fig 17   Mannheim Lattice
         Shell

Fig 18   Mannheim Lattice
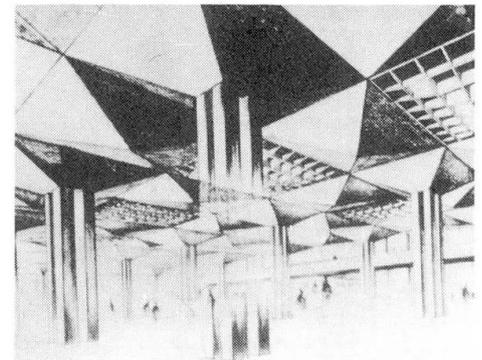   Shell

Fig 19   Articulation for
         thermal movement
         Conference Centre
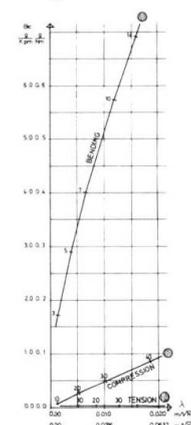   Riyadh

Fig 20   Curve of Efficiency
         Frei Otto

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.

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 $\dfrac{\Pi^2 EI}{\ell^2}$.

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.

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.
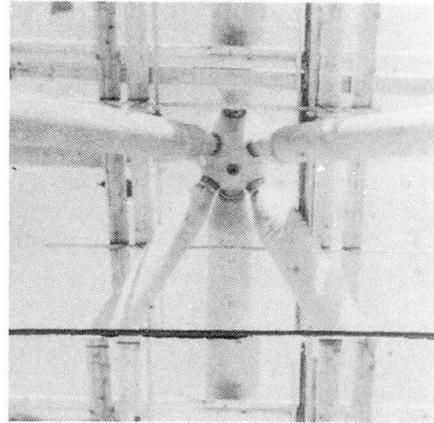

Fig 21   Joint at Expo '70
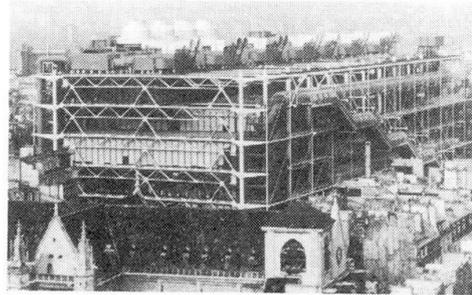   Osaka

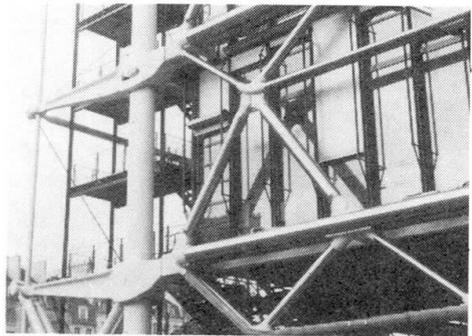Fig 22   Centre Pompidou

Fig 23   Centre Pompidou

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
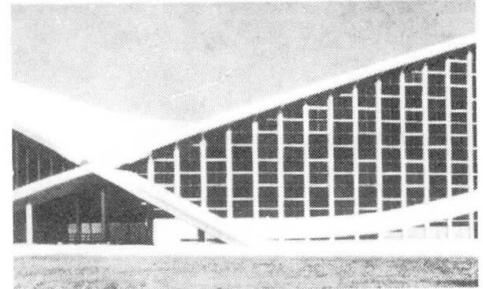

Fig 25   Raleigh Livestock
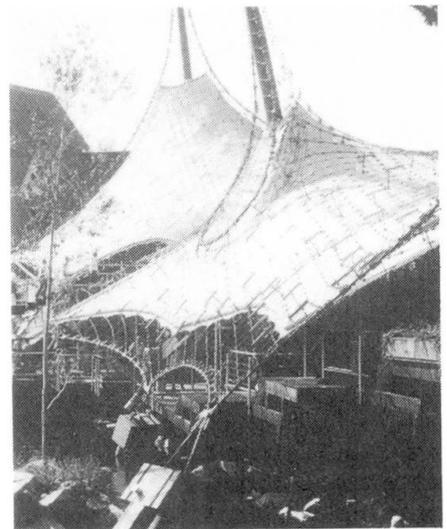   Terminal

Fig 26   West German
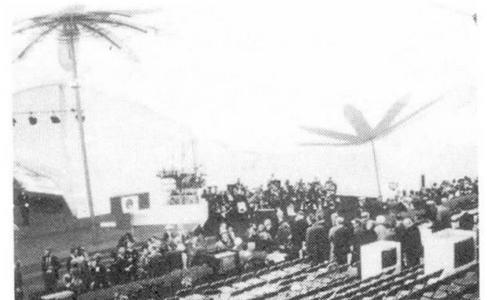   Pavilion - Expo 67

Fig 27   Tent at Dyce
         Scotland
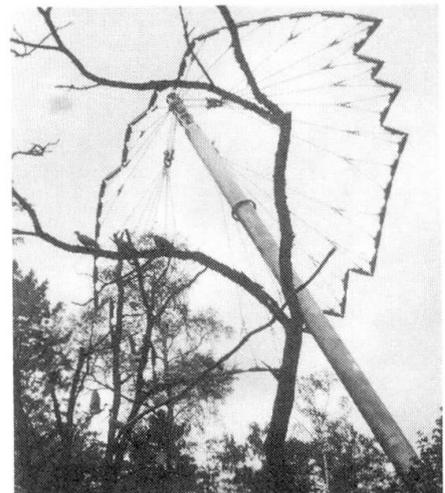
Fig 28 Munich Aviary

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

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.

Fig 30   Mast top for
         Gatlinburg

REFERENCES

1   Shorter Oxford Dictionary   Clarendon Press   Oxford   3rd Edition 1973
2   Paxton's Palace   A Bird   Cassell-London 1976
3   New York Observed   P Goldberger   Vintage Books New York 1979
4   George and Robert Stephenson   A Rolt   Longman London 1960
5   Timber Lattice Roof for the Mannheim Bundesgartenschau
     E Happold and W I Liddell   The Structural Engineer   March 1975
     Vol 53 No 3
6   Structures or why things don't fall down   J E Gordon   Pelican Books 1978
7   The Design of Structures of Least Weight   H L Cox   Pergamon 1965
8   Grundlagen Basics   F Otto and others   IL21   University of Stuttgart 1979

Structural forms in steel for earthquake resistance

La rèsistance de structures en acier aux tremblements de terre

Erdbebensichere Stahlbauten

HENRY J. DEGENKOLB
Consultant
H. J. Degenkolb Associates, Engineers
San Francisco, CA, USA

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 irregu-
larities 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
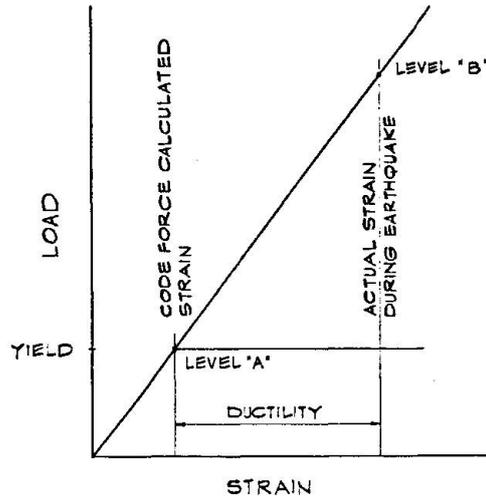changed for some reason or other.

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 characteris-
tics 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

LOAD

YIELD

CODE FORCE CALCULATED STRAIN

ACTUAL STRAIN DURING EARTHQUAKE

LEVEL 'B'

LEVEL 'A'

DUCTILITY

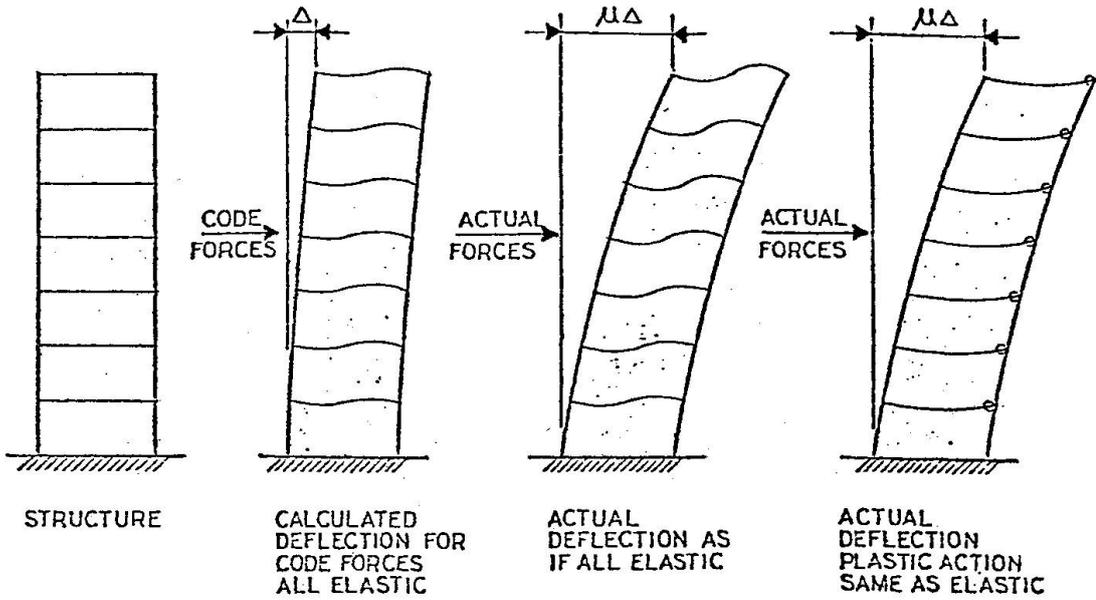STRAIN

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.
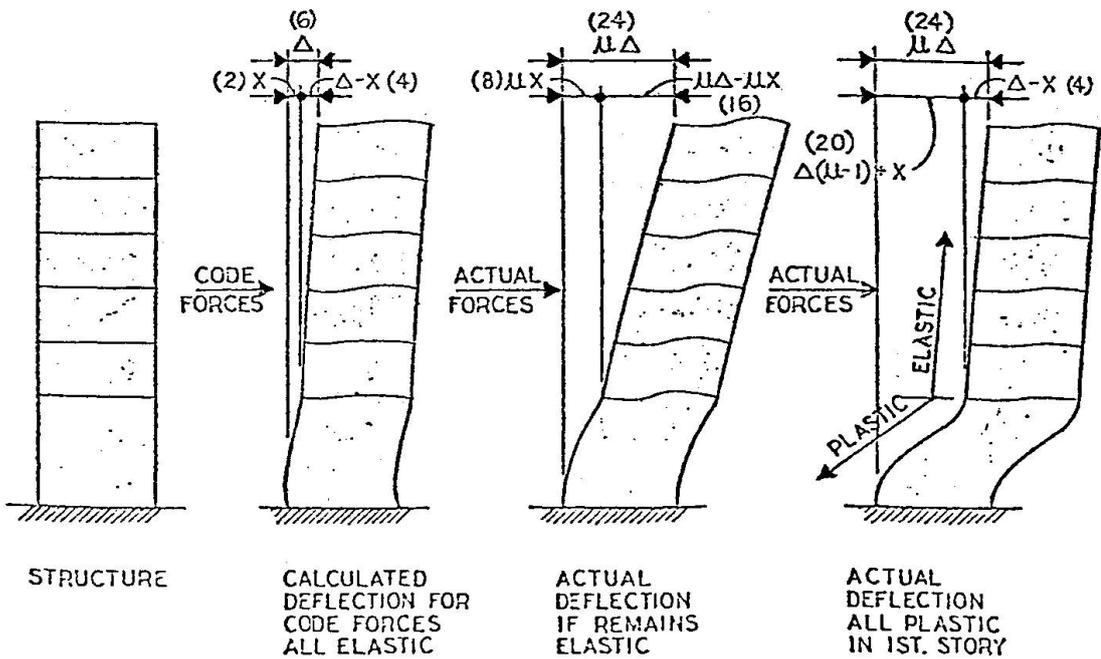
EXTERIOR FORM

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

STRUCTURE

CALCULATED
DEFLECTION FOR
CODE FORCES
ALL ELASTIC

ACTUAL
DEFLECTION AS
IF ALL ELASTIC

ACTUAL
DEFLECTION
PLASTIC ACTION
SAME AS ELASTIC

AVERAGE STRUCTURE

STRUCTURE

CALCULATED
DEFLECTION FOR
CODE FORCES
ALL ELASTIC

ACTUAL
DEFLECTION
IF REMAINS
ELASTIC

ACTUAL
DEFLECTION
ALL PLASTIC
IN 1ST. STORY

SOFT FIRST STORY

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

FIGURE 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 in-
cluding 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.
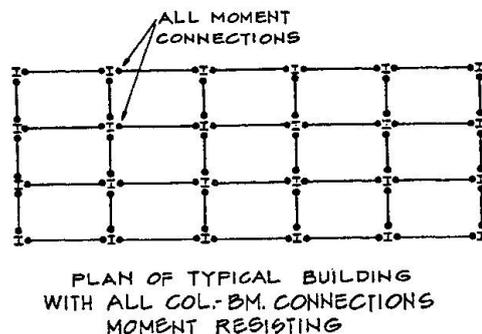

PLAN OF TYPICAL BUILDING
WITH ALL COL.-BM. CONNECTIONS
MOMENT RESISTING

FIGURE 3

MOMENT CONNECTIONS ON PERIMTER
FRAMES ONLY
(a)

(b)

PLAN OF TYPICAL BUILDING

EXTREME CASE OF PERIMETER
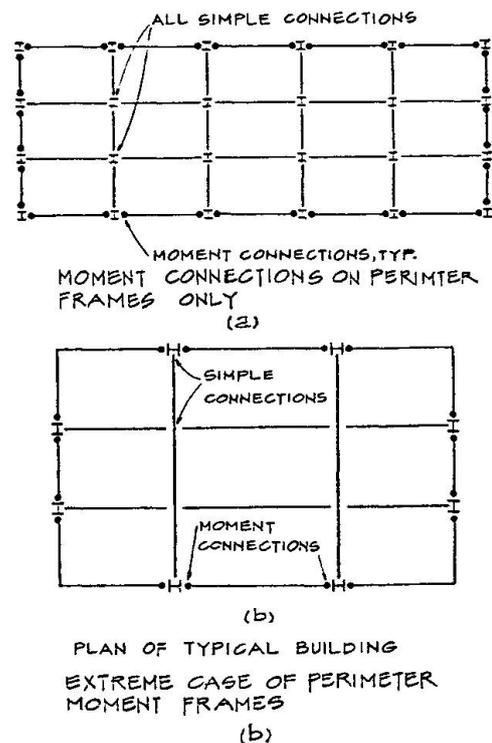MOMENT FRAMES
(b)

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.
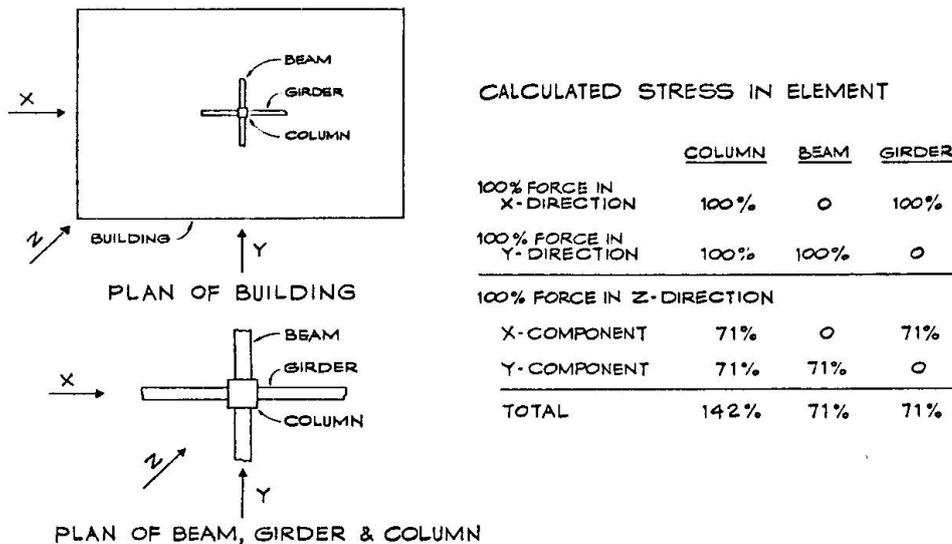
CALCULATED STRESS IN ELEMENT

	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%

PLAN OF BUILDING

PLAN OF BEAM, GIRDER & COLUMN

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

INVERTED PENDULUM
TYPE -a

HEAVY SPANDREL-SMALL PIERS
TYPE -b

SMALL SPANDREL
LARGE PIERS
TYPE-c

PIERCED WALL
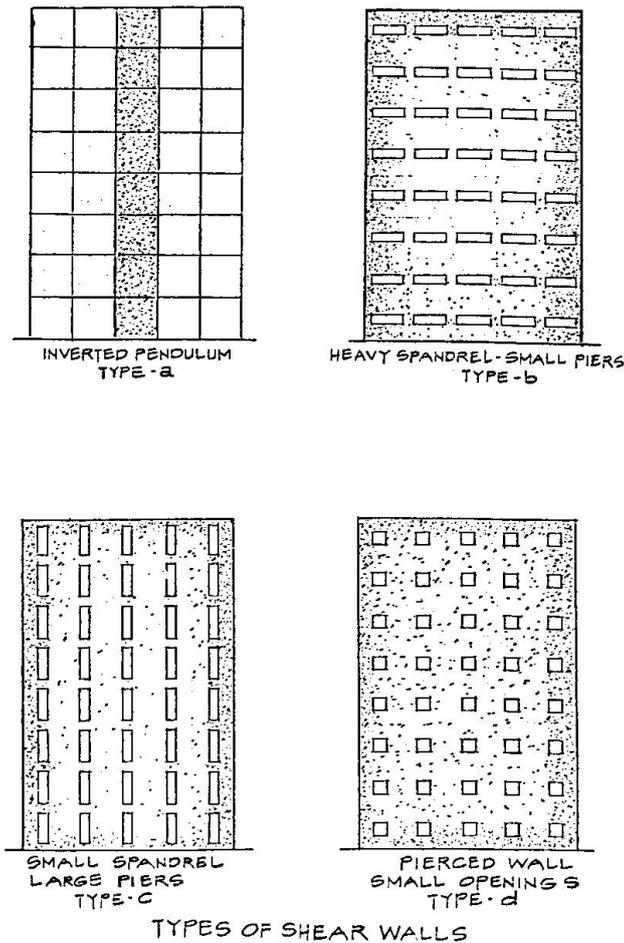SMALL OPENINGS
TYPE-d

TYPES OF SHEAR WALLS

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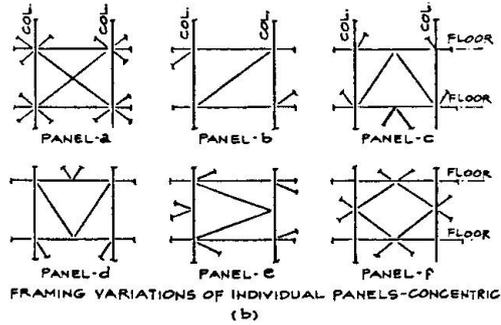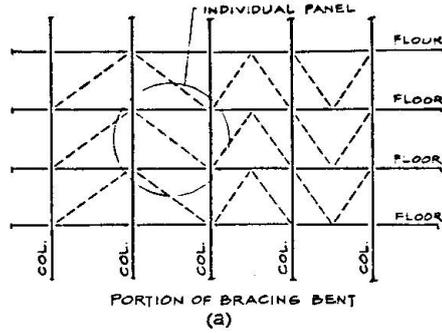
Generalized layouts of normal braced frames
with (a) showing general layout where each
individual panel may have various configura-
tions as shown in (b).

FIGURE 7
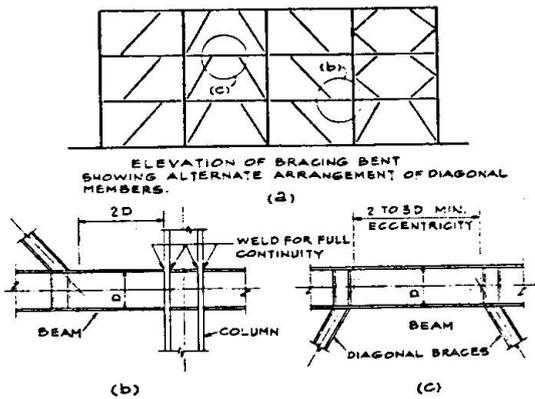
"Braced frame" bracing arrangements using
eccentric connections to absorb energy. (a)
Elevation of bracing bent showing alternate
arrangement of diagonal members.
(b), (c) Enlargements of areas shown in (a).

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.

REFERENCES

1. H. D. Degenkolb, "Practical Design (Aseismic) of Steel Structures" Canadian Journal of Civil Engineering, Vol. 6, No. 2, 1979, pages 295-298 and pages 303-307.

2. R. Clough and J. Penzien, "Dynamics of Structures" McGraw-Hill, 1975, page 602.

3. H. Yamahara, "Ground Motions During Earthquakes and the Input Loss of Earthquake Power to an Excitation of Buildings" Soils and Foundations, Vol. X, June 1970, No. 2, page 145 - The Japanese Society of Soil Mechanics and Foundation Engineering.

4. J. E. Luco and H. L. Wong, "Response of Structures to Non-Vertically Incident Sesimic Waves" Bulletin Seismological Society of America (In Press).

5. H. J. Degenkolb, "Sesimic Design-Structural Concepts" Summer Seismic Institute for Architectural Faculty, Page 65, 1977 AIA Research Corporation.

Leere Seite

Blank page

Page vide

I

Effective use of concrete

Utilisation effective du béton

Zweckmässige Verwendung von Beton

HEINZ ISLER
Dipl. Ing.
Ingenieur- und Studienbüro
Burgdorf, Switzerland

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 form-
work 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.

Leere Seite

Blank page

Page vide