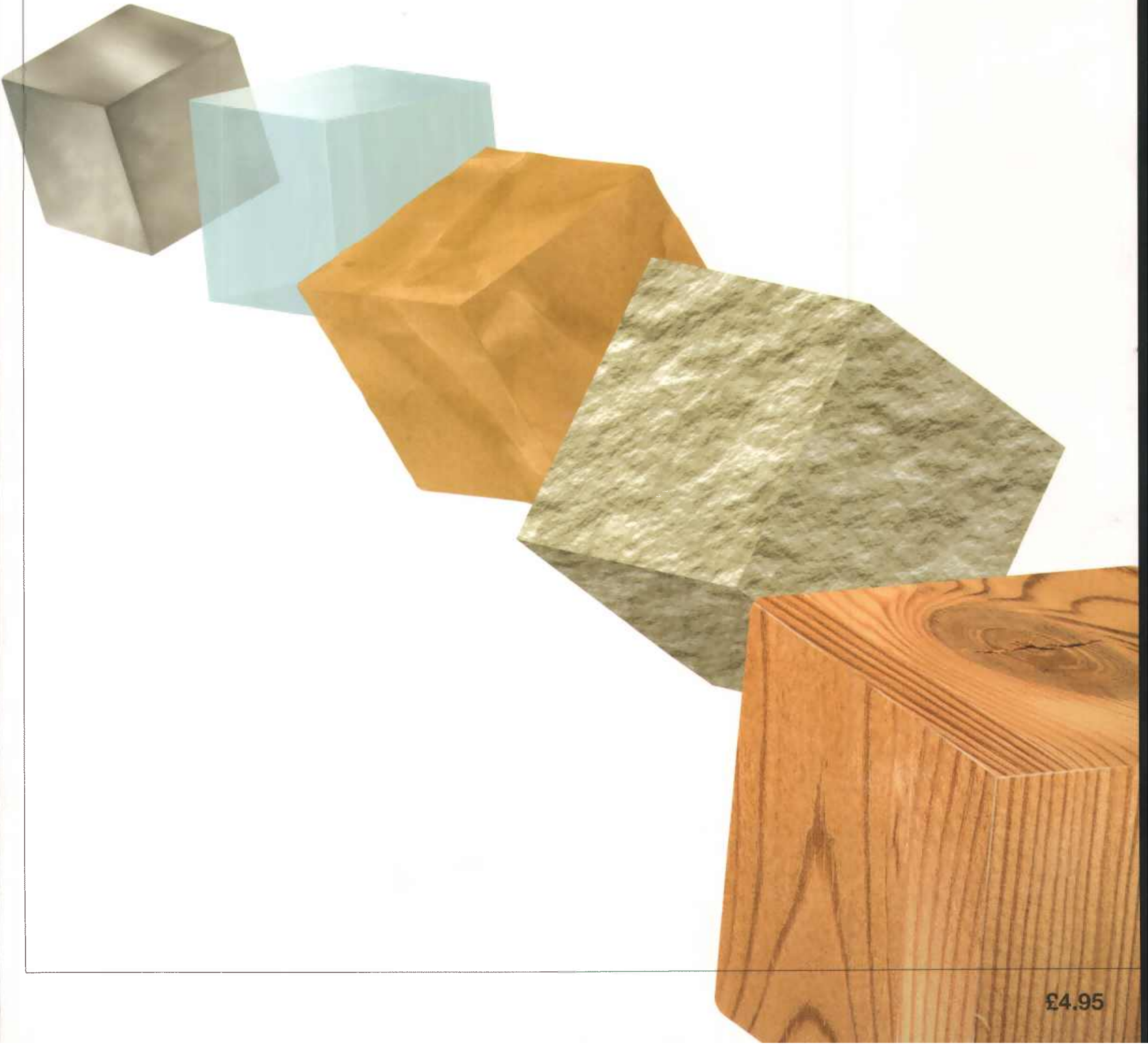
ESSAYS ON THE INNOVATIVE USE OF MATERIALS IN CONSTRUCTION

PATTERNS



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“An engineer’s craft is intensely creative, at its best it is an art, in that it extends people's vision of what is possible."

Sir Ted Happold founder of Buro Happold

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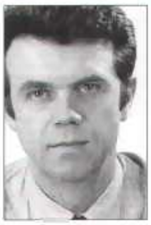

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PATTERNS

ESSAYS ON THE INNOVATIVE USE OF MATERIALS IN CONSTRUCTION

EDITORIAL

The history of engineering has been marked by the progressive discovery of new materials available to engineers and of new ways of using traditional materials, suggesting new structural solutions and new possibilities. Working in this tradition, engineers of integrity are likely – as a matter of course – to explore the potential of a material which they may want to use and specify. Buro Happold's engineers do this and they go one stage further; they make the results of their explorations available to other professionals by publishing them. Research has been collated in the journal known as *Patterns – Essays on the art and science of engineering* which first appeared in 1987.

Since then Buro Happold has become a large international practice and the quantity of its research is such that editions of *Patterns* can now cover specific themes. Sustainability was the subject of Patterns 13, published in 2001. Materials is the subject of this issue.

The essays presented here are, in most cases, recent research into engineering materials written by Buro Happold staff in Glasgow, Manchester, London, Leeds and Bath; they fall naturally into five sections – weak materials, translucent materials, lightweight and sheet materials, wood and metals. I also asked Bryan Harris to write an overview of the future of engineering materials which forms the concluding essay. Ian Liddell expressed an interest in exploring whether 'weak is good'; weakness is a property not usually associated with engineering materials but his interest was corroborated by Adrian Taylor's research into the properties of lime and by Florian Foerster's investigation of the structural potential of cardboard. Richard Harris wrote two essays to summarise some of his extensive experience of working with wood.

Several essays were based on officially-commissioned research: into comparisons between glass and ETFE foil cushions (*Spanning the future* by Syreeta Robinson-Gayle); by Angus Palmer and Robert Lerner on the development of air-beams to create large, speedily-erected enclosures, big enough to shelter army helicopters (*Beam me up*); and by Rachel Battilana, whose work has improved living conditions for refugees by better tent design (*Shelter from the storm*).

This edition of *Patterns* is full of practical information but it is more than a mere handbook; I am convinced that the reader will also find it a source of inspiration and delight. ■

Susan Dawson

Susan Dawson
Editor

Susan Dawson is an architect and
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WEAK MATERIALS

The strengths of weak materials Ian Liddell
Key lime Adrian Taylor
Card business Florian Foerster

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The STRENGTHS of weak materials

Strength is not an indispensible property of a building or structural material. **Ian Liddell** puts the case for so-called 'weak' materials and describes their advantages

Materials for buildings are selected for a variety of properties: environmental and structural performance, durability, or visual and tactile qualities. Structural engineering has tended to concentrate on the search for strong and tough materials. But this has been at the expense of research into the advantages of so-called 'weak' materials. In some situations these materials are not only acceptable but actually have advantages, as explained in this essay.

Cast iron bridge structures over railways and canals were common in the 19th century.

Photograph: Dave Jackson

What is meant by a 'strong' or a 'weak' material? The strength of a material is defined by its breaking strength, particularly in tension. The stiffness is defined by the amount of deformation under load: the less the deformation the stiffer the material. A material can also be tough or brittle depending on the mode of its failure. A brittle material will fail suddenly with very little expenditure of energy while a tough material will yield and absorb a lot of energy before it breaks. Examples of brittle materials are glass, brick and cast iron. They will suddenly snap under load and fail without warning. Examples of tough materials are steel and some polymers that are highly ductile. Rubber is really a brittle material in that it will fail suddenly under tension if a small crack is introduced. A toy balloon is a good example of this. Weak materials can be stiff or ductile in tension. If they are stiff they will usually fail so easily that they are automatically used in a way that takes this property into account. Very strong materials that are brittle, ie, that have low ductility, are very difficult to use to their full potential since they fail suddenly with no warning. Glass and cast iron are strong materials with no ductility. Cast iron was the first metallic material that allowed structures to evolve from the stone and timber age. With the industrialisation of ore extraction and processing in the 19th century it became plentiful and relatively cheap. Cast iron beams were used for railway bridges, but after a few failures a commission was appointed to investigate this use of the material and – not surprisingly – came to the conclusion that this use was inadvisable. Fortunately the Bessemer converter came into use shortly after and ductile steel rapidly surpassed brittle cast iron for important structures. Cast iron beams from the 19th century still exist in warehouses, railway structures and sometimes in domestic buildings. Occasionally failures occur, reminding us of the problems with this material but it also has several advantages – low cost of casting and greater resistance to corrosion than steel. Modern spheroidal graphite cast iron has a reasonable degree of ductility and is often used for structural components.

Iron or steel has continued to be the prime structural material for 150 years. The strength has increased only a little for general purpose rolled steels though reliability has improved. Steel of about twice the strength is available but is only used for special purposes where the additional deformation can be accepted. Developments in forming and welding have continued so that now many large, lightweight and slender structures have been completed. This has happened in conjunction with developments in the computational processing of the geometry of structures coupled to the analysis and the fabrication of the steel components. Amazingly we take the results of our structural analysis, calculated to infinitesimal accuracy, as gospel but the loads we use are at best correct to 10% and fabrication errors will cause large variations in the internal forces. The property that allows these structures to be built safely is ductility. Without that, modern welded steel structures would not be possible.

Cementitious materials

Lime mortar and concrete have been made since Roman times and probably a long time before that. Lime is made by burning limestone or chalk, basically calcium carbonate. This reduces to calcium oxide, with CO_2 being driven off, and water is added to turn this into slaked lime, $CaHO_3$. The resulting rich lime is then mixed with sand or ground limestone to make a mortar. The lime hardens by absorbing CO_2 from the air to return to calcium carbonate – a very slow process which does not happen under water. Because there is residual free lime, small cracks caused by movements can re-cement themselves. Lime mortar was used in very thin layers for ashlar masonry. Hydraulic lime is made in a similar way but using a limestone with a small clay content. This sets under water because of chemical reactions with the silica, iron or alumina. Similar effects were achieved with Pozzolana-type materials added to the lime. This originally came from a source near Mount Etna in Italy.

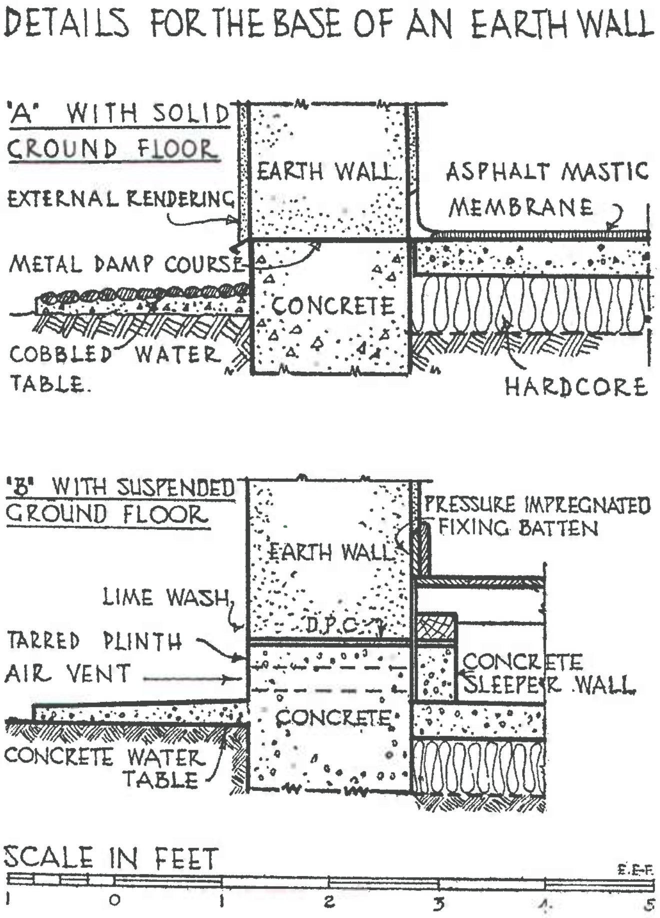
Other cements used in the 19th century included Medina cement made from soil from the Medina river on the Isle of Wight. Portland cement was first made in the early 19th century by mixing chalk and clay in suitable proportions before burning it. Today and for over 100 years Portland cement has been the dominant material in the construction industry. Cement and concrete technology has gradually improved over the years with the general aim of improving strength and durability. The table below indicates how strength has been successfully increased, by finer grinding of cement powder, by careful selection and grading of aggregates and recently by the use of additives to control setting time and to improve workability.

Concrete has become an industrialised standardised product that is supplied from central batching plants via mixer trucks.
The setting time can be delayed by delaying the addition of water and controlled by adding chemical retarders. It is delivered to the point of placement on site using pumps with long and high reach booms.

"Amazingly we take the results of our structural analysis, calculated to infinitesimal accuracy, as gospel but the loads we use are at best correct to 10%..."

	Tensile strength	Nominal compressive strength
Hydraulic lias lime mortar	0.07 mPa	
Lime mortar	0.04 mPa	
Portland cement and sand 1:3	0.7 mPa	
1-2-4 concrete 1950		20 mPa
1-1-2 concrete 1950		30 mPa
Basic concrete 2000		35 mPa
High performance concrete		80 mPa

Strength of various concrete mixes.



A construction detail from 'Cob, pisé and stabilised earth', a very practical guide to the subject written by Clough Williams–Ellis in the early 1940s.

Natural low energy materials

Today we are very conscious of the effects of burning fossil fuels on the carbon balance. Carbon is being taken from the ground and transferred as CO_2 and other organic compounds into the atmosphere faster than it can be reabsorbed by plants or converted back into $CaCO_3$ by marine organisms. The process of making lime and cement causes carbon emissions both from the fuel and from the limestone. There are also problems of increasing use of aggregates causing a downgrading of natural soils. To counter this, attempts are being made to construct buildings with less environmentally aggressive materials.

In the past, buildings were made with materials that were much less strong than those today. Cob and rammed earth (pisé) walls have been used for centuries in the south west of the UK and in Europe. In the late 40s the use of earth walls was revived, stimulated by the Arts and Crafts movement and responding to the need for houses and the lack of bricks. The material was re-revived in the 1970s with the hippy 'back to nature' movement as represented by 'The Last Whole Earth Catalogue'. Today its revival is based on the need for sustainability. Perfectly satisfactory houses – albeit with rather small windows – can be made from earth materials; they will last for several hundred years provided the walls are protected from excess rain. Repair of damaged cob or earth walls is difficult as new wet material will not stick to old so once buildings fall into disrepair they tend to be taken down. But the material is totally recyclable; the soil can be reused or returned to the ground in more or less the same condition as when it was dug.

Modern construction relies on industrialisation for speed and economy to meet the build rate of some 200,000 dwellings per year. It is difficult to conceive of estates of three-bed houses on the outskirts of Swindon being built of earth dug from the site – but it may happen. The challenge is to find low energy building materials that can be satisfactorily industrialised.

Stone

Oolitic limestone runs in a belt across England from Portland to Stamford. The most famous is Bath stone which was quarried in vast quantities in the 18th and 19th centuries. The stone is quite soft when first dug and can be readily cut into blocks. Even when hardened it can still be cut with a hand-saw. The cut blocks are thinly bedded on putty made with lime and Bath stone dust to build smooth ashlar walls. The crushing strength of a 50mm cube of Bath stone is 7-9mPa, it is one of the weakest stones on record and similarly the lime putty has practically no strength. Nevertheless Bath stone walls last for hundreds of years. Amazingly they seem to be built in huge lengths without any expansion joints yet never show any signs of cracking. In comparison, concrete, to be durable, is required to have a cube strength of 35mPa and 30mm cover to the steel. One wonders why Bath stone, Roman concrete and mediaeval concrete made with lime and flints – all of much lower strength – has lasted so well.

Another interesting feature of old Bath stone walls is that they do not have cavities, although thick walls are usually made in two skins with rubble and mortar between. In some houses in Bath the walls are single skins of 100mm thick stone blocks. Of course they do not have very

good insulation but damp penetration is not the problem that one would expect for such construction. Bath stone walls have another useful property – they can be re-modelled and repaired quite simply; damaged stones are simply cut out and replaced with new stone. After a few years it is difficult to tell the difference and stone buildings can have several different lives over a long period. Stones from demolished walls can be re-used provided lime mortar has been used.

Blocks

Bricks and blocks come in such a wide range of qualities. In the 19th century, bricks were used in vast numbers for constructing railways and docks as well as houses, which were then built with solid walls. With the use of Portland cement mortar, the walls became thinner – and the cracks larger. To overcome the problems of low insulation and water penetration, cavity walls were introduced. A complex system of cavities, wall ties, insulation and drainage was developed to achieve a satisfactory external wall.

Autoclaved, aerated concrete blocks are sold in this country and used as the inner leaf of cavity walls. On the continent they are sold as Ytong, Siporex or Xella and are used as solid external walls that provide all the necessary insulation. The inner face is skimmed with plaster and the outer face is rendered with a durable waterproofing product. The blocks come in a range of sizes up to 365 x 624 x 624mm. They are precision cut with handholds and are laid in thin beds of glue-mortar. They are of course of very limited strength – from 2-7mPa, with densities varying from 0.4-0.65kg/m^3. Yet they are used for two- and three-storey houses. Floors and roofs can also be made with Xella concrete planks and there is a range of details for junctions to maintain continuity of insulation. For some reason this system is not available in this country – probably because of the British fixation with cavity walls and brick houses. These are amazingly labour intensive and workmanship dependent, especially in terms of detailing at windows and doors. One would think that it is only a matter of time before factory finished quick-build blocks supersede our traditional methods.

Plaster

Plaster is made from lime or gypsum or a mixture of both. Both materials are weak in tension so the base material is used as a composite with fibrous materials to give it sufficient strength. Lime plaster was most often made with cow hair but hair from other animals was also used. Hair enabled the wet plaster to hang together and strengthened the hardened plaster. Between 50-60% of the mix was soft sand which acted as a filler. As with lime mortar, lime plaster sets by the absorption of atmospheric carbon dioxide and so it is a very slow process. The addition of calcium sulphate to the lime hastened the set of the plaster. Lime plaster was usually applied directly to stone or brick walls or to timber laths. The aim was to create a hard,

Above and above right: solid blockwork external walls are common in Europe

Above left: although weak, Bath stone lasts for hundreds of years.

The Reading Room at the British Museum has mouldings of papier-mâchè.

smooth, dust-free surface that could be painted. In East Anglia reeds were sometimes used instead of timber for the laths. The process of lime plastering resulted in a surface that was not precisely flat and which could not have sharp corners; edges would be mastered by timber moulds or would be well rounded by hand. While lime plaster has romantic connotations of hand finished buildings, the process is very wet and the plaster takes a long time to harden. It is not suited to modern building methods and has generally been superseded by gypsum plaster or dry-wall construction using plasterboard.

Gypsum

Gypsum plaster is cheap, ubiquitous and unfashionable. Although it has been in use for several thousand years, it is one of the primary modern building products because its production has been industrialised to make boards and fibrous plaster mouldings. Both of these are composites: plasterboard is reinforced with paper, often from recycled sources; fibrous plaster is reinforced with fibres that are very often organic, sisal or flax. A high proportion of the gypsum used to make plasterboard and other related products comes from the flue gas desulphurisation process at Drax power station. Along with 10% of UK electricity, Drax produces 16,000 tonnes of gypsum each week which is sent to British Gypsum for onward processing and comprises more than 50% of their output. Because the chemistry of gypsum is reversible, scrap plasterboard can be recycled back into new plasterboard: British Gypsum recycles 1,200 tonnes a week, a small amount but with the right incentives and organisation this could be increased.

For wet application, gypsum plaster is made with a range of fillers and additives. The main filler for base coat plaster is vermiculite which produces a light soft plaster that can be readily moulded. Finished plaster provides good fire resistance and can be readily repaired if damaged. It is not very resistant to damp, and excessive heat will cause it to break up if maintained for long periods. Gypsum concrete is used as a levelling screed and sound reduction material on timber floors in the US. The strength of this material is quoted as 8.3-13.8mPa. There is no reference to gypsum concrete being used structurally although it probably could be used with fibrous reinforcement as a composite with timber or cold formed steel joists. In domestic and dry wall construction plasterboard certainly contributes to the shear stiffness of the wall but is not normally taken into account.

Cardboard

Cardboard is in fashion as a recyclable, low energy material. As a structural material it suffers from creep; it also has to be kept dry (see the following *Patterns* article: *Card business*). As a finishing material of compacted cellulose fibres, cardboard has a long and mixed history.

The interior of the British Museum Reading Room has mouldings made from papier-mâchè, which have survived for about 150 years. Low cost ceiling tiles and wall-boards are also made from cellulose fibres; tiles perform very badly in humid conditions – they warp and eventually fall out.

Internal floors

A high percentage of structural materials go into flooring systems in housing and multi-storey commercial buildings. Around 100 years ago a popular fire resistant flooring system was a clinker concrete infill between steel joists. The clinker came from local power stations and was mixed with cement on site. It was a local solution, using a waste product, and the floors are still in use. Modern structural flooring systems are frequently based on profiled metal sheet with concrete topping. The concrete acts as a composite with the decking and helps provide fire resistance. The tendency is to use grade 35 concrete. Tests have been carried out on lightweight concrete of much lower strength but this system does not seem to be used.

The recycling of concrete is often discussed as a means of reducing aggregate extraction. At the Wessex Water headquarters in Bath, recycled concrete aggregate was used for floors but it came from old railway sleepers which had a very high strength; the resulting concrete was grade 35 and was possibly more expensive than new aggregate concrete. There seems to be no reason for the use of a high strength material; concrete used with metal deck floors could have a much lower strength – it could be aerated or made with crushed concrete or brick. Unfortunately the concrete industry is not geared up to producing such material in the large volumes that would have an impact on recycling, and clients need to be given confidence that the material will be durable.


Photograph: Mandy Reynolds, Fotoforum

The concrete floors of the Wessex Water headquarters in Bath contain recycled aggregate.

The future

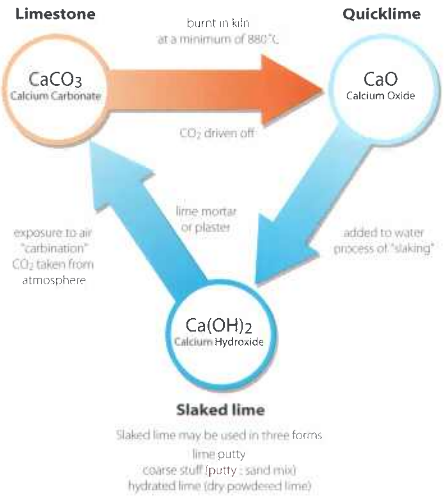
An important feature of building materials is that they have to be easy to use and readily repaired or altered, and to suit the modern construction industry they have to be suitable for industrialisation. Low energy and sustainability are becoming drivers in the selection of materials but they are not going to supersede the drive for higher quality buildings at reduced cost.
The move to industrialisation has happened progressively, driven largely by increasing labour costs and the expectations of owners for better quality at lower costs. Firstly, materials were produced in greater volumes, as with iron and cement. Next there were pressures to reduce labour costs by improving construction processes on site and through off-site prefabrication (stone and timber were both prefabricated in mediaeval times but using manual methods). We are now in a third phase where computer-aided technology is being used to prefabricate components off-site to greater accuracy, speed and quality than before. This has already happened in the case of steel components and is happening with cladding – and with steel reinforcement at the Heathrow Terminal 5 site. We can expect this trend to continue, with the prefabrication of traditionally in-situ elements such as foundations and with other elements such as internal walls, roofing and servicing components. The change will have an impact on materials and the way they are processed and used; in the process it will also reduce waste. ■

Key lime

Adrian Taylor investigates the reasons for the recent popularity of lime mortars. He describes a research project to establish data on the strength of lime mortars and outlines some recent projects in which lime was used

Lime cements, formed from limestone burnt at between 900°C and 1100°C, have a long history of use. The Romans are probably the best known users, but building lime was also a popular material in many other parts of the world. In the past 100 years lime cements have been largely replaced by Portland cements, formed from the burning of limestone and clay at approximately 1500°C, which set quicker and can develop higher strengths. But in the last decade lime cements have re-emerged as a useful building material.

The 'lime cycle' – the burning, slaking and hardening of non-hydraulic lime.



Lime as a construction material

The chemistry of lime as a construction material is best illustrated by reference to the 'lime cycle' shown below left, since there are a wide variety of methods of manufacture and use of calcium products – "limes" – in construction.

Calcium carbonate, as limestone or chalk, is burnt in a kiln to form quicklime. When immersed or soaked in water, a rigorous reaction turns quicklime into calcium hydroxide, also known as lime putty. This can be dried and ground and is then known as calcium hydrate.

A non-hydraulic (air) lime will absorb carbon dioxide into some of its mass and turn slowly back into calcium carbonate, hence the term 'lime cycle' to describe this process. A hydraulic lime, generally from rocks containing more clay than a non-hydraulic source rock, can also turn into calcium carbonate in this way. In addition, some of its clay-derived compounds will set independently of exposure to the air; this means that the set of a hydraulic lime is generally more rapid and reliable than that of a non-hydraulic lime and can, if necessary, occur to an extent in mortar deprived of air, for example underwater. The hydraulicity of a lime should be selected for its specific application: non-hydraulic limestones, and those that are only feebly or moderately hydraulic, can be adequate or even preferable to stronger morters for many common building applications including mortars. An index classifies a lime made from a certain parent stone as either 'non', 'feebly', 'moderately' or 'eminently' hydraulic, according to the relative concentrations of various key minerals.

Historical and material compatibility with masonry

What are the reasons for the re-emergence of lime mortars? One of the key functions of mortar in a masonry wall is to draw water away from the face of the masonry unit, reducing the freeze/thaw action. In a lime mortar the joint generally weathers faster than the masonry unit and occasional re-pointing will be necessary.

Lime mortars have a porous open structure which is ideal for this purpose, and are visually more attractive than a dense, close-textured joint. The denser, less absorbent mortars made from mixes rich in Portland cement or indeed, eminently hydraulic lime, tend to weather slower than the stonework and in some circumstances can actually accelerate the weathering of the stone by shedding water onto it. It is commonplace to see Portland cement-based joints standing some distance proud of the wall mass in re-pointed historic masonry, which gives an odd appearance.

Lime mortars are known to be more tolerant of thermal movement and/or settlement of foundations than rigid Portland cement mortars; they generally have greater elasticity.
Much experience/anecdotal observation of movement joint requirements for masonry built in lime mortar relates to historic 'thick' wall construction; there is a need for further investigation in order for movement joint frequency to be specified with confidence for 'thin' wall construction.

An advantage often quoted for lime mortars is the environmental benefit of the lower temperature burning process compared to the temperature required for Portland cement manufacture.
To be fair, this benefit can be offset by the relative inefficiency of some lime kilns compared to a continuous process Portland cement kiln.
The mortar will, however, re-absorb some of the carbon dioxide produced by its manufacture, during its lifetime. There is a desperate need for factual research into the whole life energy costs of the manufacture, placement and in-use processes involved in the use of lime mortar, to determine whether it offers any environmental benefits.

A large part of the market for lime cements has been the refurbishment/conservation industry, where lime mortar is often the only appropriate material for repairs/reconstruction of historic stonework. This has ensured the survival of many small-scale, craft-based practitioners familiar with lime materials. The use of lime cements in both repair and new-build work brings the added satisfaction of supporting these craft traditions.
In parts of continental Europe, notably France, masons have continued to use lime mortars in general practice. In Scandinavia most rendering work is with lime cements, often air-entrained, so that set is less affected by cold or damp conditions. Much of the recent work in the UK with lime cements has used imported products.

Research project with Paisley University

With many factory-produced lime products, modern milling practices lead to a fairly homogeneous product with little range in chemical or particle size makeup. Paisley University and some of its industrial research partners have constructed an experimental lime kiln (ELK). It uses the historic method of firing limestone; limestone and fuel are placed together in the kiln and are initially fired from the bottom of the kiln until the fuel within it starts to burn. It can burn batches of up to 20 tonnes, which is still fairly small by industrial standards. The kiln produces material with a heterogeneous distribution of particle sizes, containing a mix of unburnt and partially burnt lime due to the range of temperature distribution within the limestone/fuel mass. Mortars will be made from the resulting quicklime using the 'hot' mixing method whereby quicklime is mixed into wet sand in a paddle mixer. They will then be subjected to physical and chemical testing.
The DTI-funded research project was set up to ascertain whether or not limes produced in such a way are likely to perform better in durability and/or strength terms than mortars produced using dry milled hydrate from a larger-scale continuous burning process.

A view of the experimental lime kiln (ELK) at Paisley University.

With many factory-produced lime products, modern milling practices lead to a fairly homogeneous product with little range in chemical or particle size makeup

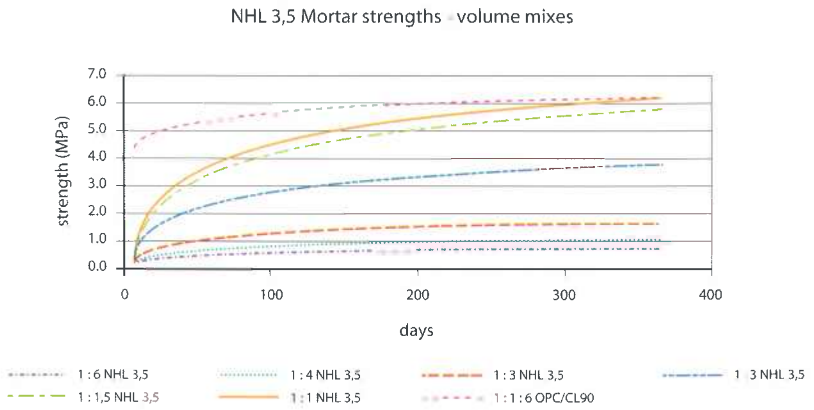
Trial panels of masonry built using lime mortar are invaluable for investigating and proving mix design, laying and protection methods

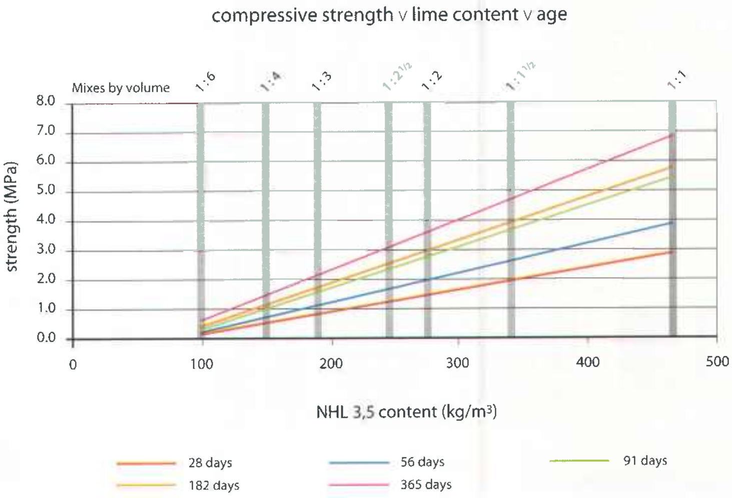
Strength data and testing

Published data for compressive strength of walls built with lime mortars includes CP111: Part 2: 1970 – the masonry code, which was the forerunner of BS 5628, whch quotes values of working stress for brick and block walls built in "hydraulic" and "non-hydraulic" lime mortars. The bridge design code BD21/93 quotes values of ultimate stress for normal brick and normal stone masonry using "lime mortar" and values derived from these are repeated in the perhaps more widely known IstructE publication, *The appraisal of existing structures*. These values should only be applied with caution: in all masonry work there can be considerable variation due to material, workmanship and climatic factors, and historically designers of masonry work have tended to allow for this. Notwithstanding this caveat it is straightforward to design calculated brick, block or stone masonry using a lime mortar, provided it can be classed into a strength category either using cube tests on samples or by its categorisation in BS 5628 terms.

The Foresight project2 by Bristol University and their partners suggests extending type (i) to (iv) designations in BS 5628 to cover lime mortars, which generally exhibit lower compressive prism strengths. Given its slower rate of strength development, 56- or 91-day mortar prism strengths are generally of more relevance than 28-day strengths. It is worth noting that walls in any kind of masonry often operate at fractions of their vertical strength capacity, because other issues such as thermal or acoustic requirements or building geometry, dominate.

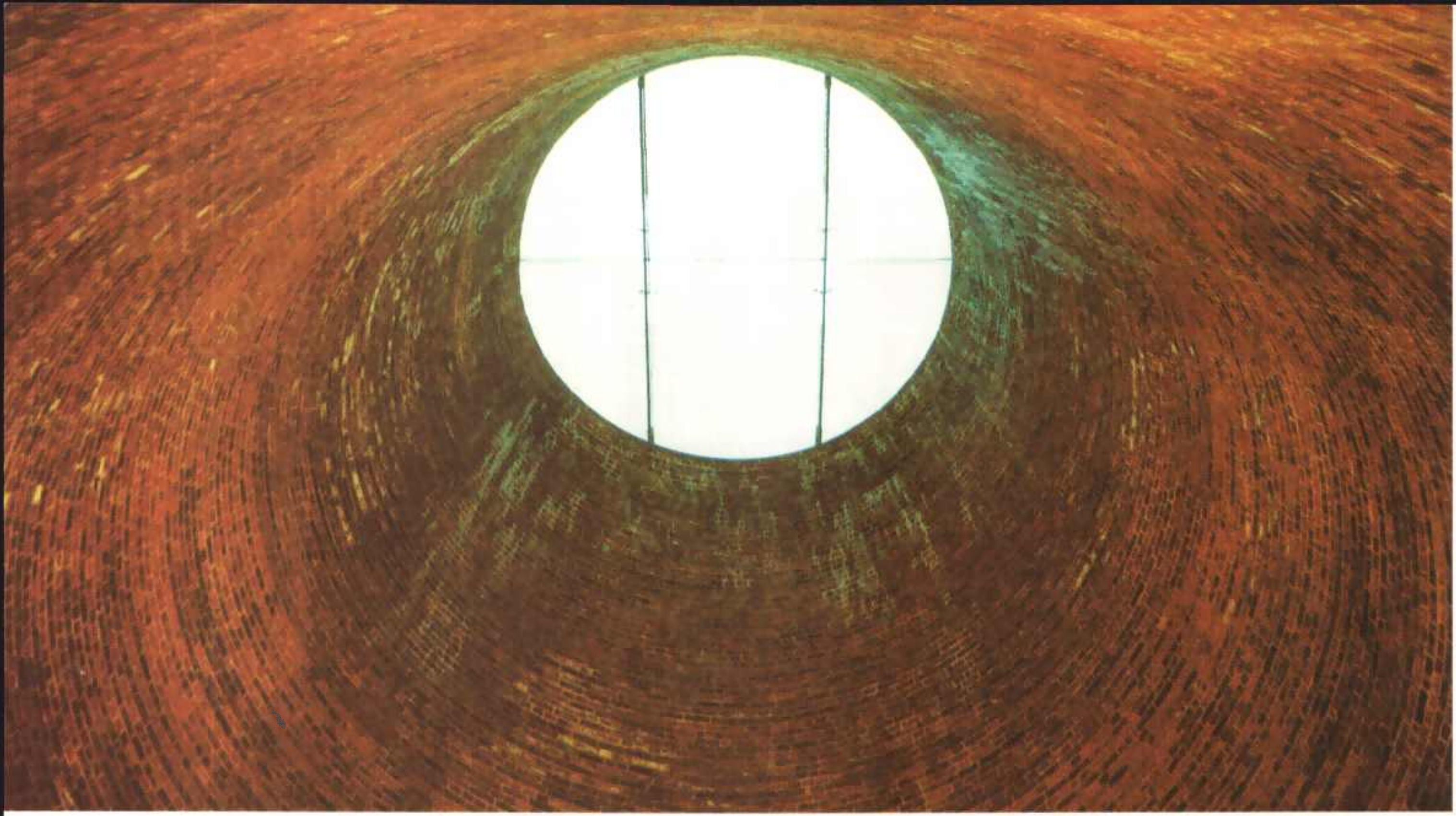
There is currently an absence (in the author's knowledge) of data on the flexural strength of masonry walls built with lime mortar; the Paisley project hopes to establish data on flexural strength parallel and perpendicular to the bed joint, from panel testing. In the author's experience, horizontal strength capacity of masonry panels is often determined by mortar/masonry unit adhesion, and this property could be expected to be good for lime mortars, which are significantly more flexible than mortars made from Portland cements. It will be interesting to see whether the data we acquire from the tests support this hypothesis.
Trial panels of masonry built using lime mortar are invaluable for investigating and proving mix design, laying and protection methods. They will also set the standards in appearance and possibly strength terms for the kind of work which will be accepted or condemned. The wise designer will specify the construction of samples for visible work even when using Portland cement mortars, both in order to establish a benchmark and to check for the risk of efflorescence or discolouration of the masonry. ■





Above: table showing strength development of hydraulic lime mortars.

Right: table showing relationship between lime content and compressive strength.



A 16m high brick cone, a reconstruction of the structure in which glass was traditionally manufactured, forms the entrance to the museum.

Case study: World of Glass, St. Helens, Merseyside

The building houses exhibitions by Pilkingtons and the St. Helens glass industry. The entrance leads through a 16m high cone of 327mm thick brickwork; this in turn leads to a glass pavilion – the circulation area and gallery – which is flanked by two brick boxes housing exhibitions. While some Portland cement was added to the mortar of the brick cone to give a rapid dependable set in the winter conditions then prevailing, the brick walls of the exhibition buildings used lime mortar from a blue lias limestone of between 'moderate' to 'eminent' hydraulicity. They were load-bearing diaphragm fin walls constructed from brick and block leaves 225-327mm thick. Construction during winter meant that the work had to be protected as it was completed. The thermal mass of the masonry forms an active part of the heating and cooling strategy for the building, absorbing and then releasing heat to its surroundings. Finished in 2000, the building combines the ancient technology of lime masonry with the relatively old technology of glazing in a modern and exciting way.

Architect: Reid Architecture
Structural and building services engineer:
Building Design Partnership and
Peter Stephens Partners

The author would like to thank John Addison of Peter Stephens Partners, John Hughes at the University of Paisley and Gavin Jack and Stuart Brumpton of Buro Happold for their input in this article.

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Card business

It is possible to design elegant and economic cardboard structures. **Florian Foerster** outlines this material's design parameters and gives examples, with construction details, of some completed cardboard structures

Cardboard and paper products have been used for decades in the fields of interior and product design. But cardboard has not been widely used in structural engineering and construction despite its potential advantages of flexibility, low material cost and ready availability.

Only a few cardboard structures have been built, each designed as a one-off by designers specifically interested in cardboard as a structural material. As structural design with cardboard and paper products is not yet codified, the designer relies not only on empirical knowledge, project specific tests and the understanding of first principles of engineering, but also on a willingness to take extra design responsibility. As a result, cardboard allows the designer to pursue structures which are not based on precedent and go beyond conventional structural ideas.

Cardboard responds well to current issues of sustainability: it is primarily manufactured from waste and can easily be repeatedly recycled; it has excellent acoustic and thermal properties; and it is very safe and easy to work with on site.

Cardboard product range

A variety of standard cardboard and paper products is available, mainly manufactured for the packaging industry.

Tubes: Tubes are manufactured by rolling multiple layers of spirally wound paper plies over a spindle. The layers are glued together by starch or PVA. The tube wall thickness depends on the number of plies but can range up to 16mm. Tube diameters up to 600mm are commonly available. The top and bottom layers of the wall can be made using a different paper, to give a treated, coloured or stronger paper on the surface. Tube size is not limited by the length of the spindle but by transportation.

The winding of the paper plies effectively means that the longitudinal fibres of the tube are not continuous. This reduces the structural capacity under bending and increases the risk of delamination.

Panels: Cardboard panels are manufactured by laminating sheets of paper or particles. Honeycomb boards can be made by pressing paper pulp into a honeycomb mould and then sandwiching the honeycomb structure between sheets of paper; by gluing multiple sheets of paper together and pulling them apart; or by gluing two halves of moulded honeycomb panels together.

Panels are generally between 1.2m and 1.5m wide and 2.4m to 3.6m long. The thickness and build-up varies from single layer sheets of 1mm thick to 65mm thick sheets of honeycomb cardboard. Sheets can be laminated or mechanically bonded together to achieve thicker sections. Sheets can be curved and easily cut in any shape. It is possible to laminate different types of paper to achieve a different surface to the interior of the panels. Honeycomb panels are the most commonly used structural cardboard products. They can be cut to size by hand or by CNC.

Sections: A number of L-shaped, T-shaped and rectangular hollow sections are available in cardboard. They are generally single layer elements up to 4mm thick. Sections are manufactured as connection and stiffening elements for furniture products or packaging. They can be used like rolled steel sections to build up larger sections or to connect tubes or panels.

Structural forms

Like other structural materials, cardboard is best used in forms that use its inherent strength and characteristics. Due to the manufacturing process cardboard is an anisotropic material, hence the material strength varies greatly depending on the direction of the stresses. It is most efficiently used to transfer only axial and in-plane stresses; this should be kept in mind when deciding the structural form and load path.

Columns: Axially loaded columns can be designed using tubes. Load bearing columns are generally of a large diameter and the ratio between the tube wall thickness and diameter is high – hence tubes tend to fail locally in buckling. Overall buckling of the tubes is less likely due to the low slenderness ratio of the sections.

Beams: Beams can be designed using sheets of honeycomb cardboard or sections. The support conditions of beams need to be considered carefully to avoid stress concentration and minimise shear deflection and shear creep. The use of tubes as beam elements is not recommended. Their bending capacity is low, as the outer surface layer is not continuous.

Walls: Flat panels can be used for the design of walls. These can either be load-bearing and self-supporting or mounted to a primary frame. In both cases the stiffness of the wall and its performance under lateral loads are critical. The stiffness can be enhanced by stiffeners, cross walls or the design of the wall as a folded plate. If the panels are mounted to a primary frame the cardboard becomes primarily a cladding material.

> "Like other structural materials cardboard is best used in forms that use its inherent strength and characteristics"

The material properties of cardboard

Cardboard tubes	
Tensile/compressive strength	8.1 N/mm^2
Design tensile/compressive strength taking account of the creep effects and a FOS of 10	0.8 N/mm^2
E value	1000 - 1500 N/mm^2
20mm thick honeycomb sheets	
Bending strength	6.9 N/mm^2
Design tensile/compressive strength taking account of the creep effects and a FOS of 10	0.6 N/mm^2
E value	1000 N/mm^2

All values relate to a stress direction parallel to the surface. Stresses perpendicular to the surface have not been tested.

Basic load test of bolted connection between sheets of honeycomb cardboard. The local playground was used as a test site.

Design parameters

As a result of the four projects described further on in this essay (see overleaf), tentative design parameters for cardboard have been established. Based on project specific tests and particular products, they can be divided into material properties and connection design. As there are no general structural requirements and standards for cardboard products, they need to be reassessed prior to each new project.

Connection design: Connections between cardboard panels can be bolted or glued. A well-bonded glued connection – it can be assumed – is stronger than the surrounding cardboard, which will be the weakest element in the design. Glues can either be PVA or epoxy based. Bolted connections behave differently and generally form critical points in the design. Failure occurs due to the different strengths of metal bolts and washers and cardboard panels. This can lead to stress concentration and in the case of failure, tearing of the cardboard. It is advisable to use large diameter bolts or sleeved bolts and large diameter washers. If possible the loads should be transferred in shear between the washers and the panels. Detailing of the joints should take account of edge distances, number of bolts and bolt spacing.

Analysis and structural models

The choice of structural models used for analysis depends on the complexity and function of the building. Cardboard structures can, in principle, be analysed in the same way as any other structure, as long as the stresses stay small and deflections low. Any analysis should concentrate on the detailing of the connection points as these tend to be difficult to represent in a model and are the areas where failure is most likely to occur. Analysis should be based on simplified models that can easily be checked by hand and clearly show the force flow. As an example, the most efficient way to check the forces for the complex shapes of the Hiroshima Art Prize project (see p24) was simple strut and tie models.

The assessment of long term deflection is highly complex as cardboard is an anisotropic material and the stiffness is also governed by factors such as moisture content, magnitude of stress and duration of loading. It is advisable to design out the need for long term deflection check. This can be achieved by a generous use of stiffeners and by avoiding the use of cardboard in bending.

Initial deflection is strongly influenced by the moisture content of the cardboard at the start of construction. Commonly, cardboard delivered to site is still 'green'; it shrinks significantly during the first month of construction and building usage, especially if the building is relatively dry and heated.

Empirical knowledge and tests

Buro Happold carried out or commissioned the following tests of cardboard structures and elements:

- Load-test on bolted and screwed connections of 20mm honeycomb boards
- Fire tests on honeycomb cardboard panels
- Load-test (bending and axial loads) on paper tubes.

Full test reports are outside the scope of this article.

Durability

Durability issues are important factors in the design and specification of cardboard structure. The strength and stiffness of cardboard is strongly influenced by the ease with which moisture can penetrate. Cardboard itself is a hygroscopic material. This means that it will try to attract moisture from the atmosphere, which can severely reduce its strength. If it is allowed to become wet, cardboard deforms and finally becomes a pulp. If used outside, water protection can be achieved in a number of ways:

Chemical treatment: Water-resistant cardboard is manufactured with additives in the paper pulp. While this achieves water resistance, the use of additives means that the boards can not be recycled.

Painting: The faces of the cardboard can be coated with polymeric paint or laminated with building paper or metallic foil. Painting cardboard surfaces tends to deform the sheets if not carried out on both sides. Therefore, the cardboard should be painted off site and during manufacture.

Overcladding and internal use: Cardboard can be limited to areas where it has no direct contact with the external atmosphere. This can be achieved by overcladding with water-resistant panels or by using it only inside the building.

Cost

Cardboard as a raw material is relatively inexpensive. However, recycling can only be achieved by a manufacturing process that is highly repetitive and standardised. Recycled cardboard is only economically available in a number of basic shapes. As long as standard elements are used, cardboard presents an economic material, especially for complex interior structures. Any external cardboard structure is likely to involve additional costs for extended design time, testing of details and materials, and modifications to the standard products.

Recycling

Cardboard is a recycled material that itself can be recycled. Consequently it is a material with very low embodied energy and almost no material take. The critical issue is not cardboard itself but other materials used for connections, weather protection or additional structural elements. ■

Case study: Westborough School After-School Club

The walls and roof of the single-storey building – the first permanent cardboard structure of its kind – are formed of cardboard tubes supporting cardboard panels which are folded in an 'origami'-like sequence. They rest on a concrete plinth.

Each 150mm thick panel consists of three 50mm thick honeycomb cardboard sheets glue-pressed together and edges with timber. Maximum panel size (1.5m by 2.7m) was determined by the length of the sheets and the width of the glue press. The timber edges allowed the cardboard panels to be jointed to other materials.

The tubes are a standard product with an aluminium 'sandwich' layer to improve durability. The thermal performance of the panels, at 0.3W/m2K, fulfilled contemporary Building Regulations requirements. Protection from external elements, especially water, involved a three-step approach:

- Water-resistant cardboard – additives were introduced into the pulp mix during manufacturing
- External coatings to various elements – a poly-coated layer was applied to the inside and building paper on the outside similar to normal practice in timber framed buildings
- Over-cladding – although a coating layer is waterproof when first installed, it would be vulnerable to moisture if damaged. A waterproof barrier was installed; internally of pin board material and externally of wood fibre and cement panels.

Architect: Cottrell + Vermeulen Architecture
Structural engineer: Buro Happold

> "Cardboard is a recycled material that itself can be recycled. Consequently it is a material with very low embodied energy and almost no material take"

Left: interior view shows folded roof panels.

Far left: the walls and roof of the after-school club are of folded cardboard panels.

Photographs: Adam Wilson

Photograph: Adam Wilson

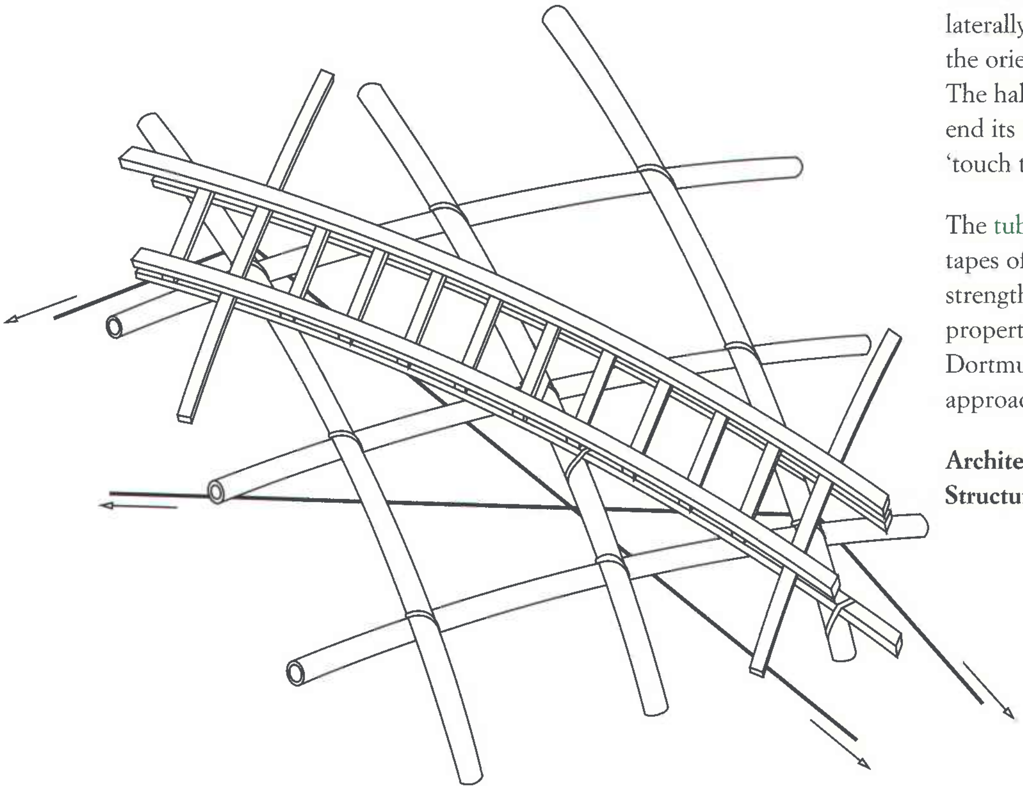
External view of the Japanese Pavilion.

Case study: Japanese pavilion, Hanover Expo

The theme of the exhibition, 'Design for planetary continuance', required pavilions to be designed to demonstrate reduced use of resources and CO_2 emissions. The architect Shigeru Ban, working with Buro Happold, designed a pavilion hall formed of cardboard tubes clad in a paper membrane. The bending flexibility of the tubes was used to create a grid shell construction. The amphora-shaped hall – 72m long, 35m at its widest point and 15.5m high – was built by pushing up a flat grid of regularly spaced tubes into a more rigid doubly-curved form, stabilised laterally by rigid end walls and longitudinally by the orientation of the tube grid on the bias. The hall was designed be totally recycled at the end its short life, reducing waste and helping to 'touch the ground lightly'.

The tubes were formed of three glued spiral card tapes of an exact moisture content and structural strength. Their design was based on the material properties established in tests at the University of Dortmund within a partial factor of safety approach similar to EC5 for timber structures.

Architect: Shigeru Ban
Structural engineer: Buro Happold



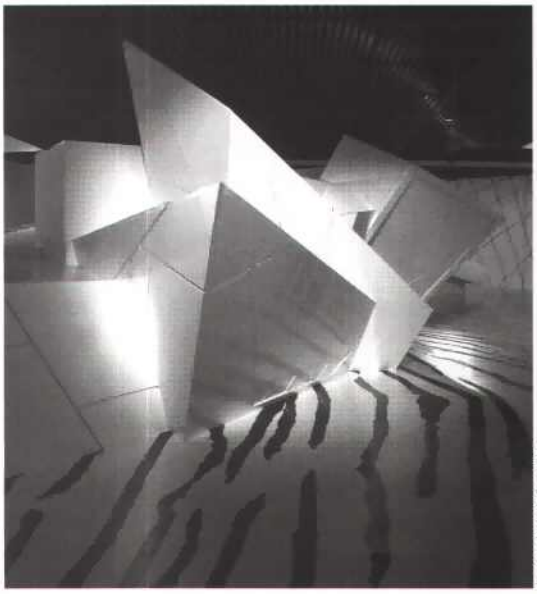
Left and below: the tubes act as armature to a series of wire-stiffened timber ladder beams, which provide in-plane shear stiffness and out-of-plane bending stiffness to prevent the shell form buckling.

Case study: Exhibition models for the Hiroshima Art Prize

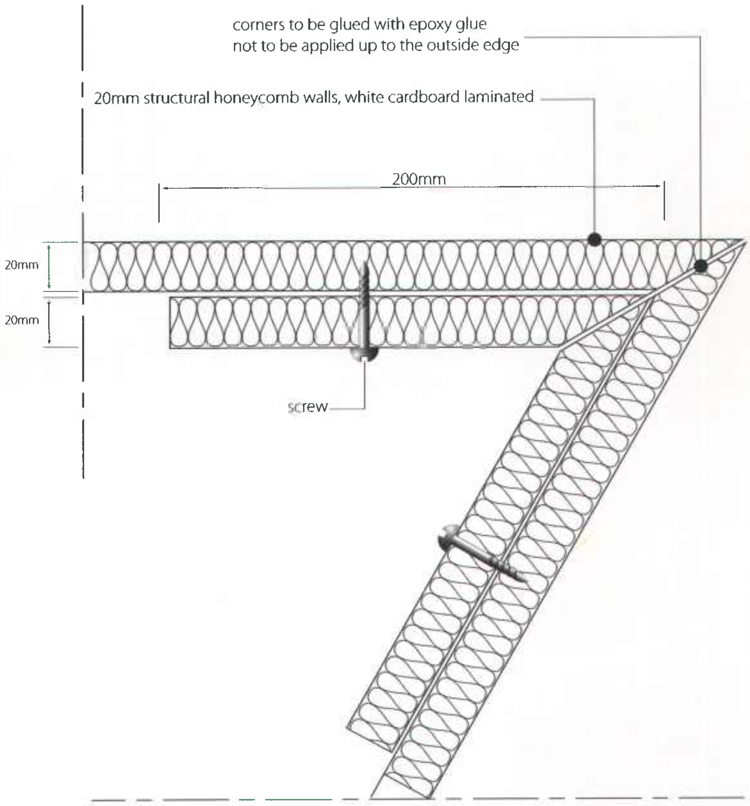
Architect Daniel Libeskind was awarded the Hiroshima Art Prize in 2001. Following this, four large-scale building models of recent projects by Studio Libeskind formed the centrepiece of an exhibition that started in the Hiroshima Museum of Contemporary Arts in July 2002 and moved to the ICC Museum in Tokyo at the end of 2002. The models are approximately 30m in plan and 10m in height. They are entirely constructed from a modular box system of 20mm honeycomb cardboard sheets, glued and jointed together. The joint – a cardboard angle glued and screwed to the inside of the facing boards – carries the forces and the screws are used for positioning only. The glued connections form a structurally rigid edge. Once glued, each box formed a stable and rigid unit which could be transported into exhibition areas and bolted to adjacent units. Small access doors in one face allowed them to be bolted together and gave access into large models.
The models were analysed using simplified plate models and hand calculations. For the larger cantilever and tower shapes a simple strut and tie model was imposed on the structure to determine the forces. The models were analysed for strength and overall stability only. Creep and long-term deflection issues were not analysed because of the temporary nature of the project, but creep issues were addressed by detailing each model as a highly redundant structural system.

Architect: Studio Libeskind
Structural engineer: Buro Happold

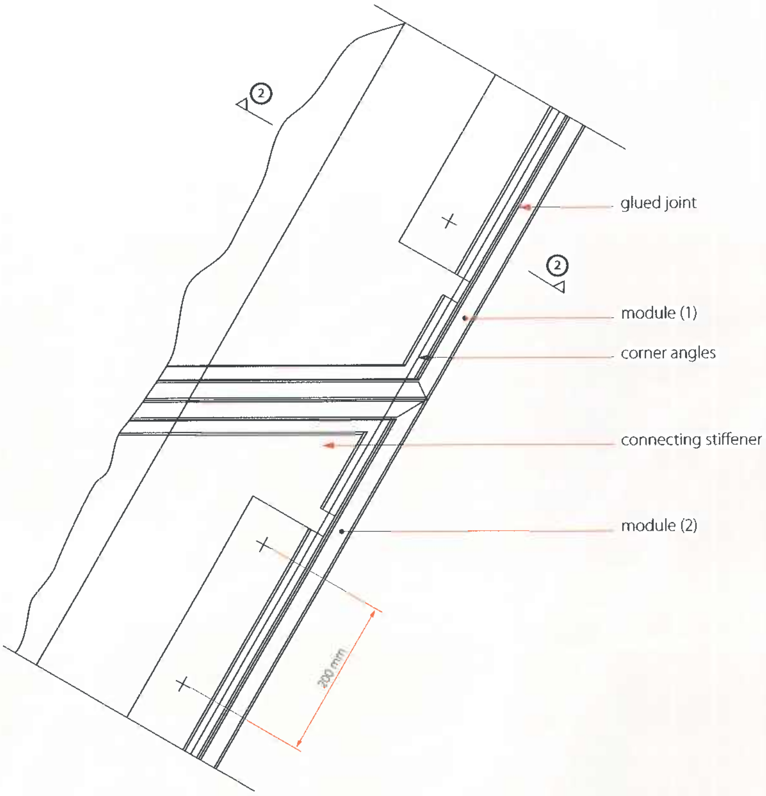
25m x 6m model of the extension to the Denver Art Gallery.



Photograph: Martin Ostermann



Typical corner connection. The inner angle can be varied to achieve different volumes.



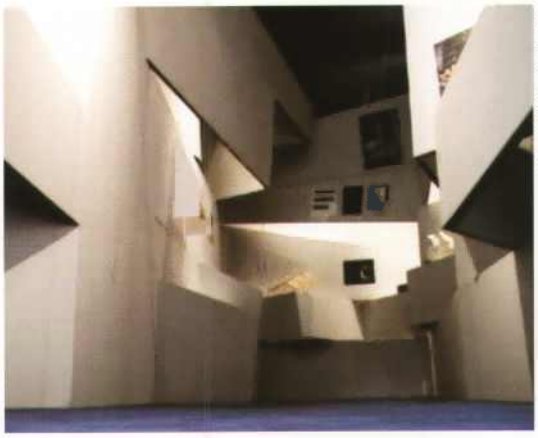
Typical connection between modules for the Hiroshima Art Prize project.

Case study: Building Centre Trust exhibition, London

The exhibition investigated the use of working models in the design process. The models are housed in a structure composed of five layers of cardboard panels, stacked to form walls which loosely follow the outline of the exhibition space. The panels change in height and fold in different directions to the ones above and below; they are all flat but not generally vertical. The folded arrangement creates steps and 'shelves' on which the designers' models are positioned.

The overall stability of the structure is achieved by the folding geometry of the walls and by overlapping the panels, so that, for example, the folded portion of an upper panel is triangulated with the straight portion of the panel below it and vice versa. The panels are of 30mm thick honeycomb cardboard, faced both sides with aluminium foil to give resistance to spread of flame; they have a thin white paper finish.
The panels are self-supporting. Folds at panel junctions are made with 50mm wide brass hinges screw-fixed to the battens; the joint is reinforced with white card angles which were glue-fixed on site, giving rigidity to each layer of panels.

Architect: magma architecture, Berlin
Structural engineer: Buro Happold


Photograph: Magma Architecture

Internal view of the Building Centre Trust exhibition.

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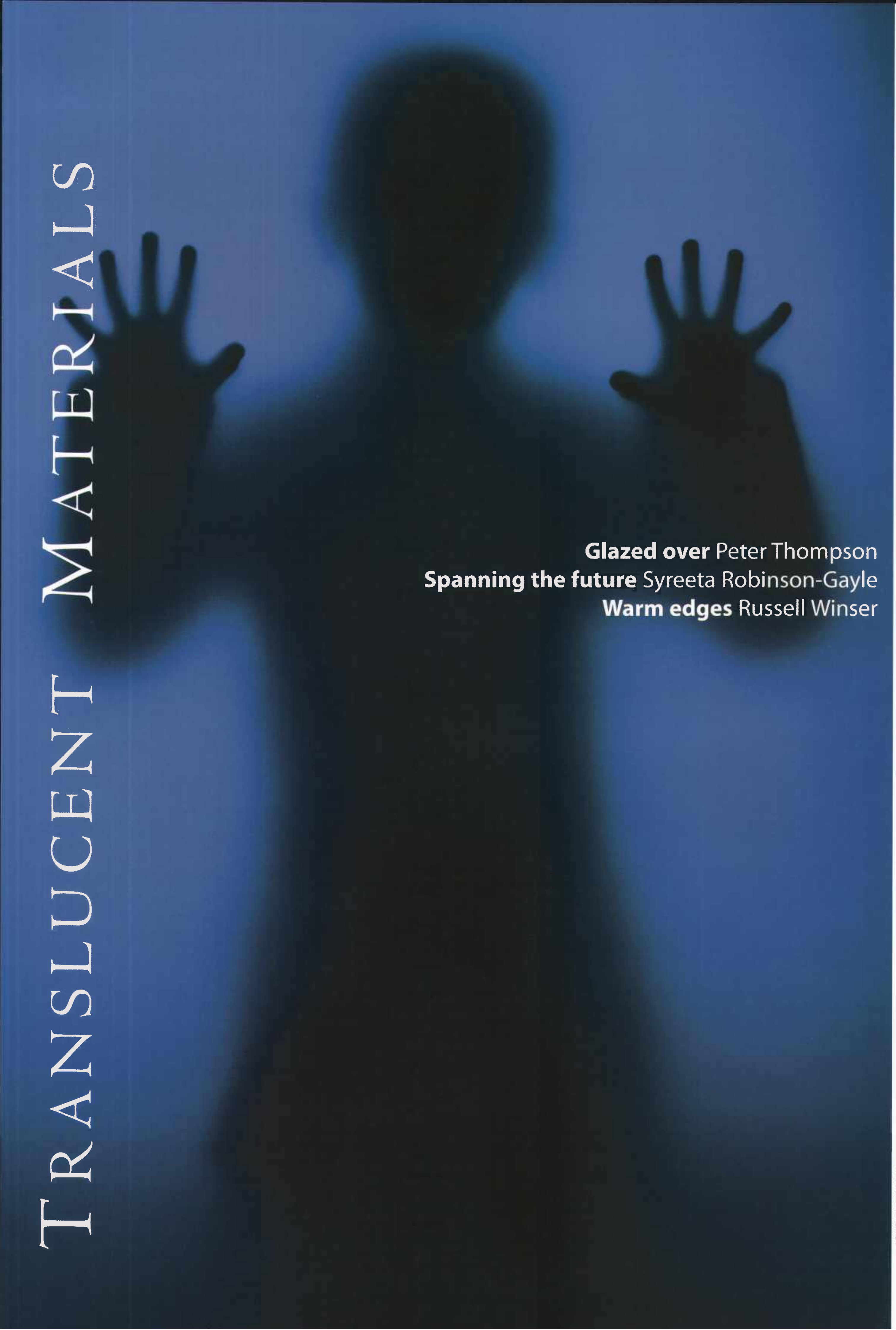


TRANSLUCENT MATERIALS

Glazed over Peter Thompson
Spanning the future Syreeta Robinson-Gayle
Warm edges Russell Winser

© Piotr Powietrzynski / Alamy

Glazed over

The specification of a glazed facade is by no means a simple task. **Peter Thompson** describes the complexities of specification, supply chain and technology of an innovative new glazed facade

New materials, processes and products are continually being developed in the search for better performance. Each supplier is striving to improve the performance of a particular material or process, with magazines devoted each month solely to 'what is new' in building and construction. Many construction products have a long and fragmented supply chain. For example: a raw material is processed to a bulk form, semi-fabricated and perhaps applied with some type of finish, and sent on to another fabrication or treatment process. It is then delivered to another product supplier (as a raw material to be combined with other similar but different raw materials) to be further fabricated or sub-assembled, supplied to another system supplier to be sub-assembled into his product and finally installed on site as a component. The terms may vary with different product areas, but such a long sequence is not unusual.

Which product has such a complicated supply chain? The answer is a sealed double-glazed unit with toughened and/or laminated glass with a solar control or low E coating on the glass, installed in a unitised curtain wall system. This is one of the most common ways of cladding modern glazed buildings and is widely used throughout the industry. For the architect, who is responsible for the design of the form and aesthetic concept of the building, it is becoming increasingly difficult to keep up to date with all the technical developments in specific product and material areas, especially those with long and complex supply chains.

This has led to three problems:

- Individual suppliers may develop processes which are not always compatible with all other possible processes either upstream or downstream of them in the supply chain, so that it can sometimes be impossible to incorporate a particular required performance-enhancing characteristic
- The architect at the top of the design process, as the accepted primary specifier, may not have enough specialist technical knowledge or time to deal with the first problem
- No single party in the fragmented supply chain has the breadth of design responsibility to control or manage the reconciliation of the conflicting design and performance issues, although one may be handed this responsibility.

Photograph: Adam Wilson

As a result a specification may be issued with a number of performance requirements, each perfectly reasonable in its own right, but impossible to satisfy in a single solution.

When this problem occurs with materials in the building envelope, as the double-glazing example shown here, a specialist facade engineer can help. They can fill the gap between architect and supply chain, and by bringing specialist technical knowledge to bear, can develop the design with the architect so that it can be provided by the supply chain and meet performance requirements.

Buro Happold Facade Engineers carried out this task on a complex design for Palestra, a speculative office block in London designed by Alsop Architects. The building has inclined facades and the glazing has strong colours. The glazing, of which there is a high proportion on all four facades, had to satisfy the new Part L Building Regulations 2002; this meant high levels of control of energy loss in winter and of solar gain in summer. Parts of the glazing also had to provide fairly high levels of acoustic insulation. As the glazing was all full-height, it had to provide full restraint against barrier loading to prevent falls through the glazing for uniformly distributed loads, line loads and point loads.

The first problem was to decide how to reconcile the need for a reasonable number of solid panels with high insulation, necessary to meet Part L2 insulation requirements, with complex arrangements of colours.

Three options were examined:

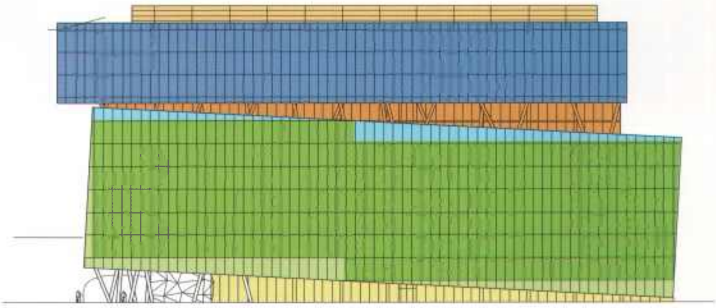
❶ The first approach was to use body-tinted glass in front of vertical bands of coloured aluminium perforated mesh panels for the glazed areas, and similar mesh panels in front of white metal faced insulated spandrel panels for the non-vision areas. Although this met the aesthetic requirement, it was difficult to access the inside face of the glass for cleaning.

❷ The second approach was to use full-height body-tinted glass for the vision glazing with separate glazed look-alike insulated spandrel panels with full ceramic coating on their glass outer panels. This required an external joint between the panels at the junction of the colours, which was not the preferred aesthetic.

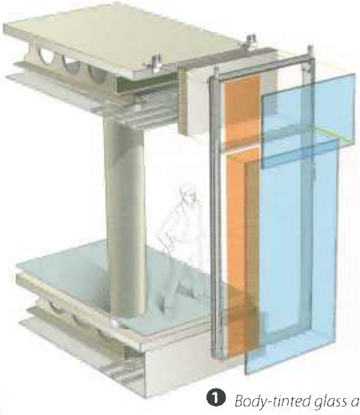
❸ The third approach was to use glass panels which were fritted on part of their surface for the vision glazing and similar panels in front of solid insulation for the non-vision spandrel panels. This gave the preferred seamless joint detail, but is an expensive approach, because the rate for fritting the glass is applied to the whole panel, not just the fritted area.

While these options were being evaluated, attention was focusing on the actual fritting process. The architect wanted a dual colour frit, with different colours visible on each side of the glass. As frit is a fired-on ceramic, this meant that two different coloured (liquid) ceramic solutions, one over the other, had to be applied to the same surface and exactly aligned using the silk screen printing process. Normally a dotted pattern is used, but it was very difficult to align the two colour screens, so the pattern had to be changed to a linear one.

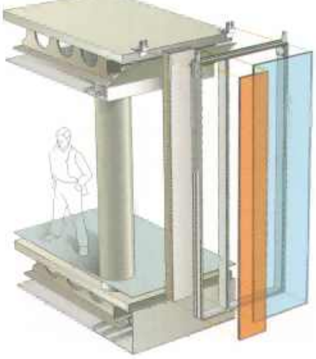
> "...a specialist facade engineer can help. They can fill the gap between architect and supply chain, and by bringing specialist technical knowledge to bear, can develop the design with the architect..."



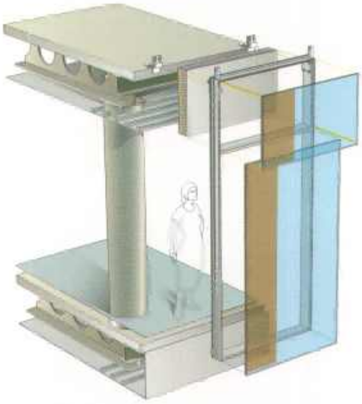
The new office building has a complex glazed south facade (Alsops Architects).



❶ Body-tinted glass and coloured perforated mesh



❷ Body-tinted glass and glazed fritted glass panel



❸ Partly fritted glass panels

> "Various experiments were made with different colours; because the frit is not actually opaque, one colour can influence the appearance of the other"

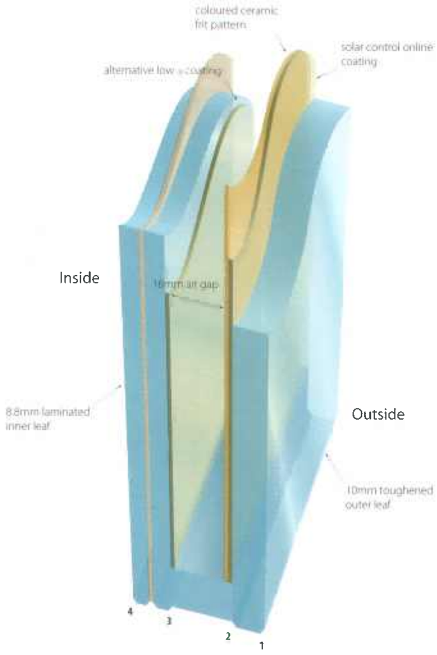
Various experiments were made with different colours; because the frit is not actually opaque, one colour can influence the appearance of the other. The frit also affects the shading factor of the glass, which has some effect on solar gain and compliance with Part L2. (The amount of framing also has an effect on the overall insulation U value for Part L2). When the relationship of glazing to solid panels, frit colours and patterns had been agreed, the next step was to distribute all the processes in the supply chain among the various panes of glass and their available surfaces. This is often the most complicated part of the process, with numerous constraints on the design. Faces of the glass panes are numbered 1, 2, 3, 4 from the outside inwards. The frit should be on face 2, but so should the solar control coating for faces exposed to solar gain. The low E coating used to prevent heat loss is not required where a solar control coating is used, but it is required on north facing elevations, where it has to be placed on face 3 for maximum effect.

The safety containment balustrade loading and glazing safety codes could strictly have been satisfied by using toughened or laminated glass, as both comply with the required standard. However, because part of the stoving process for the frit on face 2 required it to be toughened, monolithic toughened glass was used for the outer pane. For cost reasons a high performance solar control film that could be applied on the bulk production line was used. An alternative cheaper Low E hard coat was also chosen for areas of the facade where solar gain was not a problem. The frit was applied first to face 2 and the glass was tempered, then the coating was applied over it. Soft coat films are less durable before they are assembled into the inside of double glazed units, and are prone to damage by humidity, so need to be applied last in the process chain. Eventually up to 10 different glazing combinations were used on the project and some solutions are shown below left.

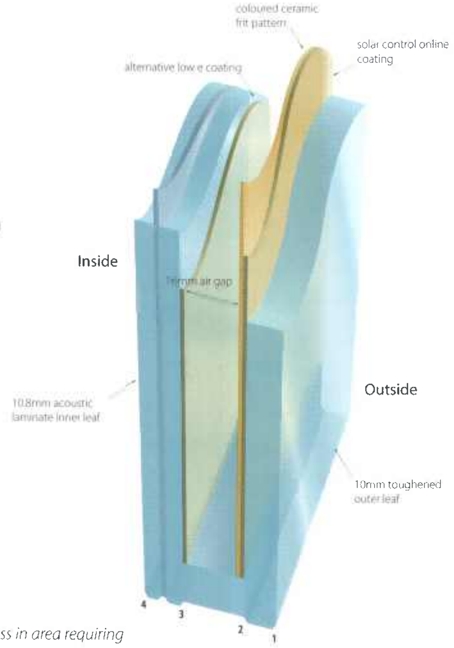
To provide the high acoustic insulation required in certain situations, a special acoustic laminate film was used – the most economical way to provide acoustic insulation. All the inner panes were laminated, some with special acoustic laminate films, but this was still not enough to achieve the required acoustic performance and so one of the laminate panes was increased in thickness to provide additional mass. This had the added benefit that with two panes of dissimilar thickness there is a further gain in performance; the resonance that occurs with similar pane thicknesses is avoided. One solution for the acoustic control areas was as illustrated to the left (lower diagram).

Although these solutions seem to be fairly conventional, the description of the process that led to them shows that there are many possibilities that need to be addressed. The description above is very much simplified and reduced; there are a number of other factors, such as thermal shock on the glass, which affect the final choice of materials and processes that have not been covered at all. The final choice of colours and glazing make up has yet to be finalised, and the client is also playing a part in this process, commenting on the final appearance, so some of the rules of the game are still changing.

The case study demonstrates the technical complexity of a modern construction material, and shows the need to employ technical specialist skills to resolve all the design issues and provide a viable solution that can be delivered by the supply chain from within their standard processes. The provision of facade glazing is clearly not a simple task. ■



Detail through glass showing coatings and specification.



Detail through glass in area requiring acoustic control.

Spanning the future

ETFE foil cushions can be a viable alternative to glass for roofs and atria. **Russell Winser** summarises research and gives an update on recent advances in ETFE technology

ETFE foil cushions have been a discussion point for the past decade but in recent years this polymer roofing system has gone from concept to construction in an increasing number of buildings. In 1997 Buro Happold began a research project, sponsored in part by the DETR, to investigate their use in buildings. This article summarises four reports which resulted from the research project and assesses how far ETFE foil cushions have advanced since the research was carried out.

Ethylene-tetra-fluoro-ethylene, or ETFE as it is more commonly known, is a co-polymer of PTFE (Teflon) and polyethylene. The mechanical properties of ETFE are comparable with those of Teflon, but while ETFE possesses a similar resistance to chemical attack, it has roughly three times the tear resistance. With the potential to provide better insulation than double-glazing at a fraction of the weight, it offers the advantages of a fabric (easy installation and low weight) but with a light transmittance similar to that of glass and good fire resistance. ETFE is used as a translucent roof system in the form of cushions, comprising three layers of ETFE which are inflated for structural integrity and thermal performance. The three layers of ETFE are bonded to a kader edge detail and clamped into position; the cushion is then inflated to the required pressure and 'topped up' intermittently using either conditioned or unconditioned air. A three-layer ETFE foil cushion system can provide a roof or atria covering with minimal structural support; it can achieve complex geometric shapes and span large areas which would be difficult to achieve with a glazed roof.

PTFE foils were first used as three-layer cushions in Arnheim, Netherlands, as the roof to a small building in the Burghers Zoo. The building housed tropical plants and aquatic life and a greenhouse effect was required internally, but at low cost and with no internal columns or structural support. PTFE foil had too low a creep threshold, but it led to the development of ETFE foil, a more robust product. One of the first ETFE foil roof buildings in the UK is also a leisure building, the Hampshire Health and Tennis Centre. Designed by Euan Borland Associates and completed in 1992, this building embodies the requirements for high light levels and an elegant structure unbroken by internal columns.

The change in the profile of ETFE as a material in the UK began with the Chelsea and Westminster hospital. Built in London in 1992

for the North West Thames RHA, the hospital, designed by Sheppard Robson, has an 116m by 85m internal atrium. It has a central aisle which gives access to all department entrances and, via walkways, to all floors. Two types of cushions are used to roof the atrium: three-layer opaque cushions around the edges of the atrium and three-layer transparent cushions in the centre. The opaque cushions were used to reduce solar gain.

The Eden Project, built in a disused china clay quarry in Cornwall, is one of the best-known projects to use ETFE foil cushions. The loamy top-soil and the massive structural grid precluded the use of glass as a roof and wall material. Instead the architect, Grimshaws, opted for a lattice of 9m diameter, hexagonal, quadruple skin ETFE foil cushions to cover the 22,000m² site. The resulting structure is a recognisable collection of domes; they connect together to form two biomes, which house the warm temperate zone and the humid tropics zone respectively.

ETFE has been used to roof office buildings, such as the Schlumberger research centre phase II (Cambridge), and Adastral and Lacon House, London, but its main use continues to be in the leisure sector. ETFE accounts for a very small section of the translucent materials market in construction. It is currently available from four suppliers in the UK: Vector SP, Covertex, Skyspan and Landrell.

EFTE: a comparison with glass

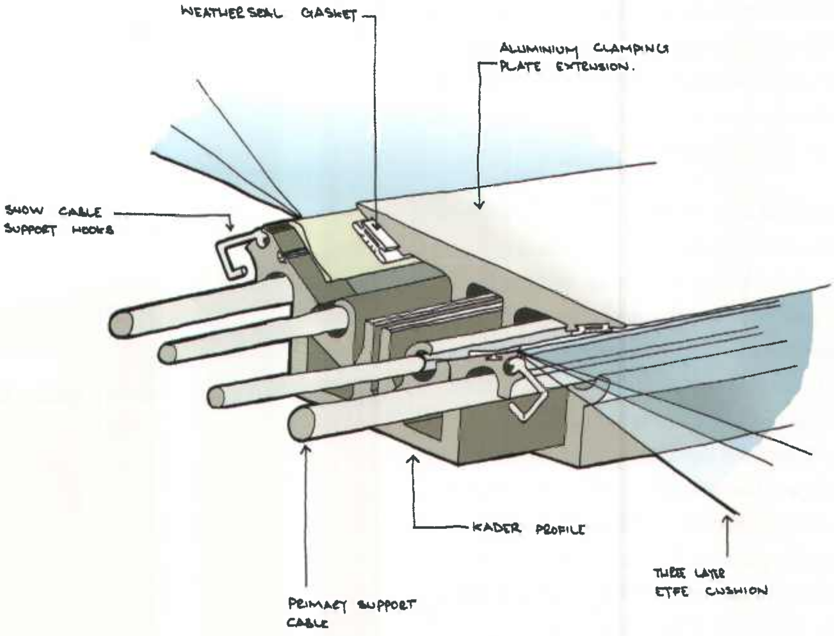
A comparison with glass in roofs and atria requires an analysis of the material and of structural differences; the performance of ETFE and its effect on internal conditions and the environmental impact of the use of ETFE foil in buildings. In cost, ETFE foil cushions are comparable to medium-range curtain walling although the price varies in accordance with the complexity of the project and the economies of scale which can be achieved.

Structural performance

Typically the grid for ETFE foil cushions is much larger than that which can be successfully achieved with glazing. Limited at its narrowest to between 3.5m and 5m, a cushion can achieve unlimited lengths although large runs will require multiple access points for inflation. A swimming pool in Prein, Germany, has arched simply supported glulam beams carrying cushions which are 3m by 30m. The internal pressure in the cushions helps to resist wind uplift and the cushions are specified so that the ETFE can support a snow load while deflated. In areas where frequent severe weather is expected, the inflation system can be designed to achieve higher internal pressures to cope with a long-term snow load on the cushions.

An ETFE atrium roof is set between curved steel tubes supported by steel 'tree' columns. Adastral House, London.

The internal view of Hampshire Health and Tennis Centre shows the large, well-lit space created by the ETFE roof structure.



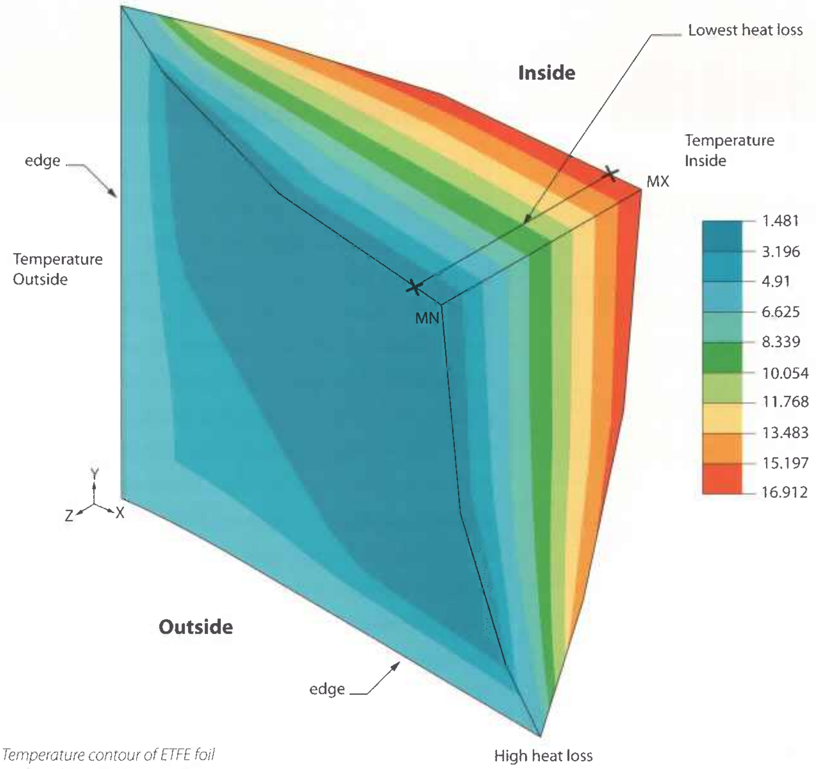
The edges of two adjacent ETFE foil cushions are clamped together in this typical detail.

performance, an advance described as 'warm edge' technology. It has additional advantages; the temperature of the warm-side glass edge is increased, reducing the risk of condensation. In colder climates warm-edge spacers can make the difference between condensation and ice!

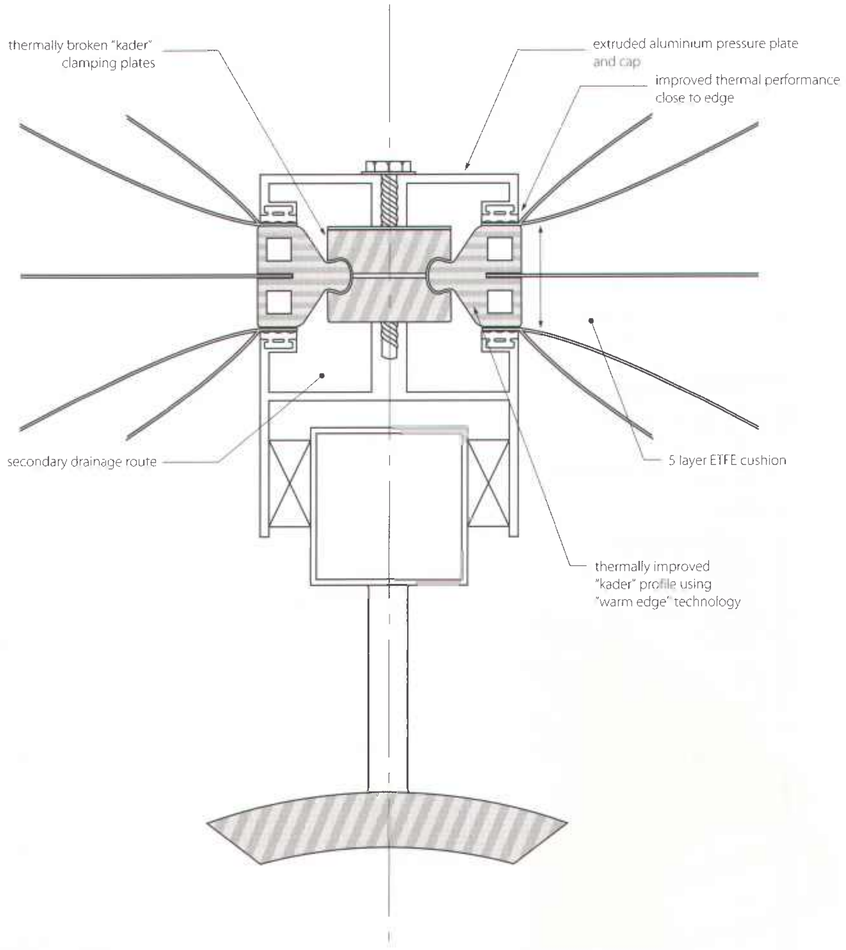
The need to enhance thermal performance of systems is also being driven by the latest, tighter requirements of the UK Building Regulations, which set minimum thermal performance levels for building envelope elements. The latest changes in 2002 now require the effect of cold bridges – or thermal weak spots – to be incorporated into the calculations, and to be designed out if the envelope is to comply.

The application of such technology would appear well suited to ETFE cushion systems. However most of the existing warm-edge spacers incorporate polymer based materials, which raises concerns of colour stability, compatibility with adjacent materials and ultra violet degradation. This is an issue particularly pertinent to ETFE as it is almost transparent to this wavelength of light. Any design concept would have to address these and other issues. Current edge-clamping technology used by ETFE cushion manufacturers should therefore be viewed as 'first generation' know-how. Although there are now more than 20 installations in the UK alone, including the Eden Project in Cornwall which has more than 30,000m^2 of cushions, if this exciting material is to continue to meet current regulations it is clear that further improvement is required at the cushion edge. Ⓒ shows a generic section through a new edge-clamping detail enhanced with a thermally improved spacer profile. It shows how the new profile could be incorporated before the cushion is delivered and installed on site. The new profile must be pre-assembled off-site to ensure that the multi-layer system is hermetically sealed along its edge. This ensures airtightness and limits vapour migration into the body of the cushion, as any internal moisture may condense on the cooler layer. The next step in the design process is to prototype this new concept in collaboration with a system manufacturer.

Full scale, hot box testing will follow to confirm system performance and viability before the technology enters the market. ■



Ⓑ *Temperature contour of ETFE foil cushion (in vertical position). Cool cushion edge is shown in blue.*



Ⓒ *Section through improved edge-clamp detail.*

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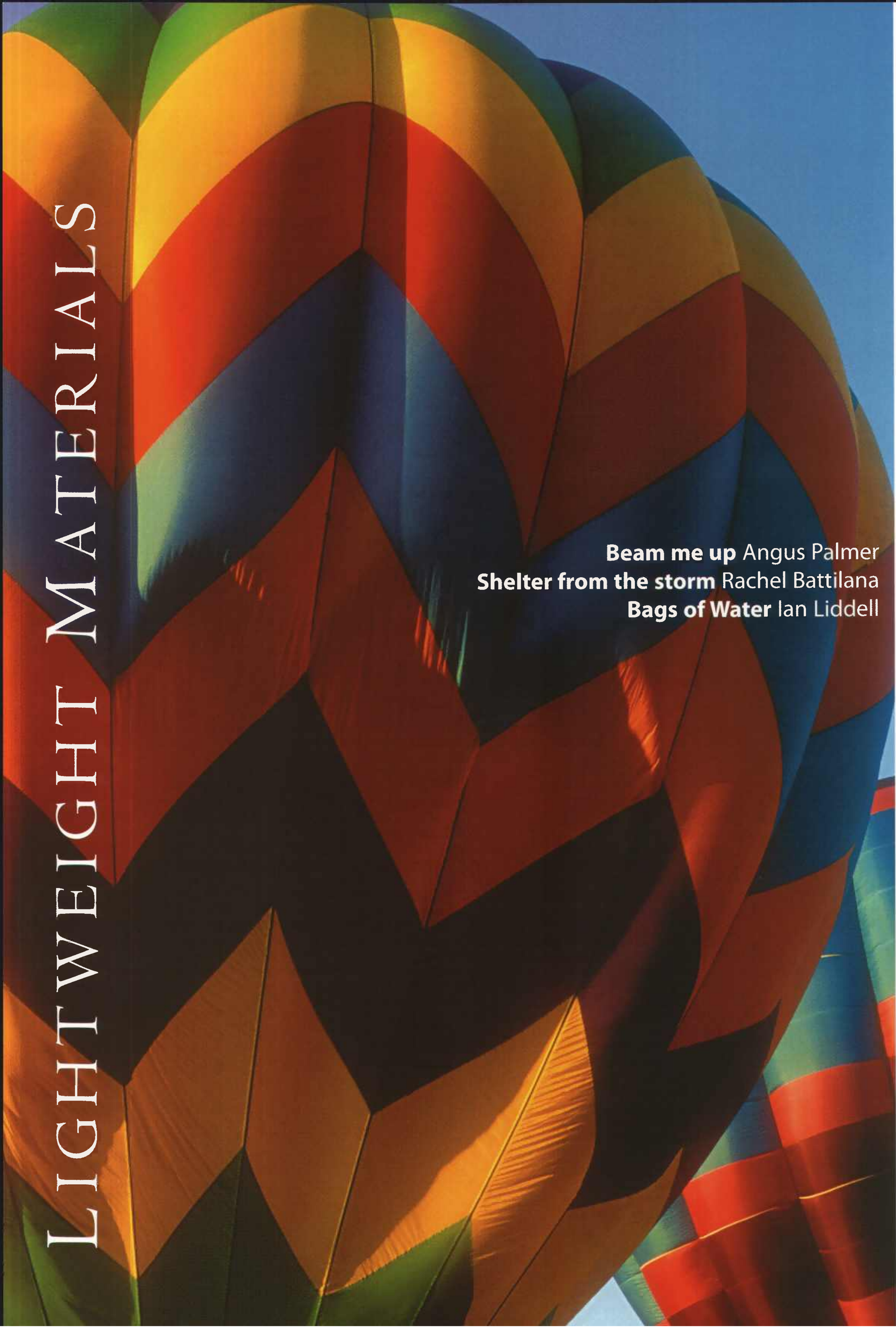
LIGHTWEIGHT MATERIALS



Beam me up Angus Palmer
Shelter from the storm Rachel Battilana
Bags of Water Ian Liddell

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Beam me up

Tubes of fabric, inflated to create structures, have huge potential; **Angus Palmer** and **Robert Lerner** investigate the development of air beams and the fabrics from which they are made

For the US Army the development of air beams has been like a search for the holy grail. In the 1960s a number of prototypes were developed that highlighted their potential but which also demonstrated the significant technical challenges that would need to be resolved. The prototypes showed that it would be possible to build structures using air beams, thereby eliminating any hard structural components. The structures are composed almost entirely of fabric elements that can be tightly folded into compact packages for easy storage and transportation, yet be rapidly assembled and self-erected within hours in the field.

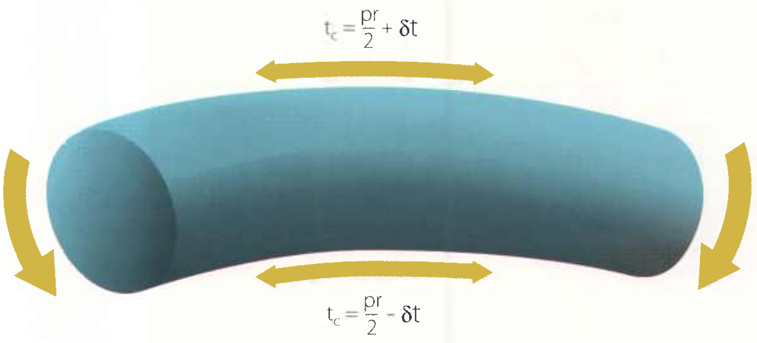
These ideas were shelved for many years until the disastrous attempt to rescue US hostages in Tehran in 1980, when the impossibility of maintaining tactical helicopters in forward-line aggressive environments was clearly demonstrated. This kick-started recent developments, in which FTL and Buro Happold have been closely involved.

The theory of air beams

In very simple terms, air beams are analogous to pre-stressed concrete beams, but the fabric has stiffness and strength only when it is in tension, rather than in compression as with concrete. Therefore an inflated tube of fabric has some inherent bending stiffness so that the tube can resist applied loads up to the point where the applied bending stresses exceed the inflation stresses. Using this principle, an equation to derive the bending capacity at the onset of wrinkling, or the 'wrinkling moment' capacity, can be derived.

$$M_w = \pi p r^3/2$$

The important thing to note from this equation is that the wrinkling moment is proportional to the pressure and to the cube of the radius. To reduce the tube diameter by 50%, as is desirable to avoid very bulky tubes, the inflation pressure needs to increase by a factor of eight to provide a tube of equivalent wrinkling moment capacity. The next concern, of which the Army had firsthand experience through previous trials, was how to manage safely the vast amounts of stored energy in the tubes, and how to maintain the high inflation pressures. If mistreated, a tear could propagate very quickly, causing an inflated tube to explode, with the potential of severe personnel injury or property damage.



The Army initiated two studies: one to design and build a prototype structure using existing technology, and the other to encourage the development of braiding and weaving technologies through the use of 'seed' grants.

Prototype structure using woven fabrics

The prototype TME (transportable maintenance enclosure) was configured to cover two Blackhawk helicopters in a blacked-out and sealed environment to allow for maintenance under hostile and aggressive conditions. A structure had to be designed in which each and every component was below a pre-specified size and weight to allow all assembly to be done manually with gloves on!

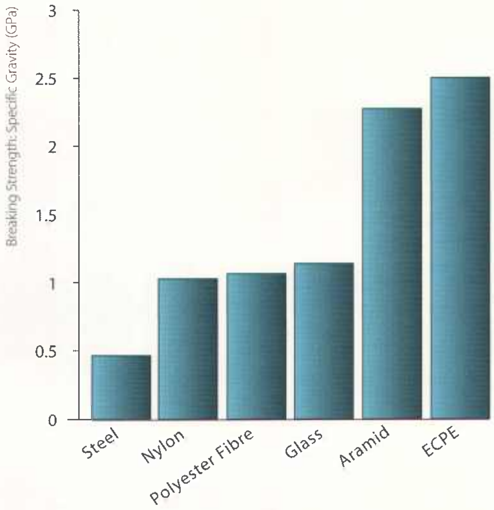
The design consisted of arched tubular members fabricated from patterned PVC-coated polyester material that were 609.6mm (24") in diameter, inflated to 14 psi and spanned 7.925m (26') to provide an internal clearance of about 6m (20'). These were restrained by a stressed fabric membrane that provided the skin to the enclosure. Inclined arched members were used at each end to provide large 'clam shell' openings with smaller light-trap entrances for personnel. The project was a great success, and demonstrated that with careful consideration to details and with good fabrication techniques, these structures did have potential. The downside was still the size and weight of the actual air beams, although advances had been made on other previous systems. At this point the development of braided tubes took over.

The development of braided fabric

At an early stage in explorations into this technology it was found that the final weight of an air beam of a given stiffness was almost independent of the chosen diameter and inflation pressure. Any decrease in diameter resulted in a large increase in inflation pressure that increased the fabric stresses, requiring a heavier fabric. This increase in fabric weight outweighed any decrease in air beam size. It was therefore clear that to reduce air beam size and weight significantly, a step change in technology would be required using new tube fabrication methods and incorporating the latest development in exotic fibres.

Internal view of TME, showing bulky nature of polyester air beams.

An exploration of suitable fibres highlighted the potential of aramid and extended long chain polyethylenes (known by the trade names Kevlar and Spectra). Both these fibres have strength-to-weight ratios nearly 2.5 times higher than polyester, although this was to the detriment of other properties: susceptibility to abrasion, reduction in strength from repeated flexing, UV degradation, cost etc. However, given the unusual nature of these structures, and disregarding any normal commercial concerns, it was felt that the potential gains outweighed the disadvantages. Up to this stage braiding technology was restricted to relatively small items and was mostly used in composite fabrication of aerospace and performance sports components. What was needed was an increase in the size of braiding machines so that they could fabricate larger diameter tubes, and a change from a batch to a continuous process to allow long lengths of tubes to be manufactured without breaks.



> "A structure had to be designed in which each and every component was below a pre-specified size and weight to allow all assembly to be done manually with gloves on!"

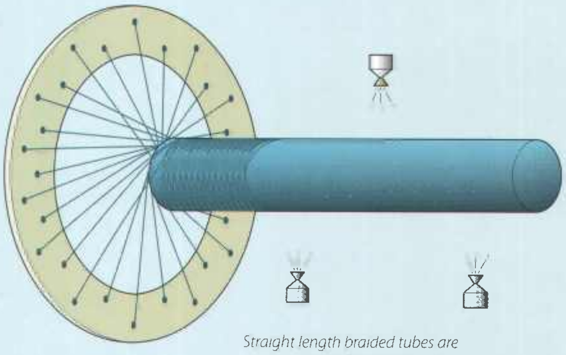
The use of braided tubes had a number of other technical advantages. As the yarns are oriented diagonally to the axis of the tubes, the principal stresses within the inflated air beam no longer align with the fibres. This has two primary benefits:

- If the air beam is damaged, the interaction of yarns prevents the tear propagation that would occur in traditional woven fabrics. This greatly reduces the risk of explosion when inflated, as air would vent through the hole. This allows a reduced factor of safety to be used in the design, resulting in more efficient use of material
- The interaction of the yarns allows the inflated air beam to flex (rather like a pressurised fireman's hose). Bending stiffness is provided by additional longitudinal yarns that are applied to the finished tube. This means that the yarns in the braided tube need resist the inflation pressures only, and that the applied yarns would resist the induced bending stresses. This enables more efficient placement of yarns at high stress points instead of increasing the material strength throughout (as in woven fabrics).

As the braiding process would only provide lengths of loosely braided fibres, further processes were required to complete the air beams, as shown here. The air beams used for the two structures described in this paper were manufactured in a two stage process with the braiding being done by Advanced Fiber Innovation in Massachusetts and the finishing done by Vertigo in California. Foster Miller and Vertigo were the prime contractors for these two projects.

① Using the braiding technology developed by Advanced Fiber Innovation, straight length braided tubes were manufactured from Spectra yarns. The loose weave and slippery nature of the fibres make such braided tubes very unstable and the first process was to coat them in polyurethane to fix the fibre matrix. This not only helped to stabilise the fibres, but also provided protection against abrasion and UV, and created the air-proof coating needed to maintain inflation pressures. ② The coated braided tubes were shipped to Vertigo in California, where they were sealed at the ends and valves added for inflation. At this stage a partially inflated tube will adopt a straight condition. ③ They were forced into the required arch profiles and restrained in this position while Kevlar tapes were applied longitudinally. ④ The tapes force the tubes into their correct profile when subsequently inflated and provide the bending stiffness required for structural strength.

①

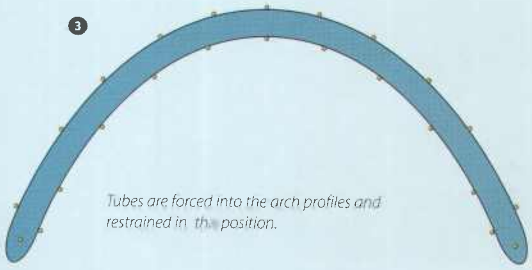


Straight length braided tubes are manufactured from Spectra yarns and coated in polyurethane to fix the fibre matrix.

②

The tubes are sealed at the ends and valves added for inflation. At this stage a partially inflated tube will adopt a straight condition.

③



Tubes are forced into the arch profiles and restrained in this position.

④

Kevlar tapes are applied longitudinally.

LANMaS (large area night maintenance shelter)

The LANMaS structure was developed and designed using the braided air beam technology as described previously. The project was similar in size to the TME, but used only 304.8mm (12") diameter air beams rather than the 609.6mm (24") tubes used for the TME. It could be inflated to 60 psi; however the working pressure was set to 30 psi which provided sufficient stiffness to resist most working loads.

The air beams for this structure were manufactured using braided Spectra as the base tube and Kevlar tape for bending stiffness. The skin of the enclosure was woven PVC polyester fabric that was patterned to provide a double-curved stressed skin that would add lateral stability to the tubes and provide some degree of composite action with them.

The maximum inflation pressure of 60 psi is equivalent to about four atmospheres – typical bicycle tyre pressure. This induced permanent circumferential stresses in the tubes of around 6 tonne/m. This pressure could be maintained for extended periods without the need of further pressurisation. This was a considerable achievement and an advance on the TME structure; it finally proved the potential of this technology.

AIMS (aviation inflatable maintenance shelter)

Building on the success of the LANMaS project and with further investment, the AIMS structure was developed using 762cm (30") diameter air beams that span more than 30m (100').
A prototype of this structure, completed in 2002, covered 743m^2 (8,000 square feet), large enough to house a Chinook helicopter. It could be deployed by eight people in one day, taking only one hour to inflate.

These two projects start to demonstrate the feasibility of air beams to replace aluminium or steel beams for the primary frames of deployable structures. The only drawback to their acceptance for more conventional structures is cost. However, as the number of manufacturers who can provide this technology increases, and costs start to come down after initial investments are realised, the use of air beams may become feasible in non-military applications.

LANMaS
(Large area night maintenance shelter)

Top left: base detail showing reinforced boot and fixing hardware.

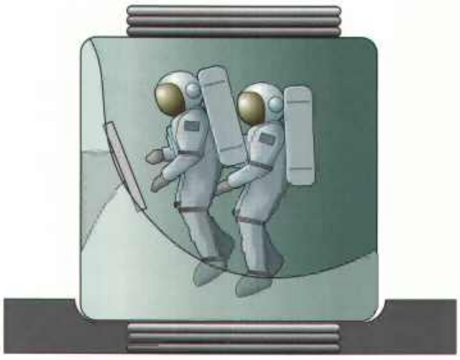
Top right: view during installation with air beams partially inflated.

Bottom left: external view of completed installation.

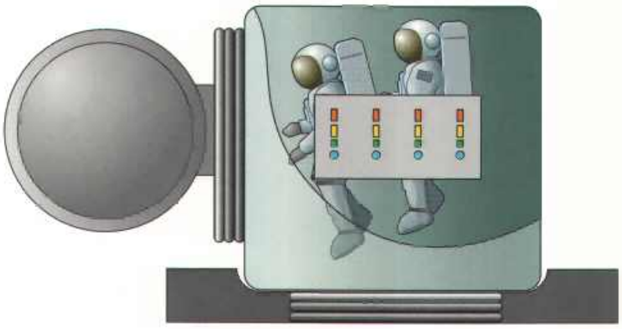
Bottom right: internal view (compare air beam size with the TME beams shown on p38).

Some of the preliminary designs of different air lock configurations

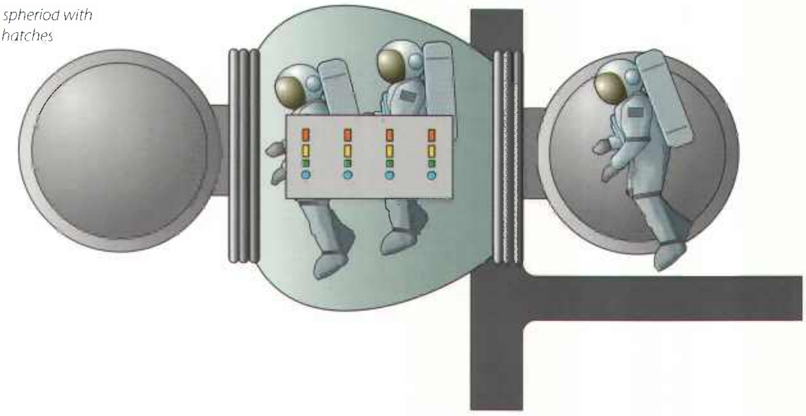
Cylinder with opposing hatches



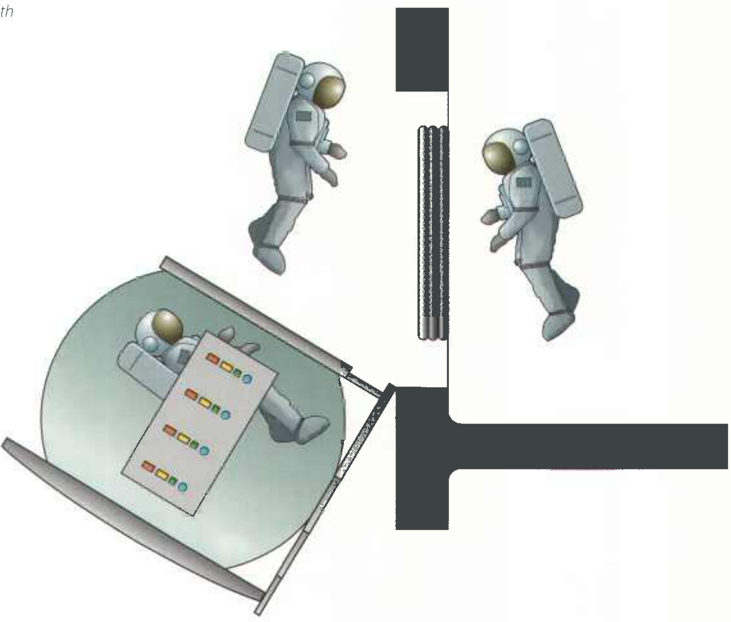
Cylinder with hatches at 90 degrees



Short boy spheriod with opposing hatches



Tilt-away spheriod with single hatch



The NASA advanced inflatable airlock

Another example of the use of braided high-strength fibres in pressurised structures was the advanced inflatable airlock (AIA) that was developed as part of NASA's search for weight and cost saving technologies for the next generation space shuttle.

The first year of development focused on solving some of the basic architectural questions as well as proposing an approach to the complete system. While several alternative scheme designs were proposed, NASA stressed that the program was primarily about technology development and not about design.

The proposed system design would have two rigid hatches and a flexible body comprising a number of layers:

- A braided Vectran restraint layer to withstand pressure differentials
- A silicon-coated nylon bladder to provide the air seal
- An internal scuff layer to protect the bladder
- A separate system of micro meteor orbital debris shielding (MMOD) plus multi-layer insulation (MLI), also made of textiles.

It was determined early on that the membrane properties of the restraint/bladder system and the MMOD/MLI system would be so different that it would be best to consider their deployment and retraction mechanisms independently. The restraint and bladder could fold in a disordered arrangement, while the stiffer MMOD/MLI system would need to fold in a more orderly fashion. The two different systems would still need to fold together side-by-side, and simultaneously.

During walks in space, the shape and functionality of the airlock would be maintained by high-pressure air beam rings inside it, which would pre-tension the innermost fabric scuff layer in the hoop direction. Axial pre-tension would be provided by external rigid telescopes. The air beams would also be fitted with handholds and foot straps to aid the mobility of astronauts.

A unique challenge was to devise a method of folding the MMOD layers. Ideally, all the fabric layers would compact both in volume and footprint. The origami approach proved unsuccessful because of low fault tolerance: if one fold goes wrong, the whole system fails and we could not depend on training the astronaut to control folding. An active system using the lesser-known technology of pneumatic muscles was adopted. Like air beams, pneumatic muscles are tubes composed of a structural outer layer and an inner bladder layer. The structural layer is applied on a bias so that when the tube is pressurised the structural sleeve expands in diameter which causes a contraction in length. In principle, the folding behaviour of the MMOD system would be controlled by air beams pushing outwards and air muscles pulling inwards. The muscles were fabricated by Shadow Robotics in London. A full-scale test article proved the viability of the concepts of deployment and retraction, and the folding behaviour of the different systems (MMOD, restraint layer and bladder).

NASA subsequently funded a further year of development to proof-load the AIA to four atmospheres of pressure. The structural system was a braided structure nearly 3m(10') long with a maximum diameter of 2.134m(84") and a minimum diameter of 1.625m(64"). The braid geometry was controlled to generate the appropriate strength and stiffness properties required for the airlock. A single layer tri-axial Vectran braid was produced on A&P Technology's 800 carrier Megabraider, currently the largest braid machine in the world. The tri-axial braid was composed of 'S' and 'Z' ribbons handling hoop stresses, and axial ribbons principally to maintain braid stability. An elastomeric coating was developed to ensure that the braid would remain stable throughout the fabrication processes. A secondary system of belts was used to restrain axial loading.

After coating, the braid, still on its mandrel, was shipped to Torrance, California, for final assembly. Subsequent operations – mandrel removal, braid termination, securing the top and bottom aluminium plates, installation of the bladder, trial inflations and belt adjustment – were all unprecedented procedures. They had been carefully planned as there was only going to be one chance to pass the pressure test. The airlock was then crated and shipped to a bomb testing facility in Santa Clarita, California. Overall, the test airlock carried the proof pressure as designed with minimal degradation. Unfortunately the EVA programme was dropped by NASA and the follow-on program of development for an advanced inflatable airlock was deemed unnecessary. Currently the airlock is on display in Houston at Johnson Space Center's New Technology Exhibit. ■

Shelter from the storm

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Tents, the traditional shelter for refugees, are not appropriate for harsh weather. **Rachel Battilana** has been involved in the development of an insulating liner to improve conditions

Stories of refugees freezing to death in harsh cold weather conditions hit the news in the winter of 2001/02 with the mass exodus of refugees from Afghanistan, following the events of 11 September. The same situation had been seen in the Balkans in 1998/99 and in Chechnya, as people were forced to abandon their homes and live in temporary accommodation in the often mountainous border regions, facing the winter in many cases with a tent as their only shelter.

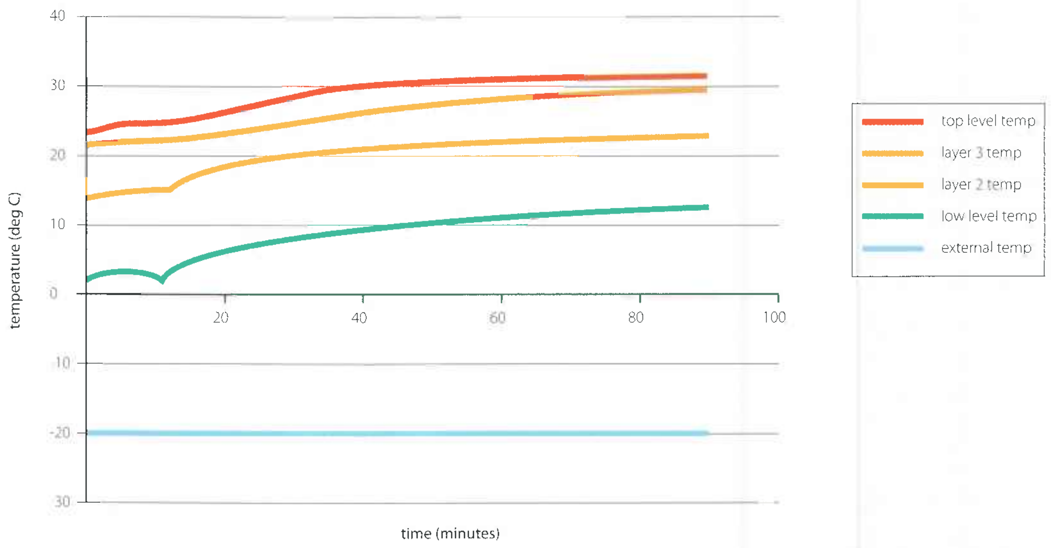
Tents are obviously inappropriate for winter conditions, but in some cases they are all that can be supplied in sufficient quantities at very short notice. The example illustrated overleaf is fairly typical of the canvas "scout" tents used as refugee shelters. This one, supplied by the United Nations High Commission for Refugees (UNHCR), is of bell-tent construction, but ridge construction is also common.

These tents are inherently draughty and have low thermal resistance, leading to large heat losses through both conduction and convection. In winter conditions, cooking stoves are used inside the tents to provide some heating, but this is highly dependent on the availability of fuel.

Shelterproject, a not-for-profit group of architects, engineers, physicists and emergency relief workers based at Cambridge University, have been developing an insulating liner for use with these tents over the past few years. Tests were carried out in a wind tunnel at the Ford Environmental Test Chamber, more commonly used for finding the limits of the latest new high-speed cars. Temperature and humidity data was recorded for tents with and without liners, in gale force winds and in temperatures down to –20°C. The best performance was achieved with a liner made from a material similar to ski-wear: a hollow fibre polyester wadding sandwich between two layers of a thinner, stronger material which transports water vapour in one direction only, similar to Gor-Tex®. The aspect of vapour transfer is a primary consideration, as the daily life of a large refugee family – washing, cooking, drying clothes – can lead to a very damp shelter in cold conditions, affecting the respiratory health of the occupants.

Test results showed that internal temperatures were up to 30 degrees higher than external when a small heater was used inside the lined tent.

Tent with liner and 2.3kW heat input
Windspeeds: 2.5 m/s



The liners have been developed to meet characteristics defined by the UNHCR: to provide a durable, lightweight, compressible insulating layer that can be retro-fitted to the standard tents. The results obtained from these tests were very positive. The lined tent maintained an internal-to-external temperature difference of up to 30°C when a small stove was used, while still being able to transport out almost all of the moisture produced by a large family. This high insulation value means that for most of the year, internal temperatures could be kept at a reasonable level through heating from human occupancy alone, a fact that is very important when fuel for heating is scarce or indeed non-existent.

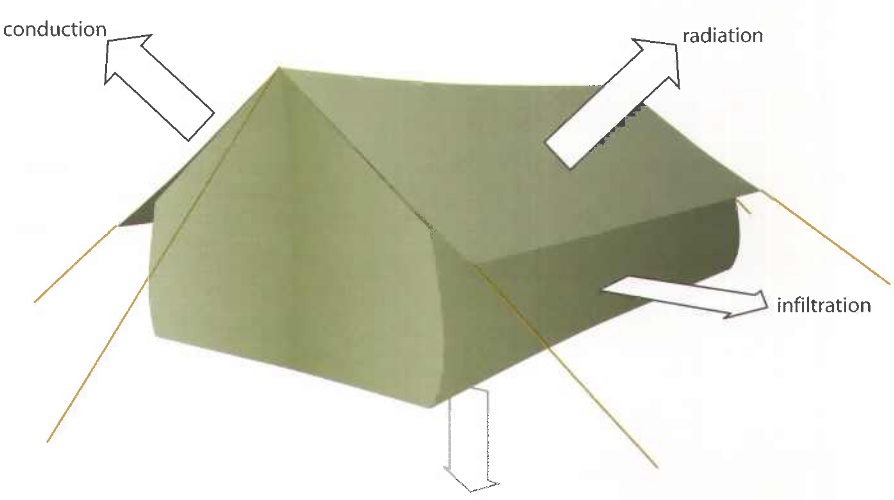
One of the major challenges that remained after these initial tests was that of cost. Aid agencies have a limited budget and the liners must be considerably cheaper than the tents themselves if they are to be purchased as well, despite the longer term savings that the liners can make on fuel. Pricing is difficult, as manufacturers are unwilling to predict costs for an item that they may have to produce in quantities up to 100,000 with a three-week lead time, and then none for several years. It became apparent that the prices being quoted for the original design were not feasible, and that the materials being used were too specialised, being produced only in Western Europe and the US. It was necessary to develop a more detailed understanding of the exact function of each of the constituent parts of the full shelter system, in order that the liner could be pared down to its most significant elements.

Heat loss from a tent is by three main mechanisms: conductive losses to the ground; conductive and radiative losses through the tent roof and walls; and convective losses due to air infiltration.

The wind tunnel testing had enabled fairly accurate measurement of the combined effect of conductive and radiative losses through the skin of the tent, by mapping out the surface and air temperature profile. These temperature results had been used to build heat flow models of the tent in order test for a wide variety of weather conditions. Assumptions were made in the model about the proportion of the remaining heat that was transported out through the floor and by infiltration.

Infiltration, or "unplanned ventilation", has been seen to be responsible for a large proportion of heat loss, with temperatures inside an unlined tent being barely warmer than those outside in high wind speeds. Refugees in Afghanistan make great efforts to seal their tents, digging in the base of the tent with mud banks that are eventually built up into walls, and using valuable blankets to seal the doors. The addition of a liner drastically cuts down the levels of infiltration, and recent tests using tracer gases to track air movement have enabled this to be quantified separately from other heat loss mechanisms. Reductions in air change rates must of course be balanced with the need to have fresh air for breathing, particularly when a stove is being used.

Heat loss to the ground is a complex mechanism that has caused difficulty in the computer modelling stages. The ground can be treated as an infinite heat sink at a constant temperature, but in fact the ground will warm up over time. For a building with such a small floor plan (around 4m by 4m), edge effects tend to be dominant, with heat being conducted directly under the walls of the building. The obvious differences between a tent wall and the masonry walls for which these effects have been quantified led us to making our own measurements of heat flux directly. The additional complication is the aspect of personal insulation from the ground. We all know instinctively not to sleep directly on the ground as our body heat will be quickly conducted away. A liner will be of little use if the refugees have no flooring or bedding available to them.



Mechanisms of heat loss from a tent.

"Aid agencies have a limited budget and the liners must be considerably cheaper than the tents themselves if they are to be persuaded to purchase liners as well"

The liner resembles a large duvet.

> "It is hoped that for winters to come, we will be able to produce a liner that the aid agencies can afford to procure, and that less people will die as the result of cold."

A further aspect that has been investigated is the split between conductive and radiative losses through the tent walls. Would it be useful to have a silvered surface to the liner, or do the extra expense and the losses in moisture transport incurred outweigh the benefits? Within the financial constraints, the additional layers of surfaces introduced by the liner were judged to make sufficient improvement without the difficulties of a silver lining.

The final test, of course, is to actually live in the tents. Some chilly nights spent camping in Cambridge and on top of a Swiss glacier have confirmed that the liners really do make a difference. Three refugee families in Afghanistan were also able to test the liners out this winter, and were enthusiastic about the improvements seen. Both the UNHCR and the ICRC are now working on producing insulating liners of their own. It is hoped that their use will mean less refugees die as a direct result of the cold. ■

above: successful use of liners in Afghanistan
top: the liners were tested by the design team

Bags of water

A project to use large flexible bags to ship water to cities in dry areas is described by **Ian Liddell**

The concept of transporting liquid by towing it in large bags has been around for some time. One example, known as Dracones, was a tubular system developed by Dunlop in the 1960s for oil transportation; the containers were only used in small sizes and it was some time until their reliability was proven. The idea was recently revived by Christopher Savage to transport fresh water to some of the Greek islands. Unlike Dracones, which were fully filled so that the fabric was under considerable tension, the new bags were only partly filled so fabric tensions were less but the bags were not rigid. A company called Aquarius has now been using these bags for ten years, initially with 2,000m^3 bags and today with larger 5,000m^3 bags. The bags are fabricated from single sheet PU-coated polyester fabric with attachment points.

The aim of the current project is to deliver water to cities in dry areas, including the north and eastern coasts of the Mediterranean, the Gulf states and southern California. These areas have expanding populations and need large amounts of water – units of 120,000m^3/day (100 acre-feet). Such water requirements could be met by coastal desalination, offshore desalination plants or delivery from distant fresh water sources. California plans to use coastal desalination plants, for which costs from \$1/m^3 to \$3/m^3 are quoted, an increase at best of 500% in the base cost of fresh water. Apart from the cost, desalination plants use large amounts of heat and/or power from around 5kWh/m^3 where waste heat is supplied from a power station to 10kWh/m^3 for reverse osmosis (RO) plants with no heat (50MW are required to produce 120,000m^3/day by RO. ref 'Seawater Desalination in California', California Coastal Commission).

To make water delivery effective and economic it has to be transported in very large quantities, ideally greater than 250,000m^3. The options are super tankers or very large flexible bags as barges. Super tankers are costly, and compared with oil, water is a low-value commodity. To make water transport economic, fast turnaround times are required, but tankers have to be filled carefully to avoid overstressing the hulls. The idea of using old single-skin tankers foundered as it was virtually impossible to clean out all the oil so that it would not pollute the water. The only alternative is to use large flexible bags. Typical sizes of these are given in the table below.

The density of seawater is 3% more than fresh water; a bag full of fresh water will float with a freeboard of 3% of the total depth at each cross section, eg, for a 14m depth the freeboard will be 420mm. This results in a pressure of 4.2kN/m^2

Volume (m^3)	Length (m)	Width (m)	Depth (m)
30,000	145	35	7
120,000	260	56	11
250, 000	350	72	14

Typical bag sizes.

to be taken on the containing membrane at the waterline, reducing to zero at the lowest level. The pressure profile is resisted by the circumferential tensions in the membrane which are constant around a particular section. This results in a changing curve below the waterline, of which the radius is equal to the tension divided by the pressure which is proportional to the depth. The shape can be found by solving the equilibrium equation iteratively or by using a large displacement fabric analysis program.The process for developing the shape and calculating the tensions under static loads can be extended for a whole bag. It is then necessary to estimate the forces from towing and wave action. When a full bag is accelerated under tow, the fabric initially moves forward through the water while the contained water stays still. To move the water forward, pressure builds up at the back and then moves forward like a wave. This phenomenon has been observed in sea trials of scale prototypes. The height of the wave will depend on the initial towing force and can be estimated, together with the consequent increase in fabric tensions. There could be dynamic effects causing waves to propagate along the bags and back, but the effects of these are unlikely to be greater than those caused by acceleration.

Forces from wave action on the bags are difficult to estimate. The waves in the sea tend to go through the bags, making them undulate, and they also surge over the top, causing additional tensions in the fabric. Wave action can cause additional drag on the towline. Repeated undulations and folding can damage the fabric especially at seams and connections where it is stiffer and heavier, so the fabric needs to be very flexible. The same problem was found to occur with hovercraft skirts and was overcome by developing a special flexible fabric and using seaming methods that did not result in great stiffness. The same approach needs to be taken with the water bags.

The factors involved in the selection of a suitable fabric are complex. As well as having suitable strength and flexibility the fabric must be buoyant so that it does not sink when the bag is empty. It must not pollute the drinking water and should ideally be environmentally friendly. Initially the team investigated a 100% polyethylene fabric made from woven highly-orientated tapes with a polyethylene outer layer laminated on with extruded film. This material meets all the above criteria but has limited strength; it is difficult to seam and the seams are not very flexible. A sample test programme, carried out by an M.Phil student at Cambridge University engineering department, investigated strength and stiffness properties as well as tear strength, with encouraging results. Seaming tests, carried out by a fabric shop, resulted in a maximum seam strength of about 60% of the strip tensile strength. As a result the team needs to find a better way of making reliable seams and is investigating other fabric constructions which will give greater reliability, although they do not have the same environmental advantages.

Apart from selecting an appropriate fabric, a form and patterning arrangement has been developed which is easy to construct and which is modular to allow repair and maintenance to be carried out. A method of handling the 40,000m^2 of fabric during launching and recovery has to be devised, together with mooring, loading and unloading procedures.

The bag or flexible barge water delivery system can also be linked to water desalination systems which use Ocean Thermal Energy Conversion (OTEC). This utilises the difference in temperature between water at 1,000m-2,000m depth and surface water to drive heat engines. The process produces distilled water as part of the heat transfers. The power generated can also be used to produce further quantities of distilled water. Since the ocean conditions are generally some distance from the land, bags or barges are required to get it ashore.

The benefits of realising this concept are the supply of fresh water to many dry parts of the world where the supply of water from underground aquifers or rivers has run out, at cost of about 70% of on-shore desalination. The concentrated brine produced as a waste product is distributed in the ocean where it can be readily diluted. Also, the deep cold water contains nutrients that encourage the growth of marine life, and the carbon emitted into the atmosphere is about 1% of that required for conventional desalination. ■

Differences between species and in growing conditions lead to different cell structures and thus different properties. To simplify the process of specifying strength, timbers of different species are grouped together and can be graded from standard tables into strength classes.

But strength alone is not the only significant factor. Wood demonstrates a range of properties from species to species. In the living tree, much of the material present is water. When wood dries, water is removed from cell cavities and subsequently, cell walls. Its behaviour, above and below this moisture content, known as the fibre saturation point, is very significant. Removal of water from within the pores leads to no change in the dimensions of the timber, but below the fibre saturation point the removal of water from the cell matrix causes shrinkage. Cellulose strands constrain longitudinal movement but the familiar cross-grain dimensional change occurs. In the log, the shrinkage is always greater tangentially than it is radially: when it dries out in a modern building the average shrinkage is 6% tangentially and 3% radially, but there are large differences between species.

Because of the difference between tangential and radial shrinkage, depending upon the way it is sawn, timber may distort when dried. Moisture content changes below the fibre saturation point are reversible; the timber shrinks and swells as the relative humidity of the environment fluctuates. The correct choice of species, method of sawing and careful detailing is very important. Some of the oldest buildings in the world are made from timber. Even in our moist climate, many mediaeval barns and churches survive. This is evidence that untreated timber is perfectly durable. There are simple rules in designing timber buildings for durability. If the wood is dried and kept dry it is not susceptible to decay or attack by insects. Other factors reduce the risk, eg, choosing species that are naturally durable or treating with chemicals, but the first and most important factor is protecting timber from continuous wet.

Trees evolved to protect themselves against fire. Wood is combustible, ie, it ignites and there can be a rapid spread of surface flame. However, rates of burning are often low, with the build up of carbon on the surface limiting oxygen availability to the underlying material. This property is used to assess fire performance of structural timber beams and columns.

Building and buildings are the biggest users of energy and generators of waste in the industrial world. Trees have the benign capacity to act as carbon sinks and so are potential climate stabilisers. By using and planting wood, we can reduce the level of carbon dioxide in the atmosphere and confer a real benefit in the post-Kyoto world. ■

"...strength alone is not the only significant factor. Wood demonstrates a range of properties from species to species"

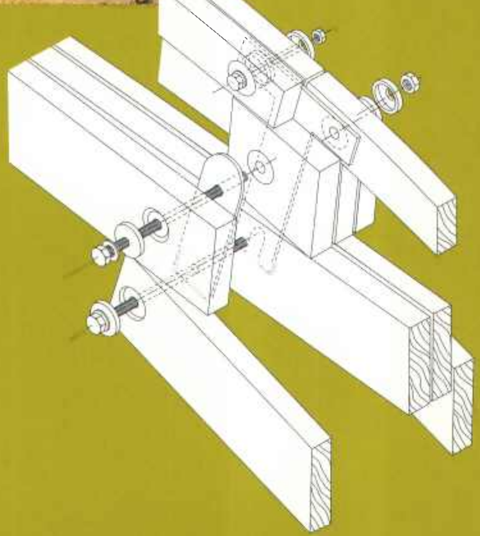
Successful fire tests on untreated oak, jointed with traditional details for the Globe Theatre, London, led to an increased respect for traditional craft skills.

Photograph: John Edwards, Linden Photography

Case study: Hampshire sailing club, Langstone Harbour

The club has a curved roof structure of recycled Victorian pitch pine. It consists of a series of structural frames spanning 10.5m in a gentle curve from front to back, set at 4.5m centres. The simple timber elements are reminiscent of traditional shipbuilding technology but the assembly method is unique. Each structural frame is formed of pairs of timber joists which interlock at their ends and at their mid-points to form a rigid structure. At each connection point two ends of paired members are bolted together; they are locked in place by a third continuous member and the fixity produced gives the roof its curved profile.

Architect: Hampshire County Council Architects
Structural engineer: Buro Happold



Detail of interlocking timber joists used to form a rigid roof structure.

Case study: The Downland Gridshell, Chichester

The building demonstrates two distinct uses of timber. The shell structure is made of high quality oak used sparingly and structurally very efficiently; a careful use of a valuable resource. It is formed of four layers of 35mm x 50mm green oak laths bolted at nodes with steel connectors. The end arches, floors and cladding are made of larch – a fast growing softwood – used in a different structural manner. The softwood comes from sustainable sources – indeed there is no reason why all timber, used everywhere, should not.

Architect: Edward Cullinan Architects
Structural engineer: Buro Happold

Photographs: Adam Wilson

Centre left: oak laths are bolted together with steel connectors to form a shell structure.

Far left and left: the shell is clad with larch boards from sustainable resources.

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Engineered wood - **bigger, better, stronger**

Richard Harris outlines advances in engineered timber technology

Photograph: Adam Wilson

Natural materials impose severe limitations on designers, and the desire to improve on what is obtained directly from trees drives the modern development of engineered wood. Engineered wood is derived from the tree but has fewer flaws and less variability. Timber – sawn from roundwood logs – was the first engineered wood.

Although timber is an engineered material, it is restricted to the size and shape of the tree from which it came. The properties of timber vary within the same tree, from forest to forest and from species to species. When working with the raw product, it is always necessary to work to much lower strengths than average to allow for this variation. The greater the variation, the lower the allowable properties used in design. Modern advances enable wood to be used to make elements larger in size, with less variability and with the natural fibres working in the most beneficial orientation.

Glue laminated timber

Glue laminated timber, known as glulam, is the simplest form of engineered wood. The raw material, timber, is cut into planks, dried and graded and gross defects are cut out before it is planed and bonded together to make pieces of the required cross section or form. High and low strength timber may be used at points of high and low stress; different species may be mixed to benefit from their different properties.
Glue laminated timber was developed in the 19th century in parallel to other techniques and products involving mechanically laminated timber. In Germany, as early as 1809, Wiebeking had proposed gluing highly curved timbers for building purposes. Perhaps he was drawing on the innovative bridge designs of the Grubenmann brothers, who built up long beams using elaborate notched interfaces between the timbers. Their work – such as the remarkable Schaffhausen bridge (built 1756-8) – inspired 19th century engineers and is still relevant today.

The first structure built with glue laminated timber was the assembly hall of King Edward College in Southampton (1860) but this remained a one-off. Otto Hetzer, a carpenter with a huge factory in Weimar, registered a number of patents between 1891 and 1910. As licences were granted to companies around the world, glue laminated timber developed. The technology advanced with the use of adhesives which made the material more reliable and longer lasting. Early structures were made with casein adhesive (derived from cows' milk) which is not moisture resistant. Today's adhesives – resorcinol and melamine formaldehyde – are both water and heat resistant.

Glulam overcomes the limitations imposed by the properties of the tree. Lamination enables the structure to be matched to the line of force – it can then be designed to span large spaces. Laminates can be chosen to provide the strength required at different positions. Glulam has the potential to create long-span roof structures, ideal for enclosures requiring column-free spaces, such as airports. It was used as the main structural element at Gardermoen airport, Oslo, and at Cork airport.

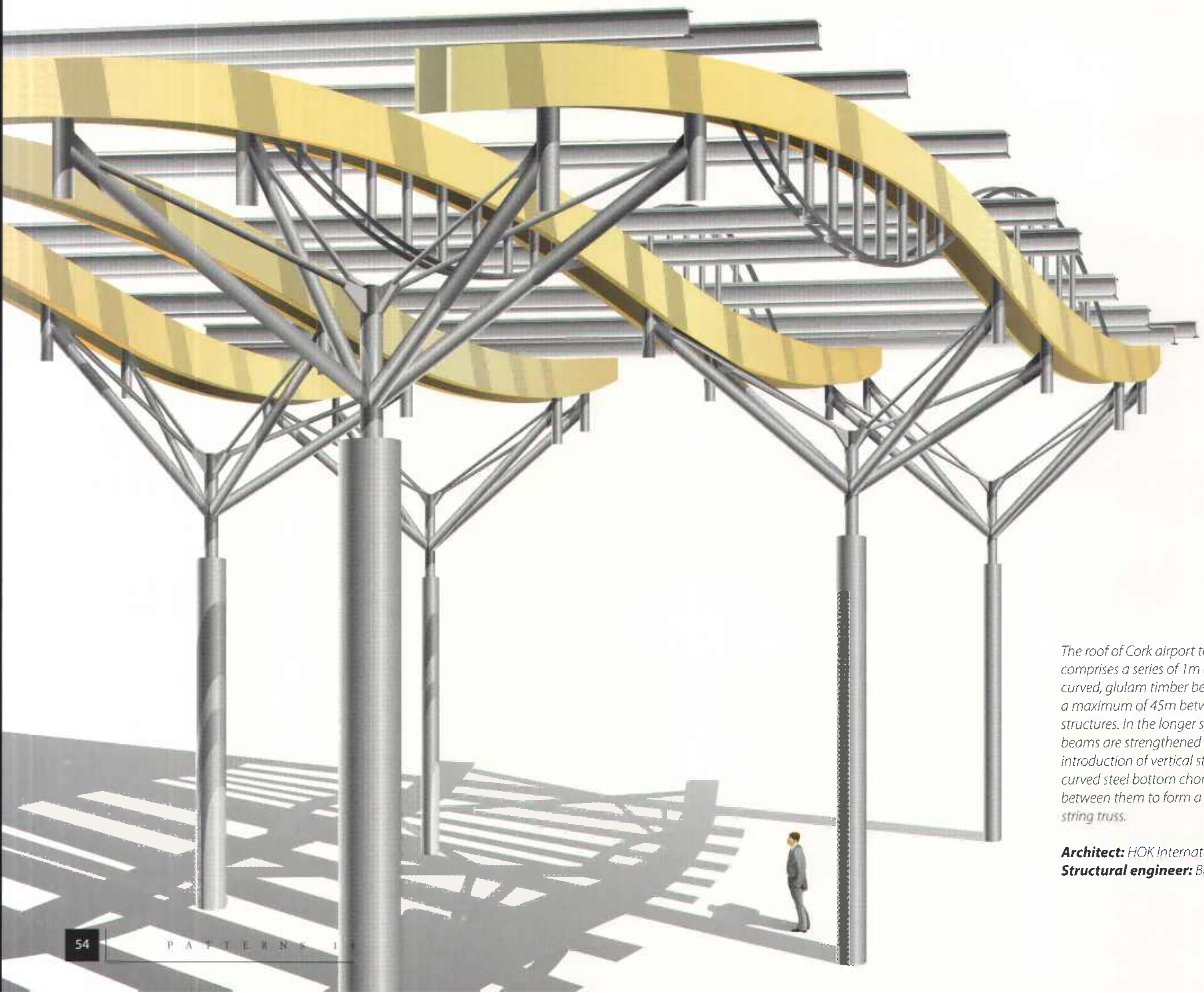
The availability of glulam has made a whole range of structures possible. A standard glulam product was developed to make flat and curved grillages for the roof structure of a school for Hampshire County Council at West Totton. The new headquarters building for Velux is a showcase for engineered wood products; the structure – a series of three-storey-high crucked glulam beams – is clearly revealed. The Sheffield Winter Garden is a demonstration of how designers can engineer glulam to its best advantage. The primary structural elements are arches, shaped as parabolas so that the line of action of the force lies within the arches when they carry the building's self-weight. The laminates are cut from commercially grown larch, a deciduous softwood of great beauty. Larch is relatively hard, resisting minor damage where it is exposed in a public space and moderately durable if detailed to ensure that it does not remain wet for long periods of time. The structure was designed using the newly introduced Eurocode EC5. There is no large UK glulam manufacturer and by using the Eurocode the structure was supplied, competitively, from the German manufacturer MERK. The Eurocode draws on the continuing development of glulam across Europe. There are some anomalies between the existing British timber design code BS 5268 and the Eurocode EC5. Depending upon the load, there is a tendency for curved structural elements to either straighten or curve more. If they tend to

> "Glulam has the potential to create long-span roof structures, ideal for enclosures requiring column-free spaces"


Photograph: Adam Wilson

A series of crucked glulam beams form the structure of the new Velux headquarters at Kettering.

Architect: White Design Associates
Structural engineer: Buro Happold



The roof of Cork airport terminal building comprises a series of 1m deep, 90m long, curved, glulam timber beams spanning a maximum of 45m between steel tree structures. In the longer span the glulam beams are strengthened with the introduction of vertical steel struts and a curved steel bottom chord which is fixed between them to form a composite bow string truss.

Architect: HOK International and Jacobs
Structural engineer: Buro Happold

The hall roof at West Totton school is supported by cylindrical glulam columns; they taper at the head to support a grillage of glulam beams.

Architect: *Hampshire County Council*
Structural engineer: *Buro Happold*

straighten, there are tension stresses built up across the thickness of the element. In this direction (across the grain) timber is weak. In designing the Sheffield Winter Garden we found the European Code to be more conservative in respect of this tension perpendicular to the grain; it led to the introduction of steel dowels drilled into the glulam to reinforce it against the tendency to split.

The European Code draws on research in Germany that shows that timber is weaker across the grain than is assumed in the British Code. In raising this matter with the code drafters, we found that this is an area of robust discussion. The German industry insists that the EC5 approval is the only safe approach. If this is so, then the British Standard could lead to the design of unsafe structures. BS 5268 is to be withdrawn shortly and the drafting committee does not appear to consider a revision to be necessary but Buro Happold is already designing major structures using the Eurocode. It is more rigorous and better grounded in research available across Europe. We can engineer our structures better and we can engineer materials better with this code.

Laminate, stressed skin and strand products

Glulam is made from solid timber, but in recent years other engineered wood products have emerged, including laminate and stressed skin products. Turning a log on a lath to peel a thin veneer of wood produces a very thin laminate. Plywood – made by bonding these veneers to make sheets – has developed in parallel with glulam. Various laminates can be combined to create different properties; new glues can improve performance and durability. The outer veneers can be chosen to be stronger, more durable or more decorative than the inner ones – it is common to use mixed species in the build up of plywood. Various structural elements can be formed of plywood sheets. Hollow box beams can be fabricated in complex cross-sectional shapes. The size of the sheet is rarely a restriction, as plywood is available in sheet sizes up to 1.9m x 4m and can be jointed or built up in lapped layers to make even larger sheets. The main constraint for the designer is that structural elements are limited by the two dimensional nature of the sheets.

The largest elements of a building – floors and walls – can be fabricated from structural panels (known as stressed skin panels) with plywood outer layers and timber or timber composite/joists/studs. Other materials can be built into panels to provide acoustic and fire resistance, offering the potential for use as floors, walls and roofs. Clearly there is much scope for integrated design – for panels with structural properties, environmental benefits and decorative surfaces.

Photograph: Mandy Reynolds, Fotoforum

The arched glulam structure of the Sheffield Winter Garden creates a dramatic interior.

Architect: *Pringle Richards Sharrat Architects*
Structural engineer: *Buro Happold*

The technology has extended beyond plywood; thin laminates are now used to make structural elements of larger cross-section. Laminated veneer lumber (LVL) is a product derived from US technology. It demands a higher investment in equipment to manufacture and there are only two products commonly available, Kerto LVL from Finland and TJM Microlam from the USA. Kerto LVL has been used widely in the UK. LVL can be designed with laminates oriented in the most structurally advantageous direction, but some laminates can also be run perpendicular to this direction, making it much more dimensionally stable than natural timber. Hounslow East station and Norwich Cathedral visitor centre have roof structures formed of Kerto LVL; in both cases it was chosen to achieve accurate fabrication. On both buildings the structural elements were manufactured to close tolerances and then brought to site and slotted together with sophisticated metal connectors and bolts. Kerto is made from natural spruce timber which has a characteristic bending strength of between 16N/mm^2 and 24 N/mm^2. Kerto S (the grain of all veneers along the longitudinal axis) has a characteristic bending strength of 48N/mm^2 and Kerto Q (some veneers transverse for ten times better dimensional stability across its width) has a characteristic strength of 36N/mm^2.

Oriented strand board (OSB) is manufactured by cutting the source wood into strands and bonding them together into larger elements. OSB originated in the US, but in contrast to LVL it has only been adopted in Europe in the manufacture of panels. Sterling Board is an OSB panel product manufactured in Scotland; the panels are made by laying chips of wood in a matrix of resin, in a manner that leads to general orientation in a chosen direction.

Another product to use strand technology is known as parallel strand lumber (PSL) and is another TJM product, Parallam, manufactured in the US. Strand technology products have good engineering properties and green credentials. In the US the raw material used is aspen, a fast growing timber that can be harvested very young to make strands, so that OSB and PSL products can be sustainably sourced. Engineered wood and timber products can be assembled to make box beams (plywood) or I-beams (sawn timber, glulam or LVL flanges with plywood, OSB or other engineered timber webs). Recent research has investigated advances in timber composites in which wood and timber are mixed with non-wood materials. Natural timber is complex composite of fibres in a resin matrix. Of course, glulam, LVL, OSB and PSL are also composites, made by combining timber or wood with resins similar to those that occur naturally in wood but in a manner to create better engineering properties. There has been recent research into building mats of carbon fibre into glulam, enabling beams to be made with less depth than a standard glulam beam but of the same strength and stiffness. In southern Europe a very successful product has been developed by combining timber with composite concrete. ■

Photographs: Graham Young

The curved roof of Hounslow East tube station is formed of an elegant diagrid structure of Kerto LVL beams connected together in a lamella sequence. The Kerto beams were bolted together with a 'Cowley' connector.

Architect: *Acanthus Lawrence & Wrightson*
Structural engineer: *Buro Happold*

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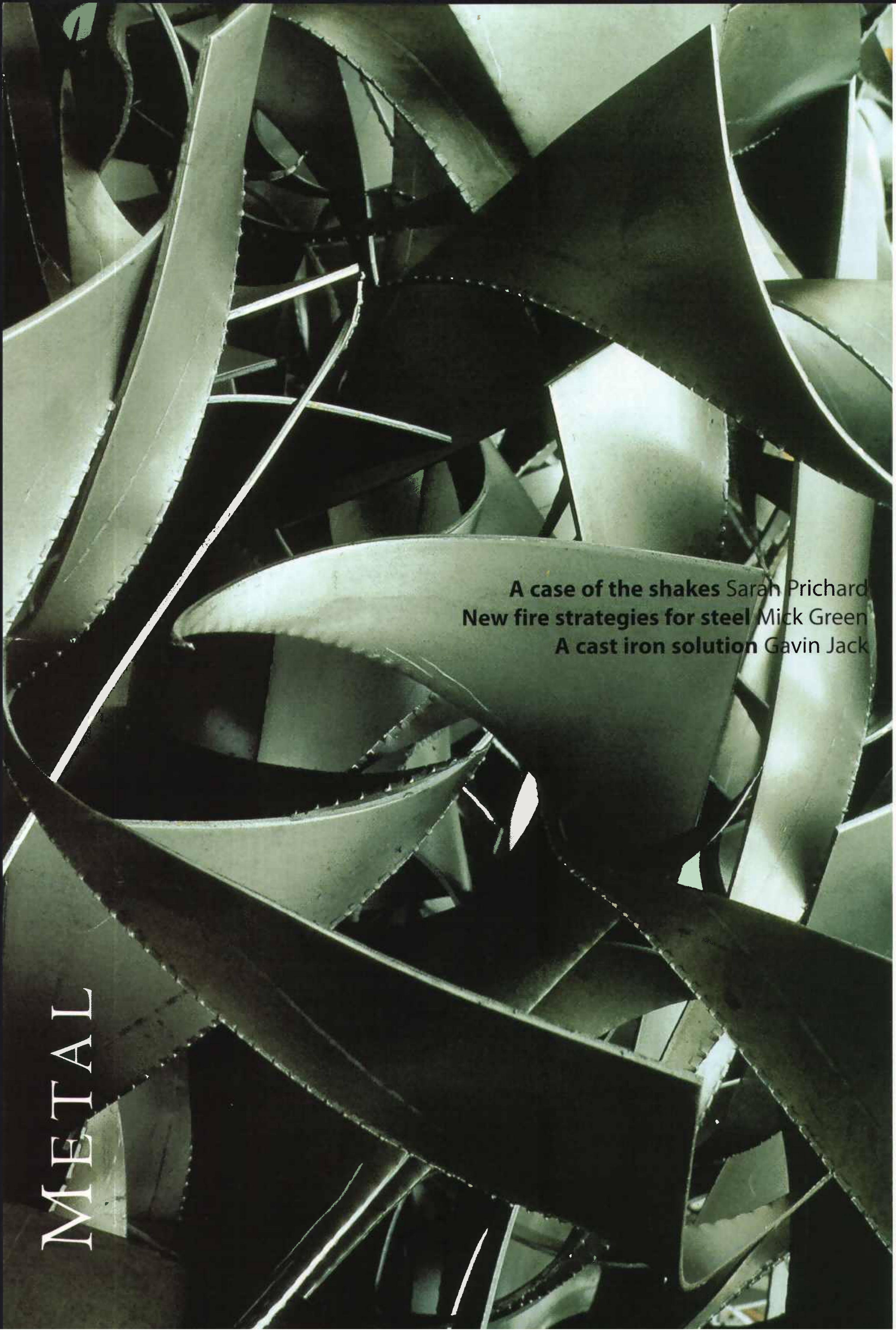

METAL

A case of the shakes Sarah Prichard

New fire strategies for steel Mick Green

A cast iron solution Gavin Jack

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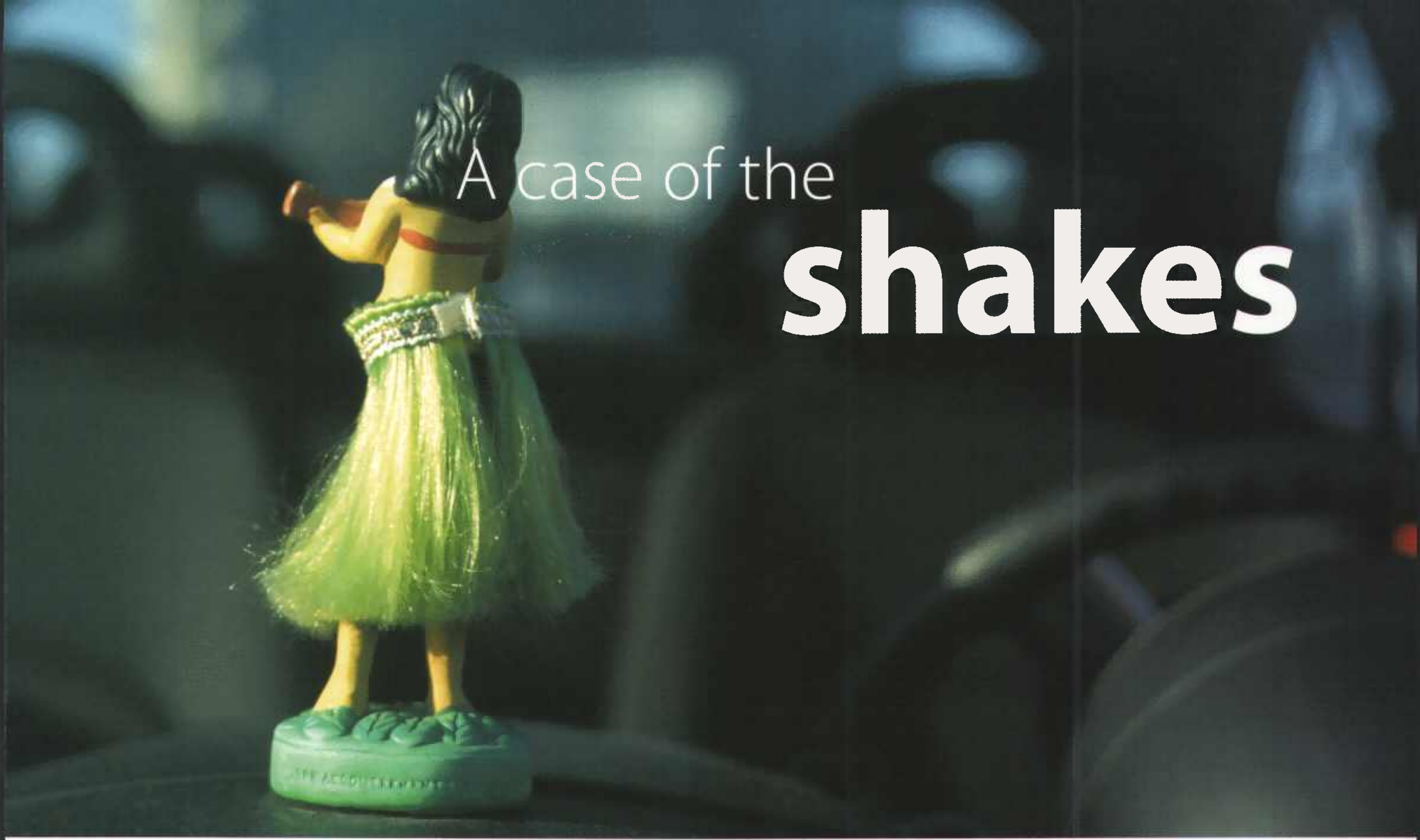


A case of the shakes

Dr Sarah Prichard compares the vibration responses of steel and concrete-framed buildings

As a result of both investigation and mishap, the effect that vibrations have on structures is becoming increasingly well understood. Footbridges, grandstands and floors are among the most susceptible to dynamic excitation and should be assessed for this form of loading prior to construction. For all three types of structure, there has been a lack of research into the nature of their responses to vibration. However, in recent times both researchers and designers are looking more closely at the subject. This is particularly when cases, such as the embarrassing closure due to lateral sway of the Millennium Bridge in London, make the national headlines. The design and assessment of structures for vibration is now vital in building design. Reasons for this include: occupants with higher expectations of the quality of their environment, both at home and in the workspace; increasing pressure for lighter, more economical, longer span structures; development of industrial, medical and research facilities which are dependant on ultra-low vibration conditions; and construction on brownfield sites adjacent to transport infrastructure and other causes of vibration.

Vibration in buildings is generally the result of people walking on the floor slabs, rhythmic people movement (for example dancing or aerobics), machinery, transportation, or, in rare cases, blast or impact. It has three distinct effects on a building structure, (a) it can compromise human comfort, (b) it can cause equipment malfunction and (c) in extreme cases it can cause structural damage. Best practice in the construction industry dictates that any machinery which might cause vibration be isolated from the structure on elastomeric bearings and that foundations are designed to prevent transmission of vibration loads from adjacent moving vehicles into the building. However, the vibration source which causes the most disturbance to building users on a day-to-day basis is from humans occupying and moving on the same floor, something which is almost impossible to isolate effectively.

The area of human-induced excitation of structures has traditionally been little appreciated by British engineering consultants (the vibration response of a structure was rarely deemed to be critical in its design). Often, simple hand calculations are used to estimate the natural frequency, and the design proceeds according to vague empirical rules which have poorly understood theoretical or experimental foundations. Furthermore, natural frequency has been shown to be an unreliable indicator of floor quality. It is considerably more important to assess the response of the floor to applied loads, in terms of the amplitude of the velocity or acceleration. Past research has helped little, producing varied results which are difficult to incorporate into current design practice.

Structural vibrations

To appreciate the problems involved in designing a building to withstand vibration, it is necessary to have some understanding of the response of a structure to a dynamic load. Its response to such a load is a function of the natural frequency of vibration, which describes the oscillation of a moving body. That frequency is proportional to the stiffness and inversely proportional to the mass. As the applied load is the force associated with the mass of the building and the stiffness is the relationship between the applied load and the resulting deflection, the natural frequency of a body can be described using the following equation:

$$f \propto \sqrt{g/\delta}$$

where f is the frequency, g is the acceleration due to gravity and δ is the deflection.

Furthermore, if we consider Newton's law, which says that force is equal to the mass multiplied by acceleration, we can deduce that, for a given applied load, the greater the mass of the building, the lower the amplitude of the frequency response. This is a key point in understanding the rationale behind the empirical selection of building forms to withstand vibrations and the developments in understanding which increasingly allow buildings to be designed to minimise disturbance from vibration loads.

Concrete and steel-framed buildings

Concrete-framed buildings were traditionally adopted when a client requested a building which needed to resist vibration. They have been chosen, empirically, because there are significant masses in the beams, slabs and columns and this mass has to be mobilised before the building can vibrate in response to a dynamic load. Inherent in the selection of a concrete-framed building is the understanding that column spacing will be limited, as concrete is unable to span large distances (the maximum economically viable grid spacing of a traditional concrete building is between 6m-8m) and there is a resulting trade-off between the mass of the concrete building and its resistance to vibration. An increase in mass generally results in a greater deflection and a corresponding reduction in natural frequency; however, shorter spans generally mean that deflection is reduced and the natural frequency is increased. Furthermore, according to Newton's law, the greater the mass, the lower the amplitude of the displacement, velocity or acceleration response.

For the reasons outlined above, life for the vibration engineer would have been simple if everybody had been happy to stick to massive, heavily damped structures. In the past decade, however, there has been increasing pressure on designers to create buildings with lighter, longer spans, which provide more economical solutions for offices, laboratories or indeed, residential buildings.

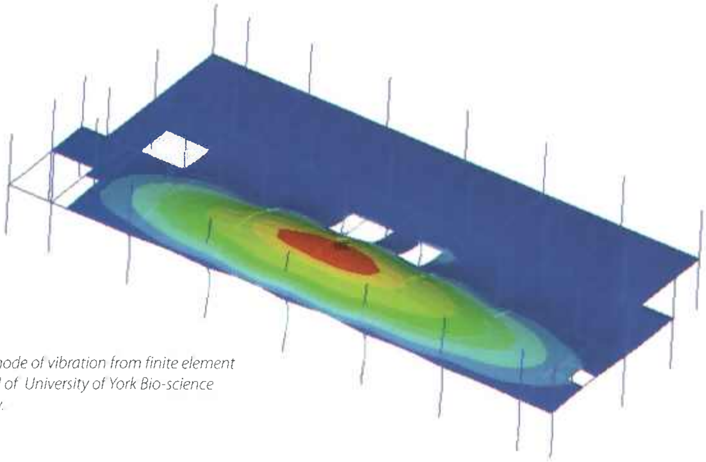
This, coupled with the relative speed of erection, has made steel-framed buildings increasingly popular. However, because of their relative lightness, designers have typically shied away from steel-framed structures when a vibration response is important. This, compounded by the reduction in the natural frequency due to the increased spans, means that unless carefully considered, steel-framed buildings will continue to be rejected in favour of their concrete cousins. When analysed, however, the difference between the two structural forms is not as great as might have been expected. The combination of long secondary floor beams and shorter primary beams spanning between columns means that a significant area (and associated mass) has to be mobilised before the building can vibrate in response to a dynamic load. The natural frequencies of the individual beams can be comparatively low, but the natural frequency of the overall panel is higher and the greater modal masses mean that the resulting accelerations are lower.

The relative abilities of building structures to provide damping is a further point of differentiation between concrete and steel-framed buildings. Energy dissipation in a bare structure occurs predominantly by material damping and, to a lesser extent, by damping at bearings and joints. Concrete, as a material, is ten times better than steel at damping. Using heavy concrete slabs on steel frames and carefully detailing beam/column connections means that the difference in the damping between the finished building forms is not as great as it might otherwise be.

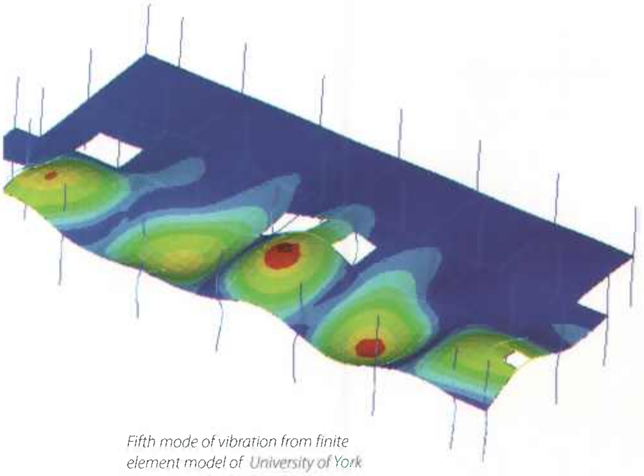
In general, the basic configuration of a floor system must be established early in the design process, normally during the scheme stage and long before the building is defined in enough detail to merit a rigorous analysis.

> "To appreciate the problems involved in designing a building to withstand vibration, it is necessary to have some understanding of the response of a structure to a dynamic load"

Photograph: Alex Pavic



First mode of vibration from finite element model of University of York Bio-science facility.



Fifth mode of vibration from finite element model of University of York Bio-science facility.

Photograph: Adam Wilson

Above: University of York Bio-science facility when completed.

Left: Floor slab during testing at University of York Bio-science facility.

Below: University of York Bio-science facility at the time of testing.

Photograph: University of York

Certain details can be incorporated into the design at this stage to give a later analyst a reasonable chance of proving definitively that the building can withstand dynamic loading and minimise interference with equipment and occupants. These include increasing the slab thickness, particularly in the case of steel-framed buildings, taking care to detail moment connections at column-beam intersections to increase resistance to bending and, therefore, associated deflections and natural frequencies, and possibly even offsetting column grids to break up modes of vibration.

Case study: Bio-science facility, University of York

The design of a £20 million bio-science research facility at the University of York commenced in 1999. During the design process, it became evident that equipment inside the building would be sensitive to vibrations caused by the movement of people around the facilities. A design solution was proposed where the most vulnerable equipment, such as electron microscopes, would be mounted on concrete isolation plinths on the ground floor of the building. For the upper floors a concrete frame was suggested, based on standard laboratory space planning parameters.

However, the contractor advised that a cost saving of between £200,000-£250,000 could be achieved if a steel-frame solution was adopted instead of a concrete frame. The structural engineering team undertook feasibility studies to assess whether a steel frame could provide a similar level of performance to that of the concrete frame. As the fundamental dynamic performance of a structure depends on mass and stiffness, the traditional 'slimflor' slab solution was modified to ensure that it had a similar mass to the concrete frame. This resulted in a 400mm deep precast plank with a 75mm structural topping, with the benefit of a large reserve of strength, reduced cost and ease of erection. Finite element modelling clearly showed that the proposed steel frame was at least as good as the original concrete framed solution and that its response could satisfy existing guidelines for the design of laboratories.

When the original analytical work was undertaken the building had not been constructed, yet its vibration response was already under scrutiny. This provided a unique opportunity to test the actual laboratory floor in its bare state and compare it to improved, and increasingly detailed, analytical models of the structure. Research experimentally determined the response of the floor and collected significant information on the response of the building to vibration. It also allowed realistic theoretical input forces, generated using modal testing of the floor and repeated measurements of walking-induced vibrations, to be determined. Finite element models and modal updating were then matched to the measured modal properties. Harmonic, transient and spectral analyses were used with different walking model inputs to determine the theoretical vibration response, which was compared with its experimental counterpart. It is hoped that the successful comparison of the theoretical and experimental results produced during this work will give future designers confidence in the use of such methods.

Architect: Anshen Dyer Architects
Structural engineer: Buro Happold

Artist's impression of New Nuffield Hosptial, Oxford.

"Engineers must always take time to assess structures for their eventual purpose, both in relation to their functionality and occupation"

Case study: New Nuffield Hospital, Oxford

The site of the new Oxford Nuffield Hospital is in a suburban area, isolated from major roads. The basement, which is to be used as an underground car park, and ground floor slab are both reinforced concrete and the upper two floors are of steel-frame construction with steel/concrete composite decking. Six operating theatres, a CT scanner and MRI scanner will be located at first floor and it is predominantly these pieces of equipment which could be affected by any vibrations within the building.

As the pieces of equipment within this facility are of high specification and are sensitive to vibration, a study of the vibration response of the suspended first floor slab was undertaken using finite element analysis. The modal response, and that of the structure to applied loads, was theoretically determined. The initial response of the floor slabs, which had been designed for appropriate dead and live loading, was nowhere close to the required response. Significant changes had to be made to the structural layout at this stage as the velocity response of the structure had to be halved. The thickness of the concrete slab and the size and spacing of the beams were modified until analysis showed that the floor had vibration characteristics suitable for an operating theatre. This means that, under dynamic loads associated with people running in the adjacent corridors, the maximum velocity of the floor was limited to 102 μm/s, which is in line with current guidelines.

However, this response was outside the limits of what was acceptable for the MRI scanner, which could only withstand a maximum velocity of 13 μm/s, and clearly this area of suspended floor slab required a significantly higher specification. Numerous finite element analyses were performed to determine the response of the area with an increased thickness of slab. The secondary beams on which the metal deck was sitting were already closely spaced and it was inappropriate to reduce this spacing. The slab thickness was eventually increased to 250mm from 180mm in the surrounding area. This resulted in the structure becoming slightly stiffer. However, it also had the effect of forcing the modes of vibration to occur in the bays surrounding the MRI scanner (which were less stiff) and the scanner bays did not vibrate significantly.

As part of the analysis, the option of replacing the area of slab and its supporting columns with reinforced concrete was considered. The analysis showed that the equivalent concrete slab would have been 350mm thick as it was an isolated area and could not mobilise the stiffness of the surrounding steel frame as the steel itself was doing. If a pair of bays of the steel structure in the area of MRI scanner had been replaced by a concrete frame then this might have provided a viable vibration response. However, substituting a small section with a concrete frame which was difficult to integrate into the surrounding structure, would have resulted in an increase in complexity, a greater volume of materials and no improvement in the vibration response.

Architect: Kendall Kingscott Partnership Architects
Structural engineer: Buro Happold

"Our work is constantly developing as clients demand greater comfort, higher specifications and lower costs"

Our work is constantly developing as clients demand greater comfort, higher specifications and lower costs. As a result of this, vibration engineers are now having to perform analyses to show that the structures can both withstand accidental blast and impact, and also provide low vibration environments for human comfort and equipment performance.

Engineers must always take time to assess structures for their eventual purpose, both in relation to their functionality and occupation. As has been shown, this is particularly important when the vibration responses are considered. The achievement of an adequate vibration environment in a laboratory or hospital, which have increasingly affordable, accurate, high specification equipment as standard, is now the primary structural design concern and leads to stiffer and more massive structural forms than would otherwise be required. Similarly, office blocks have stringent limits on the frequency and amplitude of vibration, but in this case, the issue is not equipment performance, but the well-being of its occupants. Human tolerance to vibration is dependant on the task being undertaken when vibration occurs and we are particularly sensitive to disturbance from vibration if concentrating hard on the task in hand. Furthermore, our quest for lighter, smaller objects surrounding us exacerbates vibration problems, because they do not contribute to damping and they can vibrate annoyingly, a perfect example being the new flat-screen computer monitors. People cannot distinguish easily between vibration levels which are close together and, hence, for human comfort, the vibration response needs to be halved to make any significant difference. Yet, to achieve this it is often necessary to double the steel or concrete mass or to make major adjustments to the building configuration.

Designers increasingly need practical guidance on both performance standards to be achieved and modelling techniques to be adopted for vibration analyses, particularly as current guidance suggests that all floors, regardless of their natural frequency, should be assessed for resonant excitation if their damping is less than 5%. Comparatively small modifications to corridor length, room location and associated walking speeds, all of which can be made easily in the early design stages, can result in the majority of problems associated with vibration being significantly reduced. ■

New fire strategies for steel

Mick Green describes advances in the design of steel structures to perform adequately during fire.

With the introduction of new materials – cast iron and subsequently steel – in the 19th century, structural engineering made a quantum leap. The last few decades have seen a similar revolution in the design of buildings for fire safety. A dramatic transition has taken place, from design based on testing and prescription to design based on science and fire safety engineering. New analytical methods and improved risk assessment techniques have made such performance-based design possible. Materials are now better understood and many have been improved. This has changed the way structures are designed, procured and specified.

A new fire strategy

A range of strategies is now available to ensure satisfactory structural performance during fire. The traditional approach to fire safety and prevention is prescriptive – published regulations and guidance to specify requirements for fire protection means of escape, compartmentation and access for fire fighting. The new fire safety engineering approach is holistic; calculations and engineering judgement are used to determine the impact of a real fire on a real building and its occupants. It examines the reaction of materials to fire, whole frame structures, the means of escape, the response of people to fire and smoke, their management, and how structures behave in a 'real' fire rather than in a test chamber. The choice of strategy and the degree of sophistication required will depend on the particular circumstances and design objectives. Levels of sophistication can be categorised in increasing order of complexity as in the table below.

Level	Procedure	Description
1	Use simple prescribed rules and simple structural elements.	This is relatively straightforward and usually requires reference to National Standards and manufacturer's standard literature on fire protection systems.
2	Account for reduced stress level in the structure to demonstrate improved fire performance in conjunction with the standard fire. Usually involves simple structural elements.	This is still a relatively straightforward process with simple calculations and requires reference to documents such as BS 5950 Part 8[32] for steelwork.
3	Introduce parametric fires. Parametric fires provide a reasonable representation of the time temperature profile of a real fire.	Requires additional skills and knowledge of ventilation conditions and fire levels.
4	Advanced finite element performance of structures in combination with parametric fires. Often involves whole frame structural action.	Requires considerable analytical skill in combination with engineering judgement and represents the current state-of-the-art.

"The fire safety engineering strategy is particularly appropriate for complex steel structures"

Fire safety engineering for steel structures

Fire safety engineering design is appropriate for commercial or complex steel structures. Analysis of ambient and fire load cases can be integrated, delivering better value to the client than when – as in the most common approach to steel structure design – they are dealt with independently.

Performance criteria

The objectives of the design and related acceptance criteria are an important step in progressing a successful holistic approach to fire safety engineering. Objectives agreed as part of the fire strategy that may affect the specification of the performance of structures are as follows:

- Repairability of materials and structure, which influences business continuity.
- Insurance requirements.
- Resistance to fire / explosion damage.
- The impact of earthquakes, where active fire safety systems may be damaged.
- Design against fire-initiated progressive collapse for large or complex buildings. Considerations of collateral damage will be relevant in this context.
- Review of deflections to check compliance with the fire strategy for the building.

Examples of cases where there may be a need to control deflection during fire include:

- Where there is a need to maintain business continuity in a separate compartment or floor for extended times.
- Where escape routes may be affected in the later stages of a fire, eg, in phased evacuation of tall or complex buildings.
- Cases where deflections in the structure could adversely affect compartmentation. Slabs or beams may deflect onto compartment walls but this interaction should not compromise compartmentation.
- Cases where added fire protection has only been tested up to a limiting curvature during the furnace test. The risk is that high deflections could result in damage to the fire protection unless additional evidence to the contrary can be provided.

Risk assessment

When dealing with more complex buildings there is often a need for the designer and the regulator to examine the robustness of a solution and the consequences of failure as part of the risk assessment process. Although the list below is not comprehensive, it gives an indication of the types of issues the engineer should consider and review in the context of a building's fire strategy:

- Robustness in terms of performance and maintenance. A fire protection measure with a managed certified maintenance routine is much more reliable. Some solutions require little maintenance since they are well able to withstand the rigours of day-to-day use to which buildings are subjected. A steel beam designed to achieve the required fire performance without added fire protection is a good example of this scenario.
- Margins of safety, in cases where a high degree of reliance has been placed on a single fire protection measure.
- Acceptance of lower factors of safety on individual fire protection measures, where they all combine to achieve the required standard (since the chance of every fire protection measure failing at the same time is fairly remote). In a diverse solution, the likely outcome of the failure of a single fire protection measure is a reduction in the factor of safety but not a complete failure to provide the required performance.

For further detail refer to the guide: "*Introduction to the Fire Safety Engineering of Structures*" published by the Institution of Structural Engineers (2004).

Structural fire design

The fire performance of structures can influence ambient structural design in a variety of ways. Advanced fire engineering may be necessary to demonstrate that an unusual structure is viable in terms of meeting client aspirations, or in cases where good value is sought for a repetitive form of construction, as in the GSK case study overleaf. For example, a building designed on sustainable principles may have an exposed structure – to provide thermal mass – which in turn may require fire safety solutions to be considered in greater depth. An integrated approach is essential. ■

Case study: GSK House, London

GSK House, an office development in London, consists of four buildings, the tallest of which is 15 storeys high. The external frame took the form of a Vierendeel which was used to resist wind shear; this provided some additional structural capacity that could be utilised in the fire load case. The contractor proposed a board system to fire protect the edge beams, but the design team was interested in a value engineering solution, taking into account the following:

- The requirement for a robust, safe solution.
- Off-site application of intumescent, to save time. (Thin intumescent coats are quicker to apply and the risk of transportation and erection damage is reduced).
- Reduced need for protection of workers at building edge in high rise situation, as a result of increased off-site fabrication.
- Reduced need for delivery of materials and removal of waste, which can monopolise valuable construction infrastructure.
- Reduced temperatures of edge beams resulting from natural fire considerations.

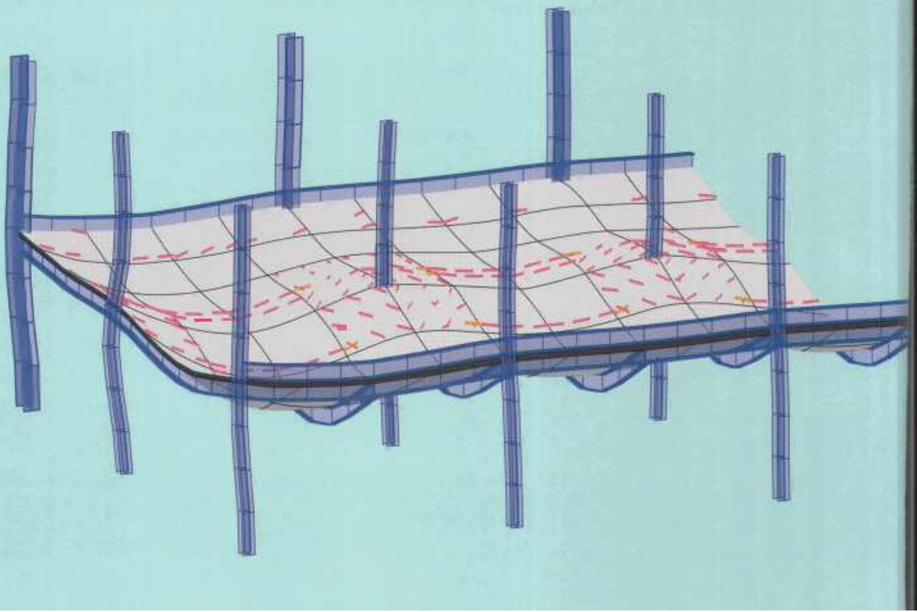
GSK House during construction.
The white intumescent-coated edge beams are clearly visible.

Photograph: Mace

The prescriptive fire resistance rating of intumescent was three to four coats, but a risk assessment was carried out, together with a Vulcan analysis, to determine the thickness of off-site intumescent required to achieve a safe solution. Due to the extra inbuilt capability of the edge beam structure and the reduced temperatures realised by the natural fire approach, the calculated amount of fire protection was very low. However, to ensure a margin of safety, 1.5 coats of intumescent were applied to give a conservative but good value solution that satisfied all parties.

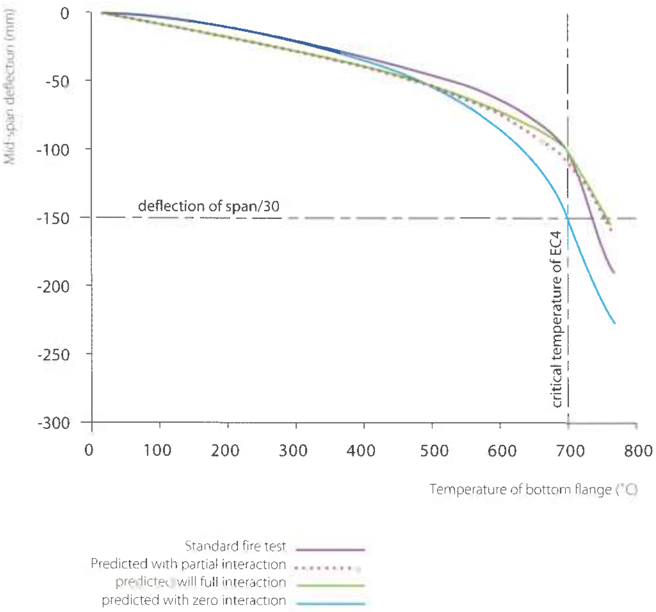
The use of Vulcan to model the behaviour of steel and composite frames under fire conditions

Computational modelling is a fundamental part of fire safety engineering and an essential part of the process of determining whether or not fire protection of steelwork is needed to achieve the required standard. Vulcan, developed jointly by Sheffield University and Buro Happold, is a non-linear three-dimensional frame analysis program, which has been developed mainly to model the behaviour of skeletal steel and composite frames, including floor slabs, under fire conditions. Temperature distributions across members can be non-uniform, causing differential thermal expansion and a spread of elastic and inelastic properties across the section. A range of cross-sections can be defined, allowing different shapes and materials to be represented. A number of comparisons have been made with classical analytical results and tests. Some of these relate to ambient temperature behaviour, and although Vulcan is intended primarily for use in modelling the structural response to high temperatures, it can also be used at an ambient temperature to analyse conventional conditions for which classical solutions are available.



Composite Slab behaviour

A typical example of a Vulcan diagram, showing deflection in the zone affected by fire.



Above: Comparison of temperature-deflection behaviour for 254 x 46mm x 43 UB composite beam with a 130mm reinforced concrete slab, subject to ISO834 fire test The results of two ISO834 standard fire tests on simply supported composite beams are compared with analytical results in these figures. They show reasonable agreement, particularly in view of the uncertainties associated with fire testing.

Case study: The Lowry Centre, Salford

The building houses a 1,400-seat theatre, a 400-seat adaptable theatre and two galleries. Many aspects of fire safety engineering were involved in different parts of the building. One of these was the support to the Lowry Gallery. An unprotected single storey-height steel truss runs along the glazed wall of the gallery; it supports the long-span concrete floor, limits deflection and controls vibration in the floor for the non-fire load case. It is also an important architectural feature. Normally, as a structural element, this truss would need to be fire protected.

The fire engineering solution involved a thorough appreciation of structural action and load paths and the different material properties of concrete and steel. Fire and ambient load cases were considered together from the outset. The solution was three-dimensional and involved the combined use of steel and concrete. It established that, in a fire condition, issues of deflection and vibration were less critical. Therefore the concrete slab and the internal column system could be designed to support the reduced loads during fire without reliance on the steel truss, which would have limited capacity at high temperatures. As the steel truss is not needed during fire it does not need to be fire protected.

Where there are alternative load paths, many other structures, which may be redundant in the fire load case when applied loads are smaller, have the potential to be considered in this way.

Architect: Michael Wilford & Partners
Structural engineer: Buro Happold

Below: The Lowry with the position of trusses illustrated.

Photograph: Mandy Reynolds, Fotoforum

Case study: Two exposed external steel structures

A basic tenet of classic modernism is that the structural support for the building should be apparent and visible. The 'natural fire' approach is gradually being introduced to the design process to enable cost effective delivery of such designs. Traditionally, the performance of steel members is based on furnace tests, which are not representative of conditions of exposure in real fires. Natural fires take into account the actual fire load, ventilation, thermal properties of the compartment enclosure, and the shape and size of the fire compartment.

The design of an unprotected external structure using natural fire technology has been around for a longer period, but it is still a valuable approach. The IBM headquarters at Bedfont Lakes and the DSS office, Newcastle-upon-Tyne, both by Hopkins Architects, demonstrate how an exposed steel structure can be integrated into the facade. This approach is well documented and involves predictions of flame projection, radiation and convective heat transfer to calculate the temperature of the external structure and ultimately its ability to carry the loads at the high temperatures. In all these cases, external intumescent paint was the first option. But the most effective solution was to shield the structure (usually with a fire resisting section in the cladding immediately behind the column) from the intense internal fire, increase the weight of the steel slightly to reduce the heating rate, and increase the load carrying capability.
This eliminated the need for the long-term maintenance of an external fire protection system.

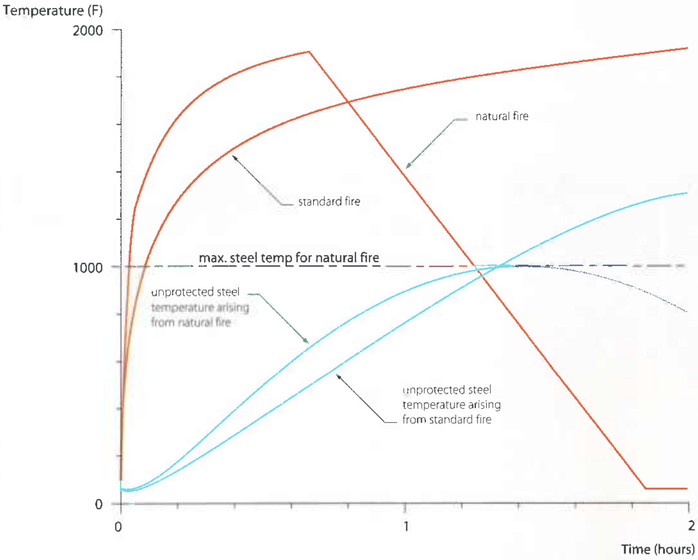
Architect: Hopkins Architects
Structural engineer: Buro Happold

> "The IBM headquarters at Bedfont Lakes and the DSS office, Newcastle-upon-Tyne, both by Hopkins Architects, demonstrate how an exposed steel structure can be integrated into the facade"

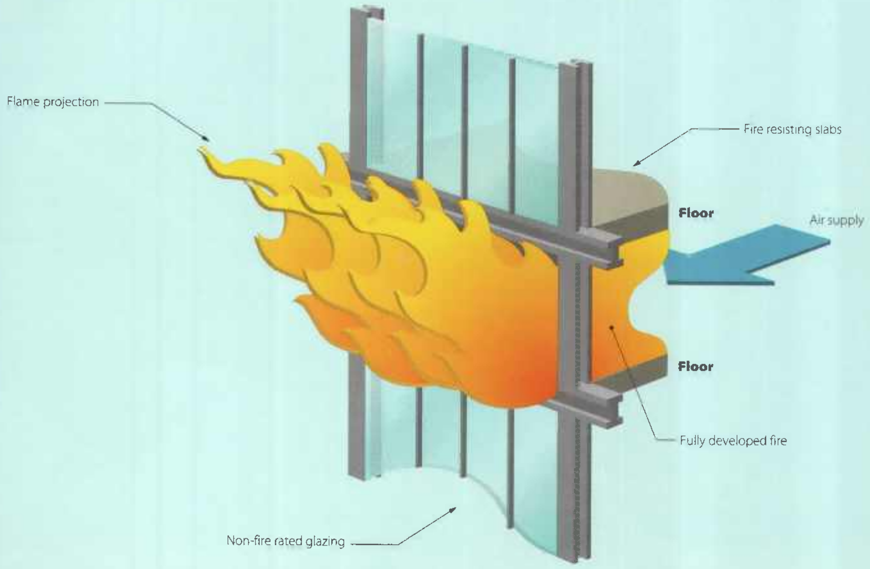
Top left: the facade of the DSS office, Newcastle-upon-Tyne, incorporates an exposed steel structure.

Photograph: Mandy Reynolds, Fotoforum

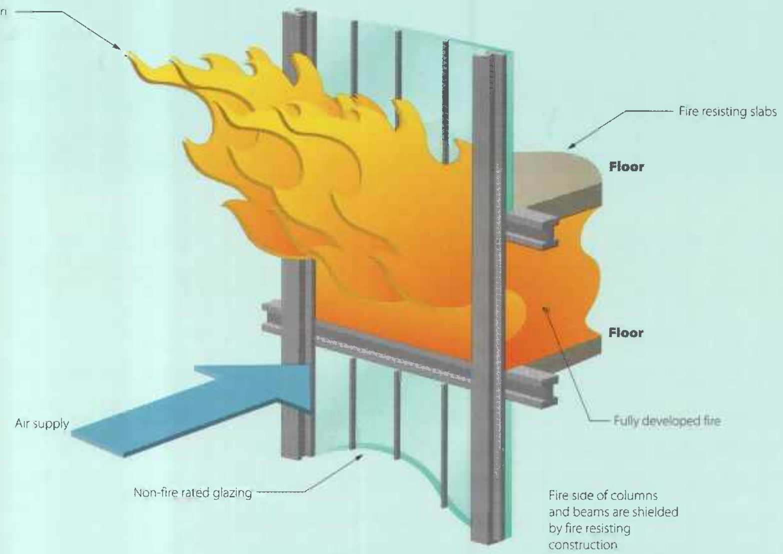
Left: the IBM headquarters at Bedfont Lakes showing beams and columns integrated into the facade.



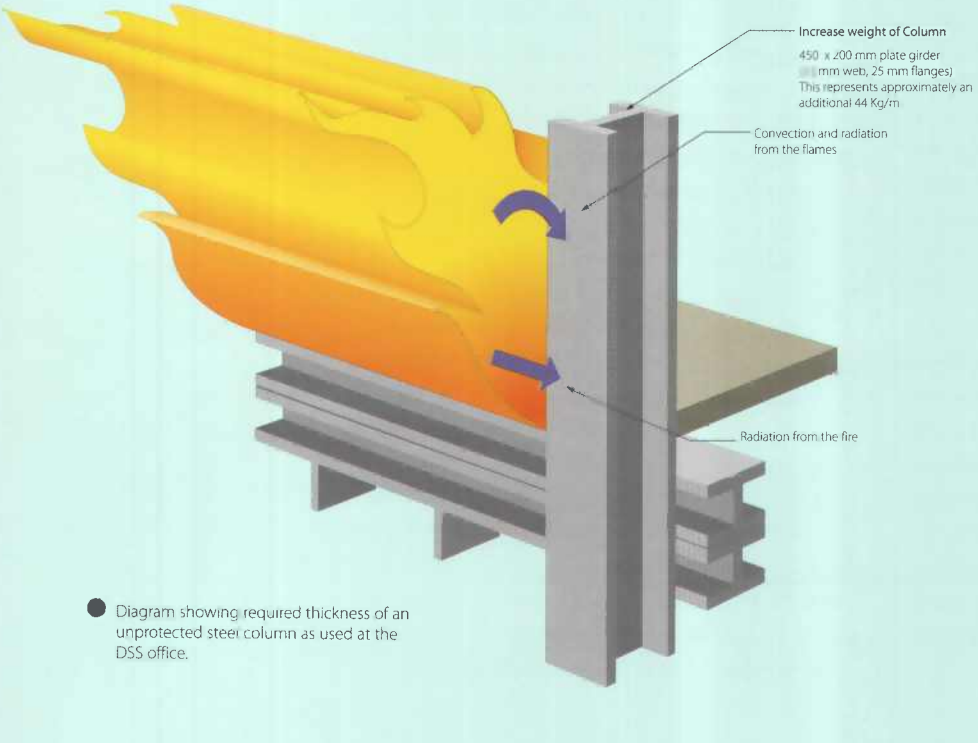
Graph shows comparison between natural and standard fire curves.



- Diagrammatic section through the facade of the IBM headquarters, showing the effects of a through-draught fire.



- Diagrammatic section through the facade of the IBM headquarters, showing the effects of a no through-draught fire.



- Diagram showing required thickness of an unprotected steel column as used at the DSS office.

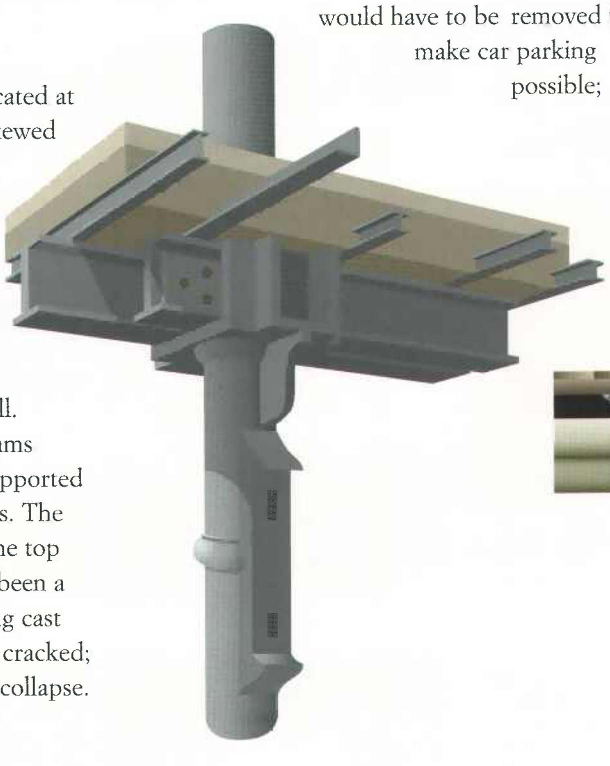
A cast iron solution

Built in 1886, the domestic finishing mill in Paisley, Glasgow, was used for the finishing of domestic sewing thread and handicrafts as part of the Lanarkshire cotton industry that thrived in the area due to the plentiful supply of water. The restoration of this Category A listed building involved converting three storeys to residential use, one to buisness use and the ground floor to car parking.

The building has two six-storey towers located at the corners of the east facade; these are skewed to align to an historic road. At the centre of the mill is an atrium running east-west and capped by a glazed iron-framed lantern light. A balcony runs at the perimeter of the atrium at each level. The balconies and the suspended floors are of concrete with wrought iron filler joists and concrete infill. Floors are supported on wrought iron beams running north-south, which in turn are supported in open saddle boxes on cast iron columns. The mill was extensively dilapidated: part of the top storey had been gutted by fire; there had been a prolonged history of water ingress; existing cast iron columns in numerous locations were cracked; and the roof-top parapet had a history of collapse.

Structural appraisal

The structural appraisal established that the fourth floor wrought iron beams would have to be strengthened to support the weight of a new mezzanine floor. Furthermore, at roof level, new beams were needed to replace those damaged by fire. In the lower storey car park, original columns would have to be removed to make car parking possible;



The experience gained from working on the restoration and refurbishment of a 19th century Scottish mill is described by

Gavin Jack

Main image: the mill was built in 1886 on a bend of the river Cart.

Below and left: section and cut-away illustration of suspended floor, wrought iron beams and saddle box resting on cast iron column.

"The image, of water spouting from a drilled hole in a cast iron hollow column, was sufficient to establish water as the cause of cracking. All columns were subsequently drilled to drain them"

The saddle box and cast iron columns

Photographs: Alan McAteer

The mill interior had a delapidated atrium

the adjacent columns and foundations had insufficient capacity to carry the transferred load and would therefore require strengthening. Detailed research into the properties and behaviour of cast iron and wrought iron was necessary to arrive at these conclusions. A well-defined protocol was developed to consider the objectives and implications of the appraisal, including available documentary information, the form and features of the structure, the load capacity against defined design criteria and the measures needed to achieve structural adequacy. The complex research and consultation process is described below under headings which highlight a series of difficulties and learning points. It should enable those undertaking similar tasks to be better informed of what to expect.

- How were the columns damaged?
- Were columns and saddles cast in one piece?
- How could the cast iron columns be repaired?
- How could the cast iron columns be strengthened?
- Laboratory tests and their results.
- The effects of fire on cast iron (CI) and wrought iron(WI).
- The mechanical properties of cast iron.

How were the columns damaged?

From the outset it was suspected that the iron columns had been damaged by frost action. Due to the extent of the cracks, however, there was no water evident in them. At the feasibility stage, there was no money available for intrusive or non-intrusive investigations to determine the type of iron from which the columns were made, whether adjacent columns were full of water and how the water could get into the hollow core in the first place. After consulting various experts, including one who concluded from the crack pattern that the columns were wrought iron, Buro Happold took their own samples which proved, with help from the University of Paisley, that the columns were actually cast iron. Investigations continued until money was released for an exhaustive appraisal investigation involving the contractor. The image, of water spouting from a drilled hole in a cast iron hollow column, was sufficient to establish water as the cause of cracking. All columns were subsequently drilled to drain them.

If it is suspected that cracking is related to flaws in the material, this can be investigated by ultrasonic means on a small random sample of (say) ten columns. Subsequent results can be used to focus requirements and limit costs.

Column with strapping

Were columns and saddles cast in one piece?

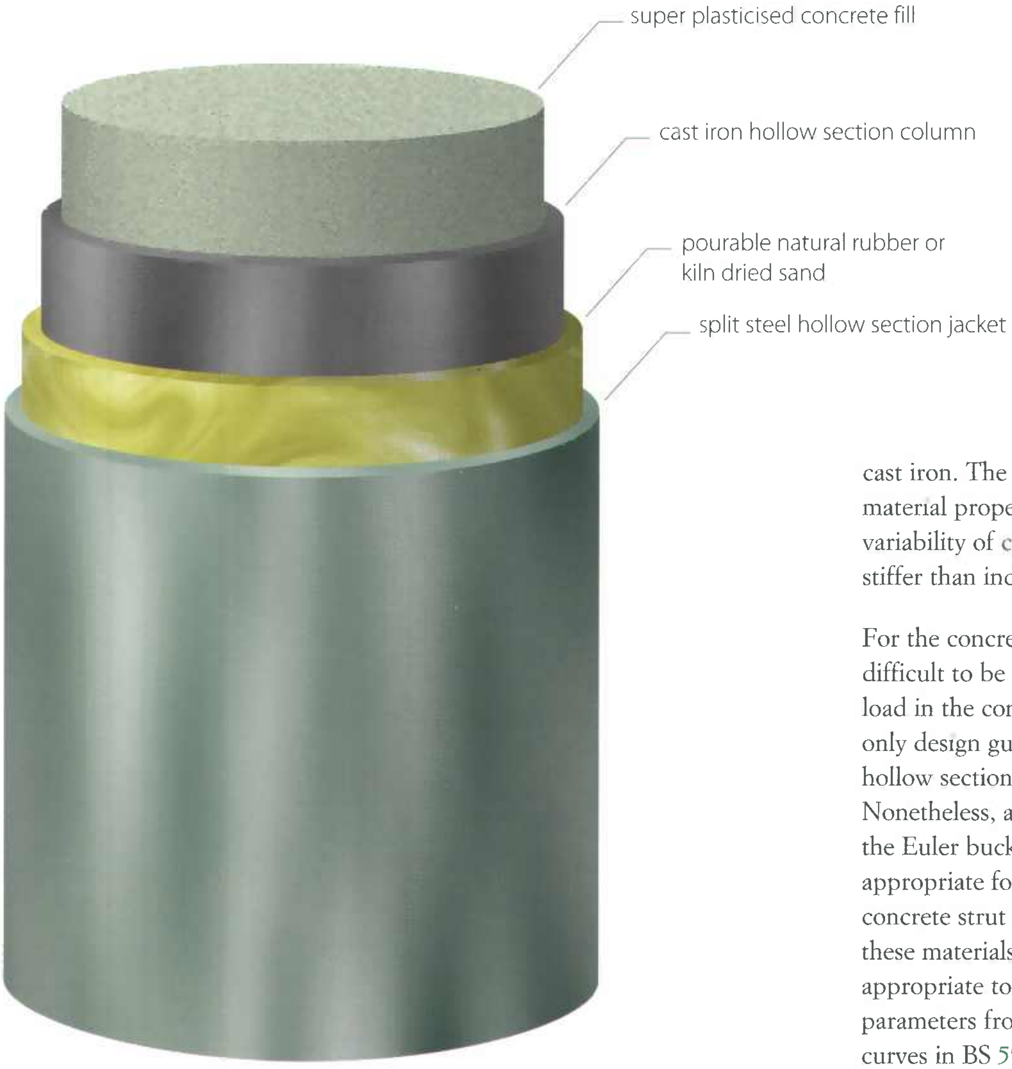
There is seldom enough vertical tying action in Victorian iron frame construction, and spigot joints may prevent any being generated at all. It was unclear whether the columns and saddle boxes at the mill were independent castings joined at the top column astragals. There was too much uncertainty about the details of the original manufacture to determine from the metallurgy if the column and saddles were different castings. Instead, ultrasonic readings were performed, supported by endoscope inspections. This process was not straightforward. The specialist testing company concluded from the endoscope inspections that the columns were closed at the head. If this was the case, no water could enter the column and the damage theory was compromised. Upon instruction, they re-surveyed and eventually proved the columns to be open at the top. The information derived from the endoscope survey was supported by a visual examination on a paint stripped column. The column proved to be cast as a single item and there were no spigot joints.

How could the cast iron columns be repaired?

Cracked iron columns can either be replaced, cold metal stitched or strapped, or welded. Replacement was not an option at the mill on the basis of cost and practicality. Welding cast iron is possible but notoriously difficult. Significant pre-heat and post-heat treatments are necessary to recover the castings original properties, and much of this detail was lacking at the time of tender. Strapping involves the fabrication and installation of hoops to band the columns across the lines of vertical cracks. Research concluded that the design of these remedial elements was far from straightforward, and historically this was done 'by eye' with no theoretical basis to rely upon. As such, metal stitching was proposed. This opinion was echoed by most experts in cast iron. Metalock is one company that specialises in cold metal stitching repairs. Such companies offer a six-month defects liability period against leakage, breakage of the locks and breakage of the parent metal within the repaired area, and warranties are limited to the full extent of the repair cost. The company liability is usually limited to the cost of the original repair or to repairing the casting without any further cost.

How could cast iron columns be strengthened?

The structural appraisal had established that the ground floor cast iron columns had to be strengthened for vertical load capacity where adjacent columns were being removed. Space restrictions in the car park dictated that strengthening methods could not increase the footprint of the existing column. Two solutions complied with this restriction: a concrete-filled column, and an advanced composite over-wrap jacket. A problem associated with both these solutions was the determination of the elastic modulus (Young's Modulus of Elasticity, E) of the modified columns. For calculation purposes, it was important to establish an effective modulus determined from the stiffness of the two materials and their relative proportions. Cast iron is not a linear elastic material and determination of the modulus is difficult. The range of E-value is large and depends on the grade of cast iron involved. One or two samples of approximately 200mm x 50mm x 20mm can be removed from different locations in the column for subsequent testing in a properly calibrated test rig. The tests measure load against deflection under simple bending using strain gauges or an electronic extensometer to measure the micro-strains. An alternative to the



The column is enclosed with a split steel hollow section and the gap is then filled with a low modulus rubber compound or mixed dry sand.

three point bend test is ultrasonic velocity testing. This test gives a reasonable estimate of the low-strain modulus by conversion from measurements of pulse velocity. It is best done ex-situ on samples prepared with parallel ends and machined or ground faces. This will give the tangent modulus close to the origin when not subject to load.

When over-wrapping a column with fibre composite, the true effective stiffness seen by the wrapping will depend on the strain level being designed into the wrapping. Normally this strain level is insignificant unless the columns are being over-wound to create auto-frettage; a means of preventing bursting by the over application of tensile hoop stress. When designing fibre composite over-wraps, the tangent modulus is what is needed.

The design of the composite jacket is usually carried out by a specialist contractor whose expertise lies in other industries and who is unlikely to be familiar with the properties of cast iron. The engineer must provide him with material properties data, advise him of the variability of cast iron and the likelihood that it is stiffer than indicated in text books.

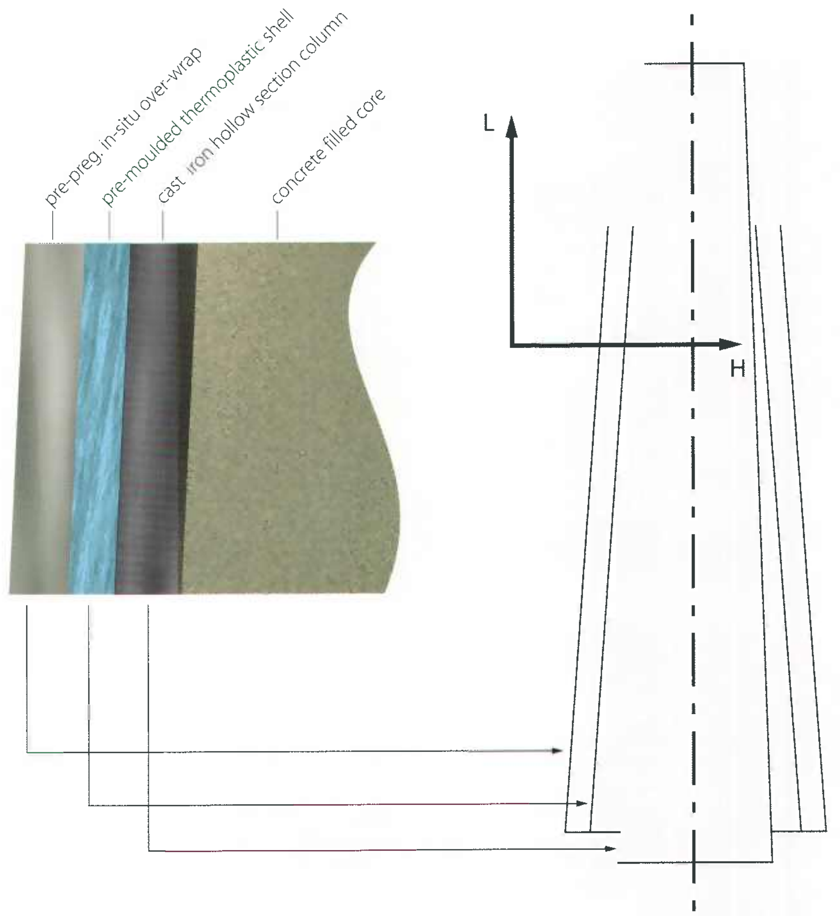
For the concrete filled column solution, it is difficult to be sure of the effective concrete failure load in the confined state within the column – the only design guidance available is for ductile steel hollow section columns with core concrete. Nonetheless, a similar design approach based on the Euler buckling formula is expected to be appropriate for a composite cast iron and concrete strut solution. Although the ductility of these materials are markedly different, it remains appropriate to extrapolate strut buckling parameters from the standard strut buckling curves in BS 5950. A safety factor of 5 after strengthening is usually an appropriate target. For the mill, the outline specification required inspections of the column's hollow core to ensure there were no obstructions. Thereafter, the column could be filled from a bottom feed point with C60 superplasticised concrete incorporating a 6mm aggregate. The aggregate helped to ensure a dense mix that could best absorb a local impact. Cast iron is susceptible to brittle fracture from concentrated impact loads and determining the degree of susceptibility is difficult without practical tests. The risk assessment for the mill concluded there was significant risk of cars coming into contact with the cast iron columns and in the lower storey car park they should be protected. Columns on upper floors were less at risk but the possibility of risk – especially the most obvious hazard of accidental or intentional hammering on the columns – should be explained to the client and occupier.

The impact protection provided to the columns within the car park is based on an energy management solution. A split steel hollow section with an inner diameter approximately 20mm larger than that of the casting is used to enclose the column. The annular gap is then filled with a low modulus rubber compound or mixed dry sand that acts to attenuate a low velocity impact by distributing the concentrated load over a wider local area.

Laboratory tests and their results

The geometric size, shape and number of samples must be sufficient to conform to standard test procedures and account for the statistical variability and bias when determining a 95% confidence figure for the characteristic strength. By explaining in a 'comments column' what engineering parameters you need to establish, a materials specialists can establish which parameters and associated tests are missing from your schedule. The outputs of a specialist testing laboratory depend very much on what is or is not asked for when specimens were submitted.

- A testing schedule must be informed and explicit, eg, do you wish to derive the composition of a paint sample, or merely if the lead content exceeds the detrimental trigger level?
- Always seek an informed opinion on test results as it is easy to rely on the laboratory's interpretation, which is not always correct. Getting the laboratory to interpret results is often difficult; in most instances it will only report on the factual data. You should establish at the outset who is best placed to do the interpretation.
- Check you have been given the image magnification factors and the test machine calibration data.
- Check whether metal samples have been photographed as an etched or un-etched structure. All this information is essential for proper scrutiny and interpretation of the test results, which is best done by an expert. The very fine chemical inhomogeneity can affect the sample magnification required, and perhaps electron microprobe analysis would be necessary to learn much more about the sample's composition. This type of scrutiny is testament to the interaction required between the consultant and the specialist testing house which can only be assured by someone expert in materials. This type of investigation work can be a constantly 'moving target' that requires the acknowledgement of the client who may need to expend additional money to bring it to a final conclusion.



A combined column strengthening and impact protection detail was developed with the help of the Advanced Composites Group based in Derby. It was eventually discounted as there was insufficient time available to conclude the validity of the impact protection.

The two-stage construction is as follows: 10mm thick split shells of longitudinal pre-impregnated carbon fibres are manufactured off-site in female moulds. They are delivered to site, assembled with epoxy adhesive against the cast iron and over-wrapped with a similar pre-impregnated composite which is biased 70:30 to the hoop direction. The column is then vacuum bagged and the resin is heat cured.

The impact protection is a third overlay consisting of a replaceable 3mm thick pre-moulded thermoplastic composite shell (to replace the steel alternative described previously). Between this outer shell and the column reinforcement, a 10mm layer of low modulus one part polysulphide or natural rubber solution is injected and left to cure. The low modulus filler attenuates the impact energy, most of which is absorbed by the concrete core cast into the column.

The effects of fire on cast and wrought iron

The fire research on cast iron and wrought iron is not significant and often the references found on the subject are contradictory. The following notes record the conclusions relied upon for the repair of the fire damage to the mill. Brinell hardness tests and metallographic examinations were used to examine the ironwork's grade, tensile strength, composition and microstructural changes.

Wrought iron has a fibrous structure that makes it extremely tough. Cracks that form in the surface of the material are effectively halted by slag streamers that act as very efficient crack-stoppers. Structural wrought iron was mostly hot worked and never developed a cold-worked strain hardened structure to any great extent. Wrought iron, therefore, is not weakened by subsequent heating and temperatures of 700°C would be needed to bring on the onset of grain growth. It can therefore be concluded that if wrought ironwork shows no sign of significant distortion, it is safe to leave it where it is without further action.

Cast iron has good fire resistance properties despite its lack of high temperature strength. This is often due to its very high thermal mass and low design stresses. Cast iron is brittle and can crack under moderately low temperatures. The onset of cracking, however, is complex and results from local distortion stresses from hose streaming, stresses induced by casting defects, distortion from applied load stresses and thermally induced stresses. At 400°C, the strength of cast iron is similar to that at room temperature. The critical distortion level is somewhere above this, at around 450°C.

The mechanical properties of cast iron

It is useful in the first instance to estimate the properties of cast iron as being similar to grey cast iron of Grade 150 to BS 1452:1977. This is a reasonable approximation and conforms with references on cast ironwork. The compositions for a given grade often vary and some properties are influenced by cooling conditions after manufacture, and therefore by the dimensions and cross section of the casting. The bending strength of cast iron is referred to as the modulus of rupture and the tensile 'yield' strength is referred to as the 0.2% proof stress. Usually the compressive strength can be taken as about three times the tensile strength, and the bending strength about the same as the yield stress, although admittedly, these are crude estimates. ■

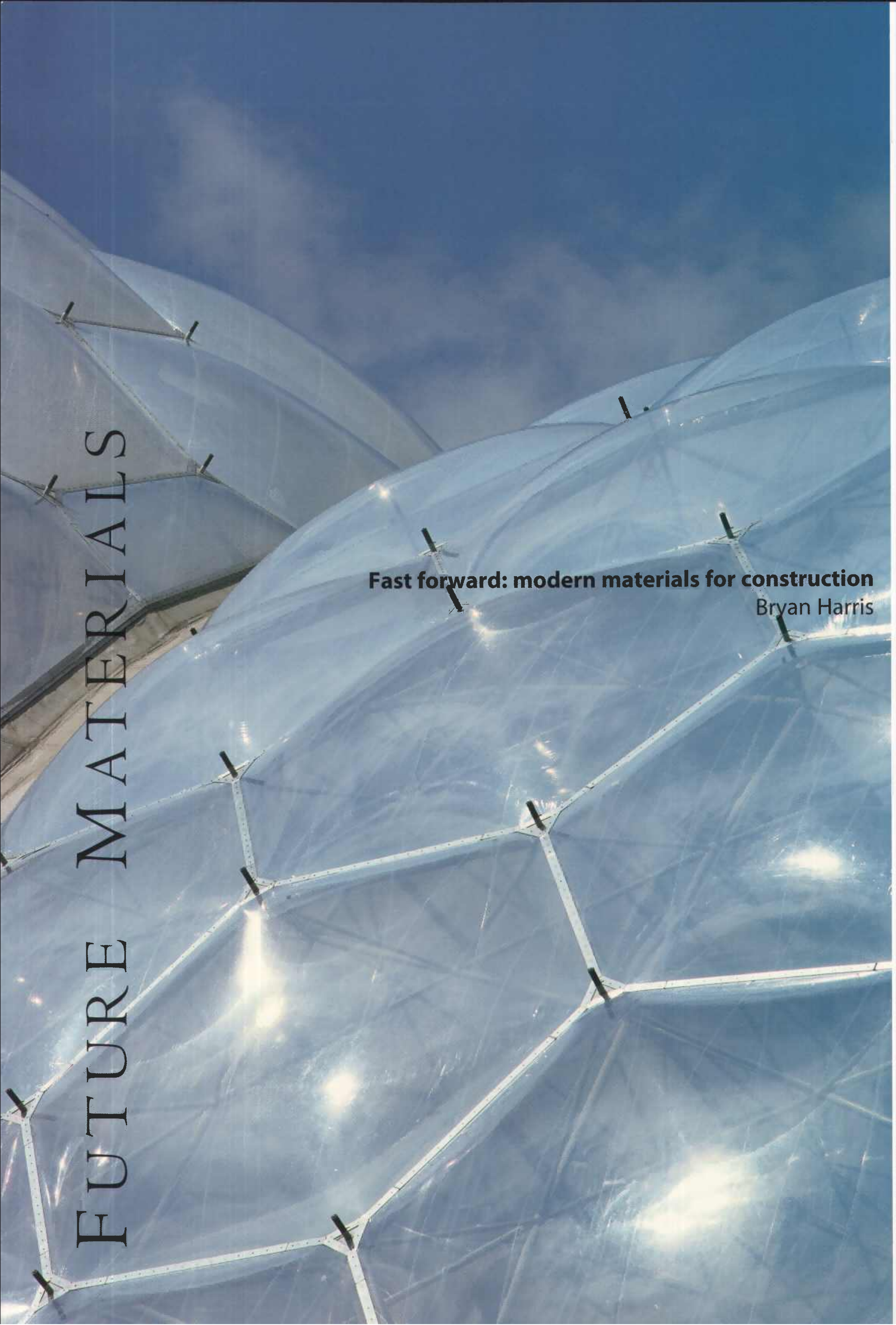
Credits

Working to adapt such buildings for the modern user is very challenging and encourages multidisciplinary thinking to fulfil the client's aspirations. Major contributions were made by my colleagues on the project team, as well as the support received from the client. To those outside the team, special thanks go to Bryan Harris, consultant to Buro Happold and Professor at the University of Bath, for his prompt, thorough and informed advice that was always willingly given.

FUTURE MATERIALS

Fast forward: modern materials for construction

Bryan Harris



Photograph: Mandy Reynolds, Fotoforum

Fast forward:

modern materials for construction

Polymers, high-strength concrete, composites and 'smart' materials are some of the new developments in materials reviewed by **Bryan Harris**

Top: The Glasgow Science Centre is an ovoid-shaped building clad with titanium sheet.

Photograph: © Keith Hunter/BDP

Facing page: ETFE cushions are used to form an insulating structure for the biodomes at the Eden Project in Cornwall.

The last half of the 20th century saw remarkable developments in materials for engineering and construction. In the 1950s the use of metallic materials in engineering, as a proportion of materials of all kinds, was at a peak. But the spawning of polymer technology from the chemical industry, and the successful creation of synthetic semiconductors, can be seen as markers of the beginning of the end of the dominance of the metallurgical industry and the emergence of a wider-ranging materials technology.

Metals

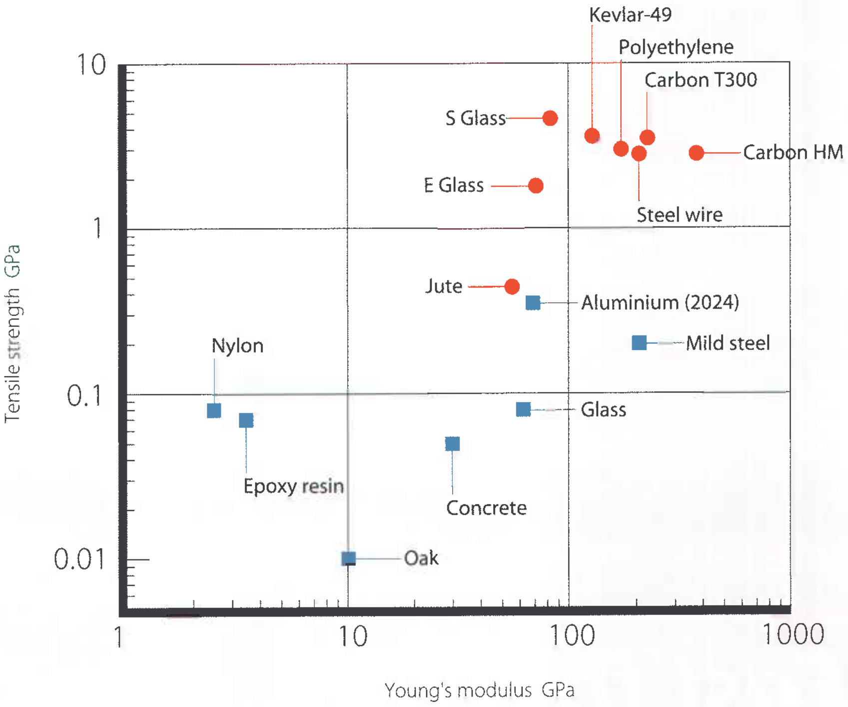
Metals offer a vast range of engineering properties, and in many respects are 'safe' because of their intrinsic ductility and ability to resist crack growth. As an alternative to steel and aluminium, titanium has many attractive characteristics: its density is only half that of steel, and its properties, including corrosion resistance, are better. But it is more costly than other structural metals and is therefore only likely to appeal for projects not limited by cost; for example titanium reinforcement rods are being used to restore antiquities and to repair concrete bridge structures. In Japan, titanium is used for roofing, window frames, flashing and curtain walls.

Polymers

Polymers are characterised by low densities, modest mechanical properties, ease of fabrication, and reasonable-to-good environmental stability, depending on circumstances. In their bulk forms they are used as moisture barriers, thermal and vibration insulators, services piping and trunking, and various decorative uses. Thermoplastics like Nylon or polyethylene soften when heated to only 100°C or so, when they are easily deformed or shaped, but they regain their original properties on cooling. Thermosets like phenolics and epoxides are resin-like compounds which polymerise on heating or by chemical reaction to form rigid structures which are insensitive to further changes in temperature. Thermoplastics are composed of long-chain molecules containing thousands or hundreds of thousands of atoms in groups of varying degrees of complexity. In some thermoplastics, such as acrylics or polycarbonates, these chains are randomly arranged and the material is transparent. In other polymers with molecules of simpler structure, however, the long chains are able to arrange themselves in crystalline arrays as a result of which the polymers are stronger and more rigid but less transparent. There are two ways of improving the mechanical properties of polymers: the first is to manipulate the molecular structure so as to make optimum use of the strong chemical bonds; and the second, discussed in the section on fibre composites, is to add strong reinforcing filaments to make reinforced plastics. If the bulk polymer is drawn or spun out into the form of a fibre, the molecular chains are aligned roughly with the fibre axis, and the strength of the polymer may be increased by several orders of magnitude, depending upon the degree of alignment. The graph (right) illustrates strengths and stiffnesses of two important textile and reinforcing fibres, polyethylene and the aromatic polyamide, Kevlar 49, compared with the strengths of other familiar fibres, including glass and carbon, and with the strengths of other (bulk) materials.

If the polymer is drawn out in two orthogonal directions the result is a film with the molecules aligned in two directions at right angles. While the properties of the film in the two directions are considerably less than those of a fibre, they are nevertheless still much greater than those of the bulk polymer. Films of various kinds, with different degrees of 'stretch', are widely used in building, from shrink-wrap films for transporting and protecting bricks to sophisticated glazing application like ETFE cushions (see *Spanning the future* p30) such as those used in the Eden project in Cornwall.

A great variety of polymeric adhesives, natural and synthetic, have long been an established part of the manufacture and erection of structural components. The established phenolic, urea and resorcinol adhesives are an essential part of modern timber technology, including the manufacture of plywood, chipboard, laminated components like glulam, continuous runs of finger-jointed timber, and structural timber joints. For more demanding applications where extra strength or environmental resistance are required, epoxide or polyurethane resins are available. Some adhesives are solvent-based, and must be used in ventilated locations, and the phenolics, including urea-formaldehyde and resorcinol-formaldehyde, may contain formaldehyde residues which can cause health problems.



High-strength concrete

The use of a high-strength concrete (HSC) permits reductions in both the cross-sectional dimensions of the structure and the dead load of the building. By and large an HSC is defined as having a compressive strength between 50MPa and 120MPa, being termed a 'super-high-strength' concrete beyond this range. Currently, 100-120MPa is considered the upper limit in the construction industry. Concrete with compressive strength greater than 100MPa was first obtained in the 1930s as a result of high-pressure compaction and by autoclave curing and, in consequence, pre-stressed HSC structures became lighter and more economic than some steel structures.

Strength improvements can be achieved by strengthening the cement matrix, by using a stronger aggregate, or by improving the bond between the cement matrix and the aggregate. The strength of the matrix depends on the strength of the hydrated paste which is porous as a consequence of the hydration process. The strength and stiffness of concrete fall exponentially with increasing porosity, and the matrix strength increases as the level of porosity is reduced by decreasing the water-to-cement ratio (w/c). Reducing w/c achieves a high-strength


Photograph: Matthew Reid

The concrete shell structures of the Sydney Opera House were bonded together by means of epoxy resin adhesives.

Top: graph comparing tensile strength and elastic modulus of some common reinforcing fibres and bulk engineering materials.

The columns of the Al Faisaliah tower, Riyadh, Saudi Arabia, are of 60N high strength concrete.

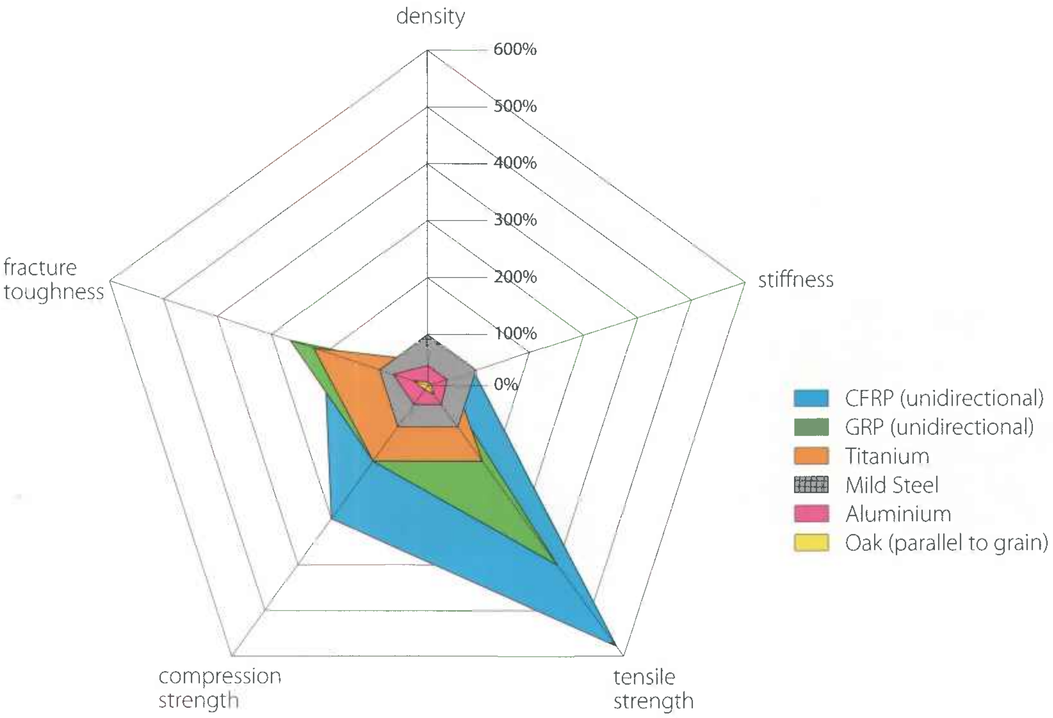
Photograph: Joe Poon

matrix but at the expense of workability.
The strength of the hydrated structure can also be improved by various mineral admixtures or by using optimum curing conditions. Pressure and centrifugal compaction can both be used to reduce porosity and to reduce w/c by expelling excess water and the compression strength of pressed cement pastes can reach 650MPa.

Superplasticizer and mineral admixtures are used in addition to normal or high-temperature pressure curing to produce HSC.
A superplasticizer is a chemical which improves the dispersibility of cement particles, resulting in a reduction in w/c and a concomitant decrease in void ratio. Superplasticizers like sulphonated naphthalene-formaldehyde condensates were first introduced in the 1960s and a variety of similar compounds are now used. Various ultra-fine powder additions are made to produce HSCs: most contain some form of reactive silica which, in the presence of water, can combine with it to form hydrated calcium silicate. The most common additives are condensed silica fume, ground granulated blast-furnace slag (ggbfs), anhydrous calcium sulphate (gypsum), and fly ash. Silica fume is a manufacturing by-product containing 70-90% of silica in the form of an ultra-fine powder with an average particle size of 0.1μ.m. Because of the fineness of the powder, it is necessary to use it with a superplasticizer to improve the workability of the concrete and ensure adequate dispersion of the silica.
The longer the curing period or the higher the curing temperature, the smaller the pore volume, so that with appropriate mix design and curing, concrete containing silica fume has high strength and excellent durability. The maximum strength at the age of 28 days with water curing is 100MPa, while for autoclave curing the strength is 140MPa at three days.

A cheaper waste product is finely ground granulated blast-furnace slag (ggbfs). Partial replacement of cement with ggbfs can improve fluidity and enhance resistance to sea water and chemical attack in addition to reducing the heat of hydration. Together with superplasticizer, the use of ultra-fine ggbfs can result in higher strength at early ages and a significantly increased long-term compressive strength. Fly ashes collected by the dust-extraction systems of coal-fired power stations, which may take the form of fine round particles, minute hollow spheres ('cenospheres'), or angular particles are also used as additives. The use of 10-15wt% of fly ash produces concretes with strengths considerably higher than can be achieved with OPC alone, and there is much interest in encouraging the use of this cheap waste product. The ecological/economic argument is often lost, however, because power stations are seldom located where the concrete is needed, /and the transport of a low-density dust is costly.

The durability of HSCs is generally greater than that of conventional concretes and the penetration of chloride ions into HSCs is so low that it is almost impossible to corrode unprotected reinforcing steel, even under accelerated test conditions. HSCs are also less sensitive to carbonation and external chemical attack because their networks of interconnected pores are less well developed.



A comparison of selected property profiles of a group of structural materials including composites is shown in this radar diagram. The distance along any radius vector is the value of the indicated material property as a percentage of the equivalent value for mild steel.

Fibre composites

Conventional materials are never as strong as we expect because they all contain defects of various kinds which cannot be eliminated in practical manufacturing operations. The strength of bulk glass and other ceramics is determined not by their strong covalent bonds, but by the tiny pores or sharp cracks that exist either on the surface or in the interior. The strength of any sample of a glass or ceramic is determined by the size of the largest defect or crack which it happens to contain, and the strength of the best bulk ceramic will rarely exceed about one thousandth of its theoretical strength. If flaw sizes can be reduced by control of the manufacturing process, the strength of the material will be raised and its variability reduced. One of the most effective ways of doing this is to produce the material in the form of a fine fibre, and an indication of the extent to which this can be achieved in glass, carbon, and polymers has already been shown. If these strong fibres are embedded in a matrix of some other material, such as a polymeric resin or cement paste, the resulting composite provides a structural material with characteristics quite different from those of the separate components which can be tailored to suit specific requirements.

The main reinforcing filaments currently used in structural composites are glass, carbon, and polymeric fibres including aromatic polyamides like Kevlar and polyethylene. Most of these commercial fibres are obtainable in a variety of forms, including continuous tows, woven or braided tows, and chopped bundles. For the reinforcement of cement and concrete, special alkali-resistant glass fibres have to be used, and cold-drawn steel wire is another common reinforcement.

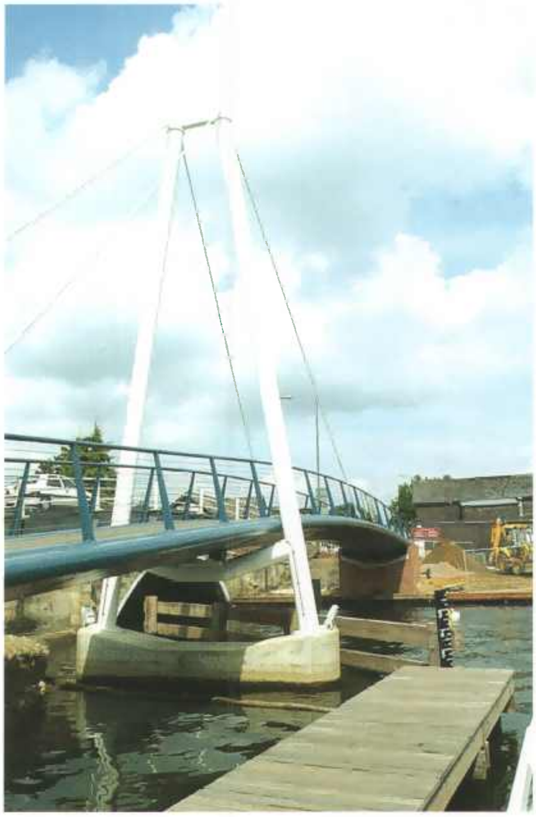
In using engineering composites it is important to recognise that they are materials with profiles of properties quite different from those of other engineering materials. They can be made in forms which are highly anisotropic or they may be made isotropic – and they must be used accordingly. The best (and most expensive) materials have high strengths and rigidities, but only in one direction. One of their most attractive features is that many composites exhibit very high levels of toughness.

Fibre-reinforced plastics

The main types of composite currently used in construction are glass-reinforced plastics (GRPs), rather less use being made of carbon – and aramid-fibre composites on account of their cost. Reasons for a wider use of fibre-reinforced plastics (FRPs) in structural engineering include: an increasing level of corrosion of reinforced and pre-stressed concrete structures, the rise in labour costs in construction, the need to reduce energy consumption and pollution of the environment and the potential for loss of life and infrastructure caused by earthquakes. FRPs offer flexibility – they can be tailored to specific requirements, especially if used in combination with steel or concrete. The materials costs of fibres and resins are almost always greater than their equivalent in steel or concrete although the final solution, including construction costs, is often cheaper. The ability of FRPs to meet the above challenges may be summarised in terms of their attractive features, as follows:

- High strength/weight and stiffness/weight ratios compared with steel and concrete.
- Rapid installation without heavy lifting equipment.
- Resistance to harsh environments (hot, cold, wet, chemical).
- Flame retardants can be added: FRPs exhibit ablative properties in fire (like space-shuttle tiles) which increases the time available for evacuation of a burning structure.
- Transparency to electromagnetic radiation.
- Good impact and blast resistance.
- Wide variety of surface appearances/ finishes/colours (including optical transparency, if required).
- Good quality products normally require little maintenance (although not 'maintenance-free').
- Excellent means of repairing/strengthening other materials by adhesive bonding.

Pultruded FRP shapes are used as structural elements and shear stiffeners for concrete structures, as concrete rebars, as components in composite/concrete structures, as externally applied impact-containment supports, and as patches for damaged concrete bridgework. The low inherent stiffness of GRP is easily overcome by the use of double curvature and folded-plate structures. GRP is used in cladding and decorative panels, services mouldings and ducting, racking, pipework, rainwater goods, water tanks, and complete small structures like footbridges and small vehicle bridges.



The soffit of a pedestrian footbridge at Wroxham is clad with 2m-wide GRP panels which provide a crisp finish and contain services.

Carbon-fibre-reinforced plastics (CFRPs) have been less used until recently because of their cost, but are increasingly being considered for building lightweight structures and in the upgrading of existing bridge structures by externally applied composite components. Farmer and Gee identified FRPs as an "inviting class of new materials for the new millennium", describing the use of CFRPs as a structural strengthener, for stay cables and anchorage systems, and as fabrics for wrapping around concrete columns to increase their impact resistance. They also discussed the use of reinforced plastics in composite beams with concrete, the internal confinement of concrete with aramid (Kevlar) fibres, the use of FRPs as post-tensioning cables, and retrofit-strengthening to improve the shear capacity of concrete. A more detailed evaluation of FRPs and their advantages, written by Buro Happold staff, was recently published by CIRIA.

Fibre-reinforced cement and concrete

Plain concrete is brittle, with a low tensile failure strain which engineers cope with by using it in compression or with macroscopic reinforcing bars to carry tensile loads. The fibre reinforcement of concrete has been widely studied, with attempts to produce stronger, stiffer and tougher structural materials by adding fibres of asbestos, glass, steel, polymers and carbon. An important early use of fibre-reinforcement was in the production of asbestos-fibre-reinforced cement which was attractive because of its low cost, high production rates, and good mechanical properties, but this is now unacceptable on health grounds. But FRCs are likely to attract the more adventurous designer with lightweight concrete structures in mind (thin shell structures, for example). For both economic and manufacturing reasons, quite small additions of fibre are made: these do little to increase the strength or stiffness of cement, but by introducing complex cracking and failure modes they substantially improve the work of fracture.

Fibre-reinforced cementitious materials range from those with fragile fibres (carbon and glass), used in an aggregate-free matrix to avoid fibre damage, to those made with robust fibres (steel, polypropylene and aramid fibres) that can withstand the rigours of mixing with coarse aggregate. The main problems encountered are the need to achieve uniform dispersion of the filaments, and the necessity of dealing with the mixture-stiffening effect of the fibres which reduces workability. The stiffening of the mix caused by the elongated shape and high surface area of the fibres limits the type of fibre, the fibre aspect ratio (length to diameter ratio), and the amount of fibre that can be uniformly distributed in a given matrix, and hence the degree of improvement in the mechanical properties that can be achieved in the hardened concrete. Fibre content and aspect ratio should be as high as possible because the reinforcing effectiveness of the fibres depend directly on these factors, both of which also increase the stiffening effect, reducing the workability, raising the tendency to clumping or 'balling', and thus increasing the difficulties of fabrication. Steel fibres are often textured, crimped or hooked in order to increase the pull-out resistance, and this also aggravates the clumping effect.

Of the common manufacturing processes, the 'Shotcreting' process is less severe on fibres than conventional mixing, although they still have to withstand bending, impact and abrasion. Slurry infiltration, where a highly fluid mortar or cement paste is poured or forced directly into a fibre preform, is even better. In reinforced concrete, fibres must be distributed within the cement paste, so the higher the aggregate content, the fewer the fibres that can be accommodated and uniformly distributed without excessive loss of workability. Maximum coarse aggregate size is also limited because the number of steel fibres that can be accommodated in a given volume of cement reduces as aggregate size increases. Hence, we find two main types of composite: fibre-reinforced cements with 3-13vol% of fibres, and fibre-reinforced concrete with 1% of fibres or less. However, much higher volume fractions of well-aligned fibres can be obtained by vacuum de-watering and filament-winding and the products of these processes can be used in much thinner sections than is normal with concrete.

Glass-fibre-reinforced cement and concrete (GRC)

Although ordinary E-glass borosilicate reinforcement was used in the 1970s in pre-cast facade panels and the like, the corrosion of the fibres in an alkaline cement matrix led to a reluctance to use GRCs for load-bearing applications. The development of alkali-resistant (AR) varieties of glass fibre gave a measure of increased confidence to designers and there is now extensive use of GRCs reinforced. The AR fibres, supplied in tows of about 100, 200 or 400 filaments, are coated with a size to protect them from abrasion and prevent them from separating during mixing. Dispersion is assisted by chemical admixtures which lubricate the fibre surfaces and increase the viscosity of the mixing water. GRCs made by the spray de-watering process typically contain 5wt% of fibres in 25-50mm long strands. By the use of high-through-put spraying processes GRC sheets can be manufactured on a nearly continuous basis at speeds of 10m/minute or more, comparable with those previously obtained with asbestos cements. Under wet and natural weathering conditions, the strength and impact resistance of AR-glass GRCs are adversely affected, although the properties are stable in dry air. GRC sheets are energy efficient by comparison with similar products in metal or plastics and are non-combustible. GRCs with about 3wt% of AR fibres can be made as corrugated roofing, pipes, guttering etc. by standard asbestos-cement processing methods with properties that exceed existing BS values for only a small cost penalty.

Photograph: Spurgeon Walker

The steel-lined tunnel which serves the Heathrow Express high-speed rail link is lined with coffered GRC panels

Filament-winding techniques are also used for manufacturing various types of fibre/cement composites, including continuous-fibre, cross-ply, and angle-ply laminates, pipes, and pultruded sections with both glass and polypropylene fibres. The tensile strengths of such composites can exceed 50MPa with 5wt% of AR glass fibres. GRCs have a wide range of applications including; folded-plate and shaped-shell building structures, sandwich constructions with foamed polystyrene cores, wall systems including single-skin, doubly curved, and sandwich cladding and facades, wall linings, prefabricated insulating panels for cold storage, moulded canopies, shelters and kiosks, window frames, acoustic enclosures and noise barriers, concrete form-work, spun pipes, tunnel and sewer linings, bridge coffer units, street, park and garden furniture and decorative features.

Polymer-fibre-reinforced cement and concrete

A wide range of fibres, including conventional polymer fibres and natural fibres, is used in reinforcing cement, including polyesters (eg, Terylene/Dacron), polyamides (eg, Nylons), polypropylene, polyethylene, aramids, jute, hemp, etc. To refer to these fibres as reinforcements is contentious because they do little to strengthen or stiffen the cement matrix, being added mainly to prevent crack growth and confer increased toughness. A major group of polymer-fibre-reinforced concretes utilises filaments or nets of polyolefin polymers, mainly polypropylene (PP), a polymer with good resistance to environmental deterioration. Cheaper forms of reinforcement, including chopped fibre bundles and fibrillated networks produced by piercing and stretching drawn film, became well established in the 1970s. Hannant has confirmed the excellent strength-retention characteristics of PP fibres. A main objective of fibre ‘reinforcement’ in cement-based composites is to modify their stress/strain behaviour and thereby improve their toughness, and Aïtcin confirms that PP is of little interest in HSC applications except to increase impact properties. Steel-fibre-reinforced cement (SFRC) is particularly successful in this respect but it has been shown that the impact resistance of polyolefin-fibre-reinforced material containing 1.5vol% of fibre displayed essentially the same behaviour as a similar SFRC product, in terms of both toughness and maximum impact load.

Aramid fibres have high inherent toughness, and are also used to reinforce cement. Chopped aramid fibres, like carbon fibres, are difficult to disperse during mixing but unlike carbon and glass they are much more resistant to damage during mixing. It is vital to exercise careful control of the mixing regime in order to achieve good fibre dispersion, with low-speed mixing and the addition of silica fume to the mix to break up fibre clumps.

Steel-fibre-reinforced cement and concrete

Chopped steel fibre is much stiffer than glass- or polymer-fibre-reinforced materials because it will also tolerate extensive plastic deformation. The high tensile strength of a drawn steel wire cannot be made use of in raising the strength of a composite because the amount of fibre that can be added is limited by mixing considerations, but its plastic deformability adds to the toughness of a composite containing randomly distributed fibres. The impact resistance of steel-fibre-reinforced concrete is of major interest to designers, particularly for applications such as pavement slabs for new roads and aircraft runways, concrete overlays for the repair of roads. They have also been used for the inflation-forming of SFRC domes (up to 3m diameter) for shelters.

Natural fibre composites

Natural fibres have great potential as reinforcements, particularly as a replacement for glass fibre in FRPs but also as reinforcements for cement and concrete. Amongst the most suitable of the natural fibres are the bast (bark) fibres, of which flax is currently the most widely cultivated in Europe. Flax has excellent mechanical properties, especially when viewed on a specific basis. Other fibres such as hemp, jute sisal, kenaf and cotton also show promise. The table below provides some basic information on the mechanical properties of these fibres and a comparison with some synthetic fibres.

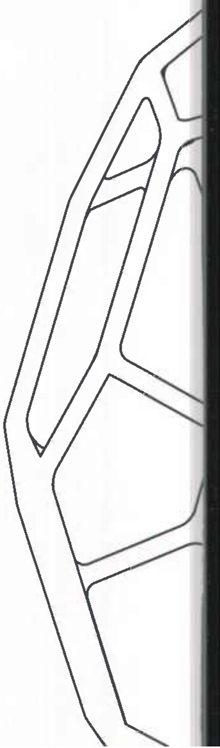
Natural fibres have an affinity for moisture and swell with the uptake of water. Unlike most synthetic fibres, all are non-thermoplastic and do not soften when heat is applied. At temperatures below the decomposition point, they show little sensitivity to dry heat: there is no shrinkage or high extensibility upon heating and they are embrittled if cooled below freezing. Natural fibres tend to yellow on exposure to sunlight and moisture, and extended exposure results in loss of strength. They are also susceptible to microbial decomposition. Protection against microbial damage and insect attacks can be obtained by chemical modification of the fibre substrate and modern developments allow treatment of the fibres to confer immunity. Fire-protection finishes are also necessary on account of the inflammability of the fibres.

Unlike glass fibres, which are continuous smooth mono-filaments, technical natural fabrics are made from spun yarns which possess an internal structure, and this structure must be allowed for when used in composites. Maximum wetting of fibres with resin is an essential condition for optimum composite properties. Ultrasonic treatment is a possible method of optimising the impregnation process.

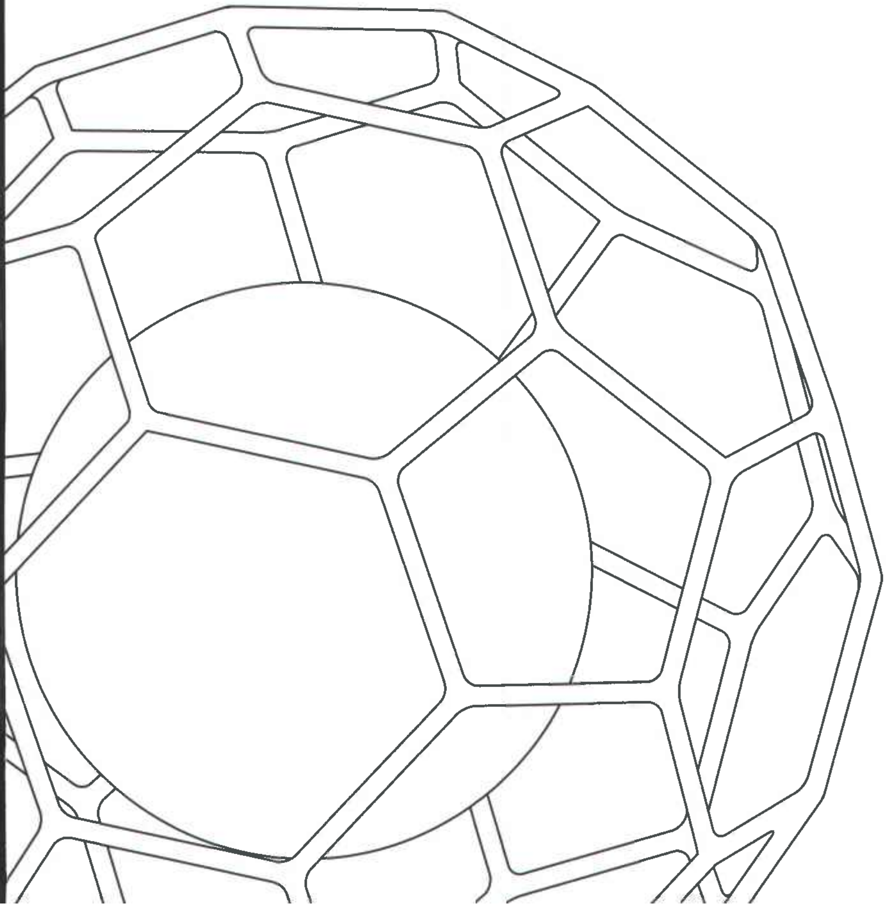
An indication of current levels of commercial interest and research in the use of natural fibres as reinforcements for composite materials can be seen from the proceedings of a recent conference on Eco-Composites. In an analysis of the properties of composites of polypropylene reinforced with various natural fibres, Wambua and others concluded that in most cases the specific properties of the natural-fibre composites compare favourably with those of GRP.

Selected physical and material properties of some synthetic and natural (plant) fibres.

Material	Density	Young's Modulus	Tensile Strength	Failure Strain
Syntheic fibres	**Mgm^{-3}**	**GPs**	**MPa**	**%**
E-glass	2.56	76	2000	2.6
High-strength carbon	1.75	230	3400	3.4
Kevlar (aramid)	1.45	130	3000	3.4
Boron	2.6	400	4000	1
Natural fibres	**Mgm^{-3}**	**GPs**	**MPa**	**%**
Flax	1.4-1.5	50-70	500-900	1.3-3.3
Hemp	1.48	30-60	310-730	2-4
Jute	1.4	20-55	200-450	2-3
Sisal	1.45	9-22	80-840	3-14
Cotton	1.5	6-10	300-600	6-8



For structural engineering applications, the use of natural fibres, recycled textiles and paper pulp offers the possibility of a cheap additive with reinforcing characteristics essentially similar to those of the less exotic polymer fibres. Jute-fibre-reinforced concrete, for example, is a feasible material for low-cost projects where cheap jute is readily available. Products like sheets and boards are light in weight and ideal for roofing and ceilings, or where impact resistance or shatter-proof qualities are needed such as in earthquake-resistant construction. They are also suitable for pavements, slabs and shell structures. Bisanda described the manufacture of corrugated sisal-fibre-reinforced panels suitable for roofing and other construction purposes in tropical developing countries. The matrix was a cheap, phenol-based resin obtained from cashew-nut-shell liquid. Others have also reported useful properties in composites of hemp fibres in cashewnut shell resin. Bamboo is another woody fibre which shows some promise as a reinforcement for cementitious and polymeric composites. Increasing use worldwide is now being made of wood/polymer composites as substitutes for natural wood and for applications where wood was not previously used.



Representation of a carbon C60 molecule, or buckyball, named after Buckminster Fuller.

Biodegradable composites

By modifying resin systems appropriately, biocomposites can be designed to be stable or biodegradable. At the end of their life cycle, apart from re-use or recycling, products can then also be conveniently removed, ie, by CO_2-neutral combustion, biodegradation, or composting. They are fully integrated into natural cycles and can also meet the increasingly stringent environmental demands of legislative authorities. The Finnish research organisation VTT is developing biodegradable composites based on natural raw materials such as polylactic acid resins combined with flax and other natural fibres. The resulting composites can be used indoors or out where biodegradation is desirable, such as in agricultural products. The use of biodegradable composites supports sustainable development and reduces disposal costs; VTT aims to develop these materials as a viable alternative to conventional fibre-reinforced polyolefins. So far, tensile strengths of 70-80MPa have been achieved with 40wt% of flax fibres. The fibre content and coupling agent can be tailored to suit the application. As long as they are protected from heat and moisture, the materials retain their properties for lengthy periods of time. An overview of recent research into all aspects of environmentally compatible polymers was presented at a 1999 conference.

Nanomaterials

Nanomaterials may be metals, ceramics, polymers, or combinations of these. Their defining characteristic is a basic cell or unit size in the range of one to 100 nanometers (nm), a nanometre being of the order of a few atomic diameters. Larger than atoms and smaller than the silica fume particles added to concrete, nano-scale structures and systems have novel properties and functions because of their size, and these can, in principle, be exploited for a variety of structural and non-structural applications.

In the mid-1980s came the trumpeted discovery of a new form of carbon, hollow carbon spheres known as 'buckyballs' or 'fullerenes', in honour of Buckminster Fuller whose geodesic domes exhibited a similar geometry to teh carbom spheres' molecular structure – 60 carbon atoms bonded together in a ball-shaped molecule27. This research led to the fabrication of carbon nano-fibres, with diameters smaller than 100nm, and in 1991 NEC in Japan reported the first observation of carbon nanotubes which excited great interest on account of their potential as reinforcing fibres; these are already produced in commercial quantities.

Nanotechnology could potentially improve many construction materials, including steels and polymers. Concrete, with its complicated, nano-scale structures of cement and its hydrates, is an excellent candidate for nano-technology manipulation and control. Nanotechnology is perceived as being of great relevance to the construction sector overall, with a substantial R&D investment now being made.

Applications of nanomaterials include cutting tools and high-sensitivity sensors used in smoke detectors and devices for the in-situ monitoring of structures. The addition of nano-scale particles to concrete can improve the control of concrete microstructure beyond what is possible with existing technologies, resulting in stronger, tougher and more durable concrete. The most commercially advanced polymeric nano-composites are those that involve the dispersion of small amounts of nano-particles in a polymer matrix. Clays have been found to impart amazing properties: adding only 2% by volume of silicate nano-particles to a polyimide resin increases the strength by 100%. The addition of nano-particles has also been shown to improve thermal stability and reduce inflammability, and composites can also be prepared by conventional plastics processing methods.

Aerogels are nano-crystalline materials synthesised by the sol-gel process. They are porous and of extremely low density, consisting of 90-95% air, yet they can withstand loads up to 100 times their weight. They are non-toxic and non-inflammable and can be made transparent, and their porosity is such that one gramme may cover an area of 1,000m^2. Aerogels are currently being used for insulation in buildings and for the passive exploitation of solar energy, in the panelling of house walls, for coating solar-energy collectors, and for 'smart' windows which behave like photo-chromic spectacle lenses.

Carbon nano-tubes can be used as a form of fibre reinforcement. They have unique properties, including stiffness and strength higher than those of any other material and extraordinary electronic properties. Although much of the published work on nano-composites remains at the laboratory level, the first carbon nano-fibre bridge has been completed. It combines innovative sandwich structural techniques with braided fabric composite materials and carbon nano-fibres. Processes involving particulate or fibrous material of dimensions smaller than the natural pores in human tissue offer a potential health threat because the particles may be absorbed into the body through these pores. Public and professional concern about the potential health hazards associated with nanotechnology has been recognised by the Government's recent commissioning (11 June 2003) of an independent study into the benefits and risks of nanotechnology.

Smart materials and structures

'Smart' or 'responsive' materials are ones which are able to transform a physical stimulus of one kind – strain, for example – into other physical phenomena – such as electrical charge, and vice versa. The most familiar include piezoelectric ceramics, shape-memory alloys, magnetostrictive materials, photo-chromic glasses, and fibre-optic systems. Depending on changes in external conditions, smart materials may change their properties, appearance, structure, composition, or functions. For the most part, smart materials are embedded in systems whose inherent properties can be favourably changed to meet performance needs. They have the ability to both sense and respond to environmental stimuli, in addition to being capable of active control of their response. But they are not 'intelligent', as their 'smartness' derives from systems behaviour, where sensor and actuator components are integrated into a structure capable of achieving enhanced functionality.

Piezoelectric ceramics, currently the most widely used smart materials, are compounds which expand and contract when voltage is applied and vice versa. Although not as forceful as shape-memory alloys, they respond more quickly, making them ideal for precise, high-speed actuation. They are used to generate electrically stimulated movement or to record movement by providing a movement-related electric response and demand for them is driven largely by their application as device actuators. Piezoelectric ceramics, of which the most common is lead zirconate titanate, or PZT, have some limitations, being brittle, heavy, and difficult to scale to larger applications because of their limited stroke or displacement.

Magnetostrictive materials resemble piezoelectrics but respond to magnetic rather than electric fields. They are typically used in sonar

The west mill bridge in Oxfordshire, opened in October 2002, is the first public highway bridge in Europe to be built from advanced composite materials. Its structural performance is being continuously monitored by a fibre-optic system with Bragg-grating sensors, data from which are to be collected remotely for analysis. The bridge, constructed from a hybrid glass/carbon composite material, was developed as an EU project led by Mouchel Parkman

Photograph: Dr Sam Luke, Rail Structures South Devision, Mouchel Parkman

transducers, motors, and hydraulic actuators, but are thought to be promising candidates for achieving active damping of vibrations. Shape-memory alloys (SMAs) are metallic alloys that can be deformed and then returned to their original shape by gentle heating, generating an actuating force in the process. The best-known alloys are a nickel/titanium alloy known as Nitinol and the copper-based alloys Cu-Zn-Al and Cu-Al-Ni. Nitinol has greater shape memory strain (up to 8% compared to 4%-5% for the copper-based alloys), is more thermally stable, has excellent corrosion resistance compared to the more modest resistance of the copper alloys, and has much higher ductility. Copper alloys are much less expensive, are easily melted and fabricated in air, and have a wider range of potential transformation temperatures.

Shape-memory devices, which utilise a shape-memory effect due to phase transformation to recover a particular shape upon heating above the transformation temperature, may act without constraint so as to recover their trained shape, or they can be fully constrained so that they provide a force, or they can be partially constrained so as to perform work. Common actuation temperatures are human body temperature and boiling water temperature. The most successful example of constrained recovery devices is hydraulic pipe couplings. These fittings are cylindrical sleeves of a diameter slightly smaller than that of the metal pipe or tubing they are to join. Their diameters are expanded while in the martensitic state and on warming into the austenite range they then shrink in diameter and grip the tube ends strongly developing residual stresses sufficient to create a joint which is superior to a welded joint. Copper-based SMAs have been used in fire safety valves and ventilator controllers. A serious limitation of SMAs is that they can respond only as quickly as the temperature can shift, which is often too slow for many advanced applications. Perhaps one of the most important fields of application of SMAs in engineering is in vibration damping and earthquake control.

Optical fibres are wave-guides consisting of a 50µm diameter glass core and an optical glass cladding, giving an outside diameter of about 120µm. They use total internal reflection to confine light within the core of the fibre, carrying communications or computer data signals as light pulses over large distances without the need for repeaters. Sensor devices based on optical fibres make use of changes in various characteristics to provide indications of the condition of surrounding material or an adjacent structural component. They are immune from electromagnetic interference and can be surface-mounted on conventional structures or embedded in a composite material during manufacture. They can be used to monitor temperature, pressure, strain, and chemical characteristics, and they offer important possibilities for on-line application, both for process optimisation and in-service health monitoring.

The simplest form of health assessment, the detection of impact damage, depends on the fact that optical fibres will fracture when a composite in which they are embedded suffers an impact, and this reflects the related damage that will be sustained by the main load-bearing fibres. More sensitive assessment of the presence of strain or a rise in temperature of the composite can be obtained by the use of fibres which have Bragg gratings written into their cores or the somewhat cheaper Fabry-Perot sensors in which changes in the length of an air gap are measured by interferometry. These provide a means of monitoring strain with a high degree of accuracy and resolution, and provided the separate effects of thermal expansion and elastic strain can be isolated, such sensors can also provide information about temperature changes in the material.

Although there is a natural synthesis in the use of fibre-optic systems in combination with FRP structures, fibre-optic sensors are also used for the monitoring of conventional engineering structures, including joints, repairs and concrete elements. They are also used in combination with shape-memory alloy actuators in the design of smart structures. Elsewhere in construction there are systems which employ motion and light sensors for controlling lighting, security systems, heating and air conditioning. The next generation of viable smart-structure technology will be in applications for monitoring structural integrity, noise reduction, and vibration suppression.

Phase-change materials

Another group of compounds which could also be described as ‘smart’ materials are ‘phase-change’ materials (PCMs). A substance can exist in the solid, liquid or gaseous states depending on the temperature and pressure of the storage conditions. The three phases may co-exist together in equilibrium (eg, ice, water and water vapour) although two-phase states (the condensed states) are more usual in practice. Changes from one phase to another are associated with the absorption or release of latent heat at constant temperature: when ice melts, for example, it absorbs 335kJ/kg in the isothermal transformation, and the same amount of heat is released to the surroundings when water freezes. Conventional heat-storage materials absorb heat through standard heat-transfer mechanisms - radiation, conduction, and convection. As the materials cool off at night or on cloudy days, they release the stored heat. In PCMs the thermal-energy transfer occurs when a material changes from solid to liquid, or vice versa: it is the latent heat of the phase change which is being stored and released. When PCMs reach the temperature at which they change phase (the melting point) they absorb large amounts of latent heat at constant temperature. When the ambient temperature in the space around the PCM material drops, the PCM solidifies, releasing the stored latent heat. Latent thermal storage materials are very effective in the human comfort range of 20-30°C and store five to 14 times more heat per unit volume than ordinary storage materials like water, masonry and rock. PCMs also provide the advantages of smaller size, constant temperature during phase change and lower stand-by losses over conventional bulk energy storage materials.

The commonest PCMs are eutectics, mixtures of two or more chemicals which, when mixed in a particular ratio, have a freezing/melting point which is lower than the corresponding freezing points of the component chemicals. During the phase change the compositions of the solid and liquid phases are identical. The range of available compounds is such that two or more substances may be mixed so as to provide any particular desired melting/freezing point. Eutectic salts have long been used as thermal-energy storage media for refrigerated transportation, but it is only recently that their use in construction has become more widespread.

Typical applications are in solar-heat storage, and as drywall and attic insulation. The main applications for PCMs are when space restrictions limit larger thermal storage units in direct gain or sun-space passive solar systems. PCMs may also be used in solar domestic hot-water heating or passive solar-space heating systems. Phase-change drywall, currently under development, incorporates PCMs inside common wallboard to increase its heat-storage capacity. The US Department of Energy has also developed a building envelope application as attic insulation for which the PCM is installed between two layers of conventional insulation. Elsewhere, research is being conducted on methods of incorporating PCMs into other lightweight building materials such as plywood and ceiling and floor tiles. Possible commercial applications include use in paving materials to minimise night-time icing on bridges and overpasses, while also reducing surface damage from freeze-thaw cycling. ■

Photograph: Mandy Reynolds, Fotoforum

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