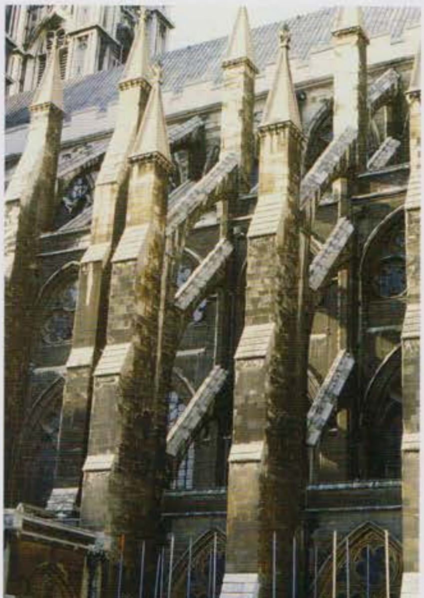


Stone structures – arch and buttress: Bridge (above) and Westminster Cathedral (right) (photos: Bill Addis)

# DIGITAL TECTONICS

## Historical Perspective – Future Prospect

Mike Cook

**Introduction**

The past twenty years has seen a revolution in our understanding of nature and materials. Genetic engineering, and perhaps soon nanotechnology, will give us the ability to make the materials we want rather than accept the constraints of traditional science. And we have seen the digital revolution – computers that can extend the capacity of our imaginations and allow us to communicate as never before.

Behind all this, we have seen how easy it is to harm the planet, abuse its resources and set up our own extinction. We are developing the tools to revolutionise what we build – but we have barely started to use them properly.

Digital tectonics explores the potential of our new-found rapid manipulation of numbers to influence 'design'. But this new apparent freedom from the old constraints could easily lead us down inappropriate paths. Therefore it is worth looking back to appreciate what have been the major factors influencing the form of what man has built.

There have been three key factors:

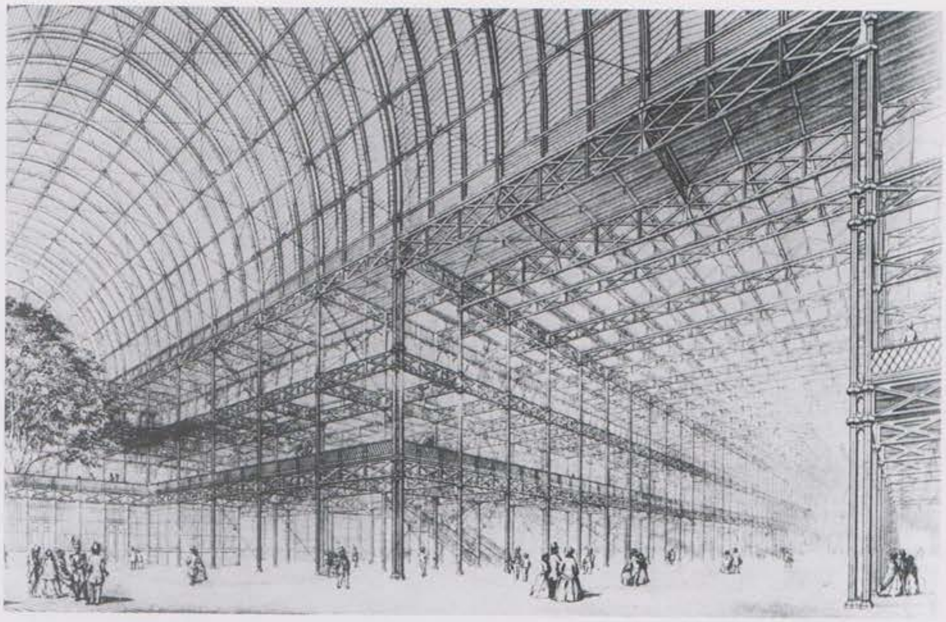
Material: our ability to use what is around us or to find ways of adapting it.
Ability: our ability to assemble, our ability to come together as a work force and collaborate, and our ability to communicate an idea.
Need: our reason for needing the building, from safe shelter to a symbol of power, something of utility or something of beauty.

These have been the fundamental determinants of what we build and we should look back to appreciate the strength of these influences before we look forward to where we are going and where we might be able to go.

**The History**

### Material

The form that a building can take depends on the laws of physics and the choice of material. Stone, brick, ice are all good in compression and poor in tension. As building materials they have the advantage of being stackable – compression holds them up. Compression structures are straight (columns) or curved (arches or domes). They are well suited to the small-scale construction of the one-man band; as components they can be made small enough to handle. These were the principal compression materials



**Iron structure: The Crystal Palace, London**

of early man – found material or materials like clay that was easily adapted. They are still important and, with the skill of masons and teams of labourers, great cathedrals and mosques bear witness to the potential of stone in compression. The form of such buildings was determined in part by the capability of the material to hold its shape, creating domes, vaults, soaring columns and flying buttresses. Concrete is a compression material too, but we have found ways to adapt it by adding steel or fibre to carry the tension and this allows it to be used in building frames in ways that stone and pure compression materials cannot.

Timber comes in long, narrow pieces: branches or trunks. It can carry tension as well as compression. It can be used as framing rather than the solid of brick and stone. It is light, too, so it can make useful frames for animal skins, to provide shelter.

Plant fibres or animal hair, bundled or woven, can also become a construction material. This material carries tension and can provide the basis for rope bridges and tents.

Extraction of large quantities of iron from rock gave us a more adaptable material; something that could be cast into shapes and assembled into building frames of great strength and durability. A new scale of building became possible and new form could be achieved. Two noteworthy examples of the new potential have to be the iron bridge at Coalbrookdale, Shropshire, and the Crystal Palace, London. Closer control of the process has given us steel; a relatively cheap and adaptable material that handles tension and compression well. It is an essential part of reinforced concrete and the basis of building frames, and construction over the past a 150 years has relied on steel to form the non-domestic environment that we know. Our recent history has been shaped by steel.

In the past fifty years, plastics and fibres have played a part in construction and have been especially important in the field of long span structures and tension structures, forming weather-tight skins for buildings of exceptional lightness.

The forms we see in the buildings around us have been determined in part by the physical properties of the materials available to us. These properties have been imposed by the laws of physics.

## Ability

The second factor determining form is our ability to use the materials available to us.

In the beginning we took for shelter what nature gave us: a cave, a tree. Slowly we gained an ability to adapt nature. Firstly using materials in their raw state and then adapting materials to make bricks, weave cloth, tan hide and so on. Tools helped us shape the raw materials. Fire helped us initiate chemical reactions and find new materials like bronze and iron, but iron was initially too precious to build from.

Drawing as a means of communication allowed us to record ideas and convey them to others. A system of master and apprentice helped transfer experience and perpetuate techniques and understanding; sometimes misunderstanding.

Physical models helped explore ideas and show others how the real thing would look.

Broader education led to broader understanding, not just of techniques that worked but of the underlying principles so that new ideas could be explored and exploited.

Improved methods of making iron made it viable as a structural skeleton – a revolution even when just reproducing old forms. As techniques of manufacture improved, steel came on the scene and revolutionised what was possible in construction and beyond. Developing our abilities to use this material led to cables with great tensile strength, and an ability to span great distances with bridges and roofs.

The ability to use materials has been as essential in shaping our man-made environment as the range of materials available to us.

**Tension: Spider web (photo: Bill Addis)**

**Jeddah: Cable supported structure (Buro Happold)**

## Needs

We cannot ignore the importance of changing needs in influencing the decisions we make and hence the forms of buildings we create:

The need for shelter, temporary or permanent, generated small, domestic buildings.

The need for greater security led to us clustering into secure communities and collecting together to build defences.

The need to have a faith in the future with a controlling force to believe in led us to stretch our abilities to the utmost and build giant edifices such as the pyramids, great temples and cathedrals.

The need to harness nature led us to develop dams and spacecraft.

The need to communicate and exchange goods led to the ship, the car and the plane.

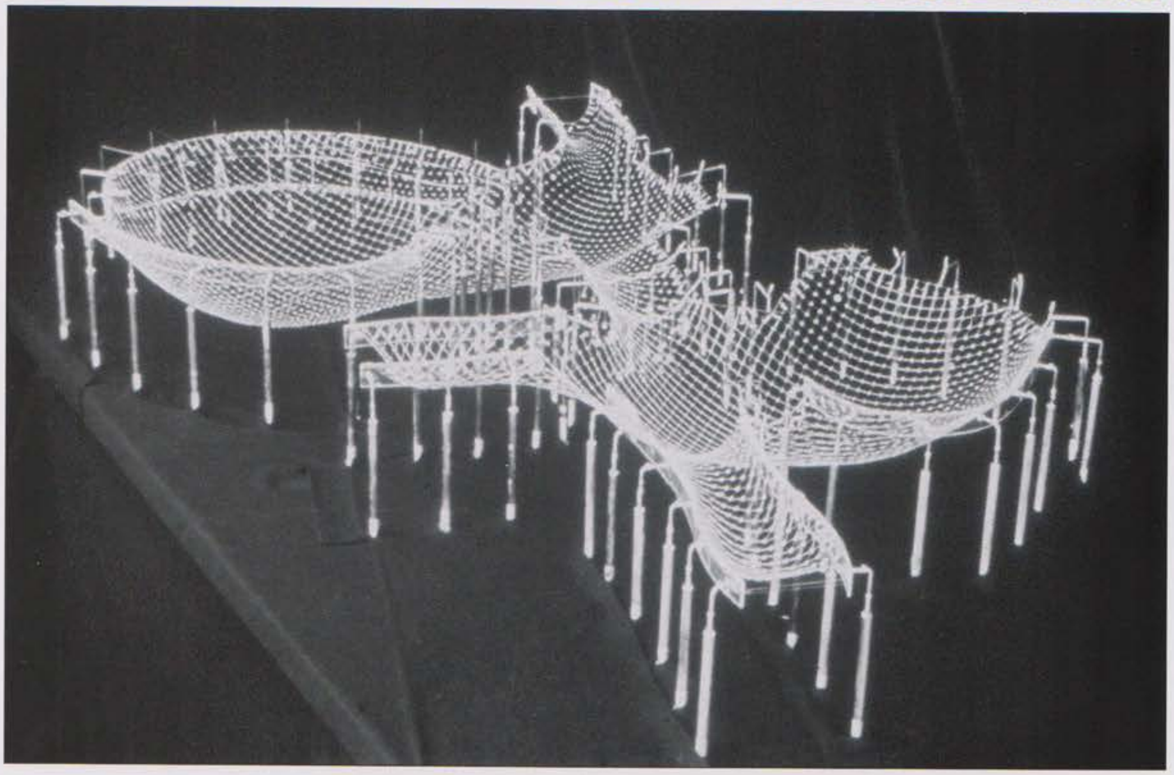
There is no change without need, and certainly there will be no revolution in the way we build unless an urgent need for it is perceived.

# The Future

Having considered the way that materials, our ability and our needs have influenced the evolution of our built environment we can look at the influences that are likely to affect the future.

## Materials

Genetics has given us a deeper understanding of life's code and an increasing ability to grow things of our choosing. New (organic) materials can be grown to order. This nanotechnology promises us the potential to engineer new materials at a molecular level. Much of this is for the future but it is starting to impact on our everyday world.



**Compression: Mannheim – Baumgartenshau grid shell (1974) architect Frei Otto.**
TOP **as built, aerial view;** BOTTOM **hanging chain model (photos: Bill Addis)**

### Ability

The digital revolution has opened new doors both in our ability to generate descriptions of buildings (virtual buildings) and to communicate this information to other people and machines that will make components. It has also given us the ability to model the physical behaviour of a building – how it stands up. Yet our ability to construct has barely advanced at all. Our building sites would be familiar places to Brunel, Wren and even the early cathedral builders.

### Need

The strongest present-day need is to find ways to provide shelter, comfort and even pleasure to the world's population without exhausting its resources or destroying it. The new need is to conserve material and reduce waste. Ultimately there could also be a higher need – one that makes life of greater value once our essential needs are met – but for now our priority has to be environmental survival.

The question should be – how do we harness the new ability of digital creation to use our materials and satisfy the need?

## Natural Determinism

We need to take note from nature. Nature has a way of minimising its use of material – material is expensive in nature. It uses valuable resources and energy. Nothing is wasted. This alone is reason to take heed.

### In Tension

A spider spins silk of different types, to build a snare for its prey. The silk can be given properties to suit the need. It can have fantastic tensile strength and high stiffness or strength with very low stiffness. The orb spider exploits this by making the radial spokes of the web strong and stiff, thereby holding the web together, but on the other hand circumferential fibres are made stretchy and sticky. With this combination the impact of the prey is absorbed, the web's primary structure is kept intact and the captive insect is glued to the web. When the web needs rebuilding the spider eats it and recycles the material.

Using materials which stretch allows different spiders to lay down webs of different forms to fulfil different functions. The shapes are defined by the forces in the material. Learning from this we can define shapes that are determined by the forces within them.

The soap film is a good example of a material that will stretch to a new form in a strictly controlled manner. The physical laws of surface tension and fluid flow ensure that, whatever the forces acting on the film, it will move to a form where the level of stress in the skin is equal in all directions. Stress concentrations cannot develop. The material is used to its optimum across the whole surface.

Starting in the 1950s, Frei Otto used this as an early means to generate minimal shapes for tension structures so that the material would be used efficiently. Computer modelling has displaced the soap film and broken away from the need to generate surface with uniform stress. The freedom given by the computer has led us to less efficient designs. The constraints of the physical model, one that had to obey the laws of physics, were actually of benefit.

**Sage Music Centre, Gateshead (architect: Norman Foster and Partners)**

### In Compression

The snail generates calcium carbonate to extrude a shell around its body that is extremely thin yet remarkably strong. This is achieved by respecting the material's capabilities in compression and generating a shape that uses these to the full. The forms of man-made shells often take into account the optimum shape that requires the least material.

The cathedral builders sometimes used a hanging chain to define the profile of arches, to ensure that the line of thrust was likely to fall within the stonework of even a relatively shallow arch. Gaudí used a three-dimensional hanging chain model for a similar purpose. And it gave him a way to define, explain and even test a big unified idea in a way that conventional drawings could not. He believed that, as a unified three-dimensional idea it took him 'nearer the angels'. It certainly took him nearer to nature.

Frei Otto used the same technique for compression structures. The timber lattice shell roof for the Bundesgartenschau of 1974 is an excellent example of a building that derived its form from a funicular model and hence achieved direct compression in all members under self-weight. Another interesting thing about Mannheim and this way of building a compression structure is that it is built like a tension structure – assembled flat on the ground and hauled into position in one move.

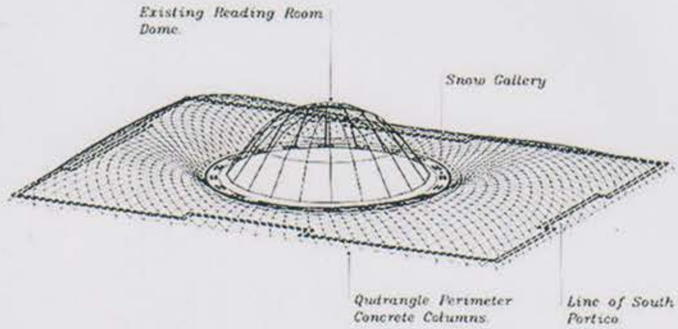
It is interesting to note that Buckminster Fuller's domes, whilst seeking to achieve efficiency of material, were content to follow a spherical form. Their method of construction was the incremental, traditional compression route of sequential assembly. Simple fabrication and assembly was given precedence over total efficiency.

### Efficiency and Buildability

The simultaneous consideration of efficiency of form and reality of construction is the essence of good engineering. Traditionally, the synthesis of form and building method has come from trial and error, and passing down experience through the generations. Physical models that would capture the laws of physics and use them to define form have also played an important part. Such models also helped the builder develop construction methods – the model being the prototype. Now we are free from such constraints it is important to ensure we do not lose our way.

## Recent Examples

For the Sage Music Centre, Gateshead (architect Norman Foster), the driving force had



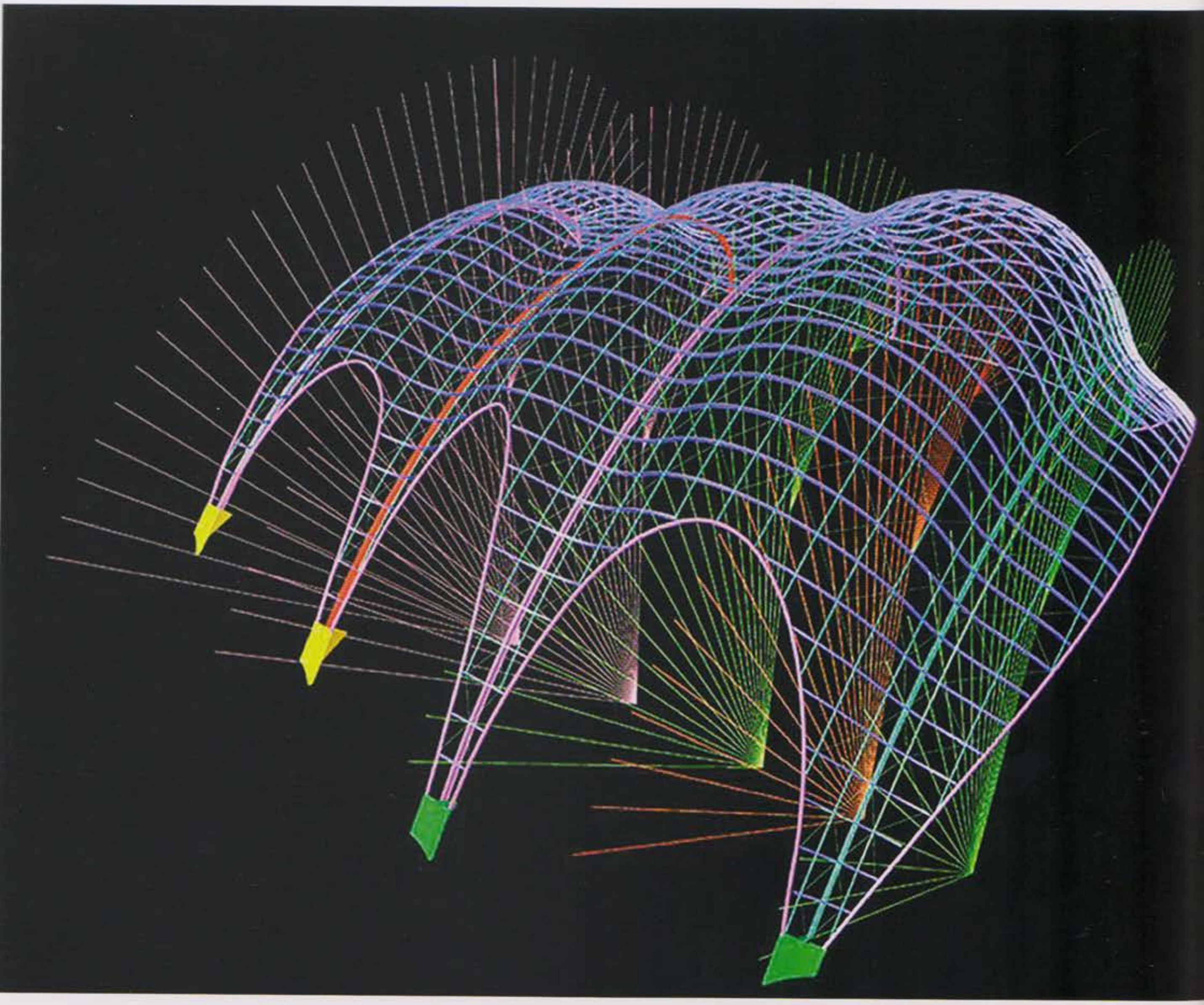

The British Museum Great Court roof – as built aerial view (photo: Mary Reynolds), and analytical drawing (Buro Happold)

to be economy of materials and ease of construction. This was the only way to meet the building's budget. The concept was to provide three independent halls beneath a single 'free-form' roof. This roof was to be curved like a shell to give it strength as well as creating a stunning image across the river. The waveform is generated using single circular arcs swept through space. This is a 'graphic' method rather than a 'natural' method and did not seek to generate a 'pure' compression form. Rather, the focus was on ease of construction. By exercising this degree of control over the geometry, the pieces that the roof would be made from could be highly repetitive and very easily made on conventional equipment. The form-generation took into account the way the roof would be split into elements and went about generating these elements – it was not a free-form generation but had a grid imposed on it. This means that the roof could be built sequentially in the air over the new hall buildings that would already be in place. There was no flat site such as at Mannheim and no chance of using a lattice approach.

In contrast, the new roof to the Great Court at the British Museum (architect Norman Foster) faced a major constraint in the geometry of the surrounding buildings that the roof had to match – a central circle and an outer rectangle. A second consideration was to make the structure invisible – using as little material as possible so that the sky would be more visible than the roof. A third consideration was to keep the height down to satisfy the planning constraints imposed on the design. A fourth was to ensure that it could be built whilst the museum was working. A fifth was to ensure a pattern of roof elements that would support the glass skin and flow naturally between the circle and the rectangle like a single 'web'.

Finding a form for the roof began with a 'naturally' formed surface. A soap-film stretched between the circle and rectangle inflated into an undulating shell. Ideally, vertical gravity forces would have been used to define the shape rather than pressure, which is normal to the surface, but as the roof was going to be rather flat anyway due to the planning constraint on height it did not make a great deal of difference. Finding this form to be horribly bulbous, Chris Williams (of Bath University), who assisted the form-finding process for Buro Happold, played with the stress levels in the bubble – effectively tightening it in areas intended to be lower and slackening it in areas where it should be higher. In the end this wasn't quite enough and he resorted to describing the form analytically, though with a residual memory of the soap-film form.

For the construction methods, expert fabricators became involved whilst the design was being developed – Wagner Biro, a firm of steel fabricators from Austria. For this site



**Sage Music Centre, Gateshead – Structural Geometry (Buro Happold)**

it was not possible to adopt the Mannheim lattice approach and the geometry was too free-form for the Gateshead approach. So the fabricators developed a way to assemble pieces of roof in multiple triangles, propped off scaffolding and held accurately in final position. Because the geometry was 'natural' – even if it had been tailored to match other constraints – there was no repetition. All steel elements were of different lengths, all nodes had different geometries and all panels of glass were different. This was not a major problem because all the information was available on our computers and this could be transferred to the fabricator's computers. From here it could be fed into the cutting and milling machines that made the pieces and cut the glass. The assembling was just a matter of getting the right pieces, all carefully marked, in the right place.

**Conclusion**

There is now a greater ability than ever before to create forms that break free from old constraints. Now the challenge is in deciding what form is 'right' – what rules or creative models should be followed?

The future that the digital age will bring is exciting; it will bring new control over our materials. But it is crucial that engineers participate in, and contribute to, the creation of form. Old physical methods of modelling and describing form are still relevant, though they have become overshadowed by digital modelling. Yet what they told us about the efficient use of our materials is still relevant, perhaps even more than ever. We need form-generation models that recognise the laws of physics and are able to create 'minimum' surfaces for compression and bending as well as tension. And we need to extend the virtual building model to virtual construction – not just conception – so that the way a building is fabricated and erected becomes as important a part of design as its efficient use of materials. This will help us create buildings that will conserve material and energy and hence go some way towards meeting today's pressing need – conservation of our global resources.